A Comprehensive Formal Security Analysis of OAuth 2.0*

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The OAuth 2.0 protocol is one of the most widely deployed authorization/single sign-on (SSO) protocols and also serves as the foundation for the new SSO standard OpenID Connect. Despite the popularity of OAuth, so far analysis efforts were mostly targeted at finding bugs in specific implementations and were based on formal models which abstract from many web features or did not provide a formal treatment at all.

In this paper, we carry out the first extensive formal analysis of the OAuth 2.0 standard in an expressive web model. Our analysis aims at establishing strong authorization, authentication, and session integrity guarantees, for which we provide formal definitions. In our formal analysis, all four OAuth grant types (authorization code grant, implicit grant, resource owner password credentials grant, and the client credentials grant) are covered. They may even run simultaneously in the same and different relying parties and identity providers, where malicious relying parties, identity providers, and browsers are considered as well. Our modeling and analysis of the OAuth 2.0 standard assumes that security recommendations and best practices are followed in order to avoid obvious and known attacks.

When proving the security of OAuth in our model, we discovered four attacks which break the security of OAuth. The vulnerabilities can be exploited in practice and are present also in OpenID Connect.

We propose fixes for the identified vulnerabilities, and then, for the first time, actually prove the security of OAuth in an expressive web model. In particular, we show that the fixed version of OAuth (with security recommendations and best practices in place) provides the authorization, authentication, and session integrity properties we specify.

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1. Introduction

The OAuth 2.0 authorization framework [21] defines a web-based protocol that allows a user to grant web sites access to her resources (data or services) at other web sites (*authorization*). The former web sites are called relying parties (RP) and the latter are called identity providers (IdP).[1] In practice, OAuth 2.0 is often used for *authentication* as well. That is, a user can log in at an RP using her identity managed by an IdP (single sign-on, SSO).

Authorization and SSO solutions have found widespread adoption in the web over the last years, with OAuth 2.0 being one of the most popular frameworks. OAuth 2.0, in the following often simply called *OAuth*,[2] is used by identity providers such as Amazon, Facebook, Google, Microsoft, Yahoo, GitHub, LinkedIn, StackExchange, and Dropbox. This enables billions of users to log in at millions of RPs or share their data with these [40], making OAuth one of the most used single sign-on systems on the web.

OAuth is also the foundation for the new single sign-on protocol OpenID Connect, which is already in use and actively supported by PayPal ("Log In with PayPal"), Google, and Microsoft, among others. Considering the broad industry support for OpenID Connect, a widespread adoption of OpenID Connect in the next years seems likely. OpenID Connect builds upon OAuth and provides clearly defined interfaces for user authentication and additional (optional) features, such as dynamic identity provider discovery and relying party registration, signing and encryption of messages, and logout.

In OAuth, the interactions between the user and her browser, the RP, and the IdP can be performed in four different flows, or *grant types*: authorization code grant, implicit grant, resource owner password credentials grant, and the client credentials grant (we refer to these as *modes* in the following). In addition, all of these modes provide further options.

The goal of this work is to provide an in-depth security analysis of OAuth. Analyzing the security of OAuth is a challenging task, on the one hand due to the various modes and options that OAuth provides, and on the other hand due to the inherent complexity of the web.

So far, most analysis efforts regarding the security of OAuth were targeted towards finding errors in specific implementations [6,10,28,38,39,41,43], rather than the comprehensive analysis of the standard itself. Probably the most detailed formal analysis carried out on OAuth so far is the one in [6]. However, none of the existing analysis efforts of OAuth account for all modes of OAuth running simultaneously, which may potentially introduce new security risks. In fact, many existing approaches analyze only the authorization code mode and the implicit mode of OAuth. Also, importantly, there are no analysis efforts that are based on a comprehensive formal web model (see below), which, however, is essential to rule out security risks that arise when running the protocol in the context of common web technologies (see Section 6 for a more detailed discussion of related work).

Contributions of this Paper. We perform the first extensive formal analysis of the OAuth 2.0 standard for all four modes, which can even run simultaneously within the same and different RPs and IdPs, based on a comprehensive web model which covers large parts of how browsers and servers interact in real-world setups. Our analysis also covers the case of malicious IdPs, RPs, and browsers/users.

Formal model of OAuth. Our formal analysis of OAuth uses an expressive Dolev-Yao style model of the web infrastructure [14] proposed by Fett, Küsters, and Schmitz (FKS). The FKS model has already been used to analyze the security of the BrowserID single sign-on system [14,16] as well as the security and privacy of the SPRESSO single sign-on system [17]. This web model is designed independently of a specific web application and closely mimics published (de-facto) standards and specifications for the web, for instance, the HTTP/1.1 and HTML5 standards and associated (proposed) standards. It is

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[1]Following the OAuth 2.0 terminology, IdPs are called *authorization servers* and *resource servers*, RPs are called *clients*, and users are called *resource owners*. Here, however, we stick to the more common terms mentioned above.

[2]Note that in this document, we consider only OAuth 2.0, which is very different to its predecessor, OAuth 1.0(a).

the most comprehensive web model to date. Among others, HTTP(S) requests and responses, including several headers, such as cookie, location, strict transport security (STS), and origin headers, are modeled. The model of web browsers captures the concepts of windows, documents, and iframes, including the complex navigation rules, as well as new technologies, such as web storage and web messaging (via postMessage). JavaScript is modeled in an abstract way by so-called *scripts* which can be sent around and, among others, can create iframes and initiate XMLHTTPRequests (XHRs). Browsers may be corrupted dynamically by the adversary.

Using the generic FKS model, we build a formal model of OAuth, closely following the OAuth 2.0 standard (RFC6749 [21]). Since this RFC does not fix all aspects of the protocol and in order to avoid known implementation attacks, we use the OAuth 2.0 security recommendations (RFC6819 [29]), additional RFCs and OAuth Working Group drafts (e.g., RFC7662 [33], [8]) and current web best practices (e.g., regarding session handling) to obtain a model of OAuth with state-of-the-art security features in place, while making as few assumptions as possible. Moreover, as mentioned above, our model includes RPs and IdPs that (simultaneously) support all four modes and can be dynamically corrupted by the adversary. Also, we model all configuration options of OAuth (see Section 2).

Formalization of security properties. Based on this model of OAuth, we provide three central security properties of OAuth: authorization, authentication, and session integrity, where session integrity in turn is concerned with both authorization and authentication.

Attacks on OAuth 2.0 and fixes. While trying to prove these properties, we discovered four attacks on OAuth. In the first attack, which breaks the authorization and authentication properties, IdPs inadvertently forward user credentials (i.e., username and password) to the RP or the attacker. In the second attack (IdP mix-up), a network attacker playing the role of an IdP can impersonate any victim. This severe attack, which again breaks the authorization and authentication properties, is caused by a logical flaw in the OAuth 2.0 protocol. Two further attacks allow an attacker to force a browser to be logged in under the attacker's name at an RP or force an RP to use a resource of the attacker instead of a resource of the user, breaking the session integrity property. We have verified all four attacks on actual implementations of OAuth and OpenID Connect. We present our attacks on OAuth in detail in Section 3. In Appendix B.1 we show how the attacks can be exploited in OpenID Connect. We also show how the attacks can be fixed by changes that are easy to implement in new and existing deployments of OAuth and OpenID Connect.

We notified the respective working groups, who confirmed the attacks and that changes to the standards/recommendations are needed. The IdP mix-up attack already resulted in a draft of a new RFC [24].

Formal analysis of OAuth 2.0. Using our model of OAuth with the fixes in place, we then were able to prove that OAuth satisfies the mentioned security properties. This is the first proof which establishes central security properties of OAuth in a comprehensive and expressive web model (see also Section 6).

We emphasize that, as mentioned before, we model OAuth with security recommendations and best practices in place. As discussed in Section 5, implementations not following these recommendations and best practices may be vulnerable to attacks. In fact, many such attacks on specific implementations have been pointed out in the literature (e.g., [6, 10, 21, 28, 29, 41, 42]). Hence, our results also provide guidelines for secure OAuth implementations.

We moreover note that, while these results provide strong security guarantees for OAuth, they do not directly imply security of OpenID Connect because OpenID Connect adds specific details on top of OAuth. We leave a formal analysis of OpenID Connect to future work. The results obtained here can serve as a good foundation for such an analysis.

Structure of this Paper. In Section 2, we provide a detailed description of OAuth 2.0 using the authorization code mode as an example. In Section 3, we present the attacks that we found during our analysis. An overview of the FKS model we build upon in our analysis is provided in Section 4, with the

formal analysis of OAuth presented in Section 5. Related work is discussed in Section 6. We conclude in Section 7. Full details, including how the attacks can be applied to OpenID Connect, further details on our model of OAuth, and our security proof, can be found in the appendix.

2. OAuth 2.0

In this section, we provide a description of the OAuth authorization code mode, with the other three modes explained only briefly. In Appendix A, we provide a detailed description of the remaining three modes (grant types).

OAuth was first intended for *authorization*, i.e., users authorize RPs to access user data (called *protected resources*) at IdPs. For example, a user can use OAuth to authorize services such as IFTTT[3] to access her (private) timeline on Facebook. In this case, IFTTT is the RP and Facebook the IdP.

Roughly speaking, in the most common modes, OAuth works as follows: If a user wants to authorize an RP to access some of the user's data at an IdP, the RP redirects the user (i.e., the user's browser) to the IdP, where the user authenticates and agrees to grant the RP access to some of her user data at the IdP. Then, along with some token (an *authorization code* or an *access token*) issued by the IdP, the user is redirected back to the RP. The RP can then use the token as a credential at the IdP to access the user's data at the IdP.

OAuth is also commonly used for *authentication*, although it was not designed with authentication in mind. A user can, for example, use her Facebook account, with Facebook being the IdP, to log in at the social network Pinterest (the RP). Typically, in order to log in, the user authorizes the RP to access a unique user identifier at the IdP. The RP then retrieves this identifier and considers this user to be logged in.

Before an RP can interact with an IdP, the RP needs to be registered at the IdP. The details of the registration process are out of the scope of the OAuth protocol. In practice, this process is usually a manual task. During the registration process, the IdP assigns credentials to the RP: a public OAuth client id and (optionally) a client secret. (Recall that in the terminology of the OAuth standard the term "client" stands for RP.) The RP may later use the client secret (if issued) to authenticate to the IdP.

Also, an RP registers one or more *redirection endpoint* URIs (located at the RP) at an IdP. As we will see below, in some OAuth modes, the IdP redirects the user's browser to one of these URIs. Note that (depending on the implementation of an IdP) an RP may also register a pattern as a redirect URI and then specify the exact redirect URI during the OAuth run.

In all modes, OAuth provides several options, such as those mentioned above. For brevity of presentation (and in contrast to our analysis), in the following descriptions, we consider only a specific set of options. For example, we assume that an RP always provides a redirect URI and shares an OAuth client secret with the IdP.

Authorization Code Mode. When the user tries to authorize an RP to access her data at an IdP or to log in at an RP, the RP first redirects the user's browser to the IdP. The user then authenticates to the IdP, e.g., by providing her user name and password, and finally is redirected back to the RP along with an *authorization code* generated by the IdP. The RP can now contact the IdP with this authorization code (along with the client id and client secret) and receive an *access token*, which the RP in turn can use as a credential to access the user's protected resources at the IdP.

Step-by-Step Protocol Flow. In what follows, we describe the protocol flow of the authorization code mode step-by-step (see also Figure 1). First, the user starts the OAuth flow, e.g., by clicking on a button

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[3]IFTTT (*If This Then That*) is a web service which can be used to automate actions: IFTTT is triggered by user-defined events (e.g., Twitter messages) and carries out user-defined tasks (e.g., posting on the user's Facebook wall).
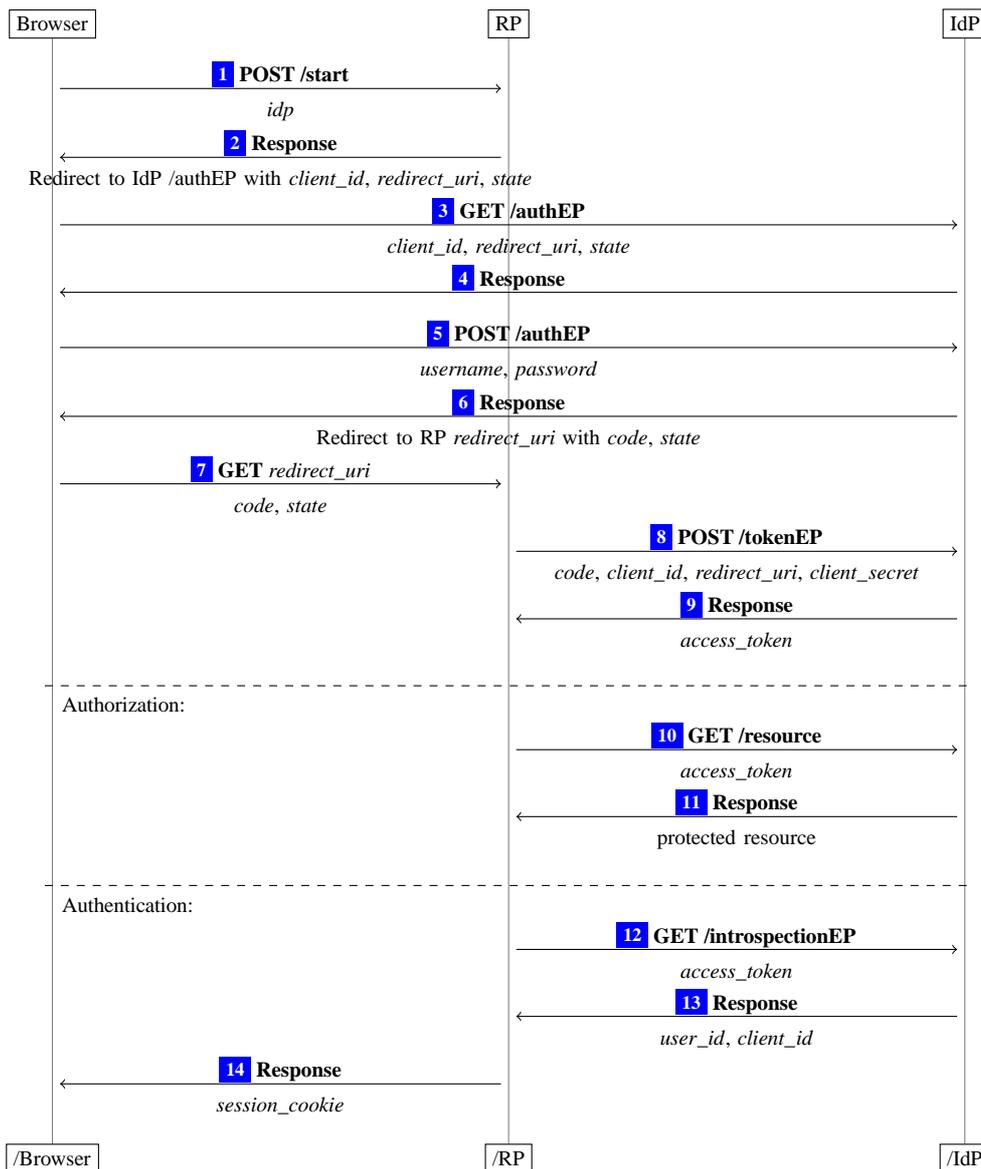
Figure 1. OAuth 2.0 authorization code mode. Note that data depicted below the arrows is either transferred in URI parameters, HTTP headers, or POST bodies.

to select an IdP, resulting in request ⊡1 being sent to the RP. The RP selects one of its redirection endpoint URIs *redirect_uri* (which will be used later in ⊡7) and a value *state* (which will serve as a token to prevent CSRF attacks). The RP then redirects the browser to the so-called *authorization endpoint* URI at the IdP in ⊡2 and ⊡3 with its *client_id*, *redirect_uri*, and *state* appended as parameters to the URI. The IdP then prompts the user to provide her username and password in ⊡4. The user's browser sends this information to the IdP in ⊡5. If the credentials are correct, the IdP creates a nonce *code* (the authorization code) and redirects the user's browser to RP's redirection endpoint URI *redirect_uri* in ⊡6 and ⊡7 with *code* and *state* appended as parameters to the URI. If *state* is the same as above, the RP contacts the IdP in ⊡8 and provides *code*, *client_id*, *client_secret*, and *redirect_uri*. Then the IdP checks whether this information is correct, i.e., it checks that *code* was issued for the RP identified by *client_id*, that *client_secret* is the secret for *client_id*, that *redirect_uri* coincides with the one in Step ⊡2, and that *code* has not been redeemed before. If these checks are successful, the IdP issues an access token *access_token* in ⊡9. Now,

the RP can use *access_token* to access the user's protected resources at the IdP (authorization) or log in the user (authentication), as described next.

When OAuth is used for *authorization*, the RP uses the access token to view or manipulate the protected resource at the IdP (illustrated in Steps ⑩ and ⑪).

For *authentication*, the RP fetches a user id (which uniquely identifies the user at the IdP) using the access token, Steps ⑫ and ⑬. The RP then issues a session cookie to the user's browser as shown in ⑭.[4]

Tracking User Intention. Note that in order for an RP which supports multiple IdPs to process Step ⑦, the RP must know which IdP a user wanted to use for authorization. There are two different approaches to this used in practice: First, the RP can use different redirection URIs to distinguish different IdPs. We call this *naïve user intention tracking*. Second, the RP can store the user intention in a session after Step ① and use this information later. We call this *explicit user intention tracking*. The same applies to the implicit mode of OAuth presented below.

Implicit Mode. This mode is similar to the authorization code mode, but instead of providing an authorization code, the IdP directly delivers an access token to the RP via the user's browser.

More specifically, in the implicit mode, Steps ①–⑤ (see Figure 1) are the same as in the authorization code mode. Instead of creating an authorization code, the IdP issues an access token right away and redirects the user's browser to RP's redirection endpoint with the access token contained in the fragment of the URI. (Recall that a fragment is a special part of a URI indicated by the '#' symbol.)

As fragments are not sent in HTTP requests, the access token is not immediately transferred when the browser contacts the RP. Instead, the RP needs to use a JavaScript to retrieve the contents of the fragment. Typically, such a JavaScript is sent in RP's answer at the redirection endpoint. Just as in the authorization code mode, the RP can now use the access token for authorization or authentication (analogously to Steps ⑩–⑭ of Figure 1).[5]

Resource Owner Password Credentials Mode. In this mode, the user gives her credentials for an IdP directly to an RP. The RP can then authenticate to the IdP on the user's behalf and retrieve an access token. This mode is intended for highly-trusted RPs, such as the operating system of the user's device or highly-privileged applications, or if the previous two modes are not possible to perform (e.g., for applications without a web browser).

Client Credentials Mode. In contrast to the modes shown above, this mode works without the user's interaction. Instead, it is started by an RP in order to fetch an access token to access the resources of RP at an IdP. For example, Facebook allows RPs to use the client credentials mode to obtain an access token to access reports of their advertisements' performance.

3. Attacks

As mentioned in the introduction, while trying to prove the security of OAuth based on the FKS web model and our OAuth model, we found four attacks on OAuth, which we call *307 redirect attack*, *IdP mix-up attack*, *state leak attack*, and *naïve RP session integrity attack*, respectively. In this section, we provide detailed descriptions of these attacks along with easily implementable fixes. Our formal analysis of OAuth (see Section 5) then shows that these fixes are indeed sufficient to establish the security of

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[4]Authentication is not part of RFC6749, but this method for authentication is commonly used in practice, for example by Amazon, Facebook, LinkedIn, and StackExchange, and is also defined in OpenID Connect [35].

[5]The response from the IdP in Step ⑬ includes the RP's OAuth client id, which is checked by the RP when *authenticating* a user (cf. RFC7662 [33]). This check prevents re-use of access tokens across RPs in the OAuth implicit mode, as explained in [42]. This check is not needed for authorization.

	attack on OAuth		applicable to OpenID Connect		
	auth code mode	implicit mode	auth code mode	implicit mode	hybrid mode
307 Redirect Attack	az + an	az + an	az + an	az + an	az + an
IdP Mix-Up Attack	az* + an	az + an	az* + an	–	az + an**
State Leak Attack	si	si	si	si	si
Naïve RP Session Integrity Att.	si	si	si	si	si

az: breaks authorization. **an:** breaks authentication. **si:** breaks session integrity. **–:** not applicable. ***** if client secrets are not used. ****** restriction: if client secrets are used, either authorization or authentication is broken, depending on implementation details.

Figure 2. Overview of attacks on OAuth 2.0 and OpenID Connect

OAuth. The attacks also apply to OpenID Connect (see Section 3.5). Figure 2 provides an overview of where the attacks apply. We have verified our attacks on actual implementations of OAuth and OpenID Connect and reported the attacks to the respective working groups who confirmed the attacks (see Section 3.6).

3.1. 307 Redirect Attack

In this attack, which breaks our authorization and authentication properties (see Section 5.2), the attacker (running a malicious RP) learns the user's credentials when the user logs in at an IdP that uses the wrong HTTP redirection status code. While the attack itself is based on a simple error, to the best of our knowledge, this is the first description of an attack of this kind.

Assumptions. The main assumptions are that (1) the IdP that is used for the login chooses the 307 HTTP status code when redirecting the user's browser back to the RP (Step 6 in Figure 1), and (2) the IdP redirects the user immediately after the user entered her credentials (i.e., in the response to the HTTP POST request that contains the form data sent by the user's browser).

Assumption (1). This assumption is reasonable because neither the OAuth standard [21] nor the OAuth security considerations [29] (nor the OpenID Connect standard [35]) specify the exact method of how to redirect. The OAuth standard rather explicitly permits any HTTP redirect:

> While the examples in this specification show the use of the HTTP 302 status code, any other method available via the user-agent to accomplish this redirection is allowed and is considered to be an implementation detail.

Assumption (2). This assumption is reasonable as many examples for redirects immediately after entering the user credentials can be found in practice, for example at `github.com` (where, however, assumption (1) is not satisfied.)

Attack. When a user uses the authorization code or implicit mode of OAuth to log in at a *malicious* RP, then she is redirected to the IdP and prompted to enter her credentials. The IdP then receives these credentials from the user's browser in a POST request. It checks the credentials and redirects the user's browser to the RP's redirection endpoint in the response to the POST request. Since the 307 status code is used for this redirection, the user's browser will send a POST request to RP that contains all form data from the previous request, including the user credentials. Since the RP is run by the attacker, he can use these credentials to impersonate the user.

Fix. Contrary to the current wording in the OAuth standard, the exact method of the redirect is not an implementation detail but essential for the security of OAuth. In the HTTP standard [19], only the 303 redirect is defined unambiguously to drop the body of an HTTP POST request. Therefore, the OAuth standard should require 303 redirects for the steps mentioned above in order to fix this problem.
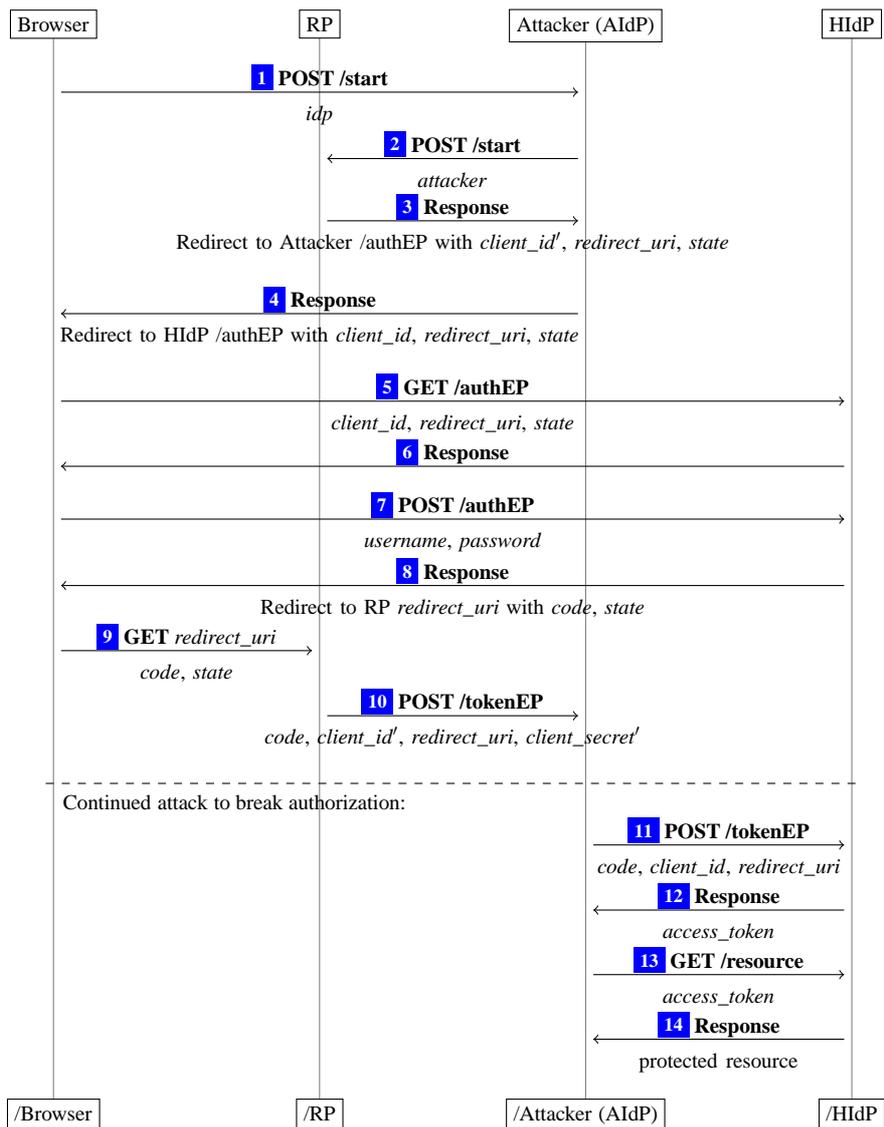
Figure 3. Attack on OAuth 2.0 authorization code mode

3.2. IdP Mix-Up Attack

In this attack, which breaks our authorization and authentication properties (see Section 5.2), the attacker confuses an RP about which IdP the user chose at the beginning of the login/authorization process in order to acquire an authentication code or access token which can be used to impersonate the user or access user data.

  This attack applies to the authorization code mode and the implicit mode of OAuth when explicit user intention tracking[6] is used by the RP. To launch the attack, the attacker manipulates the first request of the user such that the RP thinks that the user wants to use an identity managed by an IdP of the attacker (AIdP) while the user instead wishes to use her identity managed by an honest IdP (HIdP). As a result, the RP sends the authorization code or the access token issued by HIdP to the attacker. The attacker then can use this information to login at the RP under the user's identity (managed by HIdP) or access the user's protected resources at HIdP.

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[6]Recall the meaning of "user intention tracking" from Section 2.

We here present the attack in the authorization code mode. In the implicit mode, the attack is very similar and is shown in detail in Appendix B.

Assumptions. For the IdP mix-up attack to work, we need three assumptions that we further discuss below: (1) the presence of a network attacker who can manipulate the request in which the user sends her identity to the RP as well as the corresponding response to this request (see Steps $\boxed{1}$ and $\boxed{2}$ in Figure 1), (2) an RP which allows users to log in with identities provided by (some) HIdP and identities provided by AIdP, and (3) an RP that uses explicit user intention tracking and issues the same redirection URI to all IdPs.[7] We emphasize that we do not assume that the user sends any secret (such as passwords) over an unencrypted channel.

Assumption (1). It would be unrealistic to assume that a network attacker can never manipulate Steps $\boxed{1}$ and $\boxed{2}$ in Figure 1.

First, these messages are sent between the user and the RP, i.e., the attacker does not need to intercept server-to-server communication. He could, e.g., use ARP spoofing in a wifi network to mount the attack.

Second, the need for HTTPS for these steps is not obvious to users or RPs, and the use of HTTPS is not suggested by the OAuth security recommendations, since the user only selects an IdP at this point; credentials are not transferred.

Third, even if an RP intends to use HTTPS also for the first request (as in our model), it has to protect itself against TLS stripping by adding the RP domain to a browser preloaded Strict Transport Security (STS) list [11]. Other mitigations, such as the STS header, can be circumvented (see [37]), and do not work on the very first connection between the user's browser and RP. For example, when a user enters the address of an RP into her browser, browsers by default try unencrypted connections. It is therefore unrealistic to assume that all RPs are always protected against TLS stripping.

Our formal analysis presented in Section 5 shows that OAuth can be operated securely even if no HTTPS is used for the initial request (given that our fix, presented below, is applied).

Assumption (2). RPs may use different IdPs, some of which might be malicious, and hence, OAuth should provide security in this case. Using a technique called dynamic client registration, OAuth RPs can even allow the ad-hoc use of any IdP, including malicious ones. This is particularly relevant in OpenID Connect, where this technique was first implemented.

Assumption (3). Typically, RPs that use explicit user intention tracking do not register different redirection URIs for different IdPs, as in this case the RP records the IdP a user wants to authenticate with. In particular, for RPs that allow for dynamic registration, using the same URI is an obvious implementation choice. This is for example the case in the OAuth/OpenID Connect implementations *mod_auth_openidc* and *pyoidc* (see below).

Attack on Authorization Code Mode. We now describe the IdP Mix-Up attack on the OAuth authorization code mode. As mentioned, a very similar attack also applies to the implicit mode. Both attacks also work if IdP supports just one of these two modes.

The IdP mix-up attack for the authorization code mode is depicted in Figure 3. Just as in a regular flow, the attack starts when the user selects that she wants to log in using HIdP (Step $\boxed{1}$ in Figure 3). Now, the attacker intercepts the request intended for the RP and modifies the content of this request by replacing HIdP by AIdP.[8] The response of the RP $\boxed{3}$ (containing a redirect to AIdP) is then again intercepted and modified by the attacker such that it redirects the user to HIdP $\boxed{4}$. The attacker also replaces the OAuth

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[7]Alternatively, the attack would work if the RP issues different redirection URIs to different IdPs, but treats them as the same URI.

[8]At this point, the attacker could also read the session id for the user's session at RP. Our attack, however, is not based on this possibility and works even if the RP changes this session id as soon as the user is logged in and the connection is protected by HTTPS (a best practice for session management).

client id of the RP at AIdP with the client id of the RP at HIdP (which is public information). (Note that we assume that from this point on, in accordance with the OAuth security recommendations, the communication between the user's browser and HIdP and the RP is encrypted by using HTTPS, and thus, cannot be inspected or altered by the attacker.) The user then authenticates to HIdP and is redirected back to the RP ⑧. The RP thinks, due to Step ② of the attack, that the nonce *code* contained in this redirect was issued by AIdP, rather than HIdP. The RP therefore now tries to redeem this nonce for an access token at AIdP ⑩, rather than HIdP. This leaks *code* to the attacker.

Breaking Authorization. If HIdP has not issued an OAuth client secret to RP during registration, the attacker can now redeem *code* for an access token at HIdP (in ⑪ and ⑫).[9] This access token allows the attacker to access protected resources of the user at HIdP. This breaks the authorization property (see Section 5.2). We note that at this point, the attacker might even provide false information about the user or her protected resources to the RP: he could issue a self-created access token which RP would then use to access such information at the attacker.

Breaking Authentication. To break the authentication property (see Section 5.2) and impersonate the honest user, the attacker, after obtaining *code* in Step ⑩, starts a new login process (using his own browser) at the RP. He selects HIdP as the IdP for this login process and receives a redirect to HIdP, which he ignores. This redirect contains a cookie for a new login session and a fresh state parameter. The attacker now sends *code* to the RP imitating a real login (using the cookie and fresh state value from the previous response). The RP then retrieves an access token at HIdP using *code* and uses this access token to fetch the (honest) user's id. Being convinced that the attacker owns the honest user's account, the RP issues a session cookie for this account to the attacker. As a result, the attacker is logged in at the RP under the honest user's id. (Note that the attacker does not learn an access token in this case.)

Variant. There is also a variant of the IdP mix-up attack that only requires a web attacker (which does not intercept and manipulate network messages). In this variant, the user wants to log in with AIdP, but is redirected by AIdP to log in at HIdP; a fact a vigilant user might detect.

In detail, the first four steps in Figure 3 are replaced by the following steps: First, the user starts a new OAuth flow with RP using AIdP. She is then redirected by RP to AIdP's authorization endpoint. Now, instead of prompting the user for her password, AIdP redirects the user to HIdP's authorization endpoint. (Note that, as above, in this step, the attacker uses the state value he received from the browser plus the client id of RP at HIdP.) From here on, the attack proceeds exactly as in Step ⑤ in Figure 3.

Related Attacks. An attack in the same class, *cross social-network request forgery*, was outlined by Bansal, Bhargavan, Delignat-Lavaud, and Maffeis in [6]. It applies to RPs with naïve user intention tracking (rather than explicit user intention tracking assumed in our IdP mix-up attack above) in combination with IdPs, such as Facebook, that only loosely check the redirect URI.[10] Our IdP mix-up attack works even if an IdP strictly checks redirect URIs. While the attack in [6] is described in the context of concrete social network implementations, our findings show that this class of attacks is not merely an implementation error, but a more general problem in the OAuth standard. This was confirmed by the IETF OAuth Working Group, who, as mentioned, are in the process of amending the OAuth standard according to our fixes (see Section 3.6).

Another attack with a similar outcome, called *Malicious Endpoints Attack*, leveraging the OpenID Connect Discovery mechanism and therefore limited to OpenID Connect, was described in [30]. This attack assumes a CSRF vulnerability on the RP's side.

Fix. A fundamental problem in the authorization code and implicit modes of the OAuth standard is a

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[9]In the case that RP has to provide a client secret, this would not work in this mode (see also Figure 2). Recall that in this mode, client secrets are optional.

[10]Facebook, by default, only checks the origin of redirect URIs.

lack of reliable information in the redirect in Steps ⑥ and ⑦ in Figure 1 (even if HTTPS is used). The RP does not receive information from where the redirect was initiated (when explicit user intention tracking is used) or receives information that can easily be spoofed (when naïve user intention tracking is used with IdPs such as Facebook). Hence, the RP cannot check whether the information contained in the redirect stems from the IdP that was indicated in Step ①.

Our fix therefore is to include the identity of the IdP in the redirect URI in some form that cannot be influenced by the attacker, e.g., using a new URI parameter. Each IdP should add such a parameter to the redirect URI.[11] The RP can then check that the parameter contains the identity of the IdP it expects to receive the response from. (This could be used with either naïve or explicit user intention tracking, but to mitigate the *naïve RP session integrity attack* described below, we advise to use explicit user intention tracking only, see below.)

We show in Section 5 that this fix is indeed sufficient to mitigate the IdP mix-up attack (as well as the attacks pointed out in [6, 30]).

3.3. State Leak Attack

Using the state leak attack, an attacker can force a browser to be logged in under the attacker's name at an RP or force an RP to use a resource of the attacker instead of a resource of the user. This attack, which breaks our session integrity property (see Section 5.2), enables what is often called session swapping or login CSRF [7].

Attack. After the user has authenticated to the IdP in the authorization code mode, the user is redirected to RP (Step ⑦ in Figure 1). This request contains state and code as parameters. The response to this request (Step ⑭) can be a page containing a link to the attacker's website or some resource located at the attacker's website. When the user clicks the link or the resource is loaded, the user's browser sends a request to the attacker. This request contains a Referer header with the full URI of the page the user was redirected to, which in this case contains state and code.

As the state value is supposed to protect the browser's session against CSRF attacks, the attacker can now use the leaked state value to perform a CSRF attack against the victim. For example, he can redirect the victim's browser to the RP's redirection endpoint (again) and by this, overwrite the previously performed authorization. The user will then be logged in as the attacker.

Given the history of OAuth, leaks of sensitive data through the referrer header are not surprising. For example, the fact that the authorization code can leak through the Referer header was described as an attack (in a similar setting) in [22]. Since the authorization code is single-use only [21], it might already be redeemed by the time it is received by the attacker. State, however, is not limited to single use, making this attack easier to exploit in practice. Stealing the state value through the Referer header to break session integrity has not been reported as an attack before, as was confirmed by the IETF OAuth Working Group.

State Leak at IdPs. A variant of this attack exists if the login page at an IdP contains links to external resources. If the user visits this page to authenticate at the IdP and the browser follows links to external resources, the state is transferred in the Referer header. This variant is applicable to the authorization code mode and the implicit mode.

Fix. We suggest to limit state to a single use and to use the recently introduced *referrer policies* [13] to avoid leakage of the state (or code) to the attacker. Using referrer policies, a web server can instruct a web browser to (partially or completely) suppress the Referer header when the browser follows links in

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[11]The OAuth Working Group indeed created a draft for an RFC [24] that includes this fix, where this parameter is called *iss* (issuer).

or loads resources for some web page. The Referer header can be blocked entirely, or it can, for example, be stripped down to the origin of the URI of the web page. Referrer policies are supported by all modern browsers.

Our OAuth model includes this fix (such that only the origin is permitted in the Referer header for links on web pages of RPs/IdPs) and our security proof shows its effectiveness (see Section 5). The fix also protects the authorization code from leaking as in the attack described in [22].

3.4. Naïve RP Session Integrity Attack

This attack again breaks the session integrity property for RPs, where here we assume an RP that uses *naïve user intention tracking*.[12] (Note that we may still assume that the OAuth state parameter is used, i.e., RP is not necessarily stateless.)

Attack. First, an attacker starts a session with HIdP (an honest IdP) to obtain an authorization code or access token for his own account. Next, when a user wants to log in at some RP using AIdP (an IdP controlled by the attacker), AIdP redirects the user back to the redirection URI of HIdP at RP. AIdP attaches to this redirection URI the state issued by RP, and the code or token obtained from HIdP. Now, since RP performs naïve user intention tracking only, the RP then believes that the user logged in at HIdP. Hence, the user is logged in at RP using the attacker's identity at HIdP or the RP accesses the attacker's resources at HIdP believing that these resources are owned by the user.

Fix. The fix against the IdP mix-up attack (described above) does not work in this case: Since RP does not track where the user wanted to log in, it has to rely on parameters in the redirection URI which the attacker can easily spoof. Instead, we propose to always use explicit user intention tracking.

3.5. Implications to OpenID Connect

OpenID Connect [35] is a standard for authentication built on top of the OAuth protocol. Among others, OpenID Connect is used by PayPal, Google, and Microsoft.

All four attacks can be applied to OpenID Connect as well. We here outline OpenID Connect and how the attacks apply to this protocol. A detailed description can be found in Appendix B.1.

OpenID Connect extends OAuth in several ways, e.g., by additional security measures. OpenID Connect defines an *authorization code mode*, an *implicit mode*, and a *hybrid mode*. The former two are based on the corresponding OAuth modes and the latter is a combination of the two modes.

307 Redirect, State Leak, Naïve RP Session Integrity Attacks. All three attacks apply to OpenID Connect in exactly the same way as described above. The vulnerable steps are identical.

IdP Mix-Up Attack. In OpenID Connect, the mix-up attack applies to the authorization code mode and the hybrid mode. In the authorization code mode, the attack is very similar to the one on the OAuth authorization code mode. In the hybrid mode, the attack is more complicated as additional security measures have to be circumvented by the attacker. In particular, it must be ensured that the RP does not detect that the issuer of the id token, a signed cryptographic document used in OpenID Connect, is not the honest IdP. Interestingly, in the hybrid mode, depending on an implementation detail of the RP, either authorization or authentication is broken (or both if no client secret is used).

3.6. Verification and Disclosure

We verified the IdP mix-up and 307 redirect attacks on the Apache web server module *mod_auth_openidc*, an implementation of an OpenID Connect (and therefore also OAuth) RP. We also verified the IdP mix-

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[12]Recall the meaning of "naïve user intention tracking" from Section 2.

up attack on the python implementation *pyoidc*. We verified the state leak attack on the current version of the Facebook PHP SDK and the naïve RP session integrity attack on `nytimes.com`.[13]

We reported all attacks to the OAuth and OpenID Connect working groups who confirmed the attacks. The OAuth working group invited us to present our findings to them and prepared a draft for an RFC that mitigates the IdP mix-up attack (using the fix described in Section 3.2) [24]. Fixes regarding the other attacks are currently under discussion. We also notified `nytimes.com`, Facebook, and the developers of *mod_auth_openidc* and *pyoidc*.

4. FKS Model

Our formal security analysis of OAuth is based on a slightly extended version (see Section 5.1) of the FKS model, a general Dolev-Yao (DY) style web model proposed by Fett et al. in [14,17]. This model is designed independently of a specific web application and closely mimics published (de-facto) standards and specifications for the web, for example, the HTTP/1.1 and HTML5 standards and associated (proposed) standards. The FKS model defines a general communication model, and, based on it, web systems consisting of web browsers, DNS servers, and web servers as well as web and network attackers. Here, we only briefly recall the FKS model (see [14,17] for a full description, comparison with other models, and a discussion of its limitations); see also Appendices C–E.

Communication Model. The main entities in the model are *(atomic) processes*, which are used to model browsers, servers, and attackers. Each process listens to one or more (IP) addresses. Processes communicate via *events*, which consist of a message as well as a receiver and a sender address. In every step of a run, one event is chosen non-deterministically from a "pool" of waiting events and is delivered to one of the processes that listens to the event's receiver address. The process can then handle the event and output new events, which are added to the pool of events, and so on.

As usual in DY models (see, e.g., [1]), messages are expressed as formal terms over a signature Σ. The signature contains constants (for (IP) addresses, strings, nonces) as well as sequence, projection, and function symbols (e.g., for encryption/decryption and signatures). For example, in the web model, an HTTP request is represented as a term r containing a nonce, an HTTP method, a domain name, a path, URI parameters, headers, and a message body. For example, a request for the URI `http://example.com/s?p=1` is represented as

$$r := \langle \mathtt{HTTPReq}, n_1, \mathtt{GET}, \mathtt{example.com}, /\mathtt{s}, \langle\langle \mathtt{p}, 1 \rangle\rangle, \langle\rangle, \langle\rangle\rangle$$

where the body and the headers are empty. An HTTPS request for r is of the form $\mathsf{enc_a}(\langle r, k' \rangle, \mathsf{pub}(k_{\mathrm{example.com}}))$, where k' is a fresh symmetric key (a nonce) generated by the sender of the request (typically a browser); the responder is supposed to use this key to encrypt the response.

The *equational theory* associated with Σ is defined as usual in DY models. The theory induces a congruence relation $\equiv$ on terms, capturing the meaning of the function symbols in Σ. For instance, the equation in the equational theory which captures asymmetric decryption is $\mathsf{dec_a}(\mathsf{enc_a}(x, \mathsf{pub}(y)), y) = x$. With this, we have that, for example,

$$\mathsf{dec_a}(\mathsf{enc_a}(\langle r, k' \rangle, \mathsf{pub}(k_{\mathrm{example.com}})), k_{\mathrm{example.com}}) \equiv \langle r, k' \rangle$$

i.e., these two terms are equivalent w.r.t. the equational theory.

A *(DY) process* consists of a set of addresses the process listens to, a set of states (terms), an initial state, and a relation that takes an event and a state as input and (non-deterministically) returns a new

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[13]*mod_auth_openidc* and `nytimes.com` are not susceptible to the state leak attack since after the login/authorization, the user is immediately redirected to another web page at the same RP.

state and a sequence of events. The relation models a computation step of the process. It is required that the output can be computed (more formally, derived in the usual DY style) from the input event and the state.

The so-called *attacker process* is a DY process which records all messages it receives and outputs all events it can possibly derive from its recorded messages. Hence, an attacker process carries out all attacks any DY process could possibly perform. Attackers can corrupt other parties.

A *script* models JavaScript running in a browser. Scripts are defined similarly to DY processes. When triggered by a browser, a script is provided with state information. The script then outputs a term representing a new internal state and a command to be interpreted by the browser (see also the specification of browsers below). Similarly to an attacker process, the so-called *attacker script* may output everything that is derivable from the input.

A *system* is a set of processes. A *configuration* of this system consists of the states of all processes in the system, the pool of waiting events, and a sequence of unused nonces. Systems induce *runs*, i.e., sequences of configurations, where each configuration is obtained by delivering one of the waiting events of the preceding configuration to a process, which then performs a computation step.

A *web system* formalizes the web infrastructure and web applications. It contains a system consisting of honest and attacker processes. Honest processes can be web browsers, web servers, or DNS servers. Attackers can be either *web attackers* (who can listen to and send messages from their own addresses only) or *network attackers* (who may listen to and spoof all addresses and therefore are the most powerful attackers). A web system further contains a set of scripts (comprising honest scripts and the attacker script).

In our analysis of OAuth, we consider either one network attacker or a set of web attackers (see Section 5). In our OAuth model, we need to specify only the behavior of servers and scripts. These are not defined by the FKS model since they depend on the specific application, unless they are corrupt or become corrupted in which case they behave like attacker processes and attacker scripts; browsers are specified by the FKS model (see below). The modeling of OAuth servers and scripts is outlined in Section 5.1 and defined in detail in Appendices F and G.

Web Browsers. An honest browser is thought to be used by one honest user, who is modeled as part of the browser. User actions, such as following a link, are modeled as non-deterministic actions of the web browser. User credentials are stored in the initial state of the browser and are given to selected web pages when needed. Besides user credentials, the state of a web browser contains (among others) a tree of windows and documents, cookies, and web storage data (localStorage and sessionStorage).

A *window* inside a browser contains a set of *documents* (one being active at any time), modeling the history of documents presented in this window. Each represents one loaded web page and contains (among others) a script and a list of subwindows (modeling iframes). The script, when triggered by the browser, is provided with all data it has access to, such as a (limited) view on other documents and windows, certain cookies, and web storage data. Scripts then output a command and a new state. This way, scripts can navigate or create windows, send XHRs and postMessages, submit forms, set/change cookies and web storage data, and create iframes. Navigation and security rules ensure that scripts can manipulate only specific aspects of the browser's state, according to the web standards.

A browser can output messages on the network of different types, namely DNS and HTTP(S) requests as well as XHRs, and it processes the responses. Several HTTP(S) headers are modeled, including, for example, cookie, location, strict transport security (STS), and origin headers. A browser, at any time, can also receive a so-called trigger message upon which the browser non-deterministically chooses an action, for instance, to trigger a script in some document. The script now outputs a command, as described above, which is then further processed by the browser. Browsers can also become corrupted, i.e., be taken over by web and network attackers. Once corrupted, a browser behaves like an attacker process.

5. Analysis

We now present our security analysis of OAuth (with the fixes mentioned in Section 3 applied). We first present our model of OAuth. We then formalize the security properties and state the main theorem, namely the security of OAuth w.r.t. these properties. We provide full details of the model and our proof in Appendices F–I.

5.1. Model

As mentioned above, our model for OAuth is based on the FKS model outlined in Section 4. For the analysis, we extended the model to include HTTP Basic Authentication [20] and Referrer Policies [13] (the Referer header itself was already part of the model). We developed the OAuth model to adhere to RFC6749, the OAuth 2.0 standard, and follow the security considerations described in [29].

Design. Our comprehensive model of OAuth includes all configuration options of OAuth and makes as few assumptions as possible in order to strengthen our security results:

OAuth Modes. Every RP and IdP may run any of the four OAuth modes, even simultaneously.

Corruption. RPs, IdPs, and browsers can be corrupted by the attacker at any time.

Redirection URIs. RP chooses redirection URIs explicitly or the IdP selects a redirection URI that was registered before. Redirection URIs can contain patterns. This covers all cases specified in the OAuth standard. We allow that IdPs do not strictly check the redirection URIs, and instead apply loose checking, i.e., only the origin is checked (this is the default for Facebook, for example). This only strengthens the security guarantees we prove.

Client Secrets. Just as in the OAuth standard, RPs can, for a certain IdP, have a secret or not have a secret in our model.

Usage of HTTP and HTTPS. Users may visit HTTP and HTTPS URIs (e.g., for RPs) and parties are not required to use Strict-Transport-Security (STS), although we still recommend STS in practice (for example, to reduce the risk of password eavesdropping). Again, this only strengthens our results.

General User Interaction. As usual in the FKS model, the user can at any time navigate backwards or forward in her browser history, navigate to any web page, open multiple windows, start simultaneous login flows using different or the same IdPs, etc. Web pages at RPs can contain regular links to arbitrary external web sites.

Authentication at IdP. User authentication at the IdP, which is out of the scope of OAuth, is performed using username and password.

Session Mechanism at RP. OAuth does not prescribe a specific session mechanism to be used at an RP. Our model therefore includes a standard cookie-based session mechanism (as suggested in [8]).

Attack Mitigations. To prove the security properties of OAuth, our model includes the fixes against the new attacks presented in Section 3 as well as standard mitigations against known attacks. Altogether this offers clear implementation guidelines, without which OAuth would be insecure:

Honest Parties. RPs and IdPs, as long as they are honest, do not include (untrusted) third-party JavaScript on their websites, do not contain open redirectors, and do not have Cross-Site Scripting vulnerabilities. Otherwise, access tokens and authorization codes can be stolen in various ways, as described, among others, in [6, 21, 29, 41].

CSRF Protection. The *state* parameter is used with a nonce that is bound to the user's session (see [8]) to prevent CSRF vulnerabilities on the RP redirection endpoint. Omitting or incorrectly using this parameter can lead to attacks described in [6, 21, 28, 29, 41].

More specifically, a new state nonce is freshly chosen for each login attempt. Otherwise, the following attack is applicable: First, a user starts an OAuth flow at some RP using a malicious IdP. The IdP learns the state value that is used in the current user session. Then, as soon as the user starts a new OAuth flow with the same RP and an honest IdP, the malicious IdP can use the known state value to mount a CSRF attack, breaking the session integrity property.[14]

We also model CSRF protection for some URIs as follows: For RPs, we model origin header checking[15] (1) at the URI where the OAuth flow is started (for the implicit and authorization code mode), (2) at the password login for the resource owner password credentials mode, and (3) at the URI to which the JavaScript posts the access token in the implicit mode. For IdPs, we do the same at the URI to which the username and password pairs are posted. The CSRF protection of these four URIs is out of the scope of OAuth and therefore, we follow good web development practices by checking the origin header. Without this or similar CSRF protection, IdPs and RPs would be vulnerable to CSRF attacks described in [6, 41].

Referrer Policy and Status Codes. RPs and IdPs use the Referrer Policy [13] to specify that Referer headers on links from any of their web pages may not contain more than the origin of the respective page. Otherwise, RPs or IdPs would be vulnerable to the state leak attack described in Section 3.3 and the code leak attack described in [22]. IdPs use 303 redirects following our fix described in Section 3.1.

HTTPS Endpoints. All endpoint URIs use HTTPS to protect against attackers eavesdropping on tokens or manipulating messages (see, e.g., [29, 41]). Obviously, IdPs or RPs do not register URIs that point to servers other than their own. (Otherwise, access tokens or authorization codes can be stolen trivially.)

Session Cookies. Cookies are always set with the *secure* attribute, ensuring that the cookie value is only transmitted over HTTPS. Otherwise, a network attacker could read cookie values by eavesdropping on non-HTTPS connections to RPs. After successful login at an RP, the RP creates a fresh session id for that user. Otherwise, a network attacker could set a login session cookie that is bound to a known state value into the user's browser (see [44]), lure the user into logging in at the corresponding RP, and then use the session cookie to access the user's data at the RP (*session fixation*, see [31]).

Authentication to the IdP. It is assumed that the user only ever sends her password over an encrypted channel and only to the IdP this password was chosen for (or to trusted RPs, as mentioned above). (The user also does not re-use her password for different IdPs.) Otherwise, a malicious IdP would be able to use the account of the user at an honest IdP.

Authentication using Access Tokens. When an RP sends an access token to the introspection endpoint of an IdP for authentication (Step ⑫ in Figure 1), the IdP returns the user identifier and the client id for which the access token was issued (Step ⑬). The RP must check that the returned client id is its own, otherwise a malicious RP could impersonate an honest user at an honest RP (see [21, 42]). We therefore require this check.

User Intention Tracking. We use explicit user intention tracking. Otherwise, the attack described in Section 3.4 can be applied.

Concepts Used in Our Model. In our model and the security properties, we use the following concepts:

Protected Resources. Closely following RFC6749 [21], OAuth protected resources are an abstract concept for any resource an RP could use at an IdP after successful authorization. For example, if Facebook

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[14]Note that in this attack, the state value does not leak unintentionally (in contrast to the state leak attack). Also note that this attack and the mitigation we describe here, while not surprising, do not seem to have been explicitly documented so far. For example, `nytimes.com` is vulnerable also to this attack.

[15]The origin header is added to certain HTTP(S) requests by browsers to declare the origin of the document that caused the request. For example, when a user submits a form loaded from the URI `http://a/form` and this form is sent to `http://b/path` then the browser will add the origin header `http://a` in the request to `b`. All modern browsers support origin headers. See [12] for details.

gives access to the friends list of a user to an RP, this would be considered a protected resource. In our model, there is a mapping from (IdP, RP, identity) to nonces (which model protected resources). In this mapping, the identity part can be $\perp$, modeling a resource that is acquired in the client credentials mode and thus not bound to a user.

Service Tokens. When OAuth is used for authentication, we assume that after successful login, the RP sends a *service token* to the browser. The intuition is that with this service token a user can use the services of the RP. The service token consists of a nonce, the user's identifier, and the domain of the IdP which was used in the login process. The service token is a generic model for any session mechanism the RP could use to track the user's login status (e.g., a cookie). We note that the actual session mechanism used by the RP *after* a successful login is out of the scope of OAuth, which is why we use the generic concept of a service token. In our model, the service token is delivered by an RP to a browser as a cookie.

Trusted RPs. In our model, among others, a browser can choose to launch the resource owner password credentials mode with any RP, causing this RP to know the password of the user. RPs, however, can become corrupted and thus leak the password to the attacker. Therefore, to define the security properties, we define the concept of *trusted RPs*. Intuitively, this is a set of RPs a user entrusts with her password. In particular, whether an RP is trusted depends on the user. In our security properties, when we state that an adversary should not be able to impersonate a user u in a run, we would assume that all trusted RPs of u have not become corrupted in this run.

OAuth Web System with a Network Attacker. We model OAuth as a class of web systems (in the sense of Section 4) that can contain an unbounded finite number of RPs, IdPs, and browsers. We call a web system $\mathcal{OWS}^n$ an *OAuth web system with a network attacker* if it is of the form described in what follows.

Outline. The system consists of a network attacker, a finite set of web browsers, a finite set of web servers for the RPs, and a finite set of web servers for the IdPs. Recall that in $\mathcal{OWS}^n$, since we have a network attacker, we do not need to consider web attackers (as our network attacker subsumes all web attackers). The set of scripts consists of the three scripts *script_rp_index*, *script_rp_implicit*, and *script_idp_form*. We now briefly sketch RPs, IdPs, and the scripts, with full details provided in Appendix F.

Relying Parties. Each RP is a web server modeled as an atomic DY process following the description in Section 2, including all OAuth modes, as well as the fixes and mitigations discussed before. The RP can either (at any time) launch a client credentials mode flow or wait for users to start any of the other flows. RP manages two kinds of sessions: The *login sessions*, which are used only during the user login phase, and the *service sessions* (modeled by a *service token* as described above). When receiving a special message, an RP can become corrupted and then behaves like an attacker process.

Identity Providers. Each IdP is a web server modeled as an atomic DY process following the description in Section 2, again including all OAuth modes, as well as the fixes and mitigations discussed before. Users can authenticate to an IdP with their credentials. Just as RPs, IdPs can become corrupted at any time.

Scripts. The scripts which run in a user's browser are defined as follows: The script *script_rp_index* is loaded from an RP into a user's browser when the user visits the RP's web site. It starts the authorization or login process. The script *script_rp_implicit* is loaded into the user's browser from an RP during an implicit mode flow to retrieve the data from the URI fragment. It extracts the access token and state from the fragment part of its own URI. The script then sends this information in the body of an HTTPS POST request to the RP. The script *script_idp_form* is loaded from an IdP into the user's browser for user authentication at the IdP.

OAuth Web System with Web Attackers. In addition to $\mathcal{OWS}^n$, we also consider a class of web systems

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where the network attacker is replaced by an unbounded finite set of web attackers. We denote such a system by OWS^w and call it an *OAuth web system with web attackers*, Such web systems are used to analyze session integrity, see below.

Limitations of Our OAuth Model. While our model of OAuth is very comprehensive, a few aspects of OAuth were not taken into consideration in our analysis:

We do not model *expiration* of access tokens and session ids. Also, IdPs may issue so-called *refresh tokens* in Step 9 of Figure 1. In practice, an RP may use such a (long-living) refresh token to obtain a new (short-lived) access token. In our model, we overapproximate this by not expiring access tokens. We also do not model *revocation* of access tokens and *user log out*.

OAuth IdPs support controlling the *scope* of resources made available to an RP. For example, a Facebook user can grant a third party the right to read her user profile but deny access to her friends list. The scope is a property of the access token, but handled internally by the IdP with its implementation, details, and semantics highly dependent on the IdP. We therefore model that RPs always get full access to the user's data at the IdP.

In practice, IdPs can send *error messages* (mostly static strings) to RPs. We do not model these.

Limitations of the underlying FKS model are discussed in [14].

5.2. Security Properties

Based on the formal OAuth model described above, we now formulate central security properties of OAuth, namely authorization, authentication, and session integrity (see Appendix H for the full formal definitions).

Authorization. Intuitively, authorization for OWS^n means that an attacker should not be able to obtain or use a protected resource available to some honest RP at an IdP for some user unless, roughly speaking, the user's browser or the IdP is corrupted.

More formally, we say that OWS^n is *secure w.r.t. authorization* if the following holds true: if at any point in a run of OWS^n an attacker can obtain a protected resource available to some honest RP r at an IdP i for some user u, then the IdP i is corrupt or, if $u \neq \bot$, we have that the browser of u or at least one of the trusted RPs of u must be corrupted. Recall that if $u = \bot$, then the resource was acquired in the client credentials mode, and hence, is not bound to a user.

Authentication. Intuitively, authentication for OWS^n means that an attacker should not be able to login at an (honest) RP under the identity of a user unless, roughly speaking, the IdP involved or the user's browser is corrupted. As explained above, being logged in at an RP under some user identity means to have obtained a service token for this identity from the RP.

More formally, we say that OWS^n is *secure w.r.t. authentication* if the following holds true: if at any point in a run of OWS^n an attacker can obtain the service token that was issued by an honest RP using some IdP i for a user u, then the IdP i, the browser of u, or at least one of the trusted RPs of u must be corrupted.

Session Integrity. Intuitively, session integrity (for authorization) means that (a) an RP should only be authorized to access some resources of a user when the user actually expressed the wish to start an OAuth flow before, and (b) if a user expressed the wish to start an OAuth flow using some honest IdP and a specific identity, then the OAuth flow is never completed with a different identity (in the same session); similarly for authentication.

More formally, we say that OWS^w is *secure w.r.t. session integrity for authorization* if the following holds true: (a) if in a run OWS^w an OAuth login flow is completed with a user's browser, then this user started an OAuth flow. (b) If in addition we assume that the IdP that is used in the completed flow

is honest, then the flow was completed for the same identity for which the OAuth flow was started by the user. We say that the OAuth flow was completed (for some identity v) iff the RP gets access to a protected resource (of v).

We say that $\mathcal{OWS}^w$ is *secure w.r.t. session integrity for authentication* if the following holds true: (a) if in a run ρ of $\mathcal{OWS}^w$ a user is logged in with some identity v, then the user started an OAuth flow. (b) If in addition the IdP that is used in that flow is honest, then the user is logged in under exactly the same identity for which the OAuth flow was started by the user.

We note that for session integrity, as opposed to authorization and authentication, we use the web attacker as an adversary. The rationale behind this is that a *network* attacker can always forcefully log in a user under his own account (by setting cookies from non-secure to secure origins [44]), thereby defeating existing CSRF defenses in OAuth (most importantly, the state parameter). This is a common problem in the session management of web applications, independently of OAuth. This is why we restrict our analysis of session integrity to web attackers since otherwise session integrity would trivially be broken. We note, however, that more robust solutions for session integrity are conceivable (e.g., using JavaScript and HTML5 features such as web messaging and web storage). While some proprietary approaches exist, such approaches are less common and typically do not conform to the OAuth standard.

Main Theorem. We prove the following theorem (see Appendix I for the proof):

Theorem 1. Let $\mathcal{OWS}^n$ be an OAuth web system with a network attacker, then $\mathcal{OWS}^n$ is secure w.r.t. authorization and secure w.r.t. authentication. Let $\mathcal{OWS}^w$ be an OAuth web system with web attackers, then $\mathcal{OWS}^w$ is secure w.r.t. session integrity for authorization and authentication.

Note that this trivially implies that authentication and authorization properties are satisfied also if web attackers are considered.

5.3. Discussion of Results

Our results show that the OAuth standard is secure, i.e., provides strong authentication, authorization, and session integrity properties, when (1) fixed according to our proposal and (2) when adhering to the OAuth security recommendations and best practices, as explained in Section 5.1. Depending on individual implementation choices, (2) is potentially not satisfied in all practical scenarios. For example, RPs might run untrusted JavaScript on their websites. Nevertheless, our security results, for the first time, give precise implementation guidelines for OAuth to be secure and also clearly show that if these guidelines are not followed, then the security of OAuth cannot be guaranteed.

6. Related Work

We focus on work closely related to OAuth 2.0 or formal security analysis of web standards and web applications.

The work closest to our work is the already mentioned work by Bansal, Bhargavan, Delignat-Lavaud, and Maffeis [6]. Bansal et al. analyze the security of OAuth using the applied pi-calculus and the WebSpi library, along with the protocol analysis tool ProVerif. They model various settings of OAuth 2.0, often assuming the presence of common web implementation flaws resulting in, for example, CSRF and open redirectors in RPs and IdPs. They identify previously unknown attacks on the OAuth implementations of Facebook, Yahoo, Twitter, and many other websites. Compared to our work, the WebSpi model used in [6] is less expressive and comprehensive (see also the discussion in [14]), and the models of

OAuth they employ are more limited.[16] As pointed out by Bansal et al., the main focus of their work is to discover attacks on OAuth, rather than proving security. They have some positive results, which, however, are based on their more limited model. In addition, in order to prove these results further restrictions are assumed, e.g., they consider only one IdP per RP and all IdPs are assumed to be honest.

Wang et al. [42] present a systematic approach to find implicit assumptions in SDKs (e.g., the Facebook PHP SDK) used for authentication and authorization, including SDKs that implement OAuth 2.0.

In [32], Pai et al. analyze the security of OAuth in a very limited model that does not incorporate generic web features. They show that using their approach, based on the Alloy finite-state model checker, known weaknesses can be found. The same tool is used by Kumar [27] in a formal analysis of the older OAuth 1.0 protocol (which, as mentioned, is very different to OAuth 2.0).

Chari, Jutla, and Roy [9] analyze the security of the authorization code mode in the universally composability model, again without considering web features, such as semantics of HTTP status codes, details of cookies, or window structures inside a browser.

Besides these formal approaches, empirical studies were conducted on deployed OAuth implementations. In [41], Sun and Beznosov analyze the security of three IdPs and 96 RPs. In [28], Li and Mitchell study the security of 10 IdPs and 60 RPs based in China. In [43], Yang et al. perform an automated analysis of 4 OAuth IdPs and 500 RPs. Shernan et al. [39] evaluate the lack of CSRF protection in various OAuth deployments. In [10,38], practical evaluations on the security of OAuth implementations of mobile apps are performed.

In [30], Mladenov et al. perform an informal analysis of OpenID Connect. They present several attacks related to discovery and dynamic client registration, which are extensions of OpenID Connect; see also the discussion in Section 3.2 (related attacks) concerning their malicious endpoint attack.

Note that many of the works listed here led to improved security recommendations for OAuth as listed in RFC6749 [21] and RFC6819 [29]. These are already taken into account in our model and analysis of OAuth.

More generally, there have been only very few analysis efforts for web applications and standards based on formal web models so far. Work outside of the context of OAuth includes [2–5,14,16,17,26].

7. Conclusion

In this paper, we carried out the first extensive formal analysis of OAuth 2.0 based on a comprehensive and expressive web model. Our analysis, which aimed at the standard itself, rather than specific OAuth implementations and deployments, comprises all modes (grant types) of OAuth and available options and also takes malicious RPs and IdPs as well as corrupted browsers/users into account. The generic web model underlying our model of OAuth and its analysis is the most comprehensive web model to date.

Our in-depth analysis revealed four attacks on OAuth as well as OpenID connect, which builds on OAuth. We verified the attacks, proposed fixes, and reported the attacks and our fixes to the working groups for OAuth and OpenID Connect. The working groups confirmed the attacks. Fixes to the standard and recommendations are currently under discussion or already incorporated in a draft for a new RFC [24].

With the fixes applied, we were able to prove strong authorization, authentication, and session integrity properties for OAuth 2.0. Our security analysis assumes that OAuth security recommendations and

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[16]For example, only two OAuth modes are considered, the model is monotonic (e.g., cookies can only be added, but not deleted or modified), fixed bounded number of cookies per request, no precise handling of windows, documents, and iframes, no web messaging, omission of headers, such as origin. We note that while OAuth does not make use of all web features, taking such features into account is important to make positive security results more meaningful.

certain best practices are followed. We show that otherwise the security of OAuth cannot be guaranteed. By this, we also provide clear guidelines for implementations. The fact that OAuth is one of the most widely deployed authorization and authentication systems in the web and the basis for other protocols makes our analysis particularly relevant.

As for future work, our formal analysis of OAuth offers a good starting point for the formal analysis of OpenID Connect, and hence, such an analysis is an obvious next step for our research.

8. Acknowledgements

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A. OAuth 2.0

The OAuth authorization code mode was presented in Section 2. Here, we present the three other OAuth modes in detail.

A.1. Preliminaries

We now first provide some preliminary information regarding OAuth.

Endpoints. In OAuth, RPs and IdPs have to provide certain URIs to each other. The parties and services these URIs point to are called *endpoints*; often the URIs themselves are called endpoints. An IdP provides an *authorization endpoint* at which the user can authenticate to the IdP and authorize an RP to access her user data. The IdP also provides a *token endpoint* at which the RP can request access tokens. An RP provides one or more *redirection endpoints* to which the user's browser gets redirected by an IdP after the user authenticated to the IdP. The URIs of the endpoints are not fixed by the standard, but are communicated when RPs register at IdPs, as described below.

The OAuth standard [21] and the accompanying security recommendations [29] suggest that all endpoints use HTTPS. We follow this recommendation in our analysis of OAuth.

Registration. Before an RP can interact with an IdP, the RP needs to be registered at the IdP. The details of the registration process are out of the scope of the OAuth protocol. In practice, this process is usually a manual task. During the registration process, the IdP assigns to the RP a fixed OAuth client id and client secret.[17] The RP may later use the client secret to authenticate to the IdP. If the RP cannot keep the OAuth client secret confidential, e.g., if the RP is an in-browser app or a native application, the secret can be omitted. Note that the OAuth client id is public information. It is, for example, revealed to users in redirects issued by the RP.

Also, an RP registers one or more redirection endpoints at an IdP. As we will see below, in some OAuth modes, the IdP redirects the user's browser to one of these redirect URIs. If more than one redirect URI is registered, the RP must specify which redirect URI is to be used in each run of the OAuth protocol. For simplicity of presentation, we will assume that an RP always specifies its choice, although this can be omitted if there exits only one (fixed) redirect URI. Note that (depending on the implementation of an IdP) an RP may also register a pattern as a redirect URI and then specify the exact redirect URI during the OAuth run. In this case, the IdP checks if the specified redirect URI matches this pattern.

During the registration process, the (fixed) endpoints belonging to an IdP are configured at an RP as well.

Our analysis presented in Section 5 covers all the above mentioned options: absence and presence of client secrets, specified redirect URIs, and URI patterns.

Login Sessions. As mentioned before, in some OAuth modes, an RP redirects the user's browser to an IdP which later redirects the browser back to the RP. In order to prevent cross-site request forgery (CSRF) attacks, the RP typically establishes a session with the browser before the first redirect. The OAuth standard recommends that an RP selects the so-called *state* parameter and binds this value to the session, e.g., by choosing a fresh nonce and storing the nonce in the session state. When the user later gets redirected back to the RP, the *state* value must be identical. The intention is that this value should always be unknown to an attacker in order to prevent CSRF attacks. In our analysis, we follow the recommendation of using the *state* parameter.[18]

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[17]Recall that in the terminology of the OAuth standard the term "client" stands for RP.

[18]Note that the OAuth standard [21] as well as the accompanying security recommendations [29] do not specify the session
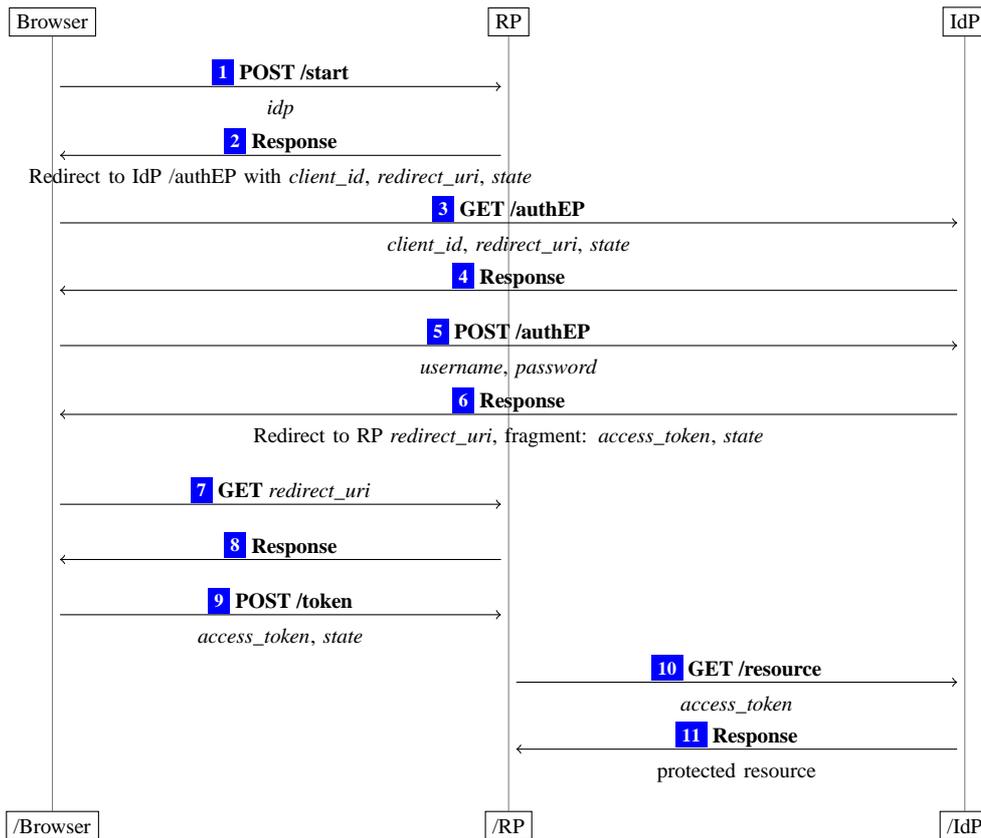
Figure 4. OAuth 2.0 implicit mode

Further Recommendations and Options. The standard and the recommendations do not specify all implementation details. For example, the precise user interaction with an RP, formatting details of messages, and the authentication of the user to an IdP (e.g., user name and password or some other mechanism) are not covered. In our security analysis of OAuth we follow all OAuth security recommendations as well as common best practices for state-of-the-art web applications in order to avoid known attacks.

OAuth allows RPs to specify which *scope* of the user's data they are requesting access to at an IdP. The scopes themselves are not defined in the standard and are considered an implementation detail of IdPs. Therefore, in our description and analysis of OAuth, we omit the scope parameter and assume that the user always grants full access to her data at the IdP.

A.2. OAuth Modes

Implicit Mode. This mode is a simplified version of the authorization code mode: instead of providing an authorization code to an RP, an IdP directly delivers an access token to the RP (via the user's browser).

Step-by-Step Protocol Flow. We now provide a step-by-step description of the protocol flow (see also Figure 4). As in the authorization code mode, the user starts the OAuth flow, e.g., by clicking on a button to select an IdP, triggering the browser to send request 1 to the RP. The RP selects the redirect

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mechanism for RPs. In our analysis we assume the usual session mechanism with session cookies following common best practices. For more details, see Section 5.1.
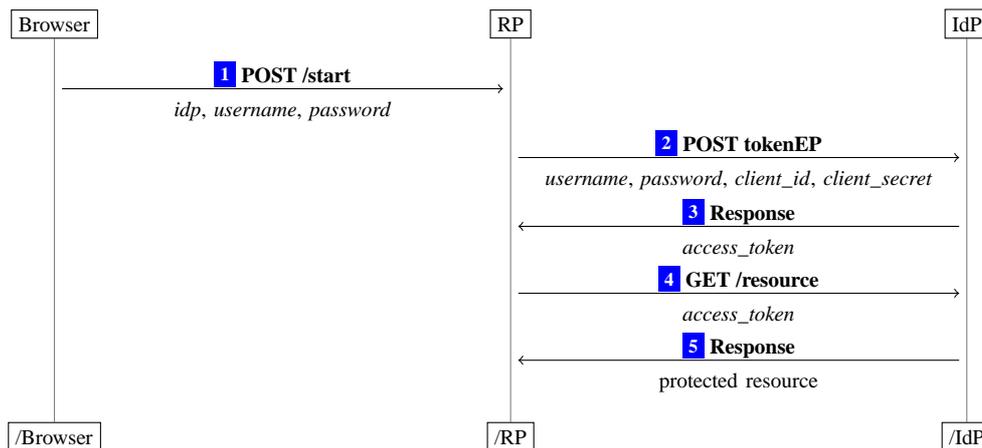
Figure 5. OAuth 2.0 resource owner password credentials mode

URI *redirect_uri* (which will be used later in [7]) and a value *state*. The RP then redirects the browser with its *client_id*, *redirect_uri*, and *state* to the authorization endpoint at the IdP[19] in [2] and [3]. The IdP prompts the user to enter her username and password in [4]. The user's browser sends this information to the IdP in [5]. If the user's credentials are correct, the IdP creates an access token *access_token* and redirects the user's browser to the RP's redirection endpoint *redirect_uri* in [6] and [7], where the IdP appends *access_token* and *state* to the fragment of the redirection URI. (Recall that a fragment is a special part of a URI indicated by the '#' symbol. When the browser opens a URI, the information in the fragment is not transferred to the server.) Hence, in Step [7] *access_token* and *state* are not transferred to the RP. To retrieve these values, the RP in [8] delivers a document containing JavaScript code. It retrieves *access_token* and *state* from the fragment and sends these to the RP in [9]. The RP then checks if *state* is the same as above. Just as in the authorization code mode, the RP can now use *access_token* for authorization (illustrated in Steps [10] and [11]); authentication is analogous to Steps [12], [13], and [14] of Figure 1.

For authentication, note that the response from the IdP includes the RP's OAuth client id, which is also checked by the RP. This check prevents re-usage of access tokens across RPs in the OAuth implicit mode as explained in [42].

We note that in the implicit mode, an IdP cannot verify the identity of the receiver of the access token, as an RP does not authenticate itself to the IdP (using *client_secret*). Hence, this mode is more suitable for RPs that do not have access to a secure, long-lived storage (for a *client_secret*) such as in-browser applications.

Resource Owner Password Credentials Mode. In this mode, the user gives her credentials for an IdP directly to an RP. The RP can then authenticate to the IdP on the user's behalf and retrieve an access token. The resource owner password credentials mode is intended for highly-trusted RPs, such as the operating system of the user's device or highly-privileged applications, or if the previous two modes are not possible to perform (e.g., for applications without a web browser). In the following, we assume that the authorization/login process is started by the user using a web browser.

Step-by-Step Protocol Flow. We now provide a step-by-step description of the resource owner password credentials mode (see also Figure 5): The user provides her username and password for the IdP to the

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[19]Note that also a fixed string "token" indicating to the IdP that implicit mode is used is appended as a parameter to the URI.
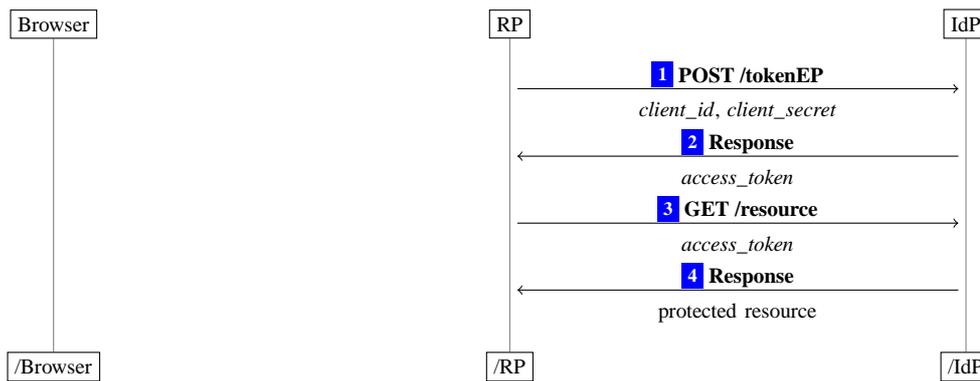
Figure 6. OAuth 2.0 client credentials mode

RP in ①. Now, the RP sends the username, the password, its *client_id* and *client_secret*[20] to the IdP in ②. The IdP then issues an access token *access_token* to the RP in ③.[21] Just as in the authorization code mode, the RP can now use *access_token* for authorization (illustrated in Steps ④ and ⑤) and authentication (as in Steps ⑫, ⑬, and ⑭ of Figure 1).

Client Credentials Mode. In contrast to the modes shown above, this mode works without the user's interaction. Instead, it is started by an RP in order to fetch an access token to access RP's own resources at an IdP or to access resources at an IdP the RP is authorized to by other means. For example, Facebook allows RPs to use the client credentials mode to obtain an access token to access reports of their advertisements' performance.

Step-by-Step Protocol Flow. The step-by-step description of the client credentials mode is as follows (see also Figure 6): First, the RP contacts the IdP with RP's *client_id* and *client_secret* in ①. The IdP now issues an *access_token* in ②. Just as in the authorization code mode, the RP can now use *access_token* for authorization (illustrated in Steps ③ and ④). In contrast to the other modes presented above, the access token is not bound to a specific user account, but only to the RP.

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[20]Note that in this mode, if an RP does not have an OAuth client secret for an IdP, the *client_secret* and *client_id* parameters are *both* omitted in this request. This option is also covered by our analysis.

[21]As in the authorization code mode, an IdP may also issue a refresh token to the RP here.

B. IdP Mix-Up Attack in the OAuth Implicit Mode

Here, we present the IdP Mix-Up attack in the implicit mode. It is depicted in Figure 7.

Just as in the authorization code mode, the attack starts when the user selects that she wants to log in using HIdP (Step 1 in Figure 7). Now, the attacker intercepts the request intended for the RP and modifies the content of this request by replacing HIdP by AIdP. The response of the RP 3 (containing a redirect to AIdP) is then again intercepted and modified by the attacker such that it redirects the user to HIdP 4. The attacker also replaces the OAuth client id of the RP at AIdP with the client id of the RP at HIdP.[22] (Note that we assume that from this point on, in accordance with the OAuth security recommendations, the communication between the user's browser and HIdP and the RP is encrypted by using HTTPS, and thus, cannot be inspected or altered by the attacker.) The user then authenticates to HIdP and is redirected back to the RP 8. The RP, however, still assumes that the access token contained in this redirect is an access token issued by AIdP, rather than HIdP. The RP therefore now uses this access token to retrieve protected resources of the user (or the user id) at AIdP 12, rather than HIdP. This leaks the access token to the attacker who can now access protected resources of the user at IdP. This breaks the authorization property (see Section 5.2 below). (We note that at this point, the attacker might even provide false information about the user or her protected resources to the RP.)

To break authentication and impersonate the honest user, the attacker now starts a new login process (using his own browser) at the RP. In 13 he selects HIdP as the IdP for this login process. He receives a redirect to HIdP, which he skips.[23] The attacker now sends the access token *access_token* captured in Step 12 to the RP imitating a real login 15. The RP now uses this access token to retrieve the user id at HIdP 16 and receives the (honest) user's id as well as its own OAuth client id 17. Being convinced that the attacker owns the honest user's account, the RP issues a session cookie for this account to the attacker 18. As a result, the attacker is logged in at the RP under the honest user's id. This breaks the authentication property of OAuth (see Section 5.2 below).

B.1. OpenID Connect and the Attacks on this Standard

We here provide a more detailed description of the OpenID Connect standard as well as on the two attacks, 307 redirect and IdP mix-up, on it.

Modes and Protocol Flow. OpenID Connect makes use of the OAuth authorization code mode and the implicit mode (both OAuth modes constitute an OpenID Connect mode), but also introduces a new *hybrid* mode, which combines both modes.

Overview. From a high-level perspective, first, the RP retrieves meta data about the IdP, such as the URLs of the IdP used in the protocol. This is the information that is "hard-wired" in the manual, out-of-band registration in a classic OAuth setup. Next, the RP automatically registers itself as an OAuth client at the IdP (using OpenID Connect dynamic client registration). Then, the OAuth protocol is started (using one of the modes mentioned above). In addition to an access token this (extended) run delivers a so-called *id token* to RP. The id token is issued by the IdP and contains a unique user identifier along with several meta data, such as the intended receiver (the RP) of the id token and the issuer of the id token (the IdP). The id token is (optionally) signed by the IdP. Finally, the RP can retrieve more meta data about the user at the *userinfo* endpoint at the IdP using the access token and consider the user to be logged in.

Step-by-Step Protocol Flow. In the step-by-step description below (see also Figure 8), we focus on the

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[22] As mentioned above, OAuth client ids are public information.

[23] Note that this redirect contains (besides a cookie for a new login session) a fresh state parameter, say *state'*. The attacker will use this information in subsequent requests to the RP.

Browser   RP   Attacker (AIdP)   HIdP

1 **POST /start**

idp

2 **POST /start**

attacker

3 **Response**

Redirect to Attacker /authEP with *client_id'*, *redirect_uri*, *state*

4 **Response**

Redirect to HIdP /authEP with *client_id*, *redirect_uri*, *state*

5 **GET /authEP**

client_id, *redirect_uri*, *state*

6 **Response**

7 **POST /authEP**

username, *password*

8 **Response**

Redirect to RP *redirect_uri*, fragment: *access_token*, *state*

9 **GET** *redirect_uri*

10 **Response**

11 **POST /token**

access_token, *state*

12 **GET /resource**

access_token

- -

Continued attack to break authentication:

13 **POST /start**

idp

14 **Response**

Redirect to HIdP /authEP with *client_id*, *redirect_uri*, *state'*

15 **POST /token**

access_token, *state'*

16 **GET /introspectionEP**

access_token

17 **Response**

user_id, *client_id*

18 **Response**

session_cookie

/Browser   /RP   /Attacker (AIdP)   /HIdP

Figure 7. IdP Mix-Up Attack on OAuth 2.0 implicit mode
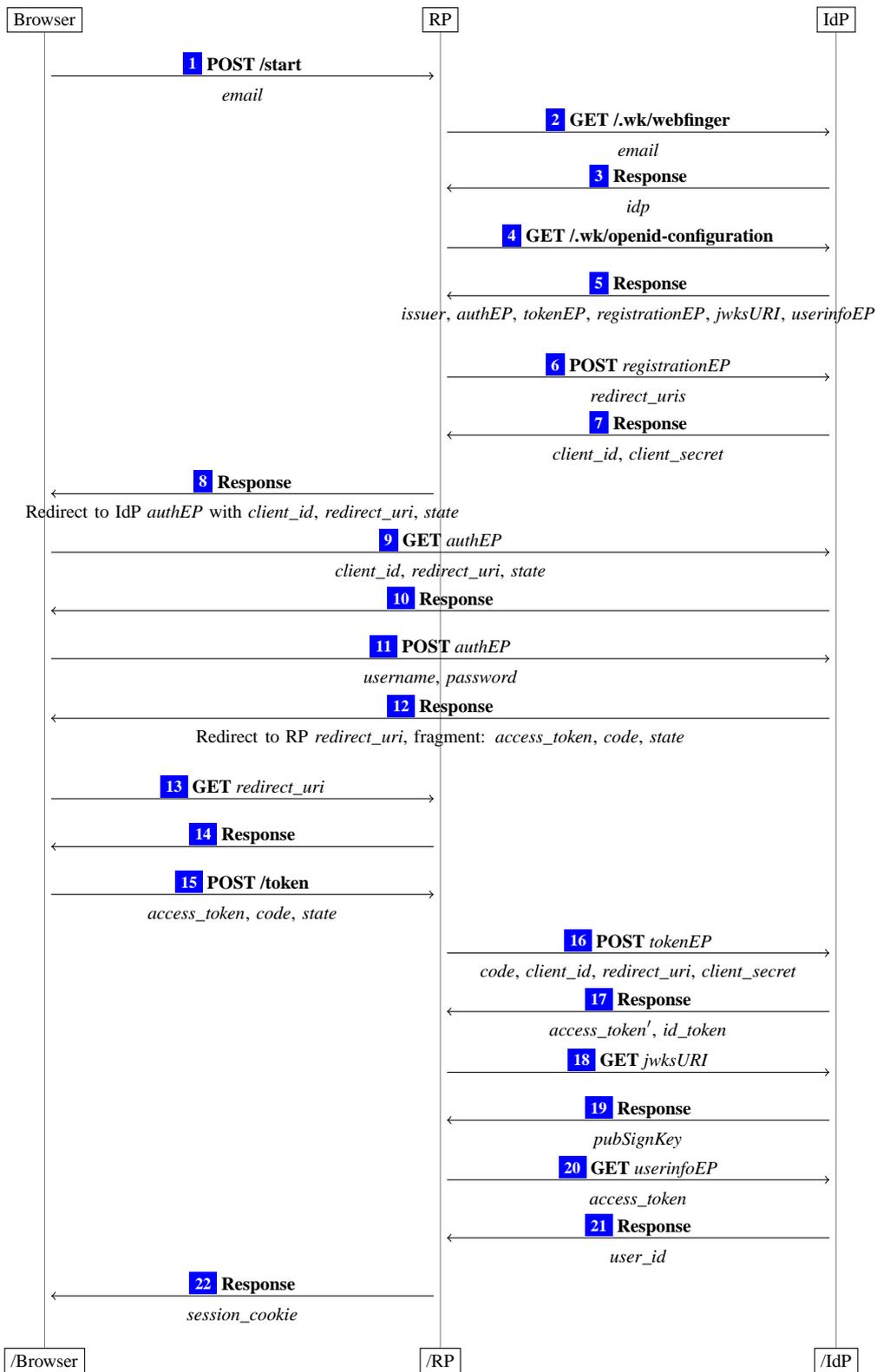
Figure 8. OpenID Connect 1.0 hybrid mode with discovery and dynamic client registration

hybrid mode only. First, the user starts the login process by entering her email address[24] in her browser (at some web page of an RP), which sends the email address to the RP in ①.

Now, the RP uses the OpenID Connect Discovery protocol [36] to gain information about the IdP: The RP uses the WebFinger [25] mechanism to discover information about which IdP is responsible for this user. For this discovery, the RP contacts the server of the user's email domain (depicted as the same party as the IdP in the figure) in ②. The result of the WebFinger request in ③ contains the domain of the server responsible for the OpenID Connect configuration (the IdP). The configuration is requested from the IdP in ④ and returned in ⑤. The configuration contains meta data about the IdP, including all endpoints at the IdP. This concludes the OpenID Discovery in this login flow.

Next, if the RP is not registered at the IdP, the RP starts the OpenID Connect dynamic client registration [34] protocol: the RP contacts the IdP in ⑥ providing its redirect URIs. Now, the IdP issues an (OAuth) client id and (optionally) an (OAuth) client secret to the RP in ⑦. This concludes the OpenID Connect dynamic client registration.

Now, the core part of the OpenID Connect protocol (based on OAuth) starts: the RP redirects the user's browser to the IdP in ⑧. This redirect contains information that the hybrid mode is used and which tokens are requested. In this description, we assume that an authorization code and an access token are requested.[25] Also, this redirect contains the (OAuth) client id of the RP, a redirect URI and a state value. As in the OAuth flows, this data is sent to the IdP in ⑨, the user authenticates to the IdP ⑩, ⑪, and the IdP redirects the user's browser back to the RP in ⑫ and ⑬ (using the redirect URI from the request in ⑨). This redirect contains an authorization code, an access token, and the state value in the fragment part of the URL.[26] Now, the RP in ⑭ sends a document containing JavaScript code which sends the parameters contained in the fragment back to the RP (in ⑮). If the state value matches, the RP contacts the IdP in ⑯ with the received authorization code, its (OAuth) client id, its (OAuth) client secret, and the redirect URI used to obtain the authorization code. The IdP sends a response with the same or a fresh access token and an id token to the RP in ⑰. Now, the RP retrieves the key that was used to sign the id token from the IdP in ⑱ and ⑲ and verifies the id token's signature. As the id token typically contains only a unique user identifier, but no other meta data about the user, RP requests this meta data (such as nickname, birthday, or address) from the IdP in ⑳ and ㉑ using one of the authorization tokens received before. Finally, the RP considers the user to be logged in and may set a session cookie at the user's browser in ㉒.

Note that the authorization code mode and the implicit mode are similar to the hybrid mode: Roughly speaking, the Steps ⑫–⑰ of the OpenID Connect hybrid mode are replaced by the corresponding steps of the OAuth authorization code or implicit mode, respectively. These OAuth modes are then extended with the transfer of an id token. In the authorization code mode, the id token is appended to the response ⑨ of Figure 1 and in the implicit mode, the id token is appended to the fragment of the redirect URI in ⑥ of Figure 4 (and later sent to the RP in Step ⑨).

The 307 Redirect Attack. The 307 redirect attack presented in Section 3.1 can also be applied to OpenID Connect. Note that the critical part of OAuth, namely the redirect of the user's browser from the IdP to the RP after the authentication of the user to the IdP, is also present in OpenID Connect. Hence, if the IdP uses an HTTP status 307 redirect immediately after the user's browser has transferred the user's credentials to IdP in a POST request, the RP receives these credentials.

The IdP Mix-Up Attack. When applying the attack presented in Section 3.2 to OpenID Connect, the attacker needs to circumvent some additional security measures: In the implicit mode of OpenID Connect, an *id_token* (as described above) is sent along with *access_token* in the redirect from HIdP

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[24]Note that OpenID Connect also allows other types of user identifiers, such as a personal URL.

[25]The Hybrid Flow allows to request several different combinations of authorization code, access token, and id token.

[26]Note that depending on the parameters in step ⑨, also an id token may be contained in the fragment part of the URL.

Browser | RP | Attacker (AIdP) | HIdP

1 POST /start
email

2 POST /start
email′

3 GET /.wk/webfinger
email′

4 Response
attacker

5 GET /.wk/openid-configuration

6 Response
issuer′, authEP, tokenEP′, registrationEP′, jwksURI, userinfoEP′,
responseTypes

7 POST *registrationEP′*
redirect_uris

8 Response
client_id, client_secret′

9 Response
Redirect to HIdP *authEP* with *client_id, redirect_uri, state*

10 GET *authEP*
client_id, redirect_uri, state

11 Response

12 POST *authEP*
username, password

13 Response
Redirect to RP *redirect_uri*, fragment: *access_token, code, state*

14 GET *redirect_uri*

15 Response

16 POST /token
access_token, code, state

17 POST *tokenEP′*
code, client_id, redirect_uri, client_secret′

18 Response
access_token′, id_token

19 GET *userinfoEP*
access_token

20 GET /protectedResource
access_token

21 Response
secret user data

/Browser | /RP | /Attacker (AIdP) | /HIdP

Figure 9. Attack on OpenID Connect 1.0 hybrid mode with discovery and dynamic client registration

to the RP. As this redirect might use HTTPS, the attacker cannot inspect or modify the corresponding network messages. As mentioned above, the id token contains the domain of the issuer of both, the access token and the id token. Therefore, the RP can detect that the user did not use AIdP (which the RP redirected to).

An attacker could try to use the authorization code mode of OpenID Connect to mount a similar attack as described above. In this case, however, the attacker does not learn a valid access token for the user's account at HIdP if a client secret is used.

In the hybrid mode, however, an attacker can learn an access token and mount the attack as follows (see also Figure 9):

As above, the user first visits the RP. When the user sends her email address to the RP in order to login ①, the attacker manipulates the domain part of the email address, to be the domain of AIdP ②. The RP then looks up the IdP to be used (which is now AIdP) using the WebFinger protocol in Steps ③ and ④. The RP fetches the OpenID Connect configuration from the attacker (⑤ and ⑥). In this document, the attacker states that the authorization endpoint is located at HIdP while all other endpoints are located at the attacker. Using parameters not shown in the figures, the attacker can also state that this IdP does not support delivering an id token in the redirect and can state that no signatures are supported. Since no signatures need to be checked, also the key retrieval is skipped in the protocol.

After retrieving the OpenID configuration, the RP registers at AIdP, as the attacker uses a domain previously unknown to the RP. (If the domain was known to the RP, this step would be skipped.) The attacker issues the same *client_id* with which the RP is registered at HIdP (⑦ and ⑧). Now, the RP redirects the user's browser to HIdP in order to log in. After the user authenticated to HIdP, HIdP redirects the user's browser back to the RP. The fragment part of the URL contains an authorization code and an access token ⑭. The RP then sends the authorization code to the attacker in ⑰.

If the RP does not have a client secret registered at HIdP, the attacker can redeem this authorization code at HIdP in order to receive an access token to access the honest user's protected resources at HIdP. This breaks the authorization of OpenID Connect (compare the OAuth authorization property in Section 5.2).

Alternatively, the attacker responds to the RP with a faked access token and a faked id token ⑱ (which the attacker can create, because he controls all security settings for this id token, see Step ⑥).

Next, the RP retrieves other meta information about the user from AIdP. The RP is now in possession of two access tokens. The OpenID Connect standard explicitly allows this situation, but fails to state which access token has to be used in subsequent requests. The RP can now chose either of the access tokens for the next steps, with different outcomes for the attacker:

First Access Token is Selected. In this case the access token originating from HIdP is selected by the RP and sent to the attacker ⑲. (This behavior was observed by us in the real-world implementation mod_auth_openidc.)

Now the attacker can use this access token to access other protected resources of the user at HIdP. This breaks authorization for OpenID Connect (compare our OAuth authorization property in Section 5.2).

Second Access Token is Selected. In this case the access token originating from AIdP is selected. This means that the attacker does not learn a valid access token for HIdP. The attacker can, however, reuse the authorization code for HIdP, which he learned in ⑰ and which is still valid as it has not been redeemed at HIdP, yet. Using this method, the attacker can impersonate the honest user at the RP. To accomplish this, the attacker starts a new login flow at the RP with the user's email address. In Step ⑮ of Figure 8, he provides the authorization code he has learned along with some (invalid) access token and the state from his (new) login flow to the RP. The RP then requests an access token and an id token from HIdP with this (still valid) authorization code. The RP receives a valid access token and a valid id token (for the honest user) from HIdP. As the RP uses this valid access token in this case, all subsequent requests from

the RP to HIdP are successful and the RP receives the user id of the honest user, the RP considers the attacker to be logged in as the honest user. This breaks the authentication of OpenID Connect (compare our OAuth authentication property in Section 5.2).

$$\mathsf{dec_a}(\mathsf{enc_a}(x, \mathsf{pub}(y)), y) = x \tag{1}$$

$$\mathsf{dec_s}(\mathsf{enc_s}(x, y), y) = x \tag{2}$$

$$\mathsf{checksig}(\mathsf{sig}(x, y), x, \mathsf{pub}(y)) = \top \tag{3}$$

$$\mathsf{extractmsg}(\mathsf{sig}(x, y)) = x \tag{4}$$

$$\pi_i(\langle x_1, \ldots, x_n \rangle) = x_i \ \ \text{if } 1 \le i \le n \tag{5}$$

$$\pi_j(\langle x_1, \ldots, x_n \rangle) = \diamond \ \ \text{if } j \notin \{1, \ldots, n\} \tag{6}$$

Figure 10. Equational theory for Σ

C. The FKS Web Model

In this and the following two sections, we present the FKS model for the web infrastructure as proposed in [14] and [15], along with the following changes and additions:

- We introduce a new header, `Authorization`, as a model for HTTP Basic Authentication.[27]

- Browsers now may have multiple passwords stored for a single origin; before, there was only one password for each origin.

- We introduce the header `ReferrerPolicy` as a model for a referrer policy delivered in an HTTP response header.

C.1. Communication Model

We here present details and definitions on the basic concepts of the communication model.

Terms, Messages and Events. The signature Σ for the terms and messages considered in this work is the union of the following pairwise disjoint sets of function symbols:

- constants $C = \mathsf{IPs} \cup \mathbb{S} \cup \{\top, \bot, \diamond\}$ where the three sets are pairwise disjoint, $\mathbb{S}$ is interpreted to be the set of ASCII strings (including the empty string ε), and IPs is interpreted to be a set of (IP) addresses,

- function symbols for public keys, (a)symmetric encryption/decryption, and signatures: $\mathsf{pub}(\cdot)$, $\mathsf{enc_a}(\cdot, \cdot)$, $\mathsf{dec_a}(\cdot, \cdot)$, $\mathsf{enc_s}(\cdot, \cdot)$, $\mathsf{dec_s}(\cdot, \cdot)$, $\mathsf{sig}(\cdot, \cdot)$, $\mathsf{checksig}(\cdot, \cdot, \cdot)$, and $\mathsf{extractmsg}(\cdot)$,

- n-ary sequences $\langle \rangle, \langle \cdot \rangle, \langle \cdot, \cdot \rangle, \langle \cdot, \cdot, \cdot \rangle$, etc., and

- projection symbols $\pi_i(\cdot)$ for all $i \in \mathbb{N}$.

For strings (elements in $\mathbb{S}$), we use a specific font. For example, `HTTPReq` and `HTTPResp` are strings. We denote by $\mathsf{Doms} \subseteq \mathbb{S}$ the set of domains, e.g., `example.com` $\in \mathsf{Doms}$. We denote by $\mathsf{Methods} \subseteq \mathbb{S}$ the set of methods used in HTTP requests, e.g., `GET`, `POST` $\in \mathsf{Methods}$.

The equational theory associated with the signature Σ is given in Figure 10.

Definition 1 (Nonces and Terms). By $X = \{x_0, x_1, \ldots\}$ we denote a set of variables and by $\mathcal{N}$ we denote an infinite set of constants (*nonces*) such that Σ, X, and $\mathcal{N}$ are pairwise disjoint. For $N \subseteq \mathcal{N}$, we define the set $\mathcal{T}_N(X)$ of *terms* over $\Sigma \cup N \cup X$ inductively as usual: (1) If $t \in N \cup X$, then t is a term. (2) If $f \in \Sigma$ is an n-ary function symbol in Σ for some $n \ge 0$ and $t_1, \ldots, t_n$ are terms, then $f(t_1, \ldots, t_n)$ is a term.

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[27] Note that although the header is called "Authorization" (following RFC2617), this is a mechanism for authentication.

By $\equiv$ we denote the congruence relation on $\mathcal{T}_{\mathcal{N}}(X)$ induced by the theory associated with Σ. For example, we have that $\pi_1(\mathsf{dec_a}(\mathsf{enc_a}(\langle \mathsf{a}, \mathsf{b} \rangle, \mathsf{pub}(k)), k)) \equiv \mathsf{a}$.

Definition 2 (Ground Terms, Messages, Placeholders, Protomessages). By $\mathcal{T}_N = \mathcal{T}_N(\emptyset)$, we denote the set of all terms over $\Sigma \cup N$ without variables, called *ground terms*. The set $\mathcal{M}$ of messages (over $\mathcal{N}$) is defined to be the set of ground terms $\mathcal{T}_{\mathcal{N}}$.

We define the set $V_{\text{process}} = \{\nu_1, \nu_2, \dots\}$ of variables (called *placeholders*). The set $\mathcal{M}^{\nu} := \mathcal{T}_{\mathcal{N}}(V_{\text{process}})$ is called the set of *protomessages*, i.e., messages that can contain placeholders.

Example 1. For example, $k \in \mathcal{N}$ and $\mathsf{pub}(k)$ are messages, where k typically models a private key and $\mathsf{pub}(k)$ the corresponding public key. For constants a, b, c and the nonce $k \in \mathcal{N}$, the message $\mathsf{enc_a}(\langle a, b, c \rangle, \mathsf{pub}(k))$ is interpreted to be the message $\langle a, b, c \rangle$ (the sequence of constants a, b, c) encrypted by the public key $\mathsf{pub}(k)$.

Definition 3 (Normal Form). Let t be a term. The *normal form* of t is acquired by reducing the function symbols from left to right as far as possible using the equational theory shown in Figure 10. For a term t, we denote its normal form as $t \downarrow$.

Definition 4 (Pattern Matching). Let *pattern* $\in \mathcal{T}_{\mathcal{N}}(\{*\})$ be a term containing the wildcard (variable $*$). We say that a term t *matches pattern* iff t can be acquired from *pattern* by replacing each occurrence of the wildcard with an arbitrary term (which may be different for each instance of the wildcard). We write $t \sim pattern$. For a sequence of patterns *patterns* we write $t \dot\sim patterns$ to denote that t matches at least one pattern in *patterns*.

For a term t' we write $t' | pattern$ to denote the term that is acquired from t' by removing all immediate subterms of t' that do not match *pattern*.

Example 2. For example, for a pattern $p = \langle \top, * \rangle$ we have that $\langle \top, 42 \rangle \sim p$, $\langle \bot, 42 \rangle \not\sim p$, and

$$\langle \langle \bot, \top \rangle, \langle \top, 23 \rangle, \langle \mathsf{a}, \mathsf{b} \rangle, \langle \top, \bot \rangle \rangle | p = \langle \langle \top, 23 \rangle, \langle \top, \bot \rangle \rangle .$$

Definition 5 (Variable Replacement). Let $N \subseteq \mathcal{N}$, $\tau \in \mathcal{T}_N(\{x_1, \dots, x_n\})$, and $t_1, \dots, t_n \in \mathcal{T}_N$.

By $\tau[t_1/x_1, \dots, t_n/x_n]$ we denote the (ground) term obtained from τ by replacing all occurrences of x_i in τ by t_i, for all $i \in \{1, \dots, n\}$.

Definition 6 (Events and Protoevents). An *event (over* IPs *and* $\mathcal{M}$ *)* is a term of the form $\langle a, f, m \rangle$, for $a, f \in$ IPs and $m \in \mathcal{M}$, where a is interpreted to be the receiver address and f is the sender address. We denote by $\mathcal{E}$ the set of all events. Events over IPs and $\mathcal{M}^{\nu}$ are called *protoevents* and are denoted $\mathcal{E}^{\nu}$. By $2^{\mathcal{E}\langle\rangle}$ (or $2^{\mathcal{E}^{\nu}\langle\rangle}$, respectively) we denote the set of all sequences of (proto)events, including the empty sequence (e.g., $\langle\rangle$, $\langle \langle a, f, m \rangle, \langle a', f', m' \rangle, \dots \rangle$, etc.).

Atomic Processes, Systems and Runs.

An atomic process takes its current state and an event as input, and then (non-deterministically) outputs a new state and a set of events.

Definition 7 (Generic Atomic Processes and Systems). A *(generic) atomic process* is a tuple

$$p = (I^p, Z^p, R^p, s_0^p)$$

where $I^p \subseteq$ IPs, $Z^p \in \mathcal{T}_{\mathcal{N}}$ is a set of states, $R^p \subseteq (\mathcal{E} \times Z^p) \times (2^{\mathcal{E}^{\nu}\langle\rangle} \times \mathcal{T}_{\mathcal{N}}(V_{\text{process}}))$ (input event and old state map to sequence of output events and new state), and $s_0^p \in Z^p$ is the initial state of p. For any new state s and any sequence of nonces $(\eta_1, \eta_2, \dots)$ we demand that $s[\eta_1/\nu_1, \eta_2/\nu_2, \dots] \in Z^p$. A *system* $\mathcal{P}$ is a (possibly infinite) set of atomic processes.

Definition 8 (Configurations). A *configuration of a system* $\mathcal{P}$ is a tuple (S,E,N) where the state of the system S maps every atomic process $p \in \mathcal{P}$ to its current state $S(p) \in Z^p$, the sequence of waiting events E is an infinite sequence[28] $(e_1, e_2, \dots)$ of events waiting to be delivered, and N is an infinite sequence of nonces $(n_1, n_2, \dots)$.

Definition 9 (Concatenating sequences). For a term $a = \langle a_1, \dots, a_i \rangle$ and a sequence $b = (b_1, b_2, \dots)$, we define the *concatenation* as $a \cdot b := (a_1, \dots, a_i, b_1, b_2, \dots)$.

Definition 10 (Subtracting from Sequences). For a sequence X and a set or sequence Y we define $X \setminus Y$ to be the sequence X where for each element in Y, a non-deterministically chosen occurence of that element in X is removed.

Definition 11 (Processing Steps). A *processing step of the system* $\mathcal{P}$ is of the form

$$(S,E,N) \xrightarrow[p \to E_{\text{out}}]{e_{\text{in}} \to p} (S', E', N')$$

where

1. (S,E,N) and (S',E',N') are configurations of $\mathcal{P}$,

2. $e_{\text{in}} = \langle a, f, m \rangle \in E$ is an event,

3. $p \in \mathcal{P}$ is a process,

4. E_{out} is a sequence (term) of events

such that there exists

1. a sequence (term) $E_{\text{out}}^{\nu} \subseteq 2^{\mathcal{E}^{\nu} \langle \rangle}$ of protoevents,

2. a term $s^{\nu} \in \mathcal{T}_{\mathcal{N}}(V_{\text{process}})$,

3. a sequence $(v_1, v_2, \dots, v_i)$ of all placeholders appearing in E_{out}^{ν} (ordered lexicographically),

4. a sequence $N^{\nu} = (\eta_1, \eta_2, \dots, \eta_i)$ of the first i elements in N

with

1. $((e_{\text{in}}, S(p)), (E_{\text{out}}^{\nu}, s^{\nu})) \in R^p$ and $a \in I^p$,

2. $E_{\text{out}} = E_{\text{out}}^{\nu}[m_1/v_1, \dots, m_i/v_i]$

3. $S'(p) = s^{\nu}[m_1/v_1, \dots, m_i/v_i]$ and $S'(p') = S(p')$ for all $p' \neq p$

4. $E' = E_{\text{out}} \cdot (E \setminus \{e_{\text{in}}\})$

5. $N' = N \setminus N^{\nu}$

We may omit the superscript and/or subscript of the arrow.

Intuitively, for a processing step, we select one of the processes in $\mathcal{P}$, and call it with one of the events in the list of waiting events E. In its output (new state and output events), we replace any occurences of placeholders v_x by "fresh" nonces from N (which we then remove from N). The output events are then prepended to the list of waiting events, and the state of the process is reflected in the new configuration.

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[28]Here: Not in the sense of terms as defined earlier.

Definition 12 (Runs). Let $\mathcal{P}$ be a system, E^0 be sequence of events, and N^0 be a sequence of nonces. A *run ρ of a system $\mathcal{P}$ initiated by E^0 with nonces N^0* is a finite sequence of configurations $((S^0, E^0, N^0), \ldots, (S^n, E^n, N^n))$ or an infinite sequence of configurations $((S^0, E^0, N^0), \ldots)$ such that $S^0(p) = s_0^p$ for all $p \in \mathcal{P}$ and $(S^i, E^i, N^i) \to (S^{i+1}, E^{i+1}, N^{i+1})$ for all $0 \leq i < n$ (finite run) or for all $i \geq 0$ (infinite run).

We denote the state $S^n(p)$ of a process p at the end of a run ρ by $\rho(p)$.

Usually, we will initiate runs with a set E^0 containing infinite trigger events of the form $\langle a, a, \mathtt{TRIGGER} \rangle$ for each $a \in \mathsf{IPs}$, interleaved by address.

Atomic Dolev-Yao Processes. We next define atomic Dolev-Yao processes, for which we require that the messages and states that they output can be computed (more formally, derived) from the current input event and state. For this purpose, we first define what it means to derive a message from given messages.

Definition 13 (Deriving Terms). Let M be a set of ground terms. We say that *a term m can be derived from M with placeholders V* if there exist $n \geq 0$, $m_1, \ldots, m_n \in M$, and $\tau \in \mathcal{T}_\emptyset(\{x_1, \ldots, x_n\} \cup V)$ such that $m \equiv \tau[m_1/x_1, \ldots, m_n/x_n]$. We denote by $d_V(M)$ the set of all messages that can be derived from M with variables V.

For example, $a \in d_{\{\}}(\{\mathsf{enc_a}(\langle a, b, c \rangle, \mathsf{pub}(k)), k\})$.

Definition 14 (Atomic Dolev-Yao Process). An *atomic Dolev-Yao process (or simply, a DY process)* is a tuple $p = (I^p, Z^p, R^p, s_0^p)$ such that (I^p, Z^p, R^p, s_0^p) is an atomic process and (1) $Z^p \subseteq \mathcal{T}_\mathcal{N}$ (and hence, $s_0^p \in \mathcal{T}_\mathcal{N}$), and (2) for all events $e \in \mathcal{E}$, sequences of protoevents E, $s \in \mathcal{T}_\mathcal{N}$, $s' \in \mathcal{T}_\mathcal{N}(V_{\mathrm{process}})$, with $((e, s), (E, s')) \in R^p$ it holds true that $E, s' \in d_{V_{\mathrm{process}}}(\{e, s\})$.

Definition 15 (Atomic Attacker Process). An *(atomic) attacker process for a set of sender addresses* $A \subseteq \mathsf{IPs}$ is an atomic DY process $p = (I, Z, R, s_0)$ such that for all events e, and $s \in \mathcal{T}_\mathcal{N}$ we have that $((e, s), (E, s')) \in R$ iff $s' = \langle e, E, s \rangle$ and $E = \langle \langle a_1, f_1, m_1 \rangle, \ldots, \langle a_n, f_n, m_n \rangle \rangle$ with $n \in \mathbb{N}$, $a_1, \ldots, a_n \in \mathsf{IPs}$, $f_0, \ldots, f_n \in A$, $m_1, \ldots, m_n \in d_{V_{\mathrm{process}}}(\{e, s\})$.

C.2. Scripts

We define scripts, which model client-side scripting technologies, such as JavaScript. Scripts are defined similarly to DY processes.

Definition 16 (Placeholders for Scripts). By $V_{\mathrm{script}} = \{\lambda_1, \ldots\}$ we denote an infinite set of variables used in scripts.

Definition 17 (Scripts). A *script* is a relation $R \subseteq \mathcal{T}_\mathcal{N} \times \mathcal{T}_\mathcal{N}(V_{\mathrm{script}})$ such that for all $s \in \mathcal{T}_\mathcal{N}$, $s' \in \mathcal{T}_\mathcal{N}(V_{\mathrm{script}})$ with $(s, s') \in R$ it follows that $s' \in d_{V_{\mathrm{script}}}(s)$.

A script is called by the browser which provides it with state information (such as the script's last state and limited information about the browser's state) s. The script then outputs a term s', which represents the new internal state and some command which is interpreted by the browser. The term s' may contain variables $\lambda_1, \ldots$ which the browser will replace by (otherwise unused) placeholders $\nu_1, \ldots$ which will be replaced by nonces once the browser DY process finishes (effectively providing the script with a way to get "fresh" nonces).

Similarly to an attacker process, we define the *attacker script R^{att}*:

Definition 18 (Attacker Script). The attacker script R^{att} outputs everything that is derivable from the input, i.e., $R^{\mathrm{att}} = \{(s, s') \mid s \in \mathcal{T}_\mathcal{N}, s' \in d_{V_{\mathrm{script}}}(s)\}$.

C.3. Web System

The web infrastructure and web applications are formalized by what is called a web system. A web system contains, among others, a (possibly infinite) set of DY processes, modeling web browsers, web servers, DNS servers, and attackers (which may corrupt other entities, such as browsers).

Definition 19. A *web system* $\mathcal{WS} = (\mathcal{W}, \mathcal{S}, \text{script}, E^0)$ is a tuple with its components defined as follows:

The first component, $\mathcal{W}$, denotes a system (a set of DY processes) and is partitioned into the sets Hon, Web, and Net of honest, web attacker, and network attacker processes, respectively.

Every $p \in \text{Web} \cup \text{Net}$ is an attacker process for some set of sender addresses $A \subseteq \text{IPs}$. For a web attacker $p \in \text{Web}$, we require its set of addresses I^p to be disjoint from the set of addresses of all other web attackers and honest processes, i.e., $I^p \cap I^{p'} = \emptyset$ for all $p' \in \text{Hon} \cup \text{Web}$. Hence, a web attacker cannot listen to traffic intended for other processes. Also, we require that $A = I^p$, i.e., a web attacker can only use sender addresses it owns. Conversely, a network attacker may listen to all addresses (i.e., no restrictions on I^p) and may spoof all addresses (i.e., the set A may be IPs).

Every $p \in \text{Hon}$ is a DY process which models either a *web server*, a *web browser*, or a *DNS server*, as further described in the following subsections. Just as for web attackers, we require that p does not spoof sender addresses and that its set of addresses I^p is disjoint from those of other honest processes and the web attackers.

The second component, $\mathcal{S}$, is a finite set of scripts such that $R^{\text{att}} \in \mathcal{S}$. The third component, script, is an injective mapping from $\mathcal{S}$ to $\mathbb{S}$, i.e., by script every $s \in \mathcal{S}$ is assigned its string representation $\text{script}(s)$.

Finally, E^0 is an (infinite) sequence of events, containing an infinite number of events of the form $\langle a, a, \text{TRIGGER} \rangle$ for every $a \in \bigcup_{p \in \mathcal{W}} I^p$.

A *run* of $\mathcal{WS}$ is a run of $\mathcal{W}$ initiated by E^0.

D. Message and Data Formats

We now provide some more details about data and message formats that are needed for the formal treatment of the web model and the analysis of BrowserID presented in the rest of the appendix.

D.1. Notations

Definition 20 (Sequence Notations). For a sequence $t = \langle t_1, \ldots, t_n \rangle$ and a set s we use $t \subset^{\langle\rangle} s$ to say that $t_1, \ldots, t_n \in s$. We define $x \in^{\langle\rangle} t \iff \exists i : t_i = x$. We write $t +^{\langle\rangle} y$ to denote the sequence $\langle t_1, \ldots, t_n, y \rangle$. For a finite set M with $M = \{m_1, \ldots, m_n\}$ we use $\langle M \rangle$ to denote the term of the form $\langle m_1, \ldots, m_n \rangle$. (The order of the elements does not matter; one is chosen arbitrarily.)

Definition 21. A *dictionary over X and Y* is a term of the form

$$\langle \langle k_1, v_1 \rangle, \ldots, \langle k_n, v_n \rangle \rangle$$

where $k_1, \ldots, k_n \in X$, $v_1, \ldots, v_n \in Y$, and the keys $k_1, \ldots, k_n$ are unique, i.e., $\forall i \neq j : k_i \neq k_j$. We call every term $\langle k_i, v_i \rangle$, $i \in \{1, \ldots, n\}$, an *element* of the dictionary with key k_i and value v_i. We often write $[k_1 : v_1, \ldots, k_i : v_i, \ldots, k_n : v_n]$ instead of $\langle \langle k_1, v_1 \rangle, \ldots, \langle k_n, v_n \rangle \rangle$. We denote the set of all dictionaries over X and Y by $[X \times Y]$.

We note that the empty dictionary is equivalent to the empty sequence, i.e., $[] = \langle \rangle$. Figure 11 shows the short notation for dictionary operations that will be used when describing the browser atomic process. For a dictionary $z = [k_1 : v_1, k_2 : v_2, \ldots, k_n : v_n]$ we write $k \in z$ to say that there exists i such that $k = k_i$. We write $z[k_j] := v_j$ to extract elements. If $k \notin z$, we set $z[k] := \langle \rangle$.

$$[k_1 : v_1, \ldots, k_i : v_i, \ldots, k_n : v_n] [k_i] = v_i \tag{7}$$

$$[k_1 : v_1, \ldots, k_{i-1} : v_{i-1}, k_i : v_i, k_{i+1} : v_{i+1} \ldots, k_n : v_n] - k_i =$$
$$[k_1 : v_1, \ldots, k_{i-1} : v_{i-1}, k_{i+1} : v_{i+1} \ldots, k_n : v_n] \tag{8}$$

Figure 11. Dictionary operators with $1 \leq i \leq n$

Given a term $t = \langle t_1, \ldots, t_n \rangle$, we can refer to any subterm using a sequence of integers. The subterm is determined by repeated application of the projection π_i for the integers i in the sequence. We call such a sequence a *pointer*:

Definition 22. A *pointer* is a sequence of non-negative integers. We write $\tau.\overline{p}$ for the application of the pointer $\overline{p}$ to the term τ. This operator is applied from left to right. For pointers consisting of a single integer, we may omit the sequence braces for brevity.

Example 3. For the term $\tau = \langle a, b, \langle c, d, \langle e, f \rangle \rangle \rangle$ and the pointer $\overline{p} = \langle 3, 1 \rangle$, the subterm of τ at the position $\overline{p}$ is $c = \pi_1(\pi_3(\tau))$. Also, $\tau.3.\langle 3, 1 \rangle = \tau.3.\overline{p} = \tau.3.3.1 = e$.

To improve readability, we try to avoid writing, e.g., $o.2$ or $\pi_2(o)$ in this document. Instead, we will use the names of the components of a sequence that is of a defined form as pointers that point to the corresponding subterms. E.g., if an *Origin* term is defined as $\langle host, protocol \rangle$ and o is an Origin term, then we can write $o.\texttt{protocol}$ instead of $\pi_2(o)$ or $o.2$. See also Example 4.

D.2. URLs

Definition 23. A *URL* is a term of the form

$$\langle \texttt{URL}, protocol, host, path, parameters, fragment \rangle$$

with *protocol* $\in \{\texttt{P},\texttt{S}\}$ (for **p**lain (HTTP) and **s**ecure (HTTPS)), *host* $\in$ Doms, *path* $\in \mathbb{S}$, *parameters* $\in \left[\mathbb{S} \times \mathcal{T}_{\mathcal{N}} \right]$, and *fragment* $\in \mathcal{T}_{\mathcal{N}}$. The set of all valid URLs is URLs.

The *fragment* part of a URL can be omitted when writing the URL. Its value is then defined to be $\bot$.

Example 4. For the URL $u = \langle \texttt{URL}, a, b, c, d \rangle$, $u.\texttt{protocol} = a$. If, in the algorithm described later, we say $u.\texttt{path} := e$ then $u = \langle \texttt{URL}, a, b, c, e \rangle$ afterwards.

D.3. Origins

Definition 24. An *origin* is a term of the form $\langle host, protocol \rangle$ with *host* $\in$ Doms and *protocol* $\in \{\texttt{P},\texttt{S}\}$. We write Origins for the set of all origins.

Example 5. For example, $\langle \texttt{FOO}, \texttt{S} \rangle$ is the HTTPS origin for the domain FOO, while $\langle \texttt{BAR}, \texttt{P} \rangle$ is the HTTP origin for the domain BAR.

D.4. Cookies

Definition 25. A *cookie* is a term of the form $\langle name, content \rangle$ where *name* $\in \mathcal{T}_{\mathcal{N}}$, and *content* is a term of the form $\langle value, secure, session, httpOnly \rangle$ where *value* $\in \mathcal{T}_{\mathcal{N}}$, *secure*, *session*, *httpOnly* $\in \{\top, \bot\}$. We write Cookies for the set of all cookies and Cookies$^{\nu}$ for the set of all cookies where names and values are defined over $\mathcal{T}_{\mathcal{N}}(V)$.

If the *secure* attribute of a cookie is set, the browser will not transfer this cookie over unencrypted HTTP connections. If the *session* flag is set, this cookie will be deleted as soon as the browser is closed. The *httpOnly* attribute controls whether JavaScript has access to this cookie.

Note that cookies of the form described here are only contained in HTTP(S) requests. In responses, only the components *name* and *value* are transferred as a pairing of the form $\langle name, value \rangle$.

D.5. HTTP Messages

Definition 26. An *HTTP request* is a term of the form shown in (9). An *HTTP response* is a term of the form shown in (10).

$$\langle \texttt{HTTPReq}, nonce, method, host, path, parameters, headers, body \rangle \tag{9}$$
$$\langle \texttt{HTTPResp}, nonce, status, headers, body \rangle \tag{10}$$

The components are defined as follows:

- *nonce* $\in \mathcal{N}$ serves to map each response to the corresponding request

- *method* $\in$ Methods is one of the HTTP methods.

- *host* $\in$ Doms is the host name in the HOST header of HTTP/1.1.

- *path* $\in \mathbb{S}$ is a string indicating the requested resource at the server side

- *status* $\in \mathbb{S}$ is the HTTP status code (i.e., a number between 100 and 505, as defined by the HTTP standard)

- *parameters* $\in \left[\mathbb{S} \times \mathcal{T}_{\mathcal{N}}\right]$ contains URL parameters

- *headers* $\in \left[\mathbb{S} \times \mathcal{T}_{\mathcal{N}}\right]$, containing request/response headers. The dictionary elements are terms of one of the following forms:

  - $\langle \mathtt{Origin}, o \rangle$ where o is an origin,
  - $\langle \mathtt{Set\text{-}Cookie}, c \rangle$ where c is a sequence of cookies,
  - $\langle \mathtt{Cookie}, c \rangle$ where $c \in, \left[\mathbb{S} \times \mathcal{T}_{\mathcal{N}}\right]$ (note that in this header, only names and values of cookies are transferred),
  - $\langle \mathtt{Location}, l \rangle$ where $l \in \mathsf{URLs}$,
  - $\langle \mathtt{Referer}, r \rangle$ where $r \in \mathsf{URLs}$,
  - $\langle \mathtt{Strict\text{-}Transport\text{-}Security}, \top \rangle$,
  - $\langle \mathtt{Authorization}, \langle u, p \rangle \rangle$ where $u, p \in \mathbb{S}$,
  - $\langle \mathtt{ReferrerPolicy}, p \rangle$ where $p \in \{\mathtt{noreferrer}, \mathtt{origin}\}$

- *body* $\in \mathcal{T}_{\mathcal{N}}$ in requests and responses.

We write HTTPRequests/HTTPResponses for the set of all HTTP requests or responses, respectively.

Example 6 (HTTP Request and Response).

$$
\begin{aligned}
r := &\langle \mathtt{HTTPReq}, n_1, \mathtt{POST}, \mathtt{example.com}, /\mathtt{show}, \langle \langle \mathtt{index}, 1 \rangle \rangle, \\
&\left[\mathtt{Origin}: \langle \mathtt{example.com}, \mathsf{S} \rangle\right], \langle \mathtt{foo}, \mathtt{bar} \rangle \rangle \tag{11} \\
s := &\langle \mathtt{HTTPResp}, n_1, 200, \langle \langle \mathtt{Set\text{-}Cookie}, \langle \langle \mathtt{SID}, \langle n_2, \bot, \bot, \top \rangle \rangle \rangle \rangle \rangle, \langle \mathtt{somescript}, x \rangle \rangle \tag{12}
\end{aligned}
$$

An HTTP GET request for the URL http://example.com/show?index=1 is shown in (11), with an Origin header and a body that contains $\langle \mathtt{foo}, \mathtt{bar} \rangle$. A possible response is shown in (12), which contains an httpOnly cookie with name SID and value n_2 as well as the string representation somescript of the script $\mathsf{script}^{-1}(\mathtt{somescript})$ (which should be an element of $\mathcal{S}$) and its initial state x.

Encrypted HTTP Messages.. For HTTPS, requests are encrypted using the public key of the server. Such a request contains an (ephemeral) symmetric key chosen by the client that issued the request. The server is supported to encrypt the response using the symmetric key.

Definition 27. An *encrypted HTTP request* is of the form $\mathsf{enc}_{\mathsf{a}}(\langle m, k' \rangle, k)$, where $k, k' \in \mathcal{N}$ and $m \in$ HTTPRequests. The corresponding *encrypted HTTP response* would be of the form $\mathsf{enc}_{\mathsf{s}}(m', k')$, where $m' \in$ HTTPResponses. We call the sets of all encrypted HTTP requests and responses HTTPSRequests or HTTPSResponses, respectively.

Example 7.

$$
\mathsf{enc}_{\mathsf{a}}(\langle r, k' \rangle, \mathsf{pub}(k_{\mathrm{example.com}})) \tag{13}
$$

$$
\mathsf{enc}_{\mathsf{s}}(s, k') \tag{14}
$$

The term (13) shows an encrypted request (with r as in (11)). It is encrypted using the public key $\mathsf{pub}(k_{\mathrm{example.com}})$. The term (14) is a response (with s as in (12)). It is encrypted symmetrically using the (symmetric) key k' that was sent in the request (13).

D.6. DNS Messages

Definition 28. A *DNS request* is a term of the form $\langle \texttt{DNSResolve}, domain, n \rangle$ where $domain \in \mathsf{Doms}$, $n \in \mathcal{N}$. We call the set of all DNS requests DNSRequests.

Definition 29. A *DNS response* is a term of the form $\langle \texttt{DNSResolved}, domain, result, n \rangle$ with $domain \in \mathsf{Doms}$, $result \in \mathsf{IPs}$, $n \in \mathcal{N}$. We call the set of all DNS responses DNSResponses.

DNS servers are supposed to include the nonce they received in a DNS request in the DNS response that they send back so that the party which issued the request can match it with the request.

D.7. DNS Servers

Here, we consider a flat DNS model in which DNS queries are answered directly by one DNS server and always with the same address for a domain. A full (hierarchical) DNS system with recursive DNS resolution, DNS caches, etc. could also be modeled to cover certain attacks on the DNS system itself.

Definition 30. A *DNS server d* (in a flat DNS model) is modeled in a straightforward way as an atomic DY process $(I^d, \{s_0^d\}, R^d, s_0^d)$. It has a finite set of addresses I^d and its initial (and only) state s_0^d encodes a mapping from domain names to addresses of the form

$$s_0^d = \langle \langle \texttt{domain}_1, a_1 \rangle, \langle \texttt{domain}_2, a_2 \rangle, \ldots \rangle \, .$$

DNS queries are answered according to this table (otherwise ignored).

E. Detailed Description of the Browser Model

Following the informal description of the browser model in Section 4, we now present a formal model. We start by introducing some notation and terminology.

E.1. Notation and Terminology (Web Browser State)

Before we can define the state of a web browser, we first have to define windows and documents.

Definition 31. A *window* is a term of the form $w = \langle nonce, documents, opener \rangle$ with $nonce \in \mathcal{N}$, $documents \subset^{\langle\rangle}$ Documents (defined below), $opener \in \mathcal{N} \cup \{\bot\}$ where $d.\texttt{active} = \top$ for exactly one $d \in^{\langle\rangle} documents$ if $documents$ is not empty (we then call d the *active document of w*). We write Windows for the set of all windows. We write $w.\texttt{activedocument}$ to denote the active document inside window w if it exists and $\langle\rangle$ else.

We will refer to the window nonce as *(window) reference*.

The documents contained in a window term to the left of the active document are the previously viewed documents (available to the user via the "back" button) and the documents in the window term to the right of the currently active document are documents available via the "forward" button.

A window a may have opened a top-level window b (i.e., a window term which is not a subterm of a document term). In this case, the *opener* part of the term b is the nonce of a, i.e., $b.\texttt{opener} = a.\texttt{nonce}$.

Definition 32. A *document d* is a term of the form

$$\langle nonce, location, headers, referrer, script, scriptstate, scriptinputs, subwindows, active \rangle$$

where $nonce \in \mathcal{N}$, $location \in$ URLs, $headers \in [\mathbb{S} \times \mathcal{T}_{\mathcal{N}}]$, $referrer \in$ URLs $\cup \{\bot\}$, $script \in \mathcal{T}_{\mathcal{N}}$, $scriptstate \in \mathcal{T}_{\mathcal{N}}$, $scriptinputs \in \mathcal{T}_{\mathcal{N}}$, $subwindows \subset^{\langle\rangle}$ Windows, $active \in \{\top, \bot\}$. A *limited document* is a term of the form $\langle nonce, subwindows \rangle$ with $nonce$, $subwindows$ as above. A window $w \in^{\langle\rangle} subwindows$ is called a *subwindow* (of d). We write Documents for the set of all documents. For a document term d we write $d.\texttt{origin}$ to denote the origin of the document, i.e., the term $\langle d.\texttt{location.host}, d.\texttt{location.protocol} \rangle \in$ Origins.

We will refer to the document nonce as *(document) reference*.

We can now define the set of states of web browsers. Note that we use the dictionary notation that we introduced in Definition 21.

Definition 33. The *set of states Z^p of a web browser atomic process p* consists of the terms of the form

$$\langle windows, ids, secrets, cookies, localStorage, sessionStorage, keyMapping,$$
$$sts, DNSaddress, pendingDNS, pendingRequests, isCorrupted \rangle$$

where

- *windows* $\subset^{\langle\rangle}$ Windows,

- *ids* $\subset^{\langle\rangle} \mathcal{T}_{\mathcal{N}}$,

- *secrets* $\in [\text{Origins} \times \mathcal{T}_{\mathcal{N}}]$,

- *cookies* is a dictionary over Doms and sequences of Cookies,

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- $localStorage \in \big[\mathsf{Origins} \times \mathcal{T}_\mathcal{N}\big]$,

- $sessionStorage \in \big[OR \times \mathcal{T}_\mathcal{N}\big]$ for $OR := \{\langle o,r\rangle \,|\, o \in \mathsf{Origins}, r \in \mathcal{N}\}$,

- $keyMapping \in \big[\mathsf{Doms} \times \mathcal{T}_\mathcal{N}\big]$,

- $sts \subset^{\langle\rangle} \mathsf{Doms}$,

- $DNSaddress \in \mathsf{IPs}$,

- $pendingDNS \in \big[\mathcal{N} \times \mathcal{T}_\mathcal{N}\big]$,

- $pendingRequests \in \mathcal{T}_\mathcal{N}$,

- and $isCorrupted \in \{\bot, \texttt{FULLCORRUPT}, \texttt{CLOSECORRUPT}\}$.

Definition 34. For two window terms w and w' we write $w \xrightarrow{\text{childof}} w'$ if

$$w \in^{\langle\rangle} w'.\texttt{activedocument.subwindows}\,.$$

We write $\xrightarrow{\text{childof}^+}$ for the transitive closure.

In the following description of the web browser relation R^p we use the helper functions Subwindows, Docs, Clean, CookieMerge and AddCookie.

Given a browser state s, Subwindows(s) denotes the set of all pointers[29] to windows in the window list $s.\texttt{windows}$, their active documents, and (recursively) the subwindows of these documents. We exclude subwindows of inactive documents and their subwindows. With Docs(s) we denote the set of pointers to all active documents in the set of windows referenced by Subwindows(s).

Definition 35. For a browser state s we denote by Subwindows(s) the minimal set of pointers that satisfies the following conditions: (1) For all windows $w \in^{\langle\rangle} s.\texttt{windows}$ there is a $\overline{p} \in$ Subwindows(s) such that $s.\overline{p} = w$. (2) For all $\overline{p} \in$ Subwindows(s), the active document d of the window $s.\overline{p}$ and every subwindow w of d there is a pointer $\overline{p'} \in$ Subwindows(s) such that $s.\overline{p'} = w$.

Given a browser state s, the set Docs(s) of pointers to active documents is the minimal set such that for every $\overline{p} \in$ Subwindows(s), there is a pointer $\overline{p'} \in$ Docs(s) with $s.\overline{p'} = s.\overline{p}.\texttt{activedocument}$.

By Subwindows$^+(s)$ and Docs$^+(s)$ we denote the respective sets that also include the inactive documents and their subwindows.

The function Clean will be used to determine which information about windows and documents the script running in the document d has access to.

Definition 36. Let s be a browser state and d a document. By Clean(s,d) we denote the term that equals $s.\texttt{windows}$ but with (1) all inactive documents removed (including their subwindows etc.), (2) all subterms that represent non-same-origin documents w.r.t. d replaced by a limited document d' with the same nonce and the same subwindow list, and (3) the values of the subterms $\texttt{headers}$ for all documents set to $\langle\rangle$. (Note that non-same-origin documents on all levels are replaced by their corresponding limited document.)

The function CookieMerge merges two sequences of cookies together: When used in the browser, *oldcookies* is the sequence of existing cookies for some origin, *newcookies* is a sequence of new cookies that was output by some script. The sequences are merged into a set of cookies using an algorithm that is based on the *Storage Mechanism* algorithm described in RFC6265.

---

[29]Recall the definition of a pointer in Definition 22.

Definition 37. For a sequence of cookies (with pairwise different names) *oldcookies* and a sequence of cookies *newcookies*, the set CookieMerge(*oldcookies*, *newcookies*) is defined by the following algorithm: From *newcookies* remove all cookies c that have c.content.httpOnly $\equiv \top$. For any c, $c' \in^{\langle\rangle}$ *newcookies*, c.name $\equiv c'$.name, remove the cookie that appears left of the other in *newcookies*. Let m be the set of cookies that have a name that either appears in *oldcookies* or in *newcookies*, but not in both. For all pairs of cookies $(c_{\text{old}}, c_{\text{new}})$ with $c_{\text{old}} \in^{\langle\rangle}$ *oldcookies*, $c_{\text{new}} \in^{\langle\rangle}$ *newcookies*, c_{old}.name $\equiv$ c_{new}.name, add c_{new} to m if c_{old}.content.httpOnly $\equiv \bot$ and add c_{old} to m otherwise. The result of CookieMerge(*oldcookies*, *newcookies*) is m.

The function AddCookie adds a cookie c received in an HTTP response to the sequence of cookies contained in the sequence *oldcookies*. It is again based on the algorithm described in RFC6265 but simplified for the use in the browser model.

Definition 38. For a sequence of cookies (with pairwise different names) *oldcookies* and a cookie c, the sequence AddCookie(*oldcookies*, c) is defined by the following algorithm: Let $m := $ *oldcookies*. Remove any c' from m that has c.name $\equiv c'$.name. Append c to m and return m.

The function NavigableWindows returns a set of windows that a document is allowed to navigate. We closely follow [23], Section 5.1.4 for this definition.

Definition 39. The set NavigableWindows($\overline{w}, s'$) is the set $\overline{W} \subseteq$ Subwindows(s') of pointers to windows that the active document in $\overline{w}$ is allowed to navigate. The set $\overline{W}$ is defined to be the minimal set such that for every $\overline{w'} \in$ Subwindows(s') the following is true:

- If $s'.\overline{w'}$.activedocument.origin $\equiv s'.\overline{w}$.activedocument.origin (i.e., the active documents in $\overline{w}$ and $\overline{w'}$ are same-origin), then $\overline{w'} \in \overline{W}$, and

- If $s'.\overline{w} \xrightarrow{\text{childof}^*} s'.\overline{w'} \wedge \nexists \overline{w''} \in$ Subwindows(s') with $s'.\overline{w'} \xrightarrow{\text{childof}^*} s'.\overline{w''}$ ($\overline{w'}$ is a top-level window and $\overline{w}$ is an ancestor window of $\overline{w'}$), then $\overline{w'} \in \overline{W}$, and

- If $\exists \overline{p} \in$ Subwindows(s') such that $s'.\overline{w'} \xrightarrow{\text{childof}^+} s'.\overline{p}$
  $\wedge s'.\overline{p}$.activedocument.origin $= s'.\overline{w}$.activedocument.origin ($\overline{w'}$ is not a top-level window but there is an ancestor window $\overline{p}$ of $\overline{w'}$ with an active document that has the same origin as the active document in $\overline{w}$), then $\overline{w'} \in \overline{W}$, and

- If $\exists \overline{p} \in$ Subwindows(s') such that $s'.\overline{w'}$.opener $= s'.\overline{p}$.nonce $\wedge \overline{p} \in \overline{W}$ ($\overline{w'}$ is a top-level window— it has an opener—and $\overline{w}$ is allowed to navigate the opener window of $\overline{w'}$, $\overline{p}$), then $\overline{w'} \in \overline{W}$.

E.2. Description of the Web Browser Atomic Process

We will now describe the relation R^p of a standard HTTP browser p. We define $((\langle\langle a, f, m\rangle\rangle, s), (M, s'))$ to belong to R^p iff the non-deterministic algorithm presented below, when given $(\langle a, f, m\rangle, s)$ as input, terminates with **stop** M, s', i.e., with output M and s'. Recall that $\langle a, f, m\rangle$ is an (input) event and s is a (browser) state, M is a sequence of (output) protoevents, and s' is a new (browser) state (potentially with placeholders for nonces).

Notations.. The notation **let** $n \leftarrow N$ is used to describe that n is chosen non-deterministically from the set N. We write **for each** $s \in M$ **do** to denote that the following commands (until **end for**) are repeated for every element in M, where the variable s is the current element. The order in which the elements are processed is chosen non-deterministically. We will write, for example,

let x, y **such that** $\langle$Constant, $x, y\rangle \equiv t$ **if possible; otherwise** doSomethingElse

for some variables x, y, a string `Constant`, and some term t to express that $x := \pi_2(t)$, and $y := \pi_3(t)$ if `Constant` $\equiv \pi_1(t)$ and if $|\langle \text{Constant}, x, y \rangle| = |t|$, and that otherwise x and y are not set and doSomethingElse is executed.

Placeholders.. In several places throughout the algorithms presented next we use placeholders to generate "fresh" nonces as described in our communication model (see Definition 1). Figure 12 shows a list of all placeholders used.

Placeholder	Usage
ν_1	Algorithm 9, new window nonces
ν_2	Algorithm 9, new HTTP request nonce
ν_3	Algorithm 9, lookup key for pending HTTP requests entry
ν_4	Algorithm 7, new HTTP request nonce (multiple lines)
ν_5	Algorithm 7, new subwindow nonce
ν_6	Algorithm 8, new HTTP request nonce
ν_7	Algorithm 8, new document nonce
ν_8	Algorithm 4, lookup key for pending DNS entry
ν_9	Algorithm 1, new window nonce
$\nu_{10}, \ldots$	Algorithm 7, replacement for placeholders in script output

Figure 12. List of placeholders used in browser algorithms

Before we describe the main browser algorithm, we first define some functions.

Functions. In the description of the following functions we use a, f, m, and s as read-only global input variables. All other variables are local variables or arguments.

The following function, GETNAVIGABLEWINDOW, is called by the browser to determine the window that is *actually* navigated when a script in the window $s'.\overline{w}$ provides a window reference for navigation (e.g., for opening a link). When it is given a window reference (nonce) *window*, this function returns a pointer to a selected window term in s':

- If *window* is the string `_BLANK`, a new window is created and a pointer to that window is returned.

- If *window* is a nonce (reference) and there is a window term with a reference of that value in the windows in s', a pointer $\overline{w'}$ to that window term is returned, as long as the window is navigable by the current window's document (as defined by NavigableWindows above).

In all other cases, $\overline{w}$ is returned instead (the script navigates its own window).

Algorithm 1 Determine window for navigation
___
1: **function** GETNAVIGABLEWINDOW($\overline{w}$, *window*, *noreferrer*, s')
2:     **if** *window* $\equiv$ `_BLANK` **then**   ▷ Open a new window when `_BLANK` is used
3:         **if** *noreferrer* $\equiv \top$ **then**
4:             **let** $w' := \langle \nu_9, \langle \rangle, \bot \rangle$
5:         **else**
6:             **let** $w' := \langle \nu_9, \langle \rangle, s'.\overline{w}.\text{nonce} \rangle$
7:         **end if**
8:         **let** $s'.\text{windows} := s'.\text{windows} +^{\langle \rangle} w'$
           ↪ **and** let $\overline{w'}$ be a pointer to this new element in s'
9:         **return** $\overline{w'}$
10:     **end if**

11:     **let** $\overline{w}' \leftarrow$ NavigableWindows$(\overline{w}, s')$ **such that** $s'.\overline{w}'$.nonce $\equiv$ *window*
       $\hookrightarrow$ **if possible; otherwise return** $\overline{w}$

12:     **return** $\overline{w}'$

13: **end function**

The following function takes a window reference as input and returns a pointer to a window as above, but it checks only that the active documents in both windows are same-origin. It creates no new windows.

Algorithm 2 Determine same-origin window

1: **function** GETWINDOW$(\overline{w}, window, s')$

2:     **let** $\overline{w}' \leftarrow$ Subwindows(s') **such that** $s'.\overline{w}'$.nonce $\equiv$ *window*
       $\hookrightarrow$ **if possible; otherwise return** $\overline{w}$

3:     **if** $s'.\overline{w}'$.activedocument.origin $\equiv s'.\overline{w}$.activedocument.origin **then**

4:         **return** $\overline{w}'$

5:     **end if**

6:     **return** $\overline{w}$

7: **end function**

The next function is used to stop any pending requests for a specific window. From the pending requests and pending DNS requests it removes any requests with the given window reference *n*.

Algorithm 3 Cancel pending requests for given window

1: **function** CANCELNAV(n, s')

2:     **remove all** $\langle n, req, key, f \rangle$ **from** s'.pendingRequests **for any** *req*, *key*, *f*

3:     **remove all** $\langle x, \langle n, message, url \rangle \rangle$ **from** s'.pendingDNS
       $\hookrightarrow$ **for any** *x*, *message*, *url*

4:     **return** s'

5: **end function**

The following function takes an HTTP request *message* as input, adds cookie and origin headers to the message, creates a DNS request for the hostname given in the request and stores the request in s'.pendingDNS until the DNS resolution finishes. For normal HTTP requests, *reference* is a window reference. For XHRs, *reference* is a value of the form $\langle document, nonce \rangle$ where *document* is a document reference and *nonce* is some nonce that was chosen by the script that initiated the request. *url* contains the full URL of the request (this is mainly used to retrieve the protocol that should be used for this message, and to store the fragment identifier for use after the document was loaded). *origin* is the origin header value that is to be added to the HTTP request.

Algorithm 4 Prepare headers, do DNS resolution, save message

1: **function** SEND(*reference*, *message*, *url*, *origin*, *referrer*, *referrerPolicy*, s')

2:     **if** *message*.host $\in^{\langle\rangle} s'$.sts **then**

3:         **let** *url*.protocol $:=$ S

4:     **end if**

5:     **let** *cookies* $:= \langle \{ \langle c.\text{name}, c.\text{content.value} \rangle | c \in^{\langle\rangle} s'.\text{cookies}[message.\text{host}]$
       $\hookrightarrow \wedge (c.\text{content.secure} \implies (url.\text{protocol} = \text{S})) \} \rangle$

6:     **let** *message*.headers[Cookie] $:=$ *cookies*

7:     **if** *origin* $\not\equiv \bot$ **then**

8:         **let** *message*.headers[Origin] $:=$ *origin*

9:     **end if**

10:    **if** *referrerPolicy* $\equiv$ noreferrer **then**

11:        **let** *referrer* $:= \bot$

12:    **end if**

13:    **if** *referrer* $\not\equiv \bot$ **then**

14:        **if** *referrerPolicy* $\equiv$ `origin` **then**

15:           **let** *referrer* := $\langle \text{URL}, referrer.\texttt{protocol}, referrer.\texttt{host}, /, \langle\rangle, \bot\rangle$ $\triangleright$ Referrer stripped down to origin.

16:        **end if**

17:        **let** *referrer*.`fragment` := $\bot$ $\triangleright$ Browsers do not send fragment identifiers in the Referer header.

18:        **let** *message*.`headers`[`Referer`] := *referrer*

19:      **end if**

20:    **let** $s'.\texttt{pendingDNS}[\nu_8] := \langle reference, message, url\rangle$

21:    **stop** $\langle\langle s'.\texttt{DNSaddress}, a, \langle\texttt{DNSResolve}, message.\texttt{host}, \nu_8\rangle\rangle\rangle, s'$

22: **end function**

The following functions navigate a window forward or backward. More precisely, they deactivate one document and activate that document's succeeding document or preceding document, respectively. If no such successor/predecessor exists, the functions do not change the state.

Algorithm 5 Navigate a window backward

1: **function** NAVBACK($\overline{w}, s'$)

2:    **if** $\exists \overline{j} \in \mathbb{N}, \overline{j} > 1$ **such that** $s'.\overline{w}.\texttt{documents}.\overline{j}.\texttt{active} \equiv \top$ **then**

3:      **let** $s'.\overline{w}.\texttt{documents}.\overline{j}.\texttt{active} := \bot$

4:      **let** $s'.\overline{w}.\texttt{documents}.(\overline{j}-1).\texttt{active} := \top$

5:      **let** $s' := $ CANCELNAV($s'.\overline{w}.\texttt{nonce}, s'$)

6:    **end if**

7: **end function**

Algorithm 6 Navigate a window forward

1: **function** NAVFORWARD($\overline{w}, s'$)

2:    **if** $\exists \overline{j} \in \mathbb{N}$ **such that** $s'.\overline{w}.\texttt{documents}.\overline{j}.\texttt{active} \equiv \top$
        $\hookrightarrow \ \wedge s'.\overline{w}.\texttt{documents}.(\overline{j}+1) \in \text{Documents}$ **then**

3:      **let** $s'.\overline{w}.\texttt{documents}.\overline{j}.\texttt{active} := \bot$

4:      **let** $s'.\overline{w}.\texttt{documents}.(\overline{j}+1).\texttt{active} := \top$

5:      **let** $s' := $ CANCELNAV($s'.\overline{w}.\texttt{nonce}, s'$)

6:    **end if**

7: **end function**

The function RUNSCRIPT performs a script execution step of the script in the document $s'.\overline{d}$ (which is part of the window $s'.\overline{w}$). A new script and document state is chosen according to the relation defined by the script and the new script and document state is saved. Afterwards, the *command* that the script issued is interpreted.

Algorithm 7 Execute a script

1: **function** RUNSCRIPT($\overline{w}, \overline{d}, s'$)

2:    **let** *tree* := $\mathsf{Clean}(s', s'.\overline{d})$

3:    **let** *cookies* := $\langle\{\langle c.\texttt{name}, c.\texttt{content.value}\rangle | c \in^{\langle\rangle} s'.\texttt{cookies}\left[s'.\overline{d}.\texttt{origin.host}\right]$
      $\hookrightarrow \ \wedge c.\texttt{content.httpOnly} = \bot$
      $\hookrightarrow \ \wedge \left(c.\texttt{content.secure} \implies \left(s'.\overline{d}.\texttt{origin.protocol} \equiv \texttt{S}\right)\right)\}\rangle$

4:    **let** *tlw* $\leftarrow s'.\texttt{windows}$ **such that** *tlw* is the top-level window containing $\overline{d}$

5:    **let** *sessionStorage* := $s'.\texttt{sessionStorage}\left[\langle s'.\overline{d}.\texttt{origin}, tlw.\texttt{nonce}\rangle\right]$

6:    **let** *localStorage* := $s'.\texttt{localStorage}\left[s'.\overline{d}.\texttt{origin}\right]$

7:    **let** *secrets* := $s'.\texttt{secrets}\left[s'.\overline{d}.\texttt{origin}\right]$

8:    **let** $R \leftarrow \mathsf{script}^{-1}(s'.\overline{d}.\texttt{script})$

9:    **let** *in* := $\langle tree, s'.\overline{d}.\texttt{nonce}, s'.\overline{d}.\texttt{scriptstate}, s'.\overline{d}.\texttt{scriptinputs}, cookies,$
      $\hookrightarrow \ localStorage, sessionStorage, s'.\texttt{ids}, secrets\rangle$

10:    **let** $state' \leftarrow \mathcal{T}_{\mathcal{N}}(V),$

$\hookrightarrow$ $cookies' \leftarrow \mathsf{Cookies}^\nu$,

$\hookrightarrow$ $localStorage' \leftarrow \mathcal{T_N}(V)$,

$\hookrightarrow$ $sessionStorage' \leftarrow \mathcal{T_N}(V)$,

$\hookrightarrow$ $command \leftarrow \mathcal{T_N}(V)$,

$\hookrightarrow$ $out^\lambda := \langle state', cookies', localStorage', sessionStorage', command \rangle$

$\hookrightarrow$ **such that** $(in, out^\lambda) \in R$

11:      **let** $out := out^\lambda[\nu_{10}/\lambda_1, \nu_{11}/\lambda_2, \dots]$

12:      **let** $s'.\mathtt{cookies}\left[s'.\overline{d}.\mathtt{origin}.\mathtt{host}\right]$

$\hookrightarrow$ $:= \langle \mathsf{CookieMerge}(s'.\mathtt{cookies}\left[s'.\overline{d}.\mathtt{origin}.\mathtt{host}\right], cookies') \rangle$

13:      **let** $s'.\mathtt{localStorage}\left[s'.\overline{d}.\mathtt{origin}\right] := localStorage'$

14:      **let** $s'.\mathtt{sessionStorage}\left[\langle s'.\overline{d}.\mathtt{origin}, tlw.\mathtt{nonce}\rangle\right] := sessionStorage'$

15:      **let** $s'.\overline{d}.\mathtt{scriptstate} := state'$

16:      **switch** $command$ **do**

17:          **case** $\langle \mathtt{HREF}, url, hrefwindow, noreferrer \rangle$

18:              **let** $\overline{w}' := \mathrm{GETNAVIGABLEWINDOW}(\overline{w}, hrefwindow, noreferrer, s')$

19:              **let** $req := \langle \mathtt{HTTPReq}, \nu_4, \mathtt{GET}, url.\mathtt{host}, url.\mathtt{path}, \langle\rangle, url.\mathtt{parameters}, \langle\rangle \rangle$

20:              **if** $noreferrer \equiv \top$ **then**

21:                  **let** $referrerPolicy := \mathtt{noreferrer}$

22:              **else**

23:                  **let** $referrerPolicy := s'.\overline{d}.\mathtt{headers}[\mathtt{ReferrerPolicy}]$

24:              **end if**

25:              **let** $s' := \mathrm{CANCELNAV}(s'.\overline{w}'.\mathtt{nonce}, s')$

26:              $\mathrm{SEND}(s'.\overline{w}'.\mathtt{nonce}, req, url, \bot, referrer, referrerPolicy, s')$

27:          **case** $\langle \mathtt{IFRAME}, url, window \rangle$

28:              **let** $\overline{w}' := \mathrm{GETWINDOW}(\overline{w}, window, s')$

29:              **let** $req := \langle \mathtt{HTTPReq}, \nu_4, \mathtt{GET}, url.\mathtt{host}, url.\mathtt{path}, \langle\rangle, url.\mathtt{parameters}, \langle\rangle \rangle$

30:              **let** $referrer := s'.\overline{w}'.\mathtt{activedocument}.\mathtt{location}$

31:              **let** $referrerPolicy := s'.\overline{d}.\mathtt{headers}[\mathtt{ReferrerPolicy}]$

32:              **let** $w' := \langle \nu_5, \langle\rangle, \bot \rangle$

33:              **let** $s'.\overline{w}'.\mathtt{activedocument}.\mathtt{subwindows}$

$\hookrightarrow$ $:= s'.\overline{w}'.\mathtt{activedocument}.\mathtt{subwindows} +^{\langle\rangle} w'$

34:              $\mathrm{SEND}(\nu_5, req, url, \bot, referrer, referrerPolicy, s')$

35:          **case** $\langle \mathtt{FORM}, url, method, data, hrefwindow \rangle$

36:              **if** $method \notin \{\mathtt{GET}, \mathtt{POST}\}$ **then** [30]

37:                  **stop** $\langle\rangle, s'$

38:              **end if**

39:              **let** $\overline{w}' := \mathrm{GETNAVIGABLEWINDOW}(\overline{w}, hrefwindow, \bot, s')$

40:              **if** $method = \mathtt{GET}$ **then**

41:                  **let** $body := \langle\rangle$

42:                  **let** $parameters := data$

43:                  **let** $origin := \bot$

44:              **else**

45:                  **let** $body := data$

46:                  **let** $parameters := url.\mathtt{parameters}$

47:                  **let** $origin := s'.\overline{d}.\mathtt{origin}$

48:              **end if**

49:              **let** $req := \langle \mathtt{HTTPReq}, \nu_4, method, url.\mathtt{host}, url.\mathtt{path}, \langle\rangle, parameters, body \rangle$

50:              **let** $referrer := s'.\overline{d}.\mathtt{location}$

51:              **let** $referrerPolicy := s'.\overline{d}.\mathtt{headers}[\mathtt{ReferrerPolicy}]$

52:              **let** $s' := \mathrm{CANCELNAV}(s'.\overline{w}'.\mathtt{nonce}, s')$

53:              $\mathrm{SEND}(s'.\overline{w}'.\mathtt{nonce}, req, url, origin, referrer, referrerPolicy, s')$

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[30] The working draft for HTML5 allowed for DELETE and PUT methods in HTML5 forms. However, these have since been removed. See http://www.w3.org/TR/2010/WD-html5-diff-20101019/#changes-2010-06-24.

54:       **case** $\langle \text{SETSCRIPT}, window, script \rangle$

55:          **let** $\overline{w}' := \text{GETWINDOW}(\overline{w}, window, s')$

56:          **let** $s'.\overline{w}'.\texttt{activedocument.script} := script$

57:          **stop** $\langle\rangle, s'$

58:       **case** $\langle \text{SETSCRIPTSTATE}, window, scriptstate \rangle$

59:          **let** $\overline{w}' := \text{GETWINDOW}(\overline{w}, window, s')$

60:          **let** $s'.\overline{w}'.\texttt{activedocument.scriptstate} := scriptstate$

61:          **stop** $\langle\rangle, s'$

62:       **case** $\langle \text{XMLHTTPREQUEST}, url, method, data, xhrreference \rangle$

63:          **if** $method \in \{\text{CONNECT}, \text{TRACE}, \text{TRACK}\} \wedge xhrreference \notin \{\mathcal{N}, \bot\}$ **then**

64:             **stop** $\langle\rangle, s'$

65:          **end if**

66:          **if** $url.\texttt{host} \not\equiv s'.\overline{d}.\texttt{origin.host}$
                $\hookrightarrow \quad \vee\ url \not\equiv s'.\overline{d}.\texttt{origin.protocol}$ **then**

67:             **stop** $\langle\rangle, s'$

68:          **end if**

69:          **if** $method \in \{\text{GET}, \text{HEAD}\}$ **then**

70:             **let** $data := \langle\rangle$

71:             **let** $origin := \bot$

72:          **else**

73:             **let** $origin := s'.\overline{d}.\texttt{origin}$

74:          **end if**

75:          **let** $req := \langle \text{HTTPReq}, \nu_4, method, url.\texttt{host}, url.\texttt{path}, , url.\texttt{parameters}, data \rangle$

76:          **let** $referrer := s'.\overline{d}.\texttt{location}$

77:          **let** $referrerPolicy := s'.\overline{d}.\texttt{headers}[\texttt{ReferrerPolicy}]$

78:          $\text{SEND}(\langle s'.\overline{d}.\texttt{nonce}, xhrreference \rangle, req, url, origin, referrer, referrerPolicy, s')$

79:       **case** $\langle \text{BACK}, window \rangle$ [31]

80:          **let** $\overline{w}' := \text{GETNAVIGABLEWINDOW}(\overline{w}, window, \bot, s')$

81:          $\text{NAVBACK}(\overline{w}, s')$

82:          **stop** $\langle\rangle, s'$

83:       **case** $\langle \text{FORWARD}, window \rangle$

84:          **let** $\overline{w}' := \text{GETNAVIGABLEWINDOW}(\overline{w}, window, \bot, s')$

85:          $\text{NAVFORWARD}(\overline{w}, s')$

86:          **stop** $\langle\rangle, s'$

87:       **case** $\langle \text{CLOSE}, window \rangle$

88:          **let** $\overline{w}' := \text{GETNAVIGABLEWINDOW}(\overline{w}, window, \bot, s')$

89:          **remove** $s'.\overline{w}'$ from the sequence containing it

90:          **stop** $\langle\rangle, s'$

91:       **case** $\langle \text{POSTMESSAGE}, window, message, origin \rangle$

92:          **let** $\overline{w}' \leftarrow \text{Subwindows}(s')$ **such that** $s'.\overline{w}'.\texttt{nonce} \equiv window$

93:          **if** $\exists \overline{j} \in \mathbb{N}$ **such that** $s'.\overline{w}'.\texttt{documents}.\overline{j}.\texttt{active} \equiv \top$
            $\hookrightarrow \quad \wedge (origin \not\equiv \bot \implies s'.\overline{w}'.\texttt{documents}.\overline{j}.\texttt{origin} \equiv origin)$ **then**

94:             **let** $s'.\overline{w}'.\texttt{documents}.\overline{j}.\texttt{scriptinputs}$
               $\hookrightarrow := s'.\overline{w}'.\texttt{documents}.\overline{j}.\texttt{scriptinputs}$
               $\hookrightarrow +^{\langle\rangle} \langle \text{POSTMESSAGE}, s'.\overline{w}.\texttt{nonce}, s'.\overline{d}.\texttt{origin}, message \rangle$

95:          **end if**

96:          **stop** $\langle\rangle, s'$

97:       **case** else

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[31] Note that navigating a window using the back/forward buttons does not trigger a reload of the affected documents. While real world browser may chose to refresh a document in this case, we assume that the complete state of a previously viewed document is restored. A reload can be triggered non-deterministically at any point (in the main algorithm).

98:    **stop** $\langle\rangle, s'$

99: **end function**

The function PROCESSRESPONSE is responsible for processing an HTTP response (*response*) that was received as the response to a request (*request*) that was sent earlier. In *reference*, either a window or a document reference is given (see explanation for Algorithm 4 above). *requestUrl* contains the URL used when retrieving the document.

The function first saves any cookies that were contained in the response to the browser state, then checks whether a redirection is requested (Location header). If that is not the case, the function creates a new document (for normal requests) or delivers the contents of the response to the respective receiver (for XHR responses).

Algorithm 8 Process an HTTP response

1: **function** PROCESSRESPONSE(*response*, *reference*, *request*, *requestUrl*, s')
2: **if** Set-Cookie $\in$ *response*.headers **then**
3: **for each** $c \in^{\langle\rangle}$ *response*.headers[Set-Cookie], $c \in$ Cookies **do**
4:   **let** s'.cookies[*request*.host]
    $\hookrightarrow$:= AddCookie(s'.cookies[*request*.host], c)
5: **end for**
6: **end if**
7: **if** Strict-Transport-Security $\in$ *response*.headers $\wedge$ *requestUrl*.protocol $\equiv$ S **then**
8: **let** s'.sts := s'.sts $+^{\langle\rangle}$ *request*.host
9: **end if**
10: **if** Referer $\in$ *request*.headers **then**
11: **let** *referrer* := *request*.headers[Referer]
12: **else**
13: **let** *referrer* := $\bot$
14: **end if**
15: **if** Location $\in$ *response*.headers $\wedge$ *response*.status $\in \{303, 307\}$ **then**
16: **let** *url* := *response*.headers[Location]
17: **if** *url*.fragment $\equiv \bot$ **then**
18:   **let** *url*.fragment := *requestUrl*.fragment
19: **end if**
20: **let** *method*$'$:= *request*.method
21: **let** *body*$'$:= *request*.body
22: **if** Origin $\in$ *request*.headers **then**
23:   **let** *origin* := $\langle$*request*.headers[Origin], $\langle$*request*.host, *url*.protocol$\rangle\rangle$
24: **else**
25:   **let** *origin* := $\bot$
26: **end if**
27: **if** *response*.status $\equiv 303 \wedge$ *request*.method $\notin \{$GET, HEAD$\}$ **then**
28:   **let** *method*$'$:= GET
29:   **let** *body*$'$:= $\langle\rangle$
30: **end if**
31: **if** $\nexists \overline{w} \in$ Subwindows(s') **such that** $s'.\overline{w}$.nonce $\equiv$ *reference* **then** $\triangleright$ Do not redirect XHRs.
32:   **stop** $\langle\rangle, s$
33: **end if**
34: **let** *req* := $\langle$HTTPReq, ν_6, *method*$'$, *url*.host, *url*.path, $\langle\rangle$, *url*.parameters, *body*$'\rangle$
35: **let** *referrerPolicy* := *response*.headers[ReferrerPolicy]
36: SEND(*reference*, *req*, *url*, *origin*, *referrer*, *referrerPolicy*, s')
37: **end if**
38: **if** $\exists \overline{w} \in$ Subwindows(s') **such that** $s'.\overline{w}$.nonce $\equiv$ *reference* **then** $\triangleright$ normal response
39: **if** *response*.body $\not\sim \langle *, * \rangle$ **then**

40:              **stop** $\{\}, s'$
41:          **end if**
42:          **let** $script := \pi_1(response.\text{body})$
43:          **let** $scriptstate := \pi_2(response.\text{body})$
44:          **let** $referrer := request.\text{headers}[\texttt{Referer}]$
45:          **let** $d := \langle \nu_7, requestUrl, response.\text{headers}, referrer, script, scriptstate, \langle\rangle, \langle\rangle, \top \rangle$
46:          **if** $s'.\overline{w}.\text{documents} \equiv \langle\rangle$ **then**
47:              **let** $s'.\overline{w}.\text{documents} := \langle d \rangle$
48:          **else**
49:              **let** $\overline{i} \leftarrow \mathbb{N}$ **such that** $s'.\overline{w}.\text{documents}.\overline{i}.\text{active} \equiv \top$
50:              **let** $s'.\overline{w}.\text{documents}.\overline{i}.\text{active} := \bot$
51:              **remove** $s'.\overline{w}.\text{documents}.(\overline{i}+1)$ and all following documents
                   $\hookrightarrow$ from $s'.\overline{w}.\text{documents}$
52:              **let** $s'.\overline{w}.\text{documents} := s'.\overline{w}.\text{documents} +^{\langle\rangle} d$
53:          **end if**
54:          **stop** $\{\}, s'$
55:      **else if** $\exists \overline{w} \in \text{Subwindows}(s'), \overline{d}$ **such that** $s'.\overline{d}.\text{nonce} \equiv \pi_1(reference)$
          $\hookrightarrow \wedge s'.\overline{d} = s'.\overline{w}.\text{activedocument}$ **then** $\triangleright$ process XHR response
56:          **let** $headers := response.\text{headers} - \texttt{Set-Cookie}$
57:          **let** $s'.\overline{d}.\text{scriptinputs} := s'.\overline{d}.\text{scriptinputs} +^{\langle\rangle}$
              $\langle \texttt{XMLHTTPREQUEST}, headers, response.\text{body}, \pi_2(reference) \rangle$
58:      **end if**
59: **end function**

Main Algorithm.. This is the main algorithm of the browser relation. It receives the message m as input, as well as a, f and s as above.

Algorithm 9 Web browser main algorithm.

Input: $\langle a, f, m \rangle, s$
 1: **let** $s' := s$
 2: **if** $s.\text{isCorrupted} \not\equiv \bot$ **then**
 3:      **let** $s'.\text{pendingRequests} := \langle m, s.\text{pendingRequests} \rangle$ $\triangleright$ Collect incoming messages
 4:      **let** $m' \leftarrow d_V(s')$
 5:      **let** $a' \leftarrow \text{IPs}$
 6:      **stop** $\langle \langle a', a, m' \rangle \rangle, s'$
 7: **end if**
 8: **if** $m \equiv \texttt{TRIGGER}$ **then** $\triangleright$ A special trigger message.
 9:      **let** $switch \leftarrow \{\texttt{script}, \texttt{urlbar}, \texttt{reload}, \texttt{forward}, \texttt{back}\}$
10:      **let** $\overline{w} \leftarrow \text{Subwindows}(s')$ **such that** $s'.\overline{w}.\text{documents} \neq \langle\rangle$
          $\hookrightarrow$ **if possible; otherwise stop** $\langle\rangle, s'$ $\triangleright$ Pointer to some window.
11:      **let** $\overline{tlw} \leftarrow \mathbb{N}$ **such that** $s'.\overline{tlw}.\text{documents} \neq \langle\rangle$
          $\hookrightarrow$ **if possible; otherwise stop** $\langle\rangle, s'$ $\triangleright$ Pointer to some top-level window.
12:      **if** $switch \equiv \texttt{script}$ **then** $\triangleright$ Run some script.
13:          **let** $\overline{d} := \overline{w} +^{\langle\rangle} \texttt{activedocument}$
14:          $\text{RUNSCRIPT}(\overline{w}, \overline{d}, s')$
15:      **else if** $switch \equiv \texttt{urlbar}$ **then** $\triangleright$ Create some new request.
16:          **let** $newwindow \leftarrow \{\top, \bot\}$
17:          **if** $newwindow \equiv \top$ **then** $\triangleright$ Create a new window.
18:              **let** $windownonce := \nu_1$
19:              **let** $w' := \langle windownonce, \langle\rangle, \bot \rangle$
20:              **let** $s'.\text{windows} := s'.\text{windows} +^{\langle\rangle} w'$
21:          **else** $\triangleright$ Use existing top-level window.
22:              **let** $windownonce := s'.\overline{tlw}.\text{nonce}$
23:          **end if**

```
24:          let protocol ← {P,S}
25:          let host ← Doms
26:          let path ← 𝕊
27:          let fragment ← 𝕊
28:          let parameters ← [𝕊 × 𝕊]
29:          let url := ⟨URL, protocol, host, path, parameters, fragment⟩
30:          let req := ⟨HTTPReq, ν₂, GET, host, path, ⟨⟩, parameters, ⟨⟩⟩
31:          SEND(windownonce, req, url, ⊥, ⊥, ⊥, s′)
32:      else if switch ≡ reload then                              ▷ Reload some document.
33:          let w̄ ← Subwindows(s′) such that s′.w̄.documents ≠ ⟨⟩
              ↪   if possible; otherwise stop ⟨⟩, s′
34:          let url := s′.w̄.activedocument.location
35:          let req := ⟨HTTPReq, ν₂, GET, url.host, url.path, ⟨⟩, url.parameters, ⟨⟩⟩
36:          let referrer := s′.w̄.activedocument.referrer
37:          let s′ := CANCELNAV(s′.w̄.nonce, s′)
38:          SEND(s′.w̄.nonce, req, url, ⊥, referrer, ⊥, s′)
39:      else if switch ≡ forward then
40:          NAVFORWARD(w̄, s′)
41:      else if switch ≡ back then
42:          NAVBACK(w̄, s′)
43:      end if
44: else if m ≡ FULLCORRUPT then                                   ▷ Request to corrupt browser
45:      let s′.isCorrupted := FULLCORRUPT
46:      stop ⟨⟩, s′
47: else if m ≡ CLOSECORRUPT then                                  ▷ Close the browser
48:      let s′.secrets := ⟨⟩
49:      let s′.windows := ⟨⟩
50:      let s′.pendingDNS := ⟨⟩
51:      let s′.pendingRequests := ⟨⟩
52:      let s′.sessionStorage := ⟨⟩
53:      let s′.cookies ⊂⟨⟩ Cookies such that
          ↪   (c ∈⟨⟩ s′.cookies) ⟺ (c ∈⟨⟩ s.cookies ∧ c.content.session ≡ ⊥)
54:      let s′.isCorrupted := CLOSECORRUPT
55:      stop ⟨⟩, s′
56: else if ∃ ⟨reference, request, url, key, f⟩ ∈⟨⟩ s′.pendingRequests
      ↪   such that π₁(dec_s(m, key)) ≡ HTTPResp then              ▷ Encrypted HTTP response
57:      let m′ := dec_s(m, key)
58:      if m′.nonce ≢ request.nonce then
59:          stop ⟨⟩, s
60:      end if
61:      remove ⟨reference, request, url, key, f⟩ from s′.pendingRequests
62:      PROCESSRESPONSE(m′, reference, request, url, s′)
63: else if π₁(m) ≡ HTTPResp ∧ ∃ ⟨reference, request, url, ⊥, f⟩ ∈⟨⟩ s′.pendingRequests
      ↪   such that m′.nonce ≡ request.key then
64:      remove ⟨reference, request, url, ⊥, f⟩ from s′.pendingRequests
65:      PROCESSRESPONSE(m, reference, request, url, s′)
66: else if m ∈ DNSResponses then                                 ▷ Successful DNS response
67:      if m.nonce ∉ s.pendingDNS ∨ m.result ∉ IPs ∨ m.domain ≢ π₂(s.pendingDNS).host then
68:          stop ⟨⟩, s
69:      end if
70:      let ⟨reference, message, url⟩ := s.pendingDNS[m.nonce]
71:      if url.protocol ≡ S then
72:          let s′.pendingRequests := s′.pendingRequests
              ↪   +⟨⟩ ⟨reference, message, url, ν₃, m.result⟩
```

57

73:            **let** $message := \mathsf{enc_a}(\langle message, \nu_3\rangle, s'.\mathtt{keyMapping}[message.\mathtt{host}])$

74:    **else**

75:        **let** $s'.\mathtt{pendingRequests} := s'.\mathtt{pendingRequests}$
           $\hookrightarrow\ +^{\langle\rangle}\ \langle reference, message, url, \bot, m.\mathtt{result}\rangle$

76:    **end if**

77:    **let** $s'.\mathtt{pendingDNS} := s'.\mathtt{pendingDNS} - m.\mathtt{nonce}$

78:    **stop** $\langle\langle m.\mathtt{result}, a, message\rangle\rangle, s'$

79: **end if**

80: **stop** $\langle\rangle, s$

F. Formal Model of OAuth with a Network Attacker

We here present the full details of our formal model of OAuth which we use to analyze all but one of the authentication and authorization properties. This model contains a network attacker. We will later derive from this model a model where the network attacker is replaced by a web attacker.

We model OAuth as a web system (in the sense of Appendix C.3). We call a web system $OWS^n = (\mathcal{W}, \mathcal{S}, \text{script}, E^0)$ an *OAuth web system with a network attacker* if it is of the form described in what follows.

F.1. Outline

The system $\mathcal{W} = \text{Hon} \cup \text{Net}$ consists of a network attacker process (in Net), a finite set B of web browsers, a finite set RP of web servers for the relying parties, a finite set IDP of web servers for the identity providers, with $\text{Hon} := \text{B} \cup \text{RP} \cup \text{IDP}$. More details on the processes in $\mathcal{W}$ are provided below. We do not model DNS servers, as they are subsumed by the network attacker. Figure 13 shows the set of scripts $\mathcal{S}$ and their respective string representations that are defined by the mapping script. The set E^0 contains only the trigger events as specified in Appendix C.3.

$s \in \mathcal{S}$	$\text{script}(s)$
R^{att}	att_script
script_rp_index	script_rp_index
script_rp_implicit	script_rp_implicit
script_idp_form	script_idp_form

Figure 13. List of scripts in $\mathcal{S}$ and their respective string representations.

This outlines OWS^n. We will now define the DY processes in OWS^n and their addresses, domain names, and secrets in more detail.

F.2. Addresses and Domain Names

The set IPs contains for the network attacker in Net, every relying party in RP, every identity provider in IDP, and every browser in B a finite set of addresses each. By addr we denote the corresponding assignment from a process to its address. The set Doms contains a finite set of domains for every relying party in RP, every identity provider in IDP, and the network attacker in Net. Browsers (in B) do not have a domain.

By addr and dom we denote the assignments from atomic processes to sets of IPs and Doms, respectively.

F.3. Keys and Secrets

The set $\mathcal{N}$ of nonces is partitioned into five sets, an infinite sequence N, an infinite set K_{SSL}, an infinite set K_{sign}, and finite sets Passwords, RPSecrets$'$ and ProtectedResources. We thus have

$$\mathcal{N} = \underbrace{N}_{\text{infinite sequence}} \dot\cup \underbrace{K_{\text{SSL}}}_{\text{finite}} \dot\cup \underbrace{\text{Passwords}}_{\text{finite}} \dot\cup \underbrace{\text{RPSecrets}'}_{\text{finite}} \dot\cup \underbrace{\text{ProtectedResources}}_{\text{finite}} .$$

We then define $\text{RPSecrets} := \text{RPSecrets} \cup \{\bot\}$. These sets are used as follows:

- The set N contains the nonces that are available for each DY process in $\mathcal{W}$ (it can be used to create a run of $\mathcal{W}$).

- The set K_{SSL} contains the keys that will be used for SSL encryption. Let $\mathsf{sslkey} \colon \mathsf{Doms} \to K_{SSL}$ be an injective mapping that assigns a (different) private key to every domain. For an atomic DY process p we define $sslkeys^p = \langle \{ \langle d, \mathsf{sslkey}(d) \rangle \mid d \in \mathsf{dom}(p) \} \rangle$.

- The set Passwords is the set of passwords (secrets) the browsers share with the identity providers. These are the passwords the users use to log in at the IdPs.

- The set RPSecrets is the set of passwords (secrets) the relying parties share with the identity providers. These are the passwords the relying parties use to log in at the IdPs. The passwords can also be blank ($\bot$).

- The set ProtectedResources contains a secret for each combination of IdP, client, and user. These are thought of as protected resources that only the owner of the resource (i.e., the user) should be able to read. (See also Definition 45.)

F.4. Identities, Passwords, and Protected Resources

Identites consist, similar to email addresses, of a user name and a domain part. For our model, this is defined as follows:

Definition 40. An *identity* (email address) i is a term of the form $\langle name, domain \rangle$ with $name \in \mathbb{S}$ and $domain \in \mathsf{Doms}$.

Let ID be the finite set of identities. By ID^y we denote the set $\{ \langle name, domain \rangle \in \mathsf{ID} \mid domain \in \mathsf{dom}(y) \}$.

We say that an ID is *governed* by the DY process to which the domain of the ID belongs. Formally, we define the mapping $\mathsf{governor} \colon \mathsf{ID} \to \mathcal{W}$, $\langle name, domain \rangle \mapsto \mathsf{dom}^{-1}(domain)$.

The governor of an ID will usually be an IdP, but could also be the attacker. Besides governor, we define the following mappings:

- By $\mathsf{secretOfID} \colon \mathsf{ID} \to \mathsf{Passwords}$ we denote the bijective mapping that assigns secrets to all identities.

- Let $\mathsf{ownerOfSecret} \colon \mathsf{Passwords} \to \mathsf{B}$ denote the mapping that assigns to each secret a browser that *owns* this secret. Now, we define the mapping $\mathsf{ownerOfID} \colon \mathsf{ID} \to \mathsf{B}$, $i \mapsto \mathsf{ownerOfSecret}(\mathsf{secretOfID}(i))$, which assigns to each identity the browser that owns this identity (we say that the identity belongs to the browser).

- Let $\mathsf{trustedRPs} \colon \mathsf{Passwords} \to 2^{\mathsf{RP}}$ denote a mapping that assigns a set of *trusted relying parties* to each password. Intuitively a trusted relying party is a relying party the user entrusts with her password (in the resource owner password credentials grant mode of OAuth).

- Let $\mathsf{clientIDOfRP} \colon (\mathsf{RP} \cup \{\bot\}) \times \mathsf{IDP} \to \mathbb{S} \cup \{\bot\}$ denote a mapping that assigns an OAuth client id for an relying party to each combination of a relying party and an identity provider. We require that $\mathsf{clientIDOfRP}(\cdot, i)$ is bijective for all $i \in \mathsf{IDP}$ and that $\mathsf{clientIDOfRP}(r, i) = \bot$ iff $r = \bot$ for all $i \in \mathsf{IDP}$.

- Let $\mathsf{secretOfRP} \colon \mathsf{RP} \times \mathsf{IDP} \to \mathsf{RPSecrets}$ denote a bijective mapping that assigns a relying party password (or the empty password $\bot$) to each combination of a relying party and an identity provider.

- As a shortcut, we define the mapping $\mathsf{secretOfClientID} : \mathbb{S} \times \mathsf{IDP} \to \mathsf{RPSecrets}$ to return the relying party password to a relying party identified by an OAuth client id (at some specific identity provider), i.e., $\mathsf{secretOfClientID}(s,i)$ maps to $\mathsf{secretOfRP}(r,i)$ with r such that $s = \mathsf{clientIDOfRP}(r,i)$.

- By $\mathsf{resourceOf} : \mathsf{IDP} \times (\mathsf{RP} \cup \{\bot\}) \times (\mathsf{ID} \cup \{\bot\}) \to \mathsf{ProtectedResources}$ we denote the injective mapping that assigns a protected resource to each combination of user identity, IdP and client (RP). We also include protected resources that are not assigned to a specific user (in this case, the user is $\bot$) and those that are not assigned to a specific RP (the RP then is $\bot$). Note that a protected resource depends not only on the IdP and user ID but also the RP. This is motivated by the fact that different RPs may get access to different protected resources at one IdP, even if they access the resources of the same user. In the resource owner password credentials mode, RPs can also access resources that do not depend on the RP, we then have that RP is $\bot$.[32]

F.5. Corruption

RPs and IdPs can become corrupted: If they receive the message CORRUPT, they start collecting all incoming messages in their state and (upon triggering) send out all messages that are derivable from their state and collected input messages, just like the attacker process. We say that an RP or an IdP is *honest* if the according part of their state ($s.\mathtt{corrupt}$) is $\bot$, and that they are corrupted otherwise.

We are now ready to define the processes in $\mathcal{W}$ as well as the scripts in $\mathcal{S}$ in more detail.

F.6. Processes in $\mathcal{W}$ (Overview)

We first provide an overview of the processes in $\mathcal{W}$. All processes in $\mathcal{W}$ contain in their initial states all public keys and the private keys of their respective domains (if any). We define $I^p = \mathsf{addr}(p)$ for all $p \in \mathsf{Hon}$.

Network Attacker. There is one atomic DY process $na \in \mathsf{Net}$ which is a network attacker (see Appendix C.3), who uses all addresses for sending and listening.

Browsers. Each $b \in \mathsf{B}$ is a web browser as defined in Appendix E. The initial state contains all secrets owned by b, stored under the origins of the respective IdP and of all trusted RPs for the respective secret. See Appendix F.8 for details.

Relying Parties. Each relying party is a web server modeled as an atomic DY process following the description in Section 2 and the fixes discussed in Section 3. The RP can either (at any time) launch a client credentials mode flow or wait for users to start any of the other flows. RP manages two kinds of sessions: The *login sessions*, which are only used during the login phase of a user, and the *service sessions* (modeled by a *service token* as described above).

When receiving a special message (CORRUPT) RPs can become corrupted. Similar to the definition of corruption for the browser, RPs then start sending out all messages that are derivable from their state.

Identity Providers. Each IdP is a web server modeled as an atomic DY process following the description in Section 2 and the fixes discussed in Section 3. In particular, users can authenticate to the IdP with their credentials. Authenticated users can interact with the authorization endpoint of the IdP (e.g., to acquire an authorization code). Just as RPs, IdPs can become corrupted.

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[32]In the resource owner password credentials mode, the RP gets the user's credentials and thus has full access to the user's account at IdP. This access is not bound to potential limitations that depend on the RP's identity.

F.7. Network Attackers

As mentioned, the network attacker *na* is modeled to be a network attacker as specified in Appendix C.3. We allow it to listen to/spoof all available IP addresses, and hence, define $I^{na} = \mathsf{IPs}$. The initial state is $s_0^{na} = \langle attdoms, sslkeys, signkeys \rangle$, where *attdoms* is a sequence of all domains along with the corresponding private keys owned by the attacker *na*, *sslkeys* is a sequence of all domains and the corresponding public keys, and *signkeys* is a sequence containing all public signing keys for all IdPs.

F.8. Browsers

Each $b \in \mathsf{B}$ is a web browser as defined in Appendix E, with $I^b := \mathsf{addr}(b)$ being its addresses.

To define the inital state, first let $\mathsf{ID}_b := \mathsf{ownerOfID}^{-1}(b)$ be the set of all IDs of b. We then define the set of passwords that a browser b gives to an origin o to consist of two parts: (1) If the origin belongs to an IdP, then the user's passwords of this IdP are contained in the set. (2) If the origin belongs to an RP, then those passwords with which the user entrusts this RP are contained in the set. To define this mapping in the initial state, we first define for some process p

$$\mathsf{Secrets}^{b,p} = \left\{ s \ \middle| \ b = \mathsf{ownerOfSecret}(s) \wedge \big((\exists i : s = \mathsf{secretOfID}(i) \wedge i \in \mathsf{governor}^{-1}(p)) \right.$$
$$\left. \vee (\exists R : p \in R \wedge s \in \mathsf{trustedRPs}^{-1}(R)) \big) \right\}.$$

Then, the initial state s_0^b is defined as follows: the key mapping maps every domain to its public (ssl) key, according to the mapping sslkey; the DNS address is an address of the network attacker; the list of secrets contains an entry $\langle \langle d, \mathsf{S} \rangle, \langle \mathsf{Secrets}^{b,p} \rangle \rangle$ for each $p \in \mathsf{RP} \cup \mathsf{IDP}$ and $d \in \mathsf{dom}(p)$; *ids* is $\langle \mathsf{ID}_b \rangle$; *sts* is empty.

F.9. Relying Parties

A relying party $r \in \mathsf{RP}$ is a web server modeled as an atomic DY process (I^r, Z^r, R^r, s_0^r) with the addresses $I^r := \mathsf{addr}(r)$. Its initial state s_0^r contains its domains, the private keys associated with its domains, the DNS server address, and information about IdPs RP is registered at. The full state additionally contains the sets of service tokens and login session identifiers the RP has issued as well as information about pending DNS and pending HTTPS requests (similar to browsers). RP only accepts HTTPS requests.

RP manages two kinds of sessions: The *login sessions*, which are only used during the login phase of a user, and the *service sessions* (we call the session identifier of a service session a *service token*). Service sessions allow a user to use RP's services. The ultimate goal of a login flow is to establish such a service session.

We now first describe how r can become corrupted, then we describe the handling of DNS and HTTPS requests and responses, before we describe the behaviour of r during a login flow.

Corruption. When r receives a corrupt message, it becomes corrupt and acts like the attacker from then on (i.e., it collects all incoming messages and non-deterministically sends out all messages derivable from its state).

Pending DNS Requests and Pending HTTPS Requests. Since the RP r also acts as an HTTPS client, it manages two kinds of records for messages that have been sent out into the network and are waiting for corresponding responses. When an HTTPS message is to be sent, the RP first needs to resolve the hostname into an IP address. To this end, the RP first stores the HTTPS request (together with some state information) in a subterm of its state called *pendingDNS* and (instead of sending the HTTPS request immediately) sends out a DNS request to the DNS server. When a DNS response arrives that matches

one of the entries in this subterm, the HTTPS request is sent out over the network (to the resolved IP address) and stored in the subterm *pendingRequests* of the RP's state. Note that this mechanism is very similar to (generic) browsers (see Appendix E).

Initial Request. In a typical flow, r will first receive an HTTP GET request from a browser for the path /. In this case, r returns the script `script_rp_index`. Besides providing arbitrary links, this script allows users to start an OAuth flow in the browser. If an OAuth flow is started, this script non-deterministically chooses an identity of the user, i.e., a combination of a username and a domain of an IdP. Further this script non-deterministically decides whether an interactive login (i.e., authorization code mode or implicit mode) or a non-interactive login (i.e., resource owner password credentials mode) is used. If an interactive login is chosen, the script instructs the browser to send an HTTPS POST request to r for the path /`startInteractiveLogin`. This POST request contains in its body the domain of the IdP.[33] If the script chooses a non-interactive login, the domain of the IdP, the username, and the user's password are sent to r in an HTTPS POST request for the path /`passwordLogin`.

As the flow now forks into different branches, we will explain (the first part of) each of these branches separately: If the script has chosen to run an interactive login, we continue our description in the paragraph *Interactive Login* below. Else, if the script has chosen to run a non-interactive login, we continue our description of this in the paragraph *Non-Interactive Login*.

Interactive Login. In this case, `script_rp_index` has sent an HTTPS POST request for the path /`startInteractiveLogin` to r containing the name of an IdP in its body. When r receives such a request, r non-deterministically decides whether the OAuth authorization code mode or the OAuth implicit mode is used. Also, r non-deterministically selects a redirect URI *redirect_uri* of its redirection endpoints (and appends the domain of the IdP to this redirect URI) or selects no redirect URI. Further, r non-deterministically selects a (fresh) nonce *state* and a (fresh) nonce as login session id. Then, r saves all the chosen information in its state. Now, r constructs and sends an HTTPS response containing an HTTP 303 location redirect or an HTTP 307 location redirect[34] (chosen non-deterministically) which points to the corresponding authorization endpoint at the IdP along with r's OAuth client id for this IdP, *state* and information which OAuth mode r has chosen. Additionally, this response also contains a Set-Cookie header, which sets a cookie containing the login session id. r also stores a record in the subterm *loginSessions* of its state. This record contains the login session id, the chosen OAuth mode, and the domain of the IdP.

Later, when IdP redirects the user's browser to r's redirection endpoint, r will receive an HTTPS GET request for the path /`redirectionEndpoint`. This request must contain a login session id cookie, which refers to the information stored in the subterm *loginSessions* in r's state. The request must also contain a parameter with the domain of the IdP and this domain must match the domain stored for this login session.

If r has stored that for this login session the OAuth authorization code mode is used, r checks if the *state* value contained in a parameter is correct (i.e., the value of this parameter is congruent to the value recorded in r's state). Then, r extracts the authorization code *code* from the parameters of the incoming request and prepares an HTTPS POST request to the IdP's token endpoint to obtain an access token as follows: r adds the authorization code to the request's body. If a redirect URI has been set by r before (according to r's state for this login session), the redirect URI is included in the request's body. If r knows an OAuth client secret for the IdP, r adds its OAuth client id and its OAuth client secret for the IdP to the header of the request, else r adds its OAuth client id for the IdP to the request's body. Now,

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[33]Note that while the script has selected an identity of the user, only the domain of the IdP is used in this case and during the authentication to the IdP, a different username may be chosen.

[34]Note that while in this paper we present an attack against OAuth based on an HTTP 307 location redirect, our analysis shows that an HTTP 307 location redirect is safe at this point in the protocol flow.

r sends a DNS request for the domain of the IdP's token endpoint to the DNS server (according to *r*'s state), saves this (prepared) request and all information belonging to the (incoming) HTTPS request *r* received from the browser (such as IP addresses, temporary HTTPS keys) in *pendingDNS* in its state. We will continue our description of which requests *r* will process next in the OAuth authorization code mode in the paragraph *Token Response* below.

If the (incoming) HTTPS request's login session at *r* states that implicit mode is used, *r* instead sends an HTTPS response to the sender of the incoming message. This HTTPS response contains the script *script_rp_implicit* and the initial state for this script in this response contains the domain of the IdP.

In a browser, this script extracts *access_token* and *state* from the fragment part of its URL and extracts the domain of the IdP from its initial state. The script then sends this information in the body of an HTTPS POST request for the path /receiveTokenFromImplicitGrant to *r*.

When *r* receives such an HTTPS POST request (for the path /receiveTokenFromImplicitGrant), *r* checks if this request contains a login session id cookie, which refers to the information stored in its state and if the values of *state* and *idp* (contained in the request) match the information there. Next, *r* prepares an HTTPS request to IdP's introspection endpoint containing the access token just received. *r* saves all information belonging to this new request and the (incoming) request it had just received in *pendingDNS* in its state and sends out a DNS request for the domain of the IdP's introspection endpoint to the DNS server.

We describe what happens when *r* later receives the response from IdP in the paragraph *Introspection Response* below.

Non-Interactive Login. In this case, script_rp_index has sent an HTTPS POST request for the path /passwordLogin to *r* containing a domain of an IdP, a username and a user's password in its body. Next, *r* constructs an HTTPS POST request to the token endpoint of the IdP. This request contains the username and the user's password in its body and if *r* knows an OAuth client secret for the IdP, the request contains an HTTP header with *r*'s OAuth client id and OAuth client secret. *r* saves all information belonging to this new request and the (incoming) request *r* has just received in the subterm *pendingDNS* in *r*'s state and sends out a DNS request for the domain of the IdP's token endpoint to the DNS server.

We describe what happens when *r* later receives the response from the IdP in the paragraph *Token Response* below.

Client Credentials Mode. When *r* receives a TRIGGER message (which models that *r* non-deterministically starts an OAuth flow in the client credentials mode), *r* first non-deterministically selects a domain of an IdP. Then, *r* constructs an HTTPS POST request to the token endpoint of the IdP. This request contains an HTTP header with *r*'s OAuth client id and OAuth client secret.[35] *r* saves all information belonging to this (prepared) request in *pendingDNS* and sends out a DNS request for the domain of the IdP's token endpoint to the DNS server.

We describe what happens when *r* later receives the response from IdP in the paragraph *Token Response* below.

Token Response. When *r* receives an encrypted HTTP response that matches a record in the subterm *pendingRequests* of its state and belongs to a request for an access token from an IdP (according to the information recorded in *pendingRequests*), then *r* extracts the access token and prepares an HTTPS request to the IdP's introspection endpoint containing the access token. *r* saves all information belonging to this new request in *pendingDNS*. Further, *r* also stores selected information, which is passed along in *r*'s state in the corresponding record of the incoming request, such as the IP address of the sender and

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[35]Note that in our model, *r* may even construct such a request if *r* does not have an OAuth client secret for the IdP. In this case, the symbol ⊥ is placed in this header instead of an OAuth client secret. The IdP, however, will drop such a request, as it is not authenticated.

the HTTPS response key of the request which initiated *r*'s request for the access token before. Then, *r* sends out a DNS request for the domain of the IdP's introspection endpoint to the DNS server.

Introspection Response. When *r* receives an encrypted HTTP response that matches a record in the sub-term *pendingRequests* in its state and this record belongs to a request to an IdP's introspection endpoint, *r* checks whether the response belongs to a flow in client credentials mode (according to the record). If that is the case, *r* stops. Otherwise, *r* non-deterministically proceeds with either an authorization flow or an authentication flow:

- If authorization is selected, *r* retrieves the protected resource from the IdP's response and sends out an HTTPS response to the IP address recorded in the record in *pendingRequests* (which contains the IP address of the browser, which initially sent either user credentials, an authorization code, or an access token).

- Else, authentication is selected. Now, if the response does not contain *r*'s OAuth client id, *r* stops. Otherwise, *r* retrieves the user id from the response and non-deterministically chooses a fresh nonce as a service token. *r* records in its state that the service token belongs to the user identified by the user id at the IdP. Now, *r* sends out a response (as above) which contains the service token in a cookie.

In both cases, *r* replies with the script *script_rp_index*, which provides arbitrary links and the possibility to start a new OAuth flow (see above).

This concludes the description of the behaviour of an RP.

Formal description. We now provide the formal definition of *r* as an atomic DY process (I^r, Z^r, R^r, s_0^r). As mentioned, we define $I^r = \text{addr}(r)$. Next, we define the set Z^r of states of *r* and the initial state s_0^r of *r*.

Definition 41. An *IdP registration record* is a term of the form

$$\langle tokenEndpoint, authorizationEndpoint, introspectionEndpoint, clientId, clientPassword \rangle$$

with *tokenEndpoint*, *authorizationEndpoint*, *introspectionEndpoint* $\in$ URLs, *clientId* $\in \mathbb{S}$, and *clientPassword* $\in \mathcal{N}$.

An *IdP registration record for an identity provider i at a relying party r* is an IdP registration record with *tokenEndpoint*.host, *authorizationEndpoint*.host, *introspectionEndpoint*.host $\in \text{dom}(i)$, *clientId* $= \text{clientIDOfRP}(r, i)$, and *clientPassword* $= \text{secretOfRP}(r, i)$.

Definition 42. A state $s \in Z^r$ of an RP *r* is a term of the form $\langle DNSAddress, idps, serviceTokens, loginSessions, keyMapping, sslkeys, pendingDNS, pendingRequests, corrupt \rangle$ where *DNSAddress* $\in$ IPs, *idps* $\in \left[\text{Doms} \times \mathcal{T}_{\mathcal{N}} \right]$ is a dictionary of IdP registration records, *serviceTokens* $\in \left[\mathcal{N} \times \mathcal{T}_{\mathcal{N}} \right]$, *loginSessions* $\in \left[\mathcal{N} \times \mathcal{T}_{\mathcal{N}} \right]$ is a dictionary of login session records, *keyMapping* $\in \left[\mathbb{S} \times \mathcal{N} \right]$, *sslkeys* $= sslkeys^r$, *pendingDNS* $\in \left[\mathcal{N} \times \mathcal{T}_{\mathcal{N}} \right]$, *pendingRequests* $\in \left[\mathcal{N} \times \mathcal{T}_{\mathcal{N}} \right]$, *corrupt* $\in \mathcal{T}_{\mathcal{N}}$.

An *initial state s_0^r of r* is a state of *r* with $s_0^r.$idps being a dictionary that maps each domain of all identity providers *i* to an IdP registration record for *i* at *r*, $s_0^r.\texttt{serviceTokens} = s_0^r.\texttt{loginSessions} = \langle \rangle$, $s_0^r.\texttt{corrupt} = \bot$, and $s_0^r.\texttt{keyMapping}$ is the same as the keymapping for browsers above.

We now specify the relation R^r. Just like in Appendix E, we describe this relation by a non-deterministic algorithm. In several places throughout this algorithm we use placeholders to generate "fresh" nonces as described in our communication model (see Definition 1). Figure 14 shows a list of all placeholders used.

Algorithm 10 Relation of a Relying Party R^r

Placeholder	Usage
ν_1	new HTTP request nonce
ν_2	lookup key for pending DNS entry
ν_3	new service token
ν_4	fresh HTTPS response key
ν_5	new HTTP request nonce
ν_6	lookup key for pending DNS entry
ν_7	new CSRF token
ν_8	new login session cookie
ν_9	new HTTP request nonce
ν_{10}	lookup key for pending DNS entry
ν_{11}	new HTTP request nonce
ν_{12}	lookup key for pending DNS entry
ν_{13}	new HTTP request nonce
ν_{14}	lookup key for pending DNS entry

Figure 14. List of placeholders used in the relying party algorithm

Input: $\langle a, f, m \rangle, s$
1: **if** s'.corrupt $\not\equiv \bot \vee m \equiv$ CORRUPT **then**
2:     **let** s'.corrupt $:= \langle \langle a, f, m \rangle, s'.\text{corrupt} \rangle$
3:     **let** $m' \leftarrow d_V(s')$
4:     **let** $a' \leftarrow$ IPs
5:     **stop** $\langle \langle a', a, m' \rangle \rangle, s'$
6: **end if**
7: **if** $\exists \langle reference, request, key, f \rangle \in^{\langle\rangle} s'$.pendingRequests
    $\hookrightarrow$ **such that** $\pi_1(\text{dec}_\text{s}(m, key)) \equiv$ HTTPResp **then**   ▷ Encrypted HTTP response
8:     **let** $m' := \text{dec}_\text{s}(m, key)$
9:     **if** m'.nonce $\not\equiv request$.nonce **then**
10:         **stop** $\langle\rangle, s$
11:     **end if**
12:     **remove** $\langle reference, request, key, f \rangle$ **from** s'.pendingRequests
13:     **let** $mode := \pi_1(reference)$
14:     **if** $mode \equiv$ code $\vee mode \equiv$ password $\vee mode \equiv$ client_credentials **then**
15:         **let** idp, a', f', n', k' **such that** $\langle mode, idp, a', f', n', k' \rangle \equiv reference$ **if possible; otherwise stop** $\langle\rangle, s$
16:         **let** $token := m'$.body[access_token]
17:         **let** $introspectionEndpoint := s'$.idps[$idp$].introspectionEndpoint
18:         **let** $parameters := introspectionEndpoint$.parameters
19:         **let** $parameters := parameters +^{\langle\rangle} \langle$token, $token \rangle$
20:         **let** $host := introspectionEndpoint$.domain
21:         **let** $path := introspectionEndpoint$.path
22:         **let** $message := \langle$HTTPReq$, \nu_1,$ GET$, host, path, parameters, \langle\rangle, \langle\rangle \rangle$
23:         **let** s'.pendingDNS[ν_2] $:= \langle \langle$introspect$, mode, idp, a', f', n', k' \rangle, message \rangle$
24:         **stop** $\langle \langle s'.\text{DNSaddress}, a, \langle$DNSResolve$, introspectionEndpoint.\text{domain}, \nu_2 \rangle \rangle \rangle, s'$
25:     **else if** $mode \equiv$ introspect **then**
26:         **let** $resource, clientId, user$ **such that**
            $\hookrightarrow \langle \langle$protected_resource$, resource \rangle, \langle$client_id$, clientId \rangle, \langle$user$, user \rangle \rangle \equiv m'$.body
            $\hookrightarrow$ **if possible; otherwise stop** $\langle\rangle, s$
27:         **let** $mode', idp, a', f', n', k'$ **such that** $\langle$introspect$, mode', idp, a', f', n', k' \rangle \equiv reference$
            $\hookrightarrow$ **if possible; otherwise stop** $\langle\rangle, s$
28:         **if** $mode' \equiv$ client_credentials **then**

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29:          **stop** $\langle\rangle$, s ▷ In client credential grant mode, no service token is issued.

30:          **end if**

31:          **let** $goal \leftarrow \{\texttt{authz}, \texttt{authn}\}$ ▷ Proceed with authorization or authentication.

32:          **if** $goal \equiv \texttt{authz}$ **then**

33:              **let** $headers := \langle\rangle$

34:          **else**

35:              **if** $clientId \equiv s'.\texttt{idps}[idp].\texttt{clientId} \vee (clientId \equiv \langle\rangle \wedge mode \equiv \texttt{password} \wedge$
                      $\hookrightarrow s'.\texttt{idps}[idp].\texttt{clientPassword} \equiv \bot)$ **then**

36:                  **if** $user \equiv \langle\rangle$ **then**

37:                      **stop** $\langle\rangle$, s

38:                  **end if**

39:              **else**

40:                  **stop** $\langle\rangle$, s

41:              **end if**

42:              **let** $serviceToken := \nu_3$

43:              **let** $s'.\texttt{serviceTokens}[serviceToken] := \langle user, idp\rangle$

44:              **let** $headers := \langle\langle\texttt{Set-Cookie}, \langle\langle\texttt{serviceToken}, \langle serviceToken, \bot, \bot, \top\rangle\rangle\rangle\rangle\rangle$

45:          **end if**

46:          **let** $headers := headers +^{\langle\rangle} \langle\texttt{ReferrerPolicy}, \texttt{origin}\rangle$

47:          **let** $m' := \mathsf{enc_s}(\langle\texttt{HTTPResp}, n', 200, headers, \langle\texttt{script\_rp\_index}, \langle\rangle\rangle\rangle, k')$

48:          **stop** $\langle\langle f', a', m'\rangle\rangle$, s'

49:        **end if**

50:        **stop** $\langle\rangle$, s

51: **else if** $m \in \text{DNSResponses}$ **then**   ▷ Successful DNS response

52:    **if** $m.\text{nonce} \notin s.\texttt{pendingDNS} \vee m.\text{result} \notin \text{IPs} \vee m.\text{domain} \not\equiv s.\texttt{pendingDNS}[m.\text{domain}].2.\text{host}$ **then**

53:        **stop** $\langle\rangle$, s

54:    **end if**

55:    **let** $\langle reference, request\rangle := s.\texttt{pendingDNS}[m.\text{nonce}]$

56:    **let** $s'.\texttt{pendingRequests} := s'.\texttt{pendingRequests}$
           $\hookrightarrow +^{\langle\rangle} \langle reference, request, \nu_4, m.\text{result}\rangle$

57:    **let** $message := \mathsf{enc_a}(\langle request, \nu_4\rangle, s'.\texttt{keyMapping}[request.\text{host}])$

58:    **let** $s'.\texttt{pendingDNS} := s'.\texttt{pendingDNS} - m.\text{nonce}$

59:    **stop** $\langle\langle m.\text{result}, a, message\rangle\rangle$, s'

60: **else if** $m \equiv \texttt{TRIGGER}$ **then**   ▷ Start Client Credentials Grant

61:    **let** $idpEntry \leftarrow s'.\texttt{idps}$

62:    **let** $idp := \pi_1(idpEntry)$

63:    **let** $tokenEndpoint := s'.\texttt{idps}[idp].\texttt{tokenEndpoint}$ ▷ $tokenEndpoint$ is a URL

64:    **let** $host := tokenEndpoint.\text{domain}$

65:    **let** $path := tokenEndpoint.\texttt{path}$

66:    **let** $parameters := tokenEndpoint.\texttt{parameters}$

67:    **let** $headers := \langle\langle\texttt{Authorization}, \langle s'.\texttt{idps}[idp].\texttt{clientId}, s'.\texttt{idps}[idp].\texttt{clientPassword}\rangle\rangle\rangle$

68:    **let** $message :=$
           $\hookrightarrow \langle\texttt{HTTPReq}, \nu_5, \texttt{POST}, host, path, parameters, headers, \langle\langle\texttt{grant\_type}, \texttt{client\_credentials}\rangle\rangle\rangle$

69:    **let** $s'.\texttt{pendingDNS}[\nu_6] := \langle\langle\texttt{client\_credentials}, idp, \bot, \bot, \bot, \bot\rangle, message\rangle$

70:    **stop** $\langle\langle s'.\texttt{DNSaddress}, a, \langle\texttt{DNSResolve}, idp.\texttt{tokenEndpoint}.\text{domain}, \nu_6\rangle\rangle\rangle$, s'

71: **else**   ▷ Handle HTTP requests

72:    **let** m_{dec}, k, k', $inDomain$ **such that**
           $\hookrightarrow \langle m_{\text{dec}}, k\rangle \equiv \mathsf{dec_a}(m, k') \wedge \langle inDomain, k'\rangle \in s.\texttt{sslkeys}$
           $\hookrightarrow$ **if possible; otherwise stop** $\langle\rangle$, s

73:    **let** n, $method$, $path$, $parameters$, $headers$, $body$ **such that**
           $\hookrightarrow \langle\texttt{HTTPReq}, n, method, inDomain, path, parameters, headers, body\rangle \equiv m_{\text{dec}}$
           $\hookrightarrow$ **if possible; otherwise stop** $\langle\rangle$, s

74:    **if** $path \equiv /$ **then**   ▷ Serve index page.

75:        **let** $headers := \langle\langle\texttt{ReferrerPolicy}, \texttt{origin}\rangle\rangle$

76:        **let** $m' := \mathrm{enc_s}(\langle \texttt{HTTPResp}, n, 200, headers, \langle \texttt{script\_rp\_index}, \langle\rangle \rangle \rangle, k)$

77:        **stop** $\langle\langle f, a, m'\rangle\rangle, s'$

78:    **else if** $path \equiv /\texttt{startInteractiveLogin} \wedge method \equiv \texttt{POST}$ **then** ▷ Serve start interactive login request.

79:        **if** $headers[\texttt{Origin}] \not\equiv \langle inDomain, \mathrm{S}\rangle$ **then**   ▷ CSRF protection.

80:           **stop** $\langle\rangle, s$

81:        **end if**

82:        **let** $idp := body$

83:        **if** $idp \notin s'.\texttt{idps}$ **then**

84:           **stop** $\langle\rangle, s$

85:        **end if**

86:        **let** $state := \nu_7$

87:        **let** $mode \leftarrow \{\texttt{code}, \texttt{token}\}$

88:        **let** $responseStatus \leftarrow \{303, 307\}$

89:        **let** $authEndpoint := s'.\texttt{idps}[idp].\texttt{authorizationEndpoint}$ ▷ $authEndpoint$ is a URL

90:        **let** $authEndpoint.\texttt{parameters} := authEndpoint.\texttt{parameters} +^{\langle\rangle} \langle \texttt{response\_type}, mode\rangle$

91:        **let** $authEndpoint.\texttt{parameters} := authEndpoint.\texttt{parameters} +^{\langle\rangle}$
           $\hookrightarrow \langle \texttt{client\_id}, s'.\texttt{idps}[idp].\texttt{clientId}\rangle$

92:        **let** $authEndpoint.\texttt{parameters} := authEndpoint.\texttt{parameters} +^{\langle\rangle} \langle \texttt{state}, state\rangle$

93:        **let** $redirectUri \leftarrow \{\bot, \top\}$

94:        **if** $redirectUri \equiv \top$ **then**

95:           **let** $sslkey' \leftarrow s'.\texttt{sslkeys}$ ▷ Choose one of RP's domains non-deterministically

96:           **let** $host' := \pi_1(sslkey')$

97:           **let** $redirectUri := \langle \texttt{URL}, \mathrm{S}, host', /\texttt{redirectionEndpoint}, \langle\langle \texttt{idp}, idp\rangle\rangle, \langle\rangle\rangle$

98:        **end if**

99:        **let** $loginSessionId := \nu_8$

100:       **let** $s'.\texttt{loginSessions} := s'.\texttt{loginSessions} +^{\langle\rangle} \langle loginSessionId, \langle idp, state, mode, redirectUri\rangle\rangle$

101:       **let** $headers := \langle\langle \texttt{Location}, authEndpoint\rangle\rangle$

102:       **let** $headers := headers +^{\langle\rangle} \langle \texttt{Set-Cookie}, \langle\langle \texttt{loginSessionId}, \langle loginSessionId, \top, \top, \top\rangle\rangle\rangle\rangle$

103:       **let** $headers := headers +^{\langle\rangle} \langle \texttt{ReferrerPolicy}, \texttt{origin}\rangle$

104:       **let** $m' := \mathrm{enc_s}(\langle \texttt{HTTPResp}, n, responseStatus, headers, \bot\rangle, k)$

105:        **stop** $\langle\langle f, a, m'\rangle\rangle, s'$

106:   **else if** $path \equiv /\texttt{redirectionEndpoint}$ **then**

107:       **let** $loginSessionId := headers[\texttt{Cookie}][\texttt{loginSessionId}]$

108:       **let** $idp, state, mode, redirectUri$ **such that** $\langle idp, state, mode, redirectUri\rangle \equiv$
       $\hookrightarrow s'.\texttt{loginSessions}[loginSessionId]$ **if possible; otherwise stop** $\langle\rangle, s$

109:       **let** $clientId := s'.\texttt{idps}[idp].\texttt{clientId}$

110:       **if** $idp \not\equiv parameters[\texttt{iss}] \vee clientId \not\equiv parameters[\texttt{client\_id}]$ **then**

111:          **stop** $\langle\rangle, s$

112:       **end if**

113:       **if** $mode \equiv \texttt{code}$ **then**   ▷ Continue Authorization Code Grant

114:          **if** $parameters[\texttt{state}] \not\equiv state$ **then**

115:             **stop** $\langle\rangle, s$

116:          **end if**

117:          **let** $code := parameters[\texttt{code}]$

118:          **let** $tokenRequestHeaders := \langle\rangle$

119:          **let** $tokenRequestBody := \langle\langle \texttt{grant\_type}, \texttt{authorization\_code}\rangle, \langle \texttt{code}, code\rangle\rangle$

120:          **if** $redirectUri \not\equiv \bot$ **then**

121:             **let** $tokenRequestBody := tokenRequestBody +^{\langle\rangle} \langle \texttt{redirect\_uri}, redirectUri\rangle$

122:          **end if**

123:          **let** $clientPassword := s'.\texttt{idps}[idp].\texttt{clientPassword}$

124:          **if** $clientPassword \equiv \bot$ **then**

125:             **let** $tokenRequestBody := tokenRequestBody +^{\langle\rangle} \langle \texttt{client\_id}, clientId\rangle$

126:          **else**

127:             **let** $tokenRequestHeaders := tokenRequestHeaders +^{\langle\rangle}$

$\hookrightarrow \langle \texttt{Authorization}, \langle clientId, clientPassword \rangle \rangle$

128:          **end if**

129:          **let** $tokenEndpoint := s'.\texttt{idps}[idp].\texttt{tokenEndpoint}$

130:          **let** $message :=$ $\langle \texttt{HTTPReq}, \nu_9, \texttt{POST}, tokenEndpoint.\texttt{domain}, tokenEndpoint.\texttt{path},$ $tokenEndpoint.\texttt{parameters}, tokenRequestHeaders, tokenRequestBody \rangle$

131:          **let** $s'.\texttt{pendingDNS}[\nu_{10}] := \langle \langle \texttt{code}, idp, a, f, n, k \rangle, message \rangle$

132:          **stop** $\langle \langle s'.\texttt{DNSaddress}, a, \langle \texttt{DNSResolve}, tokenEndpoint.\texttt{domain}, \nu_{10} \rangle \rangle \rangle, s'$

133:       **else if** $mode \equiv \texttt{token}$ **then** $\triangleright$ Continue Implicit Grant

134:          **let** $headers := \langle \langle \texttt{ReferrerPolicy}, \texttt{origin} \rangle \rangle$

135:          **let** $m' := \texttt{enc}_\texttt{s}(\langle \texttt{HTTPResp}, n, 200, headers, \langle \texttt{script\_rp\_implicit}, idp \rangle \rangle, k)$

136:          **stop** $\langle \langle f, a, m' \rangle \rangle, s'$

137:       **end if**

138:       **stop** $\langle \rangle, s$

139:     **else if** $path \equiv /\texttt{passwordLogin} \wedge method \equiv \texttt{POST}$ **then**

140:       **if** $headers[\texttt{Origin}] \not\equiv \langle inDomain, \texttt{S} \rangle$ **then** $\triangleright$ CSRF protection.

141:          **stop** $\langle \rangle, s$

142:       **end if**

143:       **let** idp, $username$, $password$ **such that** $\langle \langle username, idp \rangle, password \rangle \equiv body$ **if possible; otherwise** $\hookrightarrow$ **stop** $\langle \rangle, s$

144:       **let** $tokenRequestHeaders := \langle \rangle$

145:       **let** $tokenRequestBody := \langle \langle \texttt{grant\_type}, \texttt{password} \rangle, \langle \texttt{username}, \langle username, idp \rangle \rangle,$ $\hookrightarrow \langle \texttt{password}, password \rangle \rangle$

146:       **let** $clientId := s'.\texttt{idps}[idp].\texttt{clientId}$

147:       **let** $clientPassword := s'.\texttt{idps}[idp].\texttt{clientPassword}$

148:       **if** $clientPassword \not\equiv \bot$ **then**

149:          **let** $tokenRequestHeaders := tokenRequestHeaders +^{\langle \rangle}$ $\hookrightarrow \langle \texttt{Authorization}, \langle clientId, clientPassword \rangle \rangle$

150:       **end if**

151:       **let** $tokenEndpoint := s'.\texttt{idps}[idp].\texttt{tokenEndpoint}$

152:       **let** $message :=$ $\langle \texttt{HTTPReq}, \nu_{11}, \texttt{POST}, tokenEndpoint.\texttt{domain}, tokenEndpoint.\texttt{path},$ $tokenEndpoint.\texttt{parameters}, tokenRequestHeaders, tokenRequestBody \rangle$

153:       **let** $s'.\texttt{pendingDNS}[\nu_{12}] := \langle \langle \texttt{password}, idp, a, f, n, k \rangle, message \rangle$

154:       **stop** $\langle \langle s'.\texttt{DNSaddress}, a, \langle \texttt{DNSResolve}, tokenEndpoint.\texttt{domain}, \nu_{12} \rangle \rangle \rangle, s'$

155:     **else if** $path \equiv /\texttt{receiveTokenFromImplicitGrant} \wedge method \equiv \texttt{POST}$ **then**

156:       **if** $headers[\texttt{Origin}] \not\equiv \langle inDomain, \texttt{S} \rangle$ **then** $\triangleright$ CSRF protection.

157:          **stop** $\langle \rangle, s$

158:       **end if**

159:       **let** $loginSessionId := headers[\texttt{Cookie}][loginSessionId]$

160:       **let** idp, $state$, $mode$, $redirectUri$ **such that** $\langle idp, state, mode, redirectUri \rangle \equiv$ $\hookrightarrow s'.\texttt{loginSessions}[loginSessionId]$ **if possible; otherwise stop** $\langle \rangle, s$

161:       **let** $token$ **such that** $\langle token, state, idp \rangle \equiv body$ **if possible; otherwise stop** $\langle \rangle, s$

162:       **let** $introspectionEndpoint := s'.\texttt{idps}[idp].\texttt{introspectionEndpoint}$ $\triangleright$ $introspectionEndpoint$ is a URL

163:       **let** $parameters' := introspectionEndpoint.\texttt{parameters}$

164:       **let** $parameters' := parameters' +^{\langle \rangle} \langle \texttt{token}, token \rangle$

165:       **let** $host := introspectionEndpoint.\texttt{domain}$

166:       **let** $path' := introspectionEndpoint.\texttt{path}$

167:       **let** $message := \langle \texttt{HTTPReq}, \nu_{13}, \texttt{GET}, host, path', parameters', \langle \rangle, \langle \rangle \rangle$

168:       **let** $s'.\texttt{pendingDNS}[\nu_{14}] := \langle \langle \texttt{introspect}, \texttt{implicit}, idp, a, f, n, k \rangle, message \rangle$

169:       **stop** $\langle \langle s'.\texttt{DNSaddress}, a, \langle \texttt{DNSResolve}, introspectionEndpoint.\texttt{domain}, \nu_{14} \rangle \rangle \rangle, s'$

170:     **end if**

171: **end if**

172: **stop** $\langle \rangle, s$

In the following scripts, to extract the current URL of a document, the function

GETURL(*tree*, *docnonce*) is used. We define this function as follows: It searches for the document with the identifier *docnonce* in the (cleaned) tree *tree* of the browser's windows and documents. It then returns the URL *u* of that document. If no document with nonce *docnonce* is found in the tree *tree*, $\diamond$ is returned.

We use the helper function GETDOCWINDOW(*tree*, *docnonce*). It returns the nonce of the window in *tree* that contains the document identified by *docnonce*.

Algorithm 11 Relation of *script_rp_index*

Input: $\langle$*tree*, *docnonce*, *scriptstate*, *scriptinputs*, *cookies*, *localStorage*, *sessionStorage*, *ids*, *secrets*$\rangle$
1: **let** *switch* $\leftarrow$ {auth, link}
2: **if** *switch* $\equiv$ auth **then**
3:     **let** *url* := GETURL(*tree*, *docnonce*)
4:     **let** *id* $\leftarrow$ *ids*
5:     **let** *username* := $\pi_1(id)$
6:     **let** *domain* := $\pi_2(id)$
7:     **let** *interactive* $\leftarrow$ {$\bot$, $\top$}
8:     **if** *interactive* $\equiv$ $\top$ **then**
9:         **let** *url'* := $\langle$URL, S, *url*.host, /startInteractiveLogin, $\langle\rangle$, $\langle\rangle\rangle$
10:         **let** *command* := $\langle$FORM, *url'*, POST, *domain*, $\bot\rangle$
11:     **else**
12:         **let** *url'* := $\langle$URL, S, *url*.host, /passwordLogin, $\langle\rangle$, $\langle\rangle\rangle$
13:         **let** *secret* **such that** *secret* = secretOfID(*id*) $\wedge$ *secret* $\in$ *secrets* **if possible; otherwise**
        $\hookrightarrow$ **stop** $\langle s, cookies, localStorage, sessionStorage, \langle\rangle\rangle$
14:         **let** *command* := $\langle$FORM, *url'*, POST, $\langle id, secret\rangle$, $\bot\rangle$
15:     **end if**
16:     **stop** $\langle s, cookies, localStorage, sessionStorage, command\rangle$
17: **else**
18:     **let** *protocol* $\leftarrow$ {P, S}
19:     **let** *host* $\leftarrow$ Doms
20:     **let** *path* $\leftarrow$ $\mathbb{S}$
21:     **let** *fragment* $\leftarrow$ $\mathbb{S}$
22:     **let** *parameters* $\leftarrow$ $[\mathbb{S} \times \mathbb{S}]$
23:     **let** *url* := $\langle$URL, *protocol*, *host*, *path*, *parameters*, *fragment*$\rangle$
24:     **stop** $\langle$HREF, *url*, GETDOCWINDOW(*tree*, *docnonce*)), $\bot\rangle$
25: **end if**

Algorithm 12 Relation of *script_rp_implicit*

Input: $\langle$*tree*, *docnonce*, *scriptstate*, *scriptinputs*, *cookies*, *localStorage*, *sessionStorage*, *ids*, *secrets*$\rangle$
1: **let** *url* := GETURL(*tree*, *docnonce*)
2: **let** *url'* := $\langle$URL, S, *url*.host, /receiveTokenFromImplicitGrant, $\langle\rangle$, $\langle\rangle\rangle$
3: **let** *body* := $\langle url.$fragment[access_token], $url.$fragment[state], *scriptstate*$\rangle$
4: **let** *command* := $\langle$FORM, *url'*, POST, *body*, $\bot\rangle$
5: **stop** $\langle s, cookies, localStorage, sessionStorage, command\rangle$

F.10. Identity Providers

An identity provider $i \in$ IdPs is a web server modeled as an atomic process (I^i, Z^i, R^i, s_0^i) with the addresses $I^i := $ addr(i). Its initial state s_0^i contains a list of its domains and (private) SSL keys, the paths for the endpoints (authorization and token), a list of users, a list of clients, and information about the corruption status (initially, the IdP is not corrupted). Besides this, the full state of i further contains a list of issued authorization codes and access tokens.

Once the IdP becomes corrupted (when it receives the message corrupt), it starts collecting all input

messages and non-deterministically sending out whatever messages are derivable from its state.

Otherwise, IdPs react to three types of requests:

Requests to the authorization endpoint path: In this case, the IdP expects a POST request containing valid user credentials. If the user credentials are not supplied, or the request is not a POST request, the answer contains a script which shows a form to the user to enter her user credentials. In our model, the script just extracts the user credentials from the browser and sends a request to the IdP containing the user credentials and any OAuth parameters contained in the original request (e.g., the intended redirect URI).

If the IdP received a POST request with valid user credentials, it checks the contained client identifier against its own list of clients. If the client identifier is unknown, the IdP aborts. Otherwise, it ensures that the redirect URI, if contained in the request, is valid. For this, it checks the list of redirect URIs stored along with the client identifier. If none of the redirect URIs match the redirect URI presented in the request (see "Matching Redirect URIs" below), the IdP aborts. If no redirect URI is provided in the request, the first URI in the list of redirect URIs is chosen as the redirect URI.

Now the IdP creates a new authorization code and saves this code together with the client identifier and the redirect URI (if provided in the request) to the list of authorization codes.

Now, if the response type parameter in the request is "code", the IdP issues a Location redirect header to the redirect URI, appending (as parameters) the newly created authorization code and the state (if provided in the request).

If the reponse type is "token", the IdP redirects the browser to the redirect URI, but appends the authorization code, the state (if provided) and a fixed string (containing the token type, which is "bearer") to the hash of the redirect URI.

Requests to the token endpoint path: Requests to the token endpoint path are only accepted by the IdP if they are POST requests. The IdP then checks that the request either contains a valid client ID, provided as a parameter, or a pair of client ID and client password in a basic authentication header.

If the grant type parameter is *authorization code*, then the IdP checks that the authorization code delivered to it is contained in the list of codes. It checks that the client ID and redirect URI are the same as those stored in the list of codes. It then creates an access token and returns it in the HTTPS response (with token type "bearer").

If the grant type is *password*, the IdP checks the provided username and password and creates an access token as above.

If the grant type is *client credentials*, the IdP checks that the client was authorized with client ID and client password above. If so, it creates an access token as above.

Requests to the introspection endpoint path: In this case, the IdP expects an access token in the parameters of the request. If the access token is valid, the IdP returns the client and user id for which the access token was issued along with the protected resource for this client, user, and IdP.

Formal description. In the following, we will first define the (initial) state of i formally and afterwards present the definition of the relation R^i.

To define the initial state, we will need to add a list of all protected resources that this IdP manages. We therefore define $srlist^i := \langle \{ \mathsf{resourceOf}(i, c, u) \mid c \in \mathsf{RP} \cup \{\bot\}, u \in \mathsf{ID} \} \rangle$ for some IdP i. (Note that we do not use this term for term manipulations in the algorithm. Instead, this term ensures that the output of the atomic process is derivable from the input.)

Definition 43. A *state* $s \in Z^i$ *of an IdP* i is a term of the form $\langle sslkeys, srlist, authEndpoint, tokenEndpoint, introspectEndpoint, clients, codes, corrupt \rangle$ where $sslkeys = sslkeys^i$, $srlist = srlist^i$, $authEndpoint$, $tokenEndpoint$, $introspectEndpoint \in \mathbb{S}$, $clients \in [\mathbb{S} \times \mathcal{T}_{\mathcal{N}}]$, $codes \in \mathcal{T}_{\mathcal{N}}$, $atokens \in [\mathcal{N} \times \mathbb{S}]$.

An *initial state* s_0^i *of* i is a state of the form $\langle sslkeys^i, srlist^i, w, x, y, clients^i, \langle\rangle, \langle\rangle, \bot \rangle$ for some strings

w, x and y and a dictionary *clients^i* that for each relying party r contains an entry of the form $\langle \text{clientIDOfRP}(r,i), z\rangle$ where z is a sequence of URL terms that may contain the wildcard $*$ (see Definition 4) where for every $u \in^{\langle\rangle} z$ we have that $u.\texttt{protocol} \equiv \texttt{S}$, $u.\texttt{host} \in \text{dom}(r)$, $u.\texttt{parameters}[\texttt{iss}] \equiv d$ for some $d \in \text{dom}(i)$, $u.\texttt{parameters}[\texttt{client\_id}] \equiv \text{clientIDOfRP}(r,i)$, $u.\texttt{fragment} \equiv \langle\rangle$, and $u.\texttt{path} \equiv /\texttt{redirectionEndpoint}$. (Note that this includes the changes proposed by)

The relation R^i that defines the behavior of the IdP i is defined as follows:

Algorithm 13 Relation of IdP R^i

Input: $\langle a, f, m\rangle, s$

1: **if** $s'.\texttt{corrupt} \not\equiv \perp \vee m \equiv \texttt{CORRUPT}$ **then**
2:      **let** $s'.\texttt{corrupt} := \langle\langle a, f, m\rangle, s'.\texttt{corrupt}\rangle$
3:      **let** $m' \leftarrow d_V(s')$
4:      **let** $a' \leftarrow \text{IPs}$
5:      **stop** $\langle\langle a', a, m'\rangle\rangle, s'$
6: **end if**
7: **let** $s' := s$
8: **let** $m_\text{dec}, k, k', inDomain$ **such that**
    $\hookrightarrow$ $\langle m_\text{dec}, k\rangle \equiv \text{dec}_\text{a}(m, k') \wedge \langle inDomain, k'\rangle \in s.\texttt{sslkeys}$
    $\hookrightarrow$ **if possible; otherwise stop** $\langle\rangle, s$
9: **let** $n, method, path, parameters, headers, body$ **such that**
    $\hookrightarrow$ $\langle\texttt{HTTPReq}, n, method, inDomain, path, parameters, headers, body\rangle \equiv m_\text{dec}$
    $\hookrightarrow$ **if possible; otherwise stop** $\langle\rangle, s$
10: **if** $path \equiv s.\texttt{authEndpoint}$ **then** $\triangleright$ Authorization Endpoint.
11:      **if** $method \equiv \texttt{GET} \vee (method \equiv \texttt{POST} \wedge (body[\texttt{username}] \equiv \langle\rangle \vee body[\texttt{password}] \equiv \langle\rangle))$ **then**
12:          **let** $data := parameters$
13:          **let** $m' := \text{enc}_\text{s}(\langle\texttt{HTTPResp}, n, 200, \langle\langle\texttt{ReferrerPolicy}, \texttt{origin}\rangle\rangle, \langle\texttt{script\_idp\_form}, data\rangle\rangle, k)$
14:          **stop** $\langle\langle f, a, m'\rangle\rangle, s'$
15:      **else if** $method \equiv \texttt{POST}$ **then**
16:          **if** $headers[\texttt{Origin}] \not\equiv \langle inDomain, \texttt{S}\rangle$ **then** $\triangleright$ CSRF protection.
17:              **stop** $\langle\rangle, s$
18:          **end if**
19:          **let** $username := body[\texttt{username}]$
20:          **let** $password := body[\texttt{password}]$
21:          **let** $clientid := body[\texttt{client\_id}]$
22:          **let** $allowedredirects := s.\texttt{clients}[clientid]$
23:          **if** $password \not\equiv \text{secretOfID}(username)$ **then**
24:              **stop** $\langle\rangle, s$
25:          **end if**
26:          **if** $allowedredirects \equiv \langle\rangle$ **then**
27:              **stop** $\langle\rangle, s$
28:          **end if**
29:          **let** $redirecturi := body[\texttt{redirect\_uri}]$
30:          **if** $redirecturi \not\equiv \langle\rangle$ **then**
31:              **if not** $redirecturi \sim allowedredirects$ **then**
32:                  **stop** $\langle\rangle, s$
33:              **end if**
34:          **else**
35:              **let** $redirecturi \leftarrow allowedredirects$ $\triangleright$ Take one from list of redir URIs.
36:          **end if**
37:          **if** $body[\texttt{response\_type}] \equiv \texttt{code}$ **then**
38:              **let** $s'.\texttt{codes} := s'.\texttt{codes} +^{\langle\rangle} \langle\nu_1, \langle clientid, body[\texttt{redirect\_uri}], username\rangle\rangle$ $\triangleright$ Create authorization code.
39:              **let** $redirecturi.\texttt{parameters} := redirecturi.\texttt{parameters} +^{\langle\rangle} \langle\texttt{code}, \nu_1\rangle$

40:           **let** $redirecturi.\mathtt{parameters} := redirecturi.\mathtt{parameters} +^{\langle\rangle} \langle\mathtt{state}, body[\mathtt{state}]\rangle$

41:           **let** $m' := \mathsf{enc_s}(\langle\mathtt{HTTPResp}, n, 303, \langle\langle\mathtt{Location}, redirecturi\rangle\rangle, \langle\rangle\rangle, k)$

42:           **stop** $\langle\langle f, a, m'\rangle\rangle, s'$

43:         **else**   ▷ Assume response type token.

44:           **let** $s'.\mathtt{atokens} := s'.\mathtt{atokens} +^{\langle\rangle} \langle\nu_1, clientid, username\rangle$

45:           **let** $redirecturi.\mathtt{fragment} := redirecturi.\mathtt{fragment} +^{\langle\rangle} \langle\mathtt{access\_token}, \nu_1\rangle$

46:           **let** $redirecturi.\mathtt{fragment} := redirecturi.\mathtt{fragment} +^{\langle\rangle} \langle\mathtt{token\_type}, \mathtt{bearer}\rangle$

47:           **let** $redirecturi.\mathtt{fragment} := redirecturi.\mathtt{fragment} +^{\langle\rangle} \langle\mathtt{state}, body[\mathtt{state}]\rangle$

48:           **let** $m' := \mathsf{enc_s}(\langle\mathtt{HTTPResp}, n, 303, \langle\langle\mathtt{Location}, redirecturi\rangle\rangle, \langle\rangle\rangle, k)$

49:           **stop** $\langle\langle f, a, m'\rangle\rangle, s'$

50:         **end if**

51:       **end if**

52: **else if** $path \equiv s.\mathtt{tokenEndpoint}$ **then**   ▷ Token Endpoint.

53:     **if** $method \not\equiv \mathtt{POST}$ **then**

54:       **stop** $\langle\rangle, s$

55:     **end if**

56:     **let** $auth := \bot$

57:     **let** $clientid := \bot$

58:     **if** $body[\mathtt{client\_id}] \not\equiv \langle\rangle$ **then**   ▷ Only client ID is provided, no password.

59:       **let** $clientid := body[\mathtt{client\_id}]$

60:       **let** $clientinfo := s.\mathtt{clients}[clientid]$

61:       **if** $clientinfo \equiv \langle\rangle \vee \mathsf{secretOfClientID}(clientid, i) \not\equiv \bot$ **then**   ▷ Empty client secret allowed?

62:         **stop** $\langle\rangle, s$

63:       **end if**

64:     **else if** $headers[\mathtt{Authorization}].1 \not\equiv \langle\rangle$ **then**

65:       **let** $clientid := headers[\mathtt{Authorization}].1$

66:       **let** $clientpw := headers[\mathtt{Authorization}].2$

67:       **if** $\mathsf{secretOfClientID}(clientid, i) \not\equiv clientpw \vee clientpw \equiv \bot$ **then**

68:         **stop** $\langle\rangle, s$

69:       **end if**

70:       **let** $auth := clientid$ ▷ Authentication with client credentials.

71:     **end if**

72:     **if** $body[\mathtt{grant\_type}] \equiv \mathtt{authorization\_code}$ **then**

73:       **if** $clientid \equiv \bot$ **then**

74:         **stop** $\langle\rangle, s$

75:       **end if**

76:       **let** $codeinfo := s.\mathtt{codes}[body[\mathtt{code}]]$

77:       **if** $codeinfo \equiv \langle\rangle \vee codeinfo.1 \not\equiv clientid \vee codeinfo.2 \not\equiv body[\mathtt{redirect\_uri}]$ **then**

78:         **stop** $\langle\rangle, s$

79:       **end if**

80:       **let** $s'.\mathtt{codes} := s'.\mathtt{codes} - body[\mathtt{code}]$

81:       **let** $s'.\mathtt{atokens} := s'.\mathtt{atokens} +^{\langle\rangle} \langle\nu_1, clientid, codeinfo.3\rangle$ ▷ Add nonce, client ID and user ID to list
of tokens.

82:       **let** $m' := \mathsf{enc_s}(\langle\mathtt{HTTPResp}, n, 200, \langle\rangle, \langle\langle\mathtt{access\_token}, \nu_1\rangle, \langle\mathtt{token\_type}, \mathtt{bearer}\rangle\rangle\rangle, k)$

83:       **stop** $\langle\langle f, a, m'\rangle\rangle, s'$

84:     **else if** $body[\mathtt{grant\_type}] \equiv \mathtt{password}$ **then**

85:       **let** $username := body[\mathtt{username}]$

86:       **let** $password := body[\mathtt{password}]$

87:       **if** $password \not\equiv \mathsf{secretOfID}(username)$ **then**

88:         **stop** $\langle\rangle, s$

89:       **end if**

90:       **let** $s'.\mathtt{atokens} := s'.\mathtt{atokens} +^{\langle\rangle} \langle\nu_1, clientid, username\rangle$

91:       **let** $m' := \mathsf{enc_s}(\langle\mathtt{HTTPResp}, n, 200, \langle\rangle, \langle\langle\mathtt{access\_token}, \nu_1\rangle, \langle\mathtt{token\_type}, \mathtt{bearer}\rangle\rangle\rangle, k)$

92:       **stop** $\langle\langle f, a, m'\rangle\rangle, s'$

93:     **else if** $body[\texttt{grant\_type}] \equiv \texttt{client\_credentials}$ **then**
94:         **if** $auth \equiv \bot$ **then**
95:             **stop** $\langle\rangle, s$
96:         **end if**
97:         **let** $s'.\texttt{atokens} := s'.\texttt{atokens} +^{\langle\rangle} \langle\nu_1, clientid, \bot\rangle$
98:         **let** $m' := \mathsf{enc_s}(\langle\texttt{HTTPResp}, n, 200, \langle\rangle, \langle\langle\texttt{access\_token}, \nu_1\rangle, \langle\texttt{token\_type}, \texttt{bearer}\rangle\rangle\rangle, k)$
99:         **stop** $\langle\langle f, a, m'\rangle\rangle, s'$
100:     **end if**
101: **else if** $path \equiv s.\texttt{introspectEndpoint}$ **then**   ▷ Introspection Endpoint.
102:     **if** $method \not\equiv \texttt{GET}$ **then**
103:         **stop** $\langle\rangle, s$
104:     **end if**
105:     **let** $atoken := parameters[\texttt{token}]$
106:     **let** $clientid, userid$ **such that** $\langle atoken, clientid, userid\rangle \in^{\langle\rangle} s'.\texttt{atokens}$ **if possible; otherwise stop** $\langle\rangle, s$
107:     **let** $secret := \mathsf{resourceOf}(i, clientid, userid)$
108:     **let** $body' := \langle\langle\texttt{protected\_resource}, secret\rangle, \langle\texttt{client\_id}, clientid\rangle, \langle\texttt{user}, userid\rangle\rangle$
109:     **let** $m' := \mathsf{enc_s}(\langle\texttt{HTTPResp}, n, 200, \langle\rangle, body'\rangle, k)$
110:     **stop** $\langle\langle f, a, m'\rangle\rangle, s'$
111: **end if**
112: **stop** $\langle\rangle, s$

Algorithm 14 Relation of *script_idp_form*

Input: $\langle tree, docnonce, scriptstate, scriptinputs, cookies, localStorage, sessionStorage, ids, secrets\rangle$
1: **let** $url := \mathsf{GETURL}(tree, docnonce)$
2: **let** $url.\texttt{path} \leftarrow \mathbb{S}$
3: **let** $formdata := scriptstate$
4: **let** $id \leftarrow ids$
5: **let** $secret \leftarrow secrets$
6: **let** $formdata := formdata +^{\langle\rangle} \langle\texttt{username}, id\rangle$
7: **let** $formdata := formdata +^{\langle\rangle} \langle\texttt{password}, secret\rangle$
8: **let** $command := \langle\texttt{FORM}, url, \texttt{POST}, formdata, \bot\rangle$
9: **stop** $\langle s, cookies, localStorage, sessionStorage, command\rangle$

G. Formal Model of OAuth with Web Attackers

We now derive OWS^w (an *OAuth web system with web attackers*) from OWS^n by replacing the network attacker with a finite set of web attackers.

Definition 44. An *OAuth web system with web attackers*, OWS^w, is an OAuth web system $OWS^n = (\mathcal{W}, \mathcal{S}, \text{script}, E^0)$ with the following changes:

- We have $\mathcal{W} = \text{Hon} \cup \text{Web}$, in particular, there is no network attacker. The set Web contains a finite number of web attacker processes. The set Hon is as described above, and additionally contains a DNS server d as defined below.

- The set of IP addresses IPs contains no IP addresses for the network attacker, but instead a finite set of IP addresses for each web attacker.

- The set of Domains Doms contains no domains for the network attacker, but instead a finite set of domains for each web attacker.

- All honest parties use the DNS server d as their DNS server.

G.1. DNS Server

The DNS server d is a DNS server as defined in Definition 30. Its initial state s_0^d contains only pairings $\langle D, i \rangle$ such that $i \in \text{addr}(\text{dom}^{-1}(D))$, i.e., any domain is resolved to an IP address belonging to the owner of that domain (as defined in Appendix F.2).

G.2. Web Attackers

Web attackers, as opposed to network attackers, can only use their own IP addresses for listening to and sending messages. Therefore, for any web attacker process w we have that $I^w = \text{addr}(w)$. The inital states of web attackers are defined parallel to those of network attackers, i.e., the initial state for a web attacker process w is $s_0^w = \langle attdoms^w, sslkeys, signkeys \rangle$, where $attdoms^w$ is a sequence of all domains along with the corresponding private keys owned by the attacker w, *sslkeys* is a sequence of all domains and the corresponding public keys, and *signkeys* is a sequence containing all public signing keys for all IdPs.

H. Formal Security Properties

The security properties for OAuth are formally defined as follows.

H.1. Authorization

Intuitively, authorization for OWS^n means that an attacker should not be able to obtain or use a protected resource available to some honest RP at an IdP for some user unless certain parties involved in the authorization process are corrupted.

Definition 45 (Authorization Property). Let OWS^n be an OAuth web system with a network attacker. We say that OWS^n *is secure w.r.t. authorization* iff for every run ρ of OWS^n, every state (S^j, E^j, N^j) in ρ, every IdP $i \in \mathsf{IDP}$, every $r \in \mathsf{RP} \cup \{\bot\}$ with r being honest in S^j unless $r = \bot$, every $u \in \mathsf{ID} \cup \{\bot\}$, for $n = \mathsf{resourceOf}(i, r, u)$, n is derivable from the attackers knowledge in S^j (i.e., $n \in d_\emptyset(S^j(\mathsf{attacker}))$), it follows that

1. i is corrupted in S^j, or

2. $u \neq \bot$ and (i) the browser b owning u is fully corrupted in S^j or (ii) some $r' \in \mathsf{trustedRPs}(\mathsf{secretOfID}(u))$ is corrupted in S^j.

   Note that the protected resource n being available to the attacker also models that the attacker can use a service of the IdP i under the name of the user u (e.g., the attacker can post to the Facebook wall of the victim).

H.2. Authentication

Intuitively, authentication for OWS^n means that an attacker should not be able to login at an (honest) RP under the identity of a user unless certain parties involved in the login process are corrupted. As explained above, being logged in at an RP under some user identity means to have obtained a service token for this identity from the RP.

Definition 46 (Authentication Property). Let OWS^n be an OAuth web system with a network attacker. We say that OWS^n *is secure w.r.t. authentication* iff for every run ρ of OWS^n, every state (S^j, E^j, N^j) in ρ, every $r \in \mathsf{RP}$ that is honest in S^j, every $i \in \mathsf{IDP}$, every $g \in \mathsf{dom}(i)$, every $u \in \mathbb{S}$, every RP service token of the form $\langle n, \langle u, g \rangle \rangle$ recorded in $S^j(r).\texttt{serviceTokens}$, and n being derivable from the attackers knowledge in S^j (i.e., $n \in d_\emptyset(S^j(\mathsf{attacker}))$), then the browser b owning u is fully corrupted in S^j (i.e., the value of *isCorrupted* is FULLCORRUPT), some $r' \in \mathsf{trustedRPs}(\mathsf{secretOfID}(\langle u, g \rangle))$ is corrupted in S^j, or i is corrupted in S^j.

H.3. Session Integrity for Authorization and Authentication

Before we can define the session integrity property for authorization and authentication, we need to define the notion of *Sessions* and, in particular, *OAuth Sessions*. These capture series of processing steps related to a single OAuth flow. Note that sessions here are not the same as sessions in the web which are usually identified by some session identifier in a cookie.

Notations. In the following, given a finite run $\rho = ((S^0, E^0, N^0), \ldots, (S^n, E^n, N^n))$ or an infinite run $\rho = ((S^0, E^0, N^0), \ldots)$, we denote by Q_i the processing step $(S^i, E^i, N^i) \to (S^{i+1}, E^{i+1}, N^{i+1})$ (with $i \geq 0$ and, for finite runs, $i < n$).

Definition 47 (Emitting Events). Given an atomic process p, an event e, and a finite run $\rho = ((S^0, E^0, N^0), \dots, (S^n, E^n, N^n))$ or an infinite run $\rho = ((S^0, E^0, N^0), \dots)$ we say that p *emits* e iff there is a processing step in ρ of the form

$$(S^i, E^i, N^i) \xrightarrow[p \to E]{} (S^{i+1}, E^{i+1}, N^{i+1})$$

for some $i \geq 0$ and a set of events E with $e \in E$. We also say that p *emits* m iff $e = \langle x, y, m \rangle$ for some addresses x, y.

Sessions and OAuth Sessions. We now define a relation between processing steps. Intuitively, we say that two processing steps are connected if one processing step causes the other. This can happen either directly (i.e., one DY process handles an event output by another process) or indirectly (e.g., a script that was loaded from an earlier message runs in a browser and outputs a new message).

Definition 48 (Connected Processing Steps). We say that two processing steps

$$
\begin{aligned}
Q_x &= (S^x, E^x, N^x) \xrightarrow[p_x \to E_{\text{out},x}]{e_{\text{in},x} \to p_x} (S^{x+1}, E^{x+1}, N^{x+1}) \text{ and} \\
Q_y &= (S^y, E^y, N^y) \xrightarrow[p_y \to E_{\text{out},y}]{e_{\text{in},y} \to p_y} (S^{y+1}, E^{y+1}, N^{y+1})
\end{aligned}
$$

are *connected* iff (1) $e_{\text{in},y} \in E_{\text{out},x}$, or (2) p_y is a browser, $e_{\text{in},y}$ is a trigger event, the browser p_y selects to run a script (i.e., selects `script` in Line 9 of Algorithm 9), and the document selected in Line 13 was created as the result of an HTTP(S) message in $E_{\text{out},x}$.

Based on the notion of connected processing steps, we now define sessions to be sequences of connected processing steps.

Definition 49 (Sessions). A *Session (in a run ρ of a web system)* is a sequence of processing steps $(Q_0, \dots, Q_n)$ or $(Q_0, Q_1, \dots)$ such that (1) for all Q_i with $i > 0$, Q_i is connected to some processing step in $(Q_0, \dots, Q_{i-1})$, and (2) all processing steps appear in the same order as in ρ.

We can now define OAuth Sessions. Intuitively, an OAuth session starts when a user expresses her wish to use some identity at some RP. Each session can only contain one such request. A session ends when a authorization or log in is complete (which does not necessarily happen in all OAuth Sessions).

Definition 50 (Start and End Processing Steps for OAuth). We write $\mathsf{startsOA}(Q, b, r, i)$ iff in the processing step Q the browser b triggers the script *script_rp_index* which selects some domain of i (in Line 6 of Algorithm 11) and instructs the browser b to send a message to r in Line 16.

We write $\mathsf{endsOA}(Q, b, r, i, t)$ iff the RP r in the processing step Q receives an HTTPS response with a body of the form $\langle \langle \texttt{protected\_resource}, t \rangle, \langle \texttt{client\_id}, c \rangle, \langle \texttt{user}, u \rangle \rangle$ for some terms c and u from i and emits an event in Line 48 of Algorithm 10 that is addressed to b.

Definition 51 (OAuth Sessions). Let $\mathcal{OWS}^w$ be an OAuth web system with web attackers and ρ be a run of $\mathcal{OWS}^w$. An *OAuth Session in ρ by a browser b with an RP r and an IdP i* is a infinite session $(Q_0, Q_1, \dots)$ or a finite session $(Q_0, \dots, Q_n)$ in ρ such that $\mathsf{startsOA}(Q_0, b, r, i)$, but there is no $j > 0$, i' such that $\mathsf{startsOA}(Q_j, b, r, i')$. If there are $j > 0$, t such that $\mathsf{endsOA}(Q_j, b, r, i, t)$, then the OAuth Session is finite and $n = j$.

We write $\mathsf{OASessions}(\rho, b, r, i)$ for the set of all OAuth Sessions in ρ by b with the RP r and the IdP i.

We now introduce a notation to associate an OAuth Session with the identity that the browser selected during that session. This models the user intention to log in/authorize using a specific identity. Note that this expression of intent can take place in two places, either during the first step of an OAuth Session (in the resource owner password credentials mode) or at a later time when the user logs in at the IdP (in the implicit mode and the authorization code mode).

Definition 52 (Selected Identity in an OAuth Session). Given a run ρ of an an OAuth web system with a web attacker, a browser b, an RP r, some IdP i, and an OAuth Session $o \in \mathsf{OASessions}(\rho, b, r, i)$ we write $\mathsf{selected}_{\mathrm{nia}}(o, b, r, \langle u, g \rangle)$ iff b in (the first processing step of) o selected $id \equiv \langle u, g \rangle$ in Line 4 of Algorithm 11 and selected *interactive* $\equiv \bot$ in Line 7.

We write $\mathsf{selected}_{\mathrm{ia}}(o, b, r, \langle u, g \rangle)$ iff b in (the first processing step of) o selected *interactive* $\equiv \top$ in Line 7 and there is some Q' in o such that b triggers the script *script_idp_form* in Q' and selects $\langle u, g \rangle$ in Line 4 of Algorithm 14 and sends a message out to i.

Session Integrity Property for Authorization. This security property captures that (a) an RP should only be authorized to access some resources when the user actually expressed the wish to start an OAuth flow before, and (b) if a user expressed the wish to start an OAuth flow using some honest identity provider and a specific identity, then the OAuth flow is never completed with a different identity.

Definition 53 (Session Integrity for Authorization). Let $\mathcal{OWS}^w$ be an OAuth web system with web attackers. We say that $\mathcal{OWS}^w$ *is secure w.r.t. session integrity for authorization* iff for every run ρ of $\mathcal{OWS}^w$, every processing step Q in ρ, every browser b that is honest in Q, every $r \in \mathsf{RP}$ that is honest in Q, every $i \in \mathsf{IDP}$, every identity $\langle u, g \rangle$, some protected resource t, the following holds true: If $\mathsf{endsOA}(Q, b, r, i, t)$, then

(a) there is an OAuth Session $o \in \mathsf{OASessions}(\rho, b, r, i)$, and

(b) if i is honest in Q then Q is in o and we have that

$$\mathsf{selected}_{\mathrm{ia}}(o, b, r, \langle u, g \rangle) \iff \left(t \equiv \mathsf{resourceOf}(i, r, \langle u, g \rangle) \right)$$

or

$$\mathsf{selected}_{\mathrm{nia}}(o, b, r, \langle u, g \rangle) \iff \left(t \equiv \mathsf{resourceOf}(i, r', \langle u, g \rangle) \right)$$

for some $r' \in \{r, \bot\}$.

Session Integrity Property for Authentication. This security property captures that (a) a user should only be logged in when the user actually expressed the wish to start an OAuth flow before, and (b) if a user expressed the wish to start an OAuth flow using some honest identity provider and a specific identity, then user is not logged in under a different identity.

Definition 54 (Session Integrity for Authentication). Let $\mathcal{OWS}^w$ be an OAuth web system with web attackers. We say that $\mathcal{OWS}^w$ *is secure w.r.t. session integrity for authentication* iff for every run ρ of $\mathcal{OWS}^w$, every processing step Q_{login} in ρ, every browser b that is honest in Q_{login}, every $r \in \mathsf{RP}$ that is honest in Q_{login}, every $i \in \mathsf{IDP}$, every identity $\langle u, g \rangle$, the following holds true: If in Q_{login} a service token of the form $\langle n, \langle \langle u', g' \rangle, m \rangle \rangle$ for a domain $m \in \mathsf{dom}(i)$ and some n, u', g' is created in r (in Line 43 of Algorithm 10) and n is sent to the browser b, then

(a) there is an OAuth Session $o \in \mathsf{OASessions}(\rho, b, r, i)$, and

(b) if i is honest in Q_{login} then Q_{login} is in o and we have that

$$\left(\mathsf{selected}_{\mathrm{ia}}(o, b, r, \langle u, g \rangle) \vee \mathsf{selected}_{\mathrm{nia}}(o, b, r, \langle u, g \rangle) \right) \iff \left(\langle u, g \rangle \equiv \langle u', g' \rangle \right) .$$

I. Proof of Theorem 1

Before we present the proof for Theorem 1, we first provide a high-level proof outline. We then show some general properties of OAuth web systems with a network attacker. Afterwards, we first prove the authentication property and then the authorization property.

I.1. Proof Outline

We first show three basic lemmas that apply to honest RPs and capture specific technical details: (1) messages transferred over HTTPS connections that were initiated by honest RPs cannot be read or altered by other parties. In particular, honest RPs do not leak the encryption keys to other parties. (2) HTTP(S) messages which await DNS resolution in a state of an honest RP are later sent out over the network without being altered in between. (3) Honest RPs never send messages to other RPs or themselves, and they send only HTTPS messages that other RPs cannot decrypt.

Authentication. We then prove the authentication property, by contradiction. To this end, we show in three separate lemmas building on each other that (1) the attacker does not learn passwords of the user, (2) the attacker does not learn authorization codes that could be used to learn a relevant access token, and (3) that the attacker in fact does not learn an access token that could be used to retrieve a service token as described in the authentication property. We finally show that there is no other way for an attacker to get hold of a service token (as described in the authentication property), and that therefore, the authentication property holds true.

Authorization. As above, we assume that the authorization property does not hold and lead this to a contradiction. The proof then builds upon lemmas shown in the authentication proof. We show that the attacker would need to know an access token to acquire a protected resource. If the protected resource is bound to a user (i.e., it was not issued in the client credentials mode), then (3) from above applies and shows that the attacker cannot learn such an access token, and thus cannot learn this protected resource. If the protected resource was not assigned to a user (i.e., it was issued in the client credentials mode), then we can show that the attacker would need to know client secrets to get the protected resource. We show, however, that it is not possible for the attacker to learn the necessary client secrets (which are always required in the client credentials mode). Therefore, whether it is a user-bound protected resource or not, the attacker cannot learn it, leading our assumption to a contradiction.

Session Integrity. We first show session integrity for authorization. To this end, we show that an OAuth flow (when the browser b and the RP r are honest) can only be completed when it was actively started by the browser b, i.e., the correct script was run under an origin of r and this script started the login using some identity v. This is achieved by showing the existence of certain events, starting from the last event (where the flow is completed) and backtracing to some starting event. We then show that if i is also honest, the start and end events belong to the same flow, and that the identity v that was selected in this flow is exactly the same identity for which r accesses a resource in the last event. This is done by showing that all events (from the event where the identity was selected to the last event) are connected and that certain values (such as the chosen identity) are relayed correctly and not modified in between processing steps or messages. We then show that session integrity for authentication follows from session integrity for authorization.

I.2. Properties of $\mathcal{OWS}^n$

Let $\mathcal{OWS}^n = (\mathcal{W}, \mathcal{S}, \text{script}, E^0)$ be an OAuth web system with a network attacker. Let ρ be a run of $\mathcal{OWS}^n$. We write $s_x = (S^x, E^x, N^x)$ for the states in ρ.

Definition 55. We say that a term t *is derivably contained in (a term)* t' *for (a set of DY processes)* P *(in a processing step* $s_i \to s_{i+1}$ *of a run* $\rho = (s_0, s_1, \dots)$) if t is derivable from t' with the knowledge available to P, i.e.,

$$t \in d_\emptyset(\{t'\} \cup \bigcup_{p \in P} S^{i+1}(p))$$

Definition 56. We say that *a set of processes* P *leaks a term* t *(in a processing step* $s_i \to s_{i+1}$*) to a set of processes* P' if there exists a message m that is emitted (in $s_i \to s_{i+1}$) by some $p \in P$ and t is derivably contained in m for P' in the processing step $s_i \to s_{i+1}$. If we omit P', we define $P' := \mathcal{W} \setminus P$. If P is a set with a single element, we omit the set notation.

Definition 57. We say that an DY process p *created* a message m (at some point) in a run if m is derivably contained in a message emitted by p in some processing step and if there is no earlier processing step where m is derivably contained in a message emitted by some DY process p'.

Definition 58. We say that *a browser b accepted* a message (as a response to some request) if the browser decrypted the message (if it was an HTTPS message) and called the function PROCESSRESPONSE, passing the message and the request (see Algorithm 8).

Definition 59. We say that an atomic DY process p *knows a term* t in some state $s = (S, E, N)$ of a run if it can derive the term from its knowledge, i.e., $t \in d_\emptyset(S(p))$.

Definition 60. We say that a *script initiated a request r* if a browser triggered the script (in Line 10 of Algorithm 7) and the first component of the *command* output of the script relation is either HREF, IFRAME, FORM, or XMLHTTPREQUEST such that the browser issues the request r in the same step as a result.

The following lemma captures properties of RP when it uses HTTPS. For example, the lemma says that other parties cannot decrypt messages encrypted by RP.

Lemma 1 (RP messages are protected by HTTPS). If in the processing step $s_i \to s_{i+1}$ of a run ρ of $\mathcal{OWS}^n$ an honest relying party r (I) emits an HTTPS request of the form

$$m = \mathsf{enc_a}(\langle req, k \rangle, \mathsf{pub}(k'))$$

(where *req* is an HTTP request, k is a nonce (symmetric key), and k' is the private key of some other DY process u), and (II) in the initial state s_0 the private key k' is only known to u, and (III) u never leaks k', then all of the following statements are true:

1. There is no state of $\mathcal{OWS}^n$ where any party except for u knows k', thus no one except for u can decrypt *req*.

2. If there is a processing step $s_j \to s_{j+1}$ where the RP r leaks k to $\mathcal{W} \setminus \{u, r\}$ there is a processing step $s_h \to s_{h+1}$ with $h < j$ where u leaks the symmetric key k to $\mathcal{W} \setminus \{u, r\}$ or r is corrupted in s_j.

3. The value of the host header in *req* is the domain that is assigned the public key $\mathsf{pub}(k')$ in RP's keymapping $s_0.\mathtt{keyMapping}$ (in its initial state).

4. If r accepts a response (say, m') to m in a processing step $s_j \to s_{j+1}$ and r is honest in s_j and u did not leak the symmetric key k to $\mathcal{W} \setminus \{u, r\}$ prior to s_j, then either u or r created the HTTPS response m' to the HTTPS request m, in particular, the nonce of the HTTP request *req* is not known to any atomic process p, except for the atomic DY processes r and u.

PROOF. (1) follows immediately from the condition. If k' is initially only known to u and u never leaks k', i.e., even with the knowledge of all nonces (except for those of u), k' can never be derived from any network output of u, k' cannot be known to any other party. Thus, nobody except for u can derive req from m.

(2) We assume that r leaks k to $\mathcal{W} \setminus \{u, r\}$ in the processing step $s_j \to s_{j+1}$ without u prior leaking the key k to anyone except for u and r and that the RP is not fully corrupted in s_j, and lead this to a contradiction.

The RP is honest in s_i. From the definition of the RP, we see that the key k is always a fresh nonce that is not used anywhere else. Further, the key is stored in $pendingRequests$ (ν_4 in Lines 56f. of Algorithm 10). The information from $pendingRequests$ is not extracted or used anywhere else, except when handling the received messages, where the key is only checked against and used to decrypt the message (Lines 7ff. of Algorithm 10). Hence, r does not leak k to any other party in s_j (except for u and r). This proves (2).

(3) Per the definition of RPs (Algorithm 10), a host header is always contained in HTTP requests by RPs. From Line 57 of Algorithm 10 we can see that the encryption key for the request req was chosen using the host header of the message. It is chosen from the $keyMapping$ in RP's state, which is never changed during ρ. This proves (3).

(4) An HTTPS response m' that is accepted by r as a response to m has to be encrypted with k. The nonce k is stored by the RP in the $pendingRequests$ state information (see Line 56 of Algorithm 10). The RP only stores freshly chosen nonces there (i.e., the nonces are not used twice, or for other purposes than sending one specific request). The information cannot be altered afterwards (only deleted) and cannot be read except when the RP checks incoming messages. The nonce k is only known to u (which did not leak it to any other party prior to s_j) and r (which did not leak it either, as u did not leak it and r is honest, see (2)). This proves (4). ∎

On a high level, the following lemma shows that the contents in the list of pending HTTP requests are immutable.

Lemma 2 (Pending DNS messages become pending requests). Let r be some honest relying party in $\mathcal{OWS}^n$, $\nu \in \mathcal{N}$, $l > 0$ such that (S^l, E^l, N^l) is a state in ρ, and let $ref \in \mathcal{T}_{\mathcal{N}}$, $req \in \mathsf{HTTPRequests}$ such that $S^l(r).\mathtt{pendingDNS} \equiv S^{l-1}(r).\mathtt{pendingDNS} +^{\langle\rangle} \langle \nu, \langle ref, req \rangle \rangle$. Then we have that $\forall l'$: if there exist $ref', req', x, y \in \mathcal{T}_{\mathcal{N}}$ with $req.\mathtt{nonce} \equiv req'.\mathtt{nonce}$ and $\langle ref', req', x, y \rangle \in^{\langle\rangle} S^{l'}(r).\mathtt{pendingRequests}$ then $req \equiv req' \wedge ref \equiv ref'$.

PROOF. We first note that Algorithm 10 (of relying parties) modifies the subterm $pendingDNS$ of the RP's state only in such a way that entries are appended to or removed from this subterm, but never modified. Entries are appended in Lines 23, 69, 131, 153, and 168. At all these places in the algorithm, an HTTP message term, say req, having a fresh (HTTP) nonce, is appended (together with some term ref) to the subterm $pendingDNS$. (A processing step executing one of these parts of the algorithm results in the state (S^l, E^l, N^l) of ρ.) Entries are only removed in Line 58. In this part of the algorithm, a sequence $\langle ref'', req'', x, y \rangle$ with $x, y \in \mathcal{T}_{\mathcal{N}}$ and $req'' \equiv req$ and $ref'' \equiv ref$ (which could not have been altered in any processing step) are appended to the subterm $pendingRequests$ of RP's state (in Line 56). Besides Line 12, where some entry is removed from this subterm, there is no other part of the algorithm that alters $pendingRequests$ in any way. Hence, there we cannot have any state $(S^{l''}, E^{l''}, N^{l''})$ of ρ where we have an request in $pendingRequests$ with the same (HTTP) nonce but a different req' or a different ref'. ∎

Lemma 3 (RPs never send requests to themselves). An honest RP never sends an HTTP request to any RP (including itself), and only sends HTTPS requests to RPs that the receiving RP cannot decrypt.

PROOF. Honest RPs send HTTP requests only in Lines 22, 68, 130, 152, and 167. In all of these cases, they send the HTTPS request to an endpoint configured in the state (in idps). With Definition 42, it follows that the domains to which these requests are sent, are never a domain of an RP. All requests are sent over HTTPS, and the "correct" encryption keys (as stored in keyMapping) are used (i.e., even if the attacker changes the DNS response such that an HTTPS request is sent to an RP, it cannot be decrypted by the RP). ∎

I.3. Proof of Authentication

We here want to show that every OAuth web system is secure w.r.t. authentication, and therefore assume that there exists an OAuth web system that is not secure w.r.t. authentication. We then lead this to a contradiction, thereby showing that all OAuth web systems are secure w.r.t. authentication. In detail, we assume:

Assumption 1. There exists an OAuth web system with a network attacker $\mathcal{OWS}^n$, a run ρ of $\mathcal{OWS}^n$, a state (S^j, E^j, N^j) in ρ, some $r \in \mathsf{RP}$ that is honest in S^j, some $i \in \mathsf{IDP}$ that is honest in S^j, some $g \in \mathsf{dom}(i)$, some $u \in \mathbb{S}$ with the browser b owning u being not fully corrupted in S^j and all $r' \in \mathsf{trustedRPs}(\mathsf{secretOfID}(\langle u, g \rangle))$ being honest, some RP service token of the form $\langle n, \langle u, g \rangle \rangle$ recorded in $S^j(r).\mathtt{serviceTokens}$ such that n is derivable from the attackers knowledge in S^j (i.e., $n \in d_\emptyset(S^j(\mathtt{attacker}))$).

To show that this is a contradiction, we first show some lemmas:

Lemma 4 (Attacker does not learn passwords). There exists no $l \leq j$, (S^l, E^l, N^l) being a state in ρ such that $\mathsf{secretOfID}(u) \in d_\emptyset(S^l(\mathtt{attacker}))$.

PROOF. Let $s := \mathsf{secretOfID}(\langle u, g \rangle)$ and $R := \mathsf{trustedRPs}(s)$. Initially, in S^0, s is only contained in $S^0(b).\mathtt{secrets}[\langle d, \mathtt{S} \rangle]$ for any $d \in \bigcup_{r' \in R} \mathsf{dom}(r') \cup \mathsf{dom}(i)$ and in no other states (or waiting events). By the definition of the browser, we can see that only scripts loaded from the origins $\langle d, \mathtt{S} \rangle$ can access s. We know that i and all $r' \in R$ are honest (from the assumption). We therefore have that only the scripts *script_rp_index*, *script_rp_implicit*, and *script_idp_form* can access s (if loaded from their respective origins) and that the browser does not use or leak s in any other way. *script_rp_implicit* does not use any browser secrets. We therefore focus on the remaining two scripts:

script_rp_index. If this script was loaded and has access to s, it must have been loaded from origin $\langle d, \mathtt{S} \rangle$ for a domain d of some trusted relying party, say t ($\in R$). If *script_rp_index* selects the secret s in Line 13 of Algorithm 11, we know that it must have selected the id u in Line 4. We therefore know that in Line 14, the browser b is instructed to send (using HTTPS) $\langle u, s \rangle$ to the path /passwordLogin at d. If b sends such a request, t is the only party able to decrypt this request (see the general security properties in [15]). This message is then processed by t according to Lines 139ff. There, username and password are forwarded to some IdP, say i', using an HTTPS POST request. More precisely, this request is sent to the domain of the token endpoint URL contained in the IdP registration record for the domain contained in u. From Definitions 41 and 42 and the fact that this part of the state (of relying parties) is never changed, we can see that the request is sent to a domain of i, and therefore $i' = i$. (The attacker can also not modify or read this request, see Lemma 1.) The body of the HTTPS POST request sent to i is of the following form:

$$\langle \langle \mathtt{grant\_type}, \mathtt{password} \rangle, \langle \mathtt{username}, u \rangle, \langle \mathtt{password}, s \rangle \rangle .$$

Such a request can processed by IdP only in Lines 84ff. of Algorithm 13. There, IdP checks s and discards it. Therefore, s does not leak from i, t, or b to the attacker (or any other party).

script_idp_form. If this script was loaded and has access to s, it must have been loaded from origin $\langle d, \mathtt{S} \rangle$ for a domain d of i. This script sends s to d in an HTTPS POST request. If b sends such a request, i is the only party able to decrypt this request (see the general security properties in [15]). This message is then processed by i according to Lines 15ff. of Algorithm 13. There, the IdP i checks s and discards it. Therefore, s does not leak from i or b to the attacker (or any other party).

This proves Lemma 4.

Lemma 5 (Attacker does not learn authorization codes). There exists no $l \leq j$, (S^l, E^l, N^l) being a state in ρ, $v \in \mathcal{N}$, $y \in \mathcal{T}_{\mathcal{N}}$ such that $v \in d_\emptyset(S^l(\mathtt{attacker}))$ and $\langle v, \langle \mathsf{clientIDOfRP}(r, i), y, u \rangle \rangle \in^{\langle \rangle} S^l(i).\mathtt{codes}$.

PROOF. $S^l(i).\mathtt{codes}$ is initially empty and appended to only in Line 38 of Algorithm 13 (where an authorization code is created). From Line 15ff. it is easy to see that the request which triggers the creation of the authorization code must carry a valid password for the specific identity in the request body. With Lemma 4, we can see that such a request can not come from the attacker, as the attacker does not know the password needed in the request. It can also not originate from an IdP, as IdPs do not send requests. Further, the request can not originate from any corrupted party or an attacker-controlled origin in the honest browser (as otherwise there would be a flow where the attacker would learn the password by sending it to himself, which can be ruled out by Lemma 4). It is also impossible that the request originated from any non-attacker controlled origin in the honest browser: Such a request could be caused by either a Location redirect or a script. (We will refer to the following as *.) A Location redirect must have been issued by an honest party (otherwise, the attacker would have learned the password by the time he issued the response, see Lemma 4). There are two occasions where honest parties issue Location redirect headers:

IdP in Lines 41/48 of Algorithm 13 In this case, an HTTP status code of 303 is sent. While this causes the browser to do a new request, the new request has an empty body in any case.[36]

RP in Line 104 of Algorithm 10 In this case, a 307 redirect could be issued, causing the browser to preserve the request body. We therefore have to check what could have caused the browser to issue a request that caused this Location redirect response, and what body could be contained in such a request. For clarity, we call the request causing the redirection m. It is clear that m cannot come from the attacker (as it contains the password). It must therefore come from an honest browser. If it was caused by a redirect in the honest browser, (*) applies recursively. Otherwise, there are three scripts that could send such a request to RP: *script_rp_index*, *script_rp_implicit*, and *script_idp_form*. Of these, only *script_rp_index* causes a request for the path `/startInteractiveLogin` (which triggers the redirection in Line 104 of Algorithm 10), which, however, does not contain any secret.

A Location redirect can therefore be ruled out as the cause of the request. There are three scripts that could send such a request: *script_rp_index*, *script_rp_implicit*, and *script_idp_form*. The first two, *script_rp_index*, *script_rp_implicit*, do not send requests to any IdP (instead, they only send requests to the RP that sent the scripts to the browser, IdP does not send these scripts to the browser). The latter script, *script_idp_form*, can send the request. In this (last remaining) case, the IdP responds with a Location redirect header in the response, which, among others, carries a URL containing the critical value v (in Line 41). In this case, the browser receives the response, and immediately triggers a new

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[36]Note that at this point it is important that a 303 redirect is performed, not a 307 redirect. See Line 29 of Algorithm 8 for details.

request to the redirection URL. This URL was composed by the IdP using the list of valid redirection URIs from $S^l(i)$.clients, a part of the state of i that is not changed during any run. Definition 43 defines how $S^l(i)$.clients is initialized: For the client id $c := \mathsf{clientIDOfRP}(r,i)$, all redirection URLs carry hosts (domains) of r, have the protocol S (HTTPS), and contain a query parameter component identifying the IdP i. In the checks in Lines 22ff., it is ensured that in any case, this restriction on domain and protocol applies to the resulting redirection URI (called *redirecturi* in the algorithm) as well. Therefore, the browser's GET request which is triggered by the Location header and contains the value v is sent to r over HTTPS.

The RP r can process such a GET request only in Lines 74 and 106 of Algorithm 10. It is clear, that in Line 74, the value v does not leak to the attacker: An honest script is loaded into the browser, which does not use v in any form. If this script causes a request to the attacker (or causes a request which would be redirected to the attacker), the request does not contain v. In particular, v cannot be contained in the Referer header, because this is prevented by the Referrer Policy.

In Lines 106ff., v is forwarded to the IdP for checking its validity and retrieving the access token (there is also code for retrieving the access code from the implicit flow in this part of the code, which is not of interest here). When sending the authorization code, it is critical to ensure that v is forwarded to an honest IdP (in particular, i), and not to the attacker. This is ensured by checking the redirection URL parameters, which, as mentioned above, contain a hint for the IdP in use, in this case i. In Line 110 it is checked that the IdP, to which v is eventually sent, is i.

Therefore, we know that v is sent via POST to the honest IdP i. There, it can only be processed in Lines 52ff. Here, it is easy to see that the value v (called *body*[code] in the algorithm) is checked. However, the value is never sent out to any other party and therefore does not leak.

We have shown that the value v cannot be known to the attacker, which proves Lemma 5. ∎

Lemma 6 (Attacker does not learn access tokens). There exists no $l \leq j$, (S^l, E^l, N^l) being a state in ρ, $v \in \mathcal{N}$, such that $v \in d_\emptyset(S^l(\texttt{attacker}))$ and $\langle v, \mathsf{clientIDOfRP}(r,i), u \rangle \in^{\langle\rangle} S^l(i)$.atokens.

PROOF. Initially, we have $S^0(i)$.atokens $\equiv \langle\rangle$. $S^l(i)$.atokens is appended to only in Lines 44, 81, 90, and 97 (where in each an access token is issued) of Algorithm 13 and not altered in any other way.

In Line 97, a term of the form $\langle *, *, \bot \rangle$ is appended, which is not of the form $\langle v, \mathsf{clientIDOfRP}(r,i), u \rangle$. In what follows, we will distinguish between the lines of Algorithm 13 were $\langle v, \mathsf{clientIDOfRP}(r,i), u \rangle$ is created:

Line 44. It is easy to see, that i must have received an HTTPS POST request containing an Origin header with one of its HTTPS origins and containing (in its body) a dictionary with the entries $\langle \texttt{username}, u \rangle$, $\langle \texttt{password}, \mathsf{secretOfID}(u) \rangle$, and $\langle \texttt{client\_id}, \mathsf{clientIDOfRP}(r,i) \rangle$. (Note that in this case, $\mathsf{clientIDOfRP}(r,i) \neq \bot$, and therefore, $r \neq \bot$.) From Lemma 4 it follows that such a request cannot be assembled by the attacker. Also, neither an IdP nor an RP sends such a request. Hence, this request must have be sent from a browser. In the browser, only the scripts `script_idp_form` and the attacker script R^{att} can instruct the browser to send such a request. From Lemma 4 we know that the attacker script cannot access $\mathsf{secretOfID}(u)$ (otherwise, there would be a run ρ' in which the attacker script would send $\mathsf{secretOfID}(u)$ to the attacker instead). Hence, this request must originate from a command returned by `script_idp_form` and it must be created by the browser b (which is $\mathsf{ownerOfID}(u)$). This script only sends such a request to its own origin, which must be an HTTPS origin (it would not have access to $\mathsf{secretOfID}(u)$ otherwise). The IdP responds with a Location redirect header in the response, which among others, carries a URL containing the critical value v (in Line 48) in the fragment of the URL. In this case, the browser receives the response, and immediately triggers a new request to the redirection URL.

This URL was composed by the IdP using the list of valid redirection URIs from $S^l(i)$.clients, a part of the state of i that is not changed during any run. Definition 43 defines how $S^l(i)$.clients is initialized: For the client id $c := \text{clientIDOfRP}(r,i)$, all redirection URLs carry hosts (domains) of r, have the protocol S (HTTPS), and contain a query parameter component identifying the IdP i. In the checks in Lines 22ff., it is ensured that in any case, this restriction on domain and protocol applies to the resulting redirection URI (called *redirecturi* in the algorithm) as well. Therefore, the browser's GET request which is triggered by the Location header and contains the value v in the fragment, is sent to r over HTTPS.

The RP r can process such a GET request only in Lines 74 and 106 of Algorithm 10. It is clear, that in Line 74, the value v does not leak to the attacker: The honest script *script_rp_index* is loaded into the browser, which does not use v in any form.

In Lines 106ff., RP's algorithm branches into two different flows: (1) RP takes some value from the URL parameters (which do not contain v) and sends it to some process. RP defers its response to the browser and will (later) only send out the response in Lines 42ff. This response, however, does not contain a script and hence, the browser will not be instructed to create any new messages from the resulting document. Hence, v does not leak in this case. (2) RP sends an HTTPS response containing the script *script_rp_implicit* (and, in the script's initial state, a domain of i derived from the redirection URL), which takes v from the URL parameters and instructs the browser to send an HTTPS POST request containing v and the domain of i to the script's (secure) origin at path /receiveTokenFromImplicitGrant. RP processes such a request in Lines 155ff. where it forwards v to the IdP for checking its validity. Here, it is critical to ensure that v is forwarded to an honest IdP (in particular, i), and not to the attacker. This is fulfilled since a domain of i is contained in the request's body, and, before forwarding, it is checked that v is only forwarded to this domain.

Therefore, we know that v is sent via GET to the honest IdP i. There, it can only be processed in Lines 101ff. Here, it is easy to see that the value v is never sent out to any other party and therefore does not leak.

Line 81. In this case, i must have received an HTTPS POST request carrying a dictionary in its body containing the entries $\langle \texttt{grant\_type}, \texttt{authorization\_code}\rangle$ and $\langle \texttt{code}, code\rangle$ with $code \in \mathcal{N}$ such that $\langle code, \langle \text{clientIDOfRP}(r,i), y, u\rangle\rangle \in^{\langle\rangle} S^{l'}(i).\texttt{codes}$ for some $y \in \mathcal{T}_{\mathcal{N}}$ and $l' \leq l$.(Note that, as above, $\text{clientIDOfRP}(r,i) \neq \bot$, and therefore, $r \neq \bot$.) From Lemma 5 it follows that such a request can neither be constructed by the attacker nor by a browser instructed by the attacker script R^{att}. In a browser, the remaining honest scripts do not instruct the browser to send such a request. (Honest) IdPs do not send such requests. Hence, such a request must have been constructed by an (honest) RP. An RP prepares such a request only in Lines 119ff. (of Algorithm 10) and finally sends out this request in Line 59 (after a DNS response). With Lemma 2 and Lemma 1 we know that *reference* contains a term of the form $\langle \texttt{code}, idp, *, *, *, *\rangle$ with $idp \in \text{dom}(i)$ (as the request was sent encrypted for and to i). When RP receives the response from i, RP processes this response in Lines 7ff. where RP distinguishes between two cases based on the first subterm in *reference*. As we know that this subterm is code, we have that the response is processed only in Lines 15ff. RP takes a subterm from the response's body which might contain[37] v in Line 16 and prepares an HTTPS POST request to an URL of i (which is taken from the subterm *idps* of RP's state and this subterm is never altered and initially configured such that the URLs under the dictionary key *idp* are actually belonging to i). This HTTPS POST request contains v in the parameter token. This request is finally sent out this request in Line 59 (after a DNS response) encrypted for and to i.

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[37] The subterm actually is v.

It is now easy to see that i only accepts the request only in Lines 101ff. (of Algorithm 13). There, the IdP only checks the parameter token against its state and discards it afterwards. Hence, v does not leak.

Line 90. In this case, i must have received an HTTPS POST request carrying a dictionary in its body containing the entries $\langle \text{grant\_type}, \text{password} \rangle$, $\langle \text{username}, u \rangle$, and $\langle \text{password}, \text{secretOfID}(u) \rangle$. From Lemma 4 it follows that such a request cannot be constructed by the attacker, dishonest scripts in browsers, or any other dishonest party. (Honest) IdPs do not construct such a request. All honest scripts do not instruct a browser to send such a request. Hence, the request must have been constructed by an honest RP. An RP prepares such a request only in Lines 145ff. (of Algorithm 10) and finally sends out this request in Line 59 (after a DNS response). With Lemma 2 and Lemma 1 we know that *reference* contains a term of the form $\langle \text{password}, idp, *, *, *, * \rangle$ with $idp \in \text{dom}(i)$ (as the request was sent encrypted for and to i). When RP receives the response from i, RP processes this response in Lines 7ff. where RP distinguishes between two cases based on the first subterm in *reference*. As we know that this subterm is code, we have that the response is processed only in Lines 15ff. RP takes a subterm from the response's body which might contain[38] v in Line 16 and prepares an HTTPS POST request to an URL of i (which is taken from the subterm *idps* of RP's state and this subterm is never altered and initially configured such that the URLs under the dictionary key *idp* are actually belonging to i). This HTTPS POST request contains v in the parameter token. This request is finally sent out this request in Line 59 (after a DNS response) encrypted for and to i. It is now easy to see that i only accepts the request only in Lines 101ff. (of Algorithm 13). There, the IdP only checks the parameter token against its state and discards it afterwards. Hence, v does not leak.

We have shown that the value v cannot be known to the attacker, which proves Lemma 6. ∎

We can now show that Assumption 1 is a contradiction.

Lemma 7. Assumption 1 is a contradiction.

PROOF. The service token $\langle n, \langle u, g \rangle \rangle$ can only be created and added to the state $S^j(r).\text{serviceTokens}$ in Line 42 of Algorithm 10. To get to this point in the algorithm, in Line 27, it is checked that *reference* is a tupel of the form $\langle \text{introspect}, mode, g, a', f', n', k' \rangle$. This is taken from the pending requests, where the value is transferred to from the pending DNS subterm (see Lemma 2). Such a term (starting with introspect) is added to the pendingDNS subterm only in Lines 23 and 168. We can now do a case distinction between these two possibilities to identify the request m' to which the response containing the service token will be sent.

Subterm was added in Line 23. In this case, in Line 15, an entry of the form $\langle mode, g, a', f', n', k' \rangle$ must have existed as a reference in the pending HTTP requests, where *mode* is either code or password.[39] Such entries are created in the following lines:

Line 131. Here, a request m' must have been received which contained a valid authorization code for the identity u at the IdP i.[40] The attacker cannot know such an authorization code (see Lemma 5). The RP r does not send requests to itself or to other RPs (see Lemma 3), and no IdPs send requests. Therefore, m' must have originated from an honest browser.

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[38] The subterm actually is v.

[39] If *mode* was client_credentials, no service token is created.

[40] Otherwise, the IdP would not have returned an access token for the identity u. As $g = idp$ is the value stored in the reference, it is also clear that the authorization code was, in fact, sent to i for retrieving the access token, and not to the attacker or another identity provider. Also, the request to i was sent over HTTPS, and therefore, Lemma 1 applies.

Line 153. In this case, a request m' was received which contained a valid username and password combination for u at i. (As above, we know that i was used to verify that information as g is a domain of i, and $idp = g$.) Only the honest browser b and some relying parties know this password (see Lemma 4), but the RPs would not send such a request. The request m' was therefore sent from the browser b.

Subterm was added in Line 168. If the subterm $\langle \texttt{introspect}, mode, g, a', f', n', k' \rangle$ was added in this line, the request causing this (m') must have carried a valid access token for the identity u at i. (As above, the access token was sent to i for validation.) The attacker does not know such an access token (see Lemma 6), and other RPs or IdPs cannot send m'. Therefore, an honest browser must have sent m'.

We therefore have that in all cases, m' was sent by an honest browser. Further, m' must have been an HTTPS request (by the definition of RPs). If the request was sent as the result of an XMLHTTPRequest command from a script, that script must have been loaded from the origin $\langle g_r, \texttt{S} \rangle$ with $g_r \in \mathsf{dom}(r)$. This is a contradiction (there are no honest scripts that use XMLHTTPRequest). Otherwise, it was a "regular" request. In this case, the browser tries to load the service token as a document (which will fail). In particular, the service token $\langle n, \langle u, g \rangle \rangle$ never leaks to the attacker.

We therefore know that the attacker cannot know the service token, which is a contradiction to the assumption. ∎

I.4. Proof of Authorization

As above, we assume that there exists an OAuth web system that is not secure w.r.t. authorization and lead this to a contradiction. Note that in the following, some of the lemmas shown in Appendix I.3 are used.

Assumption 2. There exists a run ρ of an OAuth web system with a network attacker $\mathcal{OWS}^n$, a state (S^j, E^j, N^j) in ρ, some IdP $i \in \mathsf{IDP}$ that is honest in S^j, some RP $r \in \mathsf{RP} \cup \{\bot\}$ with r being honest in S^j unless $r = \bot$, some $u \in \mathsf{ID} \cup \{\bot\}$, some $n = \mathsf{resourceOf}(i, r, u)$, n being derivable from the attackers knowledge in S^j (i.e., $n \in d_\emptyset(S^j(\mathsf{attacker}))$), and $u = \bot$ or ((i) the browser b owning u is not fully corrupted in S^j and (ii) all $r' \in \mathsf{trustedRPs}(\mathsf{secretOfID}(u))$ are honest S^j).

We first show the following lemma:

Lemma 8 (Attacker does not learn RP secrets.). There exists no $l \leq j$, (S^l, E^l, N^l) being a state in ρ such that $\mathsf{secretOfRP}(r, i) \in d_\emptyset(S^l(\mathsf{attacker}))$ unless $\mathsf{secretOfRP}(r, i) \equiv \bot$.

PROOF. Following the definition of the initial states of all atomic processes (in particular Definition 42), initially, $\mathsf{secretOfRP}(r, i)$ is only known to r.

The secret is being used and sent out in an HTTPS message in Lines 61ff. of Algorithm 10 The message is being sent to the token endpoint configured for i, which, according to Definition 41, bears a host name belonging to i. With the definition of *sslkeys* in Definition 42 and Lemma 1 it can be seen that this outgoing HTTP POST request can therefore only be read by the intended receiver, i.

In i, the message cannot be processed in the authentication endpoint, Lines 15 to 51 of Algorithm 13, since it does not carry an Origin header. It can be processed in Lines 52 to 100. It is easy to see that the secret in the message is not used in any outgoing message, neither stored in the IdP's data structures. The message not be processed in Line 101ff., since it is a POST request.

The same applies when the client sends the password in Line 123ff. or Line 146ff. of Algorithm 10.

Therefore, the secret $\mathsf{secretOfRP}(r, i)$ cannot be known to the attacker. ∎

Lemma 9. Assumption 2 is a contradiction.

PROOF. At the beginning of each run, the attacker cannot know n (as defined in the initial states). Only the IdP i can send out the protected resource n, in Line 109 of Algorithm 13. In a state $(S^{l'}, E^{l'}, N^{l'})$ in ρ for some $l' < j$, for i to send out n, an HTTPS request must be received by i which contains, among others, an access token a such that $\langle a, \text{clientIDOfRP}(r, i), u \rangle \in^{\langle \rangle} S^{l'}(i).\texttt{atokens}$. We therefore note that for the attacker to learn n, it has to know a. We also note that if r requests n at the IdP i, the attacker cannot read n or a from such messages (see Lemma 1).

We now have to distinguish two cases:

Anonymous Resource, i.e., $u \equiv \bot$. In this case, the access token a was chosen by i in Line 97 of Algorithm 13. There, a is sent out in response to a request that must have contained the client credentials for r, where the client secret cannot be $\bot$ (see Line 64. With Lemma 8 we see that the attacker cannot send such a request, and therefore, cannot learn a. This implies that the attacker cannot send the request to learn n from i.

User Resource, i.e., $u \not\equiv \bot$. In this Case, Lemma 6 shows that it is not possible for the attacker to send a request to learn n.

With this, we have shown that the attacker cannot learn n, and therefore, Assumption 2 is a contradiction. ∎

I.5. Proof of Session Integrity

Before we prove this property, we highlight that in the absence of a network attacker and with the DNS server as defined for $\mathcal{OWS}^w$, HTTP(S) requests by (honest) parties can only be answered by the owner of the domain the request was sent to, and neither the requests nor the responses can be read or altered by any attacker unless he is the intended receiver. This property is important for the following proof.

We further show the following lemma, which says that an attacker (under the assumption above) cannot learn a *state* value that is used in a login session between an honest browser, an honest IdP, and an honest RP.

Lemma 10 (Third parties do not learn state). Let ρ be a run of an OAuth web system with web attackers $\mathcal{OWS}^w$, (S^j, E^j, N^j) be a state of ρ, $r \in \text{RP}$ be an RP that is honest in S_j, $i \in \text{IDP}$ be an IdP that is honest in S_j, b be a browser that is honest in S_j.

Then there exists no $l \leq j$, with (S^l, E^l, N^l) being a state in ρ, a nonce $loginSessionId \in \mathcal{N}$, a nonce $state \in \mathcal{N}$, a domain $h \in \text{dom}(r)$ of r, terms $x, y, x', y', z \in \mathcal{T}_{\mathcal{N}}$, cookie $c := \langle \texttt{loginSessionId}, \langle loginSessionId, x', y', z \rangle \rangle$, an atomic DY process $p \in \mathcal{W} \setminus \{b, i, r\}$ such that $state \in d_\emptyset(S^l(p))$, $\langle loginSessionId, \langle g, state, x, y \rangle \rangle \in^{\langle \rangle} S^l(r).\texttt{loginSessions}$ and $\langle h, c \rangle \in^{\langle \rangle} S^l(b).\texttt{cookies}$.

PROOF. To prove Lemma 10, we track where the login session identified by $loginSessionId$ is created and used.

We have that $\langle h, c \rangle \in^{\langle \rangle} S^l(b).\texttt{cookies}$. Login sessions are only created in Line 100 of Algorithm 10 (and never altered afterwards). After the session identifier $loginSessionId$ was chosen, its value is sent over the network to the party that requested the login. We have that for $loginSessionId$, this party must be b because only r can set the cookie c for the domain h in the state of b[41] and Line 100 of Algorithm 10 is actually the only place where r does so.

---

[41]Note that we have only web attackers.

Since b is honest, b follows the location redirect contained in the response sent by r. This location redirect contains the *state* (as a URL parameter). The redirect points to some domain of i.[42] The browser therefore sends (among others) *state* to i. Of all the endpoints at i where the request can be received, the authorization endpoint is the only endpoint where *state* could potentially leak to another party. (For all other endpoints, the value is dropped.) If the request is received at the authorization endpoint, *state* is only sent back to b in the initial scriptstate of *script_idp_form*. In this case, the script sends *state* back to i in a POST request to the authorization endpoint. Note that in the steps outlined here, the value $client\_id = \mathsf{clientIDOfRP}(r,i)$ is transferred alongside with *state* (and not altered in-between). Now, after receiving *state* and *client_id* in a POST request at the authorization endpoint, i looks up some redirection URI for *client_id*, which, by Definition 43, is some URI at a domain of r. The value *state* is appended to this URI (either as a parameter or in the fragment). The redirection to the redirection URI is then sent to the browser b. Therefore, b now sends a GET request to r.

If *state* is contained in the parameter, then *state* is immediately sent to r where it is compared to the stored login session records but neither stored nor sent out again. In each case, a script is sent back to b. The scripts that r can send out are *script_rp_index* and *script_rp_implicit*, none of which cause requests that contain *state*. Also, since both scripts are always delivered with a restrictive Referrer Policy header, any requests that are caused by these scripts (e.g., the start of a new login flow) do not contain *state* in the referer header.[43]

If *state* is contained in the fragment, then *state* is not immediately sent to r, but instead, a request without *state* is sent to r. Since this is a GET request, r either answers with an empty response (Lines 44ff. of Algorithm 10), a response containing *script_rp_index* (Lines 74ff.), or a response containing *script_rp_implicit* (Line 135). In case of the empty response, *state* is not used anymore by the browser. In case of *script_rp_index*, the fragment is not used. (As above, there is no other way in which *state* can be sent out, also because the fragment part of an URL is stripped in the referer header.) In the case of *script_rp_implicit* being loaded into the browser, the script sends *state* in the body of an HTTPS request to r (using the path /receiveTokenFromImplicitGrant). When r receives this request, it does not send out *state* to any party (see Lines 155ff. of Algorithm 10).

This shows that *state* cannot be known to any party except for b, i, and r. ∎

Definition 61. Let $e_1 = \langle a_1, f_1, m_1 \rangle$ and $e_2 = \langle a_2, f_2, m_2 \rangle$ be events with m_1 being a DNS request and m_2 being a DNS response or m_1 being an HTTP(S) request and m_2 being an HTTP(S) response. We say that the events *correspond* to each other if m_1 and m_2 use the same DNS/HTTP(S) message nonce, $a_1 = f_2$ and $a_2 = f_1$, and (for HTTP(S) messages) either both m_1 and m_2 are encrypted or both are not encrypted.

Given a run ρ, and two events e_1 and e_2 where e_1 is emitted in a processing step Q_1 in ρ before e_2 is emitted in a processing step Q_2 in ρ, we write $e_1 \rightsquigarrow e_2$ if e_1 corresponds to e_2 and we write $e_1 \dashrightarrow e_2$ if Q_1 is connected to Q_2.

Lemma 11. Given a run ρ, an RP r, and a browser b, if r, in the run ρ, emits an event, say $e_{\mathrm{auth}}^{\mathrm{resp}}$, in Line 48 of Algorithm 10 that is addressed to b, and b and r are not corrupted at this point in the run, then all of the following statements hold true:

(a) Events of one of the forms shown in Figure 15 exist in ρ.

(b) The event $e_{\mathrm{auth}}^{\mathrm{req}}$ was emitted by b and is addressed to r.

---

[42]This follows from Definition 41 and Definition 42.

[43]We note that, as discussed earlier, without the Referrer Policy, *state* could leak to a malicious IdP or other parties.

$$d_{\text{auth}}^{\text{req}} \rightsquigarrow d_{\text{auth}}^{\text{resp}} \dashrightarrow e_{\text{auth}}^{\text{req}} \dashrightarrow d_{\text{cred}}^{\text{req}} \rightsquigarrow d_{\text{cred}}^{\text{resp}} \dashrightarrow e_{\text{cred}}^{\text{req}} \rightsquigarrow e_{\text{cred}}^{\text{resp}} \dashrightarrow d_{\text{intr}}^{\text{req}} \rightsquigarrow d_{\text{intr}}^{\text{resp}} \dashrightarrow e_{\text{intr}}^{\text{req}} \rightsquigarrow e_{\text{intr}}^{\text{resp}} \dashrightarrow e_{\text{auth}}^{\text{resp}} \quad (15)$$

$$e_{\text{auth}}^{\text{req}} \dashrightarrow d_{\text{tokn}}^{\text{req}} \rightsquigarrow d_{\text{tokn}}^{\text{resp}} \dashrightarrow e_{\text{tokn}}^{\text{req}} \rightsquigarrow e_{\text{tokn}}^{\text{resp}} \dashrightarrow d_{\text{intr}}^{\text{req}} \rightsquigarrow d_{\text{intr}}^{\text{resp}} \dashrightarrow e_{\text{intr}}^{\text{req}} \rightsquigarrow e_{\text{intr}}^{\text{resp}} \dashrightarrow e_{\text{auth}}^{\text{resp}} \quad (16)$$

$$e_{\text{auth}}^{\text{req}} \dashrightarrow d_{\text{intr}}^{\text{req}} \rightsquigarrow d_{\text{intr}}^{\text{resp}} \dashrightarrow e_{\text{intr}}^{\text{req}} \rightsquigarrow e_{\text{intr}}^{\text{resp}} \dashrightarrow e_{\text{auth}}^{\text{resp}} \quad (17)$$

Figure 15. Events as described in Lemma 11. Here, $e_{\cdot}$ denotes events containing HTTP(S) messages, $d_{\cdot}$ denotes events containing DNS messages. (15) applies to the resource owner password credentials mode, (16) applies to the authorization code mode, and (17) applies to the implicit mode.

(c) Let $e_{\text{intr}}^{\text{resp}} = \langle a_{\text{intr}}^{\text{resp}}, f_{\text{intr}}^{\text{resp}}, m_{\text{intr}}^{\text{resp}} \rangle$ with $f_{\text{intr}}^{\text{resp}}$ being an IP adress of some party, say, i. Then there is a Q_{starts} such that $\text{startsOA}(Q_{\text{starts}}, b, r, i)$ and we have that (1) $d_{\text{auth}}^{\text{req}}$ was emitted in Q_{starts}, or (2) there are events

$$d_{\text{strt}}^{\text{req}} \rightsquigarrow d_{\text{strt}}^{\text{resp}} \dashrightarrow e_{\text{strt}}^{\text{req}} \rightsquigarrow e_{\text{strt}}^{\text{resp}}$$

such that $d_{\text{strt}}^{\text{req}}$ was emitted in Q_{starts} and $e_{\text{strt}}^{\text{resp}}$ was received by r before $e_{\text{auth}}^{\text{req}}$ was received by r.

PROOF. **(a)** We have that $e_{\text{auth}}^{\text{resp}} = \langle a_{\text{auth}}^{\text{resp}}, f_{\text{auth}}^{\text{resp}}, m_{\text{auth}}^{\text{resp}} \rangle$ was emitted by r in Line 48 of Algorithm 10. (Note that $a_{\text{auth}}^{\text{resp}}$ is an address of b.) This requires that r received (and further processed) an HTTPS response in $e_{\text{intr}}^{\text{resp}}$. Also, it is required that (before receiving this event) there is an entry in the state of r in the subterm pendingRequests of the form $ref = \langle reference, request, key, f \rangle$ for some terms $request$, key, and f. In this subterm, $request.\text{nonce}$ must be the nonce used in the HTTPS response in $e_{\text{intr}}^{\text{resp}}$, and $reference$ must be of the form $\langle \texttt{introspect}, mode', idp, f_{\text{auth}}^{\text{resp}}, a_{\text{auth}}^{\text{resp}}, n', k' \rangle$ where n' is the nonce used in $m_{\text{auth}}^{\text{resp}}$, k' is the key used to encrypt $m_{\text{auth}}^{\text{resp}}$, and idp is some domain.

A subterm of the form of ref therefore had to be created in pendingRequests before. This term is only appended to in Line 56 of Algorithm 10. There, the message in $request$ was sent out because a DNS response with some message nonce n'' was received and in the state of r the following holds true: $\texttt{pendingDNS}[n''] \equiv \langle reference, request \rangle$. Such entries in pendingDNS can only be created when a corresponding DNS request is sent out, which can happen in Lines 22, 68, 130, 152, and 167. We therefore have that the events $d_{\text{intr}}^{\text{req}}$, $d_{\text{intr}}^{\text{resp}}$, and $e_{\text{intr}}^{\text{req}}$ exist and have the mutual relations shown in (15), (16), and (17).

The string introspect is set as the first part of $reference$ in Lines 168 and 23. We examine these cases separately.

In the case that $reference$ was created in Line 168 (where also the second part of $reference$ is set to implicit), an incoming HTTPS request from $a_{\text{auth}}^{\text{resp}}$, i.e., from b, must have been received. This shows the existence and mutual relations of all events depicted in (17) for the implicit mode.

Otherwise, $reference$ was created in Line 23. This requires that r must have received an HTTPS response ($e_{\text{cred}}^{\text{resp}}$ or $e_{\text{tokn}}^{\text{resp}}$), that, as above, has a matching entry in pendingRequests, which, as above, was created by sending out an HTTPS request, which, again as above, was preceded by a DNS request and response. We therefore have that (in the resource owner password credentials mode) $d_{\text{cred}}^{\text{req}}$, $d_{\text{cred}}^{\text{resp}}$, $e_{\text{cred}}^{\text{req}}$, $e_{\text{cred}}^{\text{resp}}$ or (in the authorization code mode) $d_{\text{tokn}}^{\text{req}}$, $d_{\text{tokn}}^{\text{resp}}$, $e_{\text{tokn}}^{\text{req}}$, $e_{\text{tokn}}^{\text{resp}}$ exist and have the mutual relations shown in' (15) and (16), respectively.

It is further required that another reference term, $reference'$ was in pendingRequests when $e_{\text{cred}}^{\text{resp}}$ or $e_{\text{tokn}}^{\text{resp}}$ was received. The term $reference'$ must be of the following form:

$$reference' = \langle w, idp, f_{\text{auth}}^{\text{resp}}, a_{\text{auth}}^{\text{resp}}, n', k' \rangle$$

with $w \in \{\texttt{password}, \texttt{code}\}$.[44]

Now, as above, we can check where *reference'* was created as an entry in `pendingDNS`. This can only happen in Line 153 ($w \equiv \texttt{password}$) and 131 ($w \equiv \texttt{code}$). In both cases, an incoming HTTPS request from $a_{\text{auth}}^{\text{resp}}$, i.e., from b, must have been received. This shows the existance and mutual relations of all events depicted in (16).

For (15), it is easy to see (as above) that $d_{\text{auth}}^{\text{req}}$ and $d_{\text{auth}}^{\text{resp}}$ exist and have the mutual relations as shown.

(b) As already shown above, in all cases, $e_{\text{auth}}^{\text{req}}$ was sent by b to r.

(c) We have that $e_{\text{intr}}^{\text{resp}}$ was received from i. Therefore, $e_{\text{intr}}^{\text{req}}$ must have been sent to i. Therefore, r requested the IP address of some domain of i in $d_{\text{intr}}^{\text{req}}$. This DNS request was created for the domain of a token endpoint which was looked up in an IdP registration record stored under the key *idp*. From Definitions 42 and 41 it follows that *idp* is a domain of i.

As above, we now have to distinguish where the value *reference* is created such that the first part is `introspect`. This can happen in Lines 23 and 168. We examine these cases separately.

- From **(a)** above we have that *reference'* (which contains *idp*) was created as an entry in `pendingDNS` in Line 153 or 131.

  In the case that *reference'* was created in Line 153 we have that the HTTPS request $e_{\text{auth}}^{\text{req}}$ (which was sent by b as shown above) must have been received by r and that this request was a POST request for the path /`passwordLogin`, with a message body *body* such that $\pi_2(\pi_1(body)) \equiv idp$, and that contains an origin header for some domain of r. Such a request can only be caused by *script_rp_index* loaded into b from some domain of r. Hence, this script selected the domain *idp* in Line 6 of Algorithm 11 and we have that $\text{startsOA}(Q_{\text{auth}}, b, r, i)$ where Q_{auth} is the processing step that emitted $d_{\text{auth}}^{\text{req}}$.

  In the case that *reference'* was created in Line 131 we have that (*) the HTTPS request $e_{\text{auth}}^{\text{req}}$ must have been received by r and that in this request there is a cookie `loginSessionId` with a value, say, l such that in the state of r (when receiving the request) in the subterm `loginSessions` under the key l there is a sequence with the first element being *idp*.

  Since we have that $e_{\text{auth}}^{\text{req}}$ was sent by b (as shown above) we have that b must have received an HTTP(S) response from r which contains a Set-Cookie header for the cookie `loginSessionId` with the value l.[45] We denote the event of this message as $e_{\text{strt}}^{\text{resp}}$. This message must have been created in Line 104 and, in the same processing step, an entry in `loginSessions` under the key l as described above is created in Line 100. (There are no other places where login session entries are created.) We have that the corresponding request $e_{\text{strt}}^{\text{req}}$ is a POST request with an origin header for some domain of r, the path /`startInteractiveLogin`, and that the body must be *idp*. As above, such a request can only be caused by *script_rp_index* loaded into b from some domain of r. Hence, this script selected the domain *idp* in Line 6 of Algorithm 11, which output an HREF-command to the browser to send $e_{\text{strt}}^{\text{req}}$ to r. This request is preceded by a pair of corresponding DNS messages $d_{\text{strt}}^{\text{req}}$ and $d_{\text{strt}}^{\text{resp}}$ as defined in the browser relation. We therefore have that $\text{startsOA}(Q_{\text{strt}}, b, r, i)$ where Q_{strt} is the processing step that emitted $d_{\text{strt}}^{\text{req}}$.

- In the case that *reference* was created in Line 168 we have the same situation as in (*) and the proof continues exactly as in (*).

Lemma 12. Let $\mathcal{OWS}^w$ be an OAuth web system with web attackers, then $\mathcal{OWS}^w$ is secure w.r.t. session integrity for authorization.

---

[44]Note that w cannot be `client_credentials` because in this case, *mode'* in *reference* would have been `client_credentials`, which contradicts that in the processing step Q, an event was emitted.

[45]Note that this cookie cannot be set by any party except for r and there are no scripts sent out by r that set cookies.

PROOF. We have to show that for all OAuth web system with web attackers $\mathcal{OWS}^w$, for every run ρ of $\mathcal{OWS}^w$, every processing step Q_{ends} in ρ, every browser b that is honest in Q_{ends}, every $r \in \text{RP}$ that is honest in Q_{ends}, every $i \in \text{IDP}$, every identity $\langle u, g \rangle$, some protected resource t, the following holds true: If $\text{endsOA}(Q_{\text{ends}}, b, r, i, t)$, then

  (a) there is an OAuth Session $o \in \text{OASessions}(\rho, b, r, i)$, and

  (b) if i is honest in Q_{ends} then Q_{ends} is in o and we have that

$$\text{selected}_{\text{ia}}(o, b, r, \langle u, g \rangle) \iff (t \equiv \text{resourceOf}(i, r, \langle u, g \rangle))$$

  or

$$\text{selected}_{\text{nia}}(o, b, r, \langle u, g \rangle) \iff (t \equiv \text{resourceOf}(i, r', \langle u, g \rangle))$$

  for some $r' \in \{r, \bot\}$.

We can see that Lemma 11 applies, since $\text{endsOA}(Q_{\text{ends}}, b, r, i, t)$ where Q_{ends} is the processing step in which $e_{\text{intr}}^{\text{resp}}$ was received by r from i and $e_{\text{auth}}^{\text{resp}}$ was emitted to b. With Lemma 11 (c) and Definition 51 it immediately follows that there is an OAuth Session $o \in \text{OASessions}(\rho, b, r, i)$.

For part (b), we now show the connection between Q_{ends} and o and show that one of the logical equivalences in (b) hold true. In the following, we therefore have that i is honest.

In Lemma 11 we have already shown the existence of and the relations between the events of one of the forms shown in Figure 15. For any two events $e_1 \rightsquigarrow e_2$ in Figure 15, the processing steps where these events where emitted are connected (as i and DNS servers are honest).

$$
\begin{aligned}
d_{\text{strt}}^{\text{req}} \dashrightarrow\ & d_{\text{strt}}^{\text{resp}} \dashrightarrow e_{\text{strt}}^{\text{req}} \dashrightarrow e_{\text{strt}}^{\text{resp}} \\
\dashrightarrow\ & d_{\text{aep1}}^{\text{req}} \dashrightarrow d_{\text{aep1}}^{\text{resp}} \dashrightarrow e_{\text{aep1}}^{\text{req}} \dashrightarrow e_{\text{aep1}}^{\text{resp}} \\
\dashrightarrow\ & d_{\text{aep2}}^{\text{req}} \dashrightarrow d_{\text{aep2}}^{\text{resp}} \dashrightarrow e_{\text{aep2}}^{\text{req}} \dashrightarrow e_{\text{aep2}}^{\text{resp}} \\
\dashrightarrow\ & d_{\text{auth}}^{\text{req}} \dashrightarrow d_{\text{auth}}^{\text{resp}} \dashrightarrow e_{\text{auth}}^{\text{req}}
\end{aligned}
\tag{18}
$$

$$
\begin{aligned}
d_{\text{strt}}^{\text{req}} \dashrightarrow\ & d_{\text{strt}}^{\text{resp}} \dashrightarrow e_{\text{strt}}^{\text{req}} \dashrightarrow e_{\text{strt}}^{\text{resp}} \\
\dashrightarrow\ & d_{\text{aep1}}^{\text{req}} \dashrightarrow d_{\text{aep1}}^{\text{resp}} \dashrightarrow e_{\text{aep1}}^{\text{req}} \dashrightarrow e_{\text{aep1}}^{\text{resp}} \\
\dashrightarrow\ & d_{\text{aep2}}^{\text{req}} \dashrightarrow d_{\text{aep2}}^{\text{resp}} \dashrightarrow e_{\text{aep2}}^{\text{req}} \dashrightarrow e_{\text{aep2}}^{\text{resp}} \\
\dashrightarrow\ & d_{\text{impl}}^{\text{req}} \dashrightarrow d_{\text{impl}}^{\text{resp}} \dashrightarrow e_{\text{impl}}^{\text{req}} \dashrightarrow e_{\text{impl}}^{\text{resp}} \\
\dashrightarrow\ & d_{\text{auth}}^{\text{req}} \dashrightarrow d_{\text{auth}}^{\text{resp}} \dashrightarrow e_{\text{auth}}^{\text{req}}
\end{aligned}
\tag{19}
$$

Figure 16. Structure of run from start to redirection endpoint

Authorization Code Mode. We now show that if the events are structured as shown in (16) in Figure 15 then there also exist events as shown in (18) in Figure 16. (The event $e_{\text{auth}}^{\text{req}}$ is the same in both figures.)

Since we have that $e_{\text{auth}}^{\text{req}}$ exists and was sent by b, the DNS messages $d_{\text{auth}}^{\text{req}}$ and $d_{\text{auth}}^{\text{resp}}$ (as shown) follow immediately. The request $e_{\text{auth}}^{\text{req}}$ contains a session cookie containing a session id, say, l. The request also contains a URI parameter state with some value, say, z.[46]

With Lemma 10, we can see that the attacker (or any other party except for i, b, and r) cannot instruct the browser to send $e_{\text{auth}}^{\text{req}}$. Also, r does not instruct the browser to send such a request, and neither does

---

[46] From the proof of Lemma 11 we follow that $e_{\text{auth}}^{\text{req}}$ must be an HTTPS request for the path /redirectionEndpoint containing the parameters code, state, iss, and client_id.

any honest script. The request must therefore have been caused by a redirection contained in an event $e_{\mathrm{aep2}}^{\mathrm{resp}}$ that was sent from i to b (see Line 41 of Algorithm 13). (The redirection must have included the state parameter in the URI as above.) This requires that an event $e_{\mathrm{aep2}}^{\mathrm{resp}}$ was sent from b to i. (Which, as above, was preceded by DNS messages $d_{\mathrm{aep2}}^{\mathrm{req}}$ and $d_{\mathrm{aep2}}^{\mathrm{resp}}$.) This event must contain an HTTP(S) POST request, with an origin header value of some domain of i, and in the body there must be a dictionary with an entry for the key `client_id` containing the client id $c = \mathsf{clientIDOfRP}(r, i)$, and an entry for the key `state` with the value z. (Note that in this case, $c \neq \bot$.)

Because of the origin header value, this request can only be caused by the script *script_idp_form*. This script extracted c and z from its initial scriptstate, which was a dictionary with the keys as above.[47] The initial scriptstate must have been sent by i in an event $e_{\mathrm{aep1}}^{\mathrm{resp}}$. Such an event can only be sent out in Line 13 of Algorithm 13.

The event $e_{\mathrm{aep1}}^{\mathrm{resp}}$, as above, must have been preceded by connected events $d_{\mathrm{aep1}}^{\mathrm{req}}$, $d_{\mathrm{aep1}}^{\mathrm{resp}}$, and $e_{\mathrm{aep1}}^{\mathrm{req}}$. In $e_{\mathrm{aep1}}^{\mathrm{req}}$ the message must be an HTTP(S) request which must have two parameters, first, under the key `state`, the value z, and second, under the key `client_id`, the value l. (These parameters are used as the initial scriptstate for the script *script_idp_form* above.)

Similar to above, with Lemma 10, we have that the event $e_{\mathrm{aep1}}^{\mathrm{req}}$ (and, with that, $d_{\mathrm{aep1}}^{\mathrm{req}}$) must have been caused by a redirect that was sent from r to b. Such a response is only created by r in Line 104 of Algorithm 10. Since the state value is always chosen freshly, and we have that in this case it is z, the event containing this redirect is $e_{\mathrm{strt}}^{\mathrm{resp}}$.

It is now easy to see that the sequence of processing steps emitting the events in (18) and (16) is a session (as in Definition 49), say, o. We already know that $\mathsf{startsOA}(Q_{\mathrm{starts}}, b, r, i)$ where Q_{starts} is the processing step in which $d_{\mathrm{strt}}^{\mathrm{req}}$ was emitted. There is no other processing step in o in which the browser b triggers the script *script_rp_index*. The processing step Q_{ends} (in which $e_{\mathrm{auth}}^{\mathrm{resp}}$ is emitted) is the only processing step in which r receives a protected resource from i and emits an event in Line 48 of Algorithm 10. Therefore, o is an OAuth session, and Q_{ends} is in o.

We now show that

$$\mathsf{selected}_{\mathrm{ia}}(o, b, r, \langle u, g \rangle) \iff \big(t \equiv \mathsf{resourceOf}(i, r, \langle u, g \rangle) \big) \;.$$

Iff $\mathsf{selected}_{\mathrm{ia}}(o, b, r, \langle u, g \rangle)$ then we have that b in Q_{start} selected *interactive* $\equiv \top$ in Line 7 and there is some Q_{select} in o such that b triggers the script *script_idp_form* in Q_{select} and selects $\langle u, g \rangle$ in Line 4 of Algorithm 14 and sends a message out to i.

We therefore have that Q_{select} is the processing step where $d_{\mathrm{aep2}}^{\mathrm{req}}$ was emitted. (This is the only processing step in which the browser triggers the script *script_idp_form*.) We have that in this step, the browser selected $\langle u, g \rangle$ in Line 4 of Algorithm 14. Then, and only then, the HTTPS POST request in $e_{\mathrm{aep2}}^{\mathrm{req}}$ contained, in the body, the credentials (username and password) for the identity $\langle u, g \rangle$. From the proof of Lemma 11 we see that in $e_{\mathrm{strt}}^{\mathrm{resp}}$, in the redirection URI, and hence in the URI in $e_{\mathrm{aep1}}^{\mathrm{req}}$, the parameter `response_type` must be `code`. We therefore have that the initial scriptstate of *script_idp_form* in $e_{\mathrm{aep1}}^{\mathrm{resp}}$ contains the entry $\langle \mathtt{response\_type}, \mathtt{code} \rangle$. Now, in $e_{\mathrm{aep2}}^{\mathrm{req}}$, the body also contains the same entry. Therefore, iff i receives $e_{\mathrm{aep2}}^{\mathrm{req}}$, then it creates an entry in the subterm `codes` of its state (in Line 38 of Algorithm 13) of the form

$$\langle code, \langle c, redirecturi, \langle u, g \rangle \rangle \rangle$$

(where *redirecturi* is some URI and *code* is a freshly chosen nonce).

Then, and only then, $e_{\mathrm{aep2}}^{\mathrm{resp}}$ contains *code* in the parameter `code` of the location redirect URI (which is the URI for the HTTPS request in $e_{\mathrm{auth}}^{\mathrm{req}}$). RP sends (as shown in the proof of Lemma 11) *code* to IdP in $e_{\mathrm{tokn}}^{\mathrm{req}}$. This request contains the body $\langle \langle \mathtt{grant\_type}, \mathtt{authorization\_code} \rangle, \langle \mathtt{code}, code \rangle \rangle$.

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[47] This initial scriptstate is never changed if the script runs under the origin of an honest IdP, which it does in this case.

Then, and only then, IdP processes $e_{\text{tokn}}^{\text{req}}$ (in Line 81 of Algorithm 13) and creates an entry in the subterm `atokens` of its state of the form

$$\langle atoken, \langle c, \langle u, g \rangle \rangle \rangle$$

for a freshly chosen nonce *atoken* (as there exists an entry in the subterm `code` of the form $\langle code, \langle c, redirecturi, \langle u, g \rangle \rangle \rangle$). Then and only then, *atoken* is contained in $e_{\text{tokn}}^{\text{resp}}$. Then and only then, r sends *atoken* to i in $e_{\text{intr}}^{\text{req}}$. (In this request, *atoken* is contained in the URI parameter `token`.)

Iff there is an entry of the form $\langle atoken, \langle c, \langle u, g \rangle \rangle \rangle$ in the subterm `atokens` in the state of i and i receives $e_{\text{intr}}^{\text{req}}$ (containing *atoken* as shown) then i processed $e_{\text{intr}}^{\text{req}}$ in Line 101ff. and emitted an event $(e_{\text{intr}}^{\text{resp}})$ containing $\text{resourceOf}(i, r, \langle u, g \rangle)$.

Implicit Mode. This case is very similar to the authorization code mode above. We therefore only describe the differences between the two modes.

In this case, with the proof of Lemma 11, we have that $e_{\text{auth}}^{\text{req}}$ is an HTTPS POST request to the path `/receiveTokenFromImplicitGrant` with an origin header being some domain of r. Further, as above, $e_{\text{auth}}^{\text{req}}$ contains the state z. This request must have been created in the browser by *script_rp_implicit* running under an origin of r. This script retrieves the state value from the fragment of the URI from which the script was loaded. Therefore, there must have been a request, $e_{\text{impl}}^{\text{req}}$ containing such a fragment in the URI. This implies the presence of the events $d_{\text{impl}}^{\text{req}}$, $d_{\text{impl}}^{\text{resp}}$, and $e_{\text{impl}}^{\text{resp}}$.

We can now that Q_{ends} is in o and $\text{selected}_{\text{ia}}(o, b, r, \langle u, g \rangle) \iff (t \equiv \text{resourceOf}(i, r, \langle u, g \rangle))$ by applying the same reasoning as above, with the following differences:

- The event $e_{\text{impl}}^{\text{req}}$ takes the role of $e_{\text{auth}}^{\text{req}}$ in the proof above.

- We can show that the sequence of processing steps emitting the events in (17) in Figure 15 and (19) in Figure 16 are the OAuth session o and (as above) that Q_{ends} is in o.

- Where the parameter `response_type` was `code` above, it now is `token`. The same applies to the initial scriptstate of *script_idp_form*.

- Instead of creating *code* in the processing step that emits $e_{\text{aep2}}^{\text{resp}}$, this step now creates an access token *token* (in the same way as the token was created in the authorization code mode in the processing step that emits $e_{\text{tokn}}^{\text{resp}}$). The steps $d_{\text{tokn}}^{\text{req}}$, $d_{\text{tokn}}^{\text{resp}}$, $e_{\text{tokn}}^{\text{req}}$, and $e_{\text{tokn}}^{\text{resp}}$ are skipped.

- The redirection URI contained in $e_{\text{aep2}}^{\text{resp}}$ contains an access token instead of an authorization code, and the access token and the state value are contained in the fragment instead of in the parameters.

- As already discussed, $e_{\text{auth}}^{\text{req}}$ was created by the script *script_rp_implicit* which relays the access token from the URI fragment to r.

Resource Owner Password Credentials Mode. It is easy to see that the sequence of processing steps emitting the events in (15) is a session (as in Definition 49), say, o. In this case, $\text{startsOA}(Q_{\text{starts}}, b, r, i)$ holds true if Q_{starts} is the processing step in which $d_{\text{auth}}^{\text{req}}$ was emitted. As above, o is also an OAuth session, and Q_{ends} is in o.

We now show that

$$\text{selected}_{\text{nia}}(o, b, r, \langle u, g \rangle) \iff (t \equiv \text{resourceOf}(i, r', \langle u, g \rangle))$$

for some $r' \in \{r, \perp\}$. Iff $\text{selected}_{\text{nia}}(o, b, r, \langle u, g \rangle)$ then we have that b in Q_{start} selected $id \equiv \langle u, g \rangle$ in Line 4 of Algorithm 11 and selected *interactive* $\equiv \perp$ in Line 7.

Then and only then, $e_{\text{auth}}^{\text{req}}$ is an HTTPS POST request for the path /passwordLogin with an origin header containing some domain of r and with the identity $\langle u, g \rangle$ and the corresponding password, say p, in the body. Then and only then, the body in $e_{\text{cred}}^{\text{req}}$ is of the form

$$\langle \langle \texttt{grant\_type}, \texttt{password} \rangle, \langle \texttt{username}, \langle u, g \rangle \rangle, \langle \texttt{password}, p \rangle \rangle \ .$$

Then, and only then, IdP processes $e_{\text{cred}}^{\text{req}}$ (in Line 84ff. of Algorithm 13) and creates an entry in the subterm atokens of its state of the form

$$\langle atoken, \langle c', \langle u, g \rangle \rangle \rangle$$

for a freshly chosen nonce *atoken* (as there exists an entry in the subterm code of the form $\langle code, \langle c, redirecturi, \langle u, g \rangle \rangle \rangle$) and for $c' \in \{\text{clientIDOfRP}(r, i), \bot\}$. Then and only then, *atoken* is contained in $e_{\text{cred}}^{\text{resp}}$. Then and only then, r sends *atoken* to i in $e_{\text{intr}}^{\text{req}}$. (In this request, *atoken* is contained in the URI parameter token.)

Iff there is an entry of the form $\langle atoken, \langle c', \langle u, g \rangle \rangle \rangle$ in the subterm atokens in the state of i and i receives $e_{\text{intr}}^{\text{req}}$ (containing *atoken* as shown) then i processed $e_{\text{intr}}^{\text{req}}$ in Line 101ff. and emitted an event $(e_{\text{intr}}^{\text{resp}})$ containing $\text{resourceOf}(i, r, \langle u, g \rangle)$ if $c' \neq \bot$ and containing $\text{resourceOf}(i, \bot, \langle u, g \rangle)$ otherwise. ∎

Lemma 13. Let $\mathcal{OWS}^w$ be an OAuth web system with web attackers, then $\mathcal{OWS}^w$ is secure w.r.t. session integrity for authentication.

PROOF. We have that r sends a service token to b, and thus, $\text{endsOA}(Q_{\text{login}}, b, r, it)$ for some term t. Since $\mathcal{OWS}^w$ is secure w.r.t. session integrity for authorization, we have that (a) holds true. For (b), we see from Line 101ff. that honest IdPs, at their introspection endpoint, if they send out an HTTPS response, the body of that response is of the form

$$\langle \langle \texttt{protected\_resource}, \text{resourceOf}(i'', r'', \langle u'', g'' \rangle) \rangle, \langle \texttt{client\_id}, c'' \rangle, \langle \texttt{user}, \langle u'', g'' \rangle \rangle \rangle$$

for any $\langle u'', g'' \rangle$ and some c'', i'', r''. We therefore have that

$$\left(t \equiv \text{resourceOf}(i, r, \langle u, g \rangle) \right) \iff \left(\langle u, g \rangle \equiv \langle u', g' \rangle \right) .$$

Since $\mathcal{OWS}^w$ is secure w.r.t. session integrity for authorization, we have that (b) holds true.

With Lemma 7, Lemma 9, Lemma 12 and Lemma 13 we have proven Theorem 1.