A Comparative Analysis of Identity Standards for the Internet

Master Thesis
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«Perfection is achieved, not when there is nothing more to add, but when there is nothing left to take away.»

*Antoine de Saint-Exupéry*
1. Preface

1.1. Abstract

Many identity management systems have been proposed over the last decade to solve the problem of users having to remember too many passwords for online authentication. The present thesis introduces a characterization to capture the important aspects of these systems and suggests a new classification based on two major characteristics. The acquired features are then utilized to design a comparative study, in which I implemented a decentralized file service with SAML, OpenID, WebID and my own Virtual ID. The criteria for the evaluation were grouped into four categories, namely suitability, usability, security and privacy. After giving a few recommendations, I finally argue why the realization of the Semantic Web requires identities and why current single sign-on solutions are not adequate for building the next generation of distributed online services.

1.2. Acknowledgments

I thank Matthias Geel for supervising this work and, together with Prof. Dr. Moira C. Norrie, for giving me the opportunity to write the master thesis on my own topic. I have appreciated the received freedom and the many fruitful discussions we had so far a lot!
2. Introduction

2.1. Overview

**Problem**
In today’s Web, most platforms authenticate their users by requiring them to enter their **username** and **password**. This prevalent authentication mechanism has several problems:

- **Fatigue**: Having to remember a distinct password for each platform imposes an increasingly heavy burden on users.
- **Security**: The randomness of human-chosen secrets is so small that they are vulnerable to guessing and brute force attacks. This situation is further aggravated by the above circumstance, making users choose weak or even similar passwords at different sites with the risk of identity theft.
- **Overhead**: Creating an account and providing the same information at every site cost the users time and nerves.

**Solution**
In order to address these issues, numerous standards have been designed that allow to reuse the identity respectively the authentication of users. Each of them has its strengths and weaknesses and only the current use case determines the exact requirements for the applicable identity standard. For the sake of an **open** Web, however, only non-proprietary standards are considered in the scope of this master thesis.

![Login screen of twitter.com.](image)

![Login screen of sourceforge.net.](image)

2.2. Objectives

**Characterize**
The first goal of this thesis is to develop a **characterization** of identity standards in order to devise potential requirements.

**Compare**
The second goal is to compare selected identity standards based on concrete **criteria** derived from the requirements.

2.3. Outline

**Background**
The next chapter covers the **history** of the Web and identity, and introduces a **terminology** to analyze identity standards.

**Characterization**
This terminology is then used to explain the **characteristics** of identity standards and to introduce a new **classification**.

**Comparative Study**
Based on the understandings from the characterization, a comparative study is **designed**, **executed** and **evaluated**.

**Conclusions**
The main part of this thesis is finished by stating the made **contributions**, possible **future work** and the **overall vision**.
2.4. Related Work

Terminology
When discussing identity management systems, it is essential that everyone uses the same name to refer to the same or at least very similar concept. Depending on the author and the context, however, already the word identity is used in many different ways. Camp [Cam04] has tried to give the various terms around digital identity a uniform meaning, but lacks conceptual clarity and consistency herself. Induced by the English language, I still use the words in similar ways (3.2.). Clauss and Köhntopp [CK01] introduced the notion of partial identities that can be used in different contexts with distinct pseudonyms to prevent linkability among service providers. Pfitzmann and Hansen [PH08] provide precise definitions for the terms anonymity, unlinkability and pseudonymity (as well as some others) and show how they relate to each other. As these concepts were only used for a single criterion in the study, the explanations given in section 4.1. should suffice. Bhargav-Spantzel et al. [BCG06] also propose a taxonomy for user-centric identity management and distinguish between relationship-focused and credential-focused systems for their classification, depending on the longevity of issued tokens.

Requirements
The most famous set of requirements for any digital identity system are the Laws of Identity by Kim Cameron [Cam05]. As a single identity solution seems unrealistic, he proposed the creation of an identity metasystem that can combine multiple technologies in a single framework. The laws (interpreted as scientific observations about the world) mainly focus on the privacy of users and their experience across various contexts. The most important one for this thesis is the idea of directed identity, which is a way of realizing partial identities by using a distinct identifier for each service provider in order to avoid the unnecessary release of so-called correlation handles.

Most other requirement elicitations are conducted in order to show the deficiencies of existent solutions and to illustrate the qualities of the author’s own proposal. Kölsch et al. [KZR11] describe many soft factors that are important for users, service providers, network operators and developers with regard to PRIME (see below). Their emphasis is on the sovereignty of the various stakeholders, which ranges from privacy and trust to open standards. Due to their vague nature though, the criteria are not suited for a comparative analysis. More interesting are the design goals by Perlam and Kaufman [PK08] that have a strong focus on security and usability. Many of their requirements concern the interaction between a user and a service provider as they take the identity provider out of the equation in their suggested user-centric public key infrastructure. They also analyze existing schemes for their practical weaknesses without considering newer standards though. Very detailed metrics for evaluating identity management architectures are presented by Soaie and Bahsoon [SB12], which have executed a systematic literature review and derived a list of profile and authentication features. They have used the metrics to calculate a weighted score for a service-based system and OpenID.

Analyses
As in-depth analyses of identity standards and their security are not the topic of this master thesis, I just want to mention two worrisome papers from last year: Researchers exploited flaws in the XML Signature standard to break eleven of the 14 examined SAML frameworks (including Shibboleth) [SM012] and showed vulnerabilities in the signature verification of a lot of OpenID implementations (also OpenID4Java) [WCW12].

Comparisons
Due to the fact that the identity landscape is changing so fast, many of the papers that compare existing standards are out-of-date very soon. Moreover, a lot of papers just present some standards without actually reviewing or comparing them.

The oldest paper of interest compares OpenID, Shibboleth, Liberty and CardSpace on the basis of the Laws of Identity and some further criteria regarding their openness and flexibility [HS09]. In my judgement, the considered requirements are either too vague or too technical and do not really cover the possibilities (or lack thereof) of these four identity systems. In addition, many of the explored aspects are indiscriminative.

The paper most closely related to this work was written by Ferdous and Poet [FP12], who had chosen CardSpace, OpenID, Shibboleth, Liberty Alliance, PRIME and OAuth for their analysis. They group the selected criteria into functional requirements, security, privacy, interoperability, trustworthiness, liability and usability. Quite a few of their metrics can also be found in my characterization of identity management systems (chapter 4.), while others are rather strange and were not even included in their own tabular comparison, which is hardly readable.

Hacket and Hawkey [HH12] present an extensive analysis of BrowserID and WebID with a focus on security, privacy and usability requirements. They cover the following six aspects: compromise, phishing, recycling, tracking, robustness and also user experience. Three of them are also included in my study.

Several papers inspect the privacy of identity management systems. Birrell and Schneider [BS12] distinguish between three kinds of authentication: interactive (direct communication of identity and service providers), active-client (all messages are relayed through the client) and credential-based (issuance and presentation of credentials are independent). They name this characteristic, when the identity provider does not learn about the service provider, undetectability (I will label it calling home) and also examine forms of unlinkability and confidentiality. (A more detailed analysis of undetectability and unlinkability can be found in a similar paper by Veeningen et al. [VWZ12].)

Initiatives
The European Union has funded many research programs to promote privacy-enhancing technologies: Future of Identity in the Information Society (FIDIS), Privacy and Identity Mgmt. for Europe (PRIME), PrimeLife, Privacy and Identity Management for Community Services (PICOS) and Attribute-Based Credentials for Trust (ABC4Trust). Likewise, the American government started the National Strategy for Trusted Identities in Cyberspace (NSTIC).
3. Background

3.1. History

Web 1.0
The World Wide Web is the popular name for a number of standards, which were created by Tim Berners-Lee at CERN in the early 1990s. Among these are the Hypertext Transfer Protocol (HTTP) to exchange data, the Hypertext Markup Language (HTML) to structure documents and the Uniform Resource Locator (URL) to reference files (see A.2. for more information). Together, they form a web of linked pages.

During the first ten years, the World Wide Web was mainly used to publish documents edited by a webmaster in a unidirectional way. This was the golden age of the homepage.

Identity 1.0
In order to restrict access to certain resources, a mechanism was needed to authenticate the users of a site. Due to a lack of better alternatives, the approach of personal computers was taken to the Web with catastrophic consequences: Each person had to choose a unique username and password at every platform for identification and authentication (3.2.).

Such a platform-centric identity cannot be transferred from one site to another, which also prevents the exchange of information (like trust) across platforms. This requirement gained in importance with the Web 2.0 and its big diversity.

Web 2.0
Around the turn of the millennium, a new trend emerged: Platforms were initiated to store and share user-generated content. People started to unite in virtual communities for various topics and purposes, where they no longer just all consumed information but also provided it. The term Web 2.0 refers to a different use but not a change of technology.

Identity 2.0
An improvement to the above situation is the federation of various proprietary identity management systems so that users from one domain can access an application in another domain without reauthentication (so-called single sign-on).

True user-centric identity, however, is only achieved if the identity and service providers need not to be known before.
3.2. Terminology

User
The term user refers to all human beings interacting with a particular (computer) system. In identity management, they are usually the subjects about whom statements are made.

Client
A client (also called user agent or browser) is some program that runs on the user’s device and accesses a remote service.

Server
A server is a machine that provides some services for clients and other servers. For this, they have to be always reachable.

Entity
An entity is a concrete or abstract object that exists by itself. This can be a natural or artificial person, a client, a server, etc.

Identity (ID)
Identity is the transitive, symmetric and reflexive relation, which makes two entities the same (that is to say identical). For the purpose of access control (see below), one needs to specify a procedure for the identification and authentication of entities. It is exactly this procedure that defines the notion of identity in the current system. However, this only imitates the identity of an entity in the real world and, as it is not an inherent part of it, identities can be created, lost and stolen.

Attribute
An attribute is a piece of information that is associated with an entity. Unless the author of an attribute has authoritative power, it is just a claim about the subject of the identity. So-called ontologies define the vocabulary used for attributes.

Certification
In order to increase the trustworthiness of attributes, their validity can be confirmed by special certification authorities. Which organizations are allowed to issue which certificates and whether these can be revoked depends on the standard.

Contact
Some standards do not only support the identification and authentication of its users, but also enable them to model their social network once for the reuse by various services.

Role
Most people have different roles in different contexts, which is facilitated by allowing them to assume different identities.

Access Control
Access control ensures the appropriate admission of people to resources according to some access policy. The procedure consists of the following steps: identification of the subject, authentication of its claims and authorization for access.

The access policy can be based on several aspects of the users: their identity, their attributes and their roles, where the last is in practice just realized by one of the former two.

Furthermore, the rules of the system determine whether access control is discretionary (admission specified by the resource owner) or mandatory (enforced secrecy of data).

Identification
Whenever a resource is protected by some access policy, the requester needs to make claims about why he or she should be granted access. Corresponding to the above section, the user can either claim an identity, certain attributes or certain roles. An identity is usually declared with a locally or globally unique identifier. If no strict identification is required, some standards allow to disclose attributes pseudonymously or in a few cases even anonymously to the resource provider (the notion of (un-)linkability is explained in more detail in 4.1.).

Authentication
Whatever claims are raised, the requester needs to convince the resource provider of their authenticity. The verification of the presented evidence is called authentication and can be based on three factors: property (e.g. fingerprint, retinal pattern, signature), possession (key, badge, smart card) and knowledge (password, PIN, response to challenge). In order to increase security, multi-factor authentication is feasible.

Authorization
Once the user’s identity, attributes or roles are established, it is determined whether he or she is indeed authorized for the intended action. The term comprises having the privileges as well as granting them. This thesis focusses mainly on the second aspect and distinguishes between permissions that are authoritative (act on behalf of the user) and those that are non-authoritative (allow others access to own assets).

Accreditation
The act of giving another entity authoritative power is called accreditation. This process results in the other entity gaining a credential, which can be used to act within a certain scope on behalf of the issuer. Certification authorities can accredit intermediate authorities and users can accredit their clients.

Accountability
Accountability means that an entity can be held responsible (and thus potentially also liable) for its actions and omissions.

Identity Provider (IP)
An identity provider authenticates an entity on behalf of the service provider. (The only alternative to delegated identity management is to establish a web of trust on the user level.)

Service Provider (SP)
A service provider (sometimes erroneously called relying party) consumes the verifications of identity providers.
4. Characterization

4.1. Identification

**Identity**
Comparing the wide variety of identity standards is not easy and needs to be based on a set of objectively determinable characteristics, which I describe in the following sections.

A first important consideration is the meaning of identity in a standard. Is the real identity of the user ensured or is it possible to create arbitrary identities? In the former case, is the virtual identity also unique? Other aspects of ID include:

- **Scope**: Is the identity valid in a local, global or federated context (where the latter is a mixture of the former two)?
- **Creation**: Which entity creates the identity for the user? The user by hand, an automated client or some authority?
- **Deletion**: Is the deletion of an identity supported and if so, what exactly does it mean? (No means just stop using it.)
- **Merging**: Is it possible to merge several identities into one, which is very useful for mergers and acquisitions but also for users who started with several identities and want to reduce them? Splitting an identity makes no sense, as it is unclear which successor shall assume its rights and duties.

**Identifier**
For the identification of an entity, it is essential to be able to reference its identity by means of an identifier. Besides the question what form it takes, the criteria below are of interest:

- **Relocation**: Can an identity be moved to a new provider (by changing its identifier) without affecting the system?
- **Reusability**: Is it explicitly forbidden to reuse an identifier for a different identity (by another user) after relocation?
- **Interaction**: How do users provide their identifiers during identification? Is the interaction with the service provider implicit, explicit (e.g. with a prompt) or unspecified? There is a tradeoff between usability and privacy through clear consent among the first two options. If the procedure for identification is not specified, it cannot be to automated.
- **Frequency**: How often is identification performed? Once per browser session, per service provider or just per client?
- **Submission**: How are identifiers finally submitted to SPs?

**Attributes**
For access control, it is often sufficient to receive just certain attributes of the requester without having to know his or her full identity. Another advantage is that services can easily be customized without any overhead. Given that this feature is supported, the question is whether the attributes to convey are selected implicitly or explicitly and by whom. More points:

- **Linkability**: Can several requests to a service provider be linked to the same entity? Attribute-based identification can either be identifiable (the identifier is disclosed to SP), pseudonymous (a distinct but persistent identifier created for each SP) or anonymous (even subsequent requests to the same SP cannot be associated with each other).
- **Revocation**: Who revokes anonymity in case of misuse?

4.2. Authentication

**Mechanism**
The claims made during the identification phase are verified by the service provider in the authentication stage. Usually, the mechanism to do so either involves browser redirections or cryptographic signatures. Further important aspects are:

- **Performance**: How much effort is required to validate the claims? This is best estimated by the number of messages sent between the parties and the amount of cryptography involved when computing and verifying the signatures.
- **Compatibility**: Are assertions in other standards equally accepted after a proper conversion into the current one?
- **Requirements**: What changes are needed to deploy it?
- **Vulnerabilities**: What attacks are the most likely (see A.4.1)?
- **Privacy Issues**: Are there any privacy issues like the calling home problem, where the IP learns of all authentications?

**Identity Provider**
In authentication, the user’s identity provider plays a crucial role. A major distinction is whether the identity provider has to be online during authentication (because it is part of the communication flow) or can also be offline (since it is never contacted). The risk of being temporarily locked out and denied access to a service is higher in the former case.

- **Discovery**: How can the user’s IP be detected?
4.3. Authorization

Clents
Is it possible to give clients authoritative power over an ID?
- Rights: If yes, what is the client authorized to do at the IP?
- Permissions: With which privileges can the client also act on behalf of the user towards others? (The distinction to rights is that permissions also depend on others; see 4.7.)
- Restrictions: Can the in- and external privileges be limited?

Users
Is it also possible to authorize other users respectively their identities with similar rights and permissions as for clients?

4.4. Accountability

Signatures
Can users respectively their clients sign a message so that its origin cannot be denied (which is called non-repudiation)? If yes, where are such signatures used in the protocol (if at all)?

Liability
What is the legal status of these signatures? Furthermore:
- Duration: For what time can the issuer be held liable?
- Revocation: Is it possible to invalidate a client’s key?

Framing
Is it possible for an identity provider to assume the identity of its users? Such a misbehavior can be prevented or at least detected if the identity provider is required to keep a record of each modification to an identity. Whenever some change cannot be traced back to the original client by verifying and comparing the signatures, we can be sure that the identity provider was cheating. (Depending on the desired scenario, this property might seem less relevant than it actually is.)

4.5. Attributes

Storage
Though a lot of standards allow the association of attributes to an identity, the possibilities vary widely. Besides the major question, whether the set of attributes is predefined or freely extensible by everyone, the following aspects are of interest:
- Format: Are attributes restricted to strings or can arbitrary values be used? How are the syntax and semantics defined?
- Regulation: Who specifies the rules and policies regarding the usage of attributes by third parties (if specified at all)?
- Transmission: Can attributes be conveyed to a SP during authentication for ease or attribute-based access control?
Access
Can service providers or third parties retrieve attributes of an identity **asynchronously** (independently of authentication)? If so, can the access rules be specified on the attribute-level?
- **Policy:** How are these rules defined; what are the options?
- **Caching:** How long may attributes be stored before they are considered stale (expired) and need to be refetched?

Certification
Can attributes be **certified** in order to increase the reliability? (Trust is often implicitly given in federated identity systems.)
- **Authority:** Which entities are the certification authorities?
- **Revocation:** Is it feasible to invalidate issued certificates?
- **Liability:** Are authorities liable for incorrect certificates?

4.6. Contacts

Format
Can you add other identities as contacts to your identity so that service providers can make use of your **social graph**? If this feature is supported, how are these contacts stored?

Structure
Is there a way to **group** the contacts for easier management?

Disclosure
Is it possible to give third parties like friends and companies also **access** to your contacts? If so, how is this accomplished?

Notification
Though the concept of contacts is usually asymmetric (not mutual), can you **inform** other users about your existence?

4.7. Classification

**Crucial Characteristics**
When looking at the characteristics outlined above, it can be seen that one of the major distinctions is whether a standard is designed to **interact** with the **user** or just with their **client**. This manifests itself in the kind of **evidence** that is requested for authentication as well as in the **automation** of procedures.

A key feature of most standards is the ability to prove one’s identity towards other entities, which requires a **global** (or at least **federated**) **identifier**. In order to be considered the same identity, there has to be an identity provider so that a single change (like new evidence or a modified attribute) affects all service providers. In other words, there is also a difference whether **access** can only be given to **internal** resources (at the own provider) or also **external** ones (at other providers).

I suggest the following **terminology** for this **classification**:

<table>
<thead>
<tr>
<th>Standard</th>
<th>User</th>
<th>Client</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Internal</strong></td>
<td>(1) Authentication</td>
<td>(2) Authorization</td>
</tr>
<tr>
<td><strong>External</strong></td>
<td>(3) Federation or Sign-On</td>
<td>(4) Identity</td>
</tr>
</tbody>
</table>

**(1) Authentication Standard**
The main purpose of an **authentication standard** is to unify the user experience and **simplify** the development of apps. Typically, the user has a **local identifier** and authentication is straightforward. Example: **HTTP Authentication** [RFC2617].

**(2) Authorization Standard**
The goal of **authorization standards** is to fight the so-called **password anti-pattern**. (An anti-pattern is a procedure that was originally considered a good idea and became popular but later turned out to be counterproductive in practice.)

The most common use case is to give applications **access** to a **service** without entering the master password, which is more secure as it limits the possible damage when the client gets compromised. Example: **OAuth** [OAuth] (to protect APIs).

**(3a) Federation Standard**
A **federation standard** allows to use an identity throughout a federation. You need to be accepted by the federation to run your own identity or service provider though, which is often not a problem among **corporate** and **academic** institutions. Example: The **Security Assertion Markup Language** [SAML].

**(3b) Sign-On Standard**
A **sign-on standard** provides for each user a **global identifier** that can be used to prove one’s identity towards any service provider through authentication. Example: **OpenID** [OpenID].

**(4) Identity Standard**
In order to qualify as an **identity standard**, **global identifiers** and full **automation** with **attributes** and **contacts** are needed. **Client accountability** is also desired. Example: **WebID** [WebID].
5. Comparative Study

5.1. Standards

Selection
After having seen numerous characteristics of access control standards, it is time to examine their consequences based on representatives from each class in practice. The aim is to get an idea of their respective strengths and weaknesses, where only non-commercial standards were considered.

Another requirement for standards was to have a publicly available specification of their underlying protocol, thereby intentionally excluding mere technologies and initiatives. As pure authentication and authorization standards were of no interest for the scenario described in 5.2., those were also discarded. The following standards have then been chosen for a mixture of popularity and diversity (see appendix B. for an in-depth analysis based on the above characterization):

- **SAML**: The Security Assertion Markup Language is an XML-based data format for the exchange of authentication and authorization information between identity providers and service providers. It has been devised by the Organization for the Advancement of Structured Information Standards (OASIS) in 2001 with its second version being released in 2005. SAML has gained wide-spread deployment among governmental, academic and commercial organizations. As ETH Zurich bases the authentication of its users also on it, SAML is the perfect example of a federation standard.

- **OpenID**: The most well-known standard for authenticating users on the Web is OpenID, which was developed in 2005. After having gained tremendous momentum in 2008, its popularity is steadily declining ever since. Many service providers stopped their OpenID support due to its lack of usability as people forget and mix their OpenIDs and can no longer recover their accounts. (I discuss the difficulties with Google as the largest OpenID provider in 5.5.) Though many service providers are turning away from it, OpenID is still the sign-on standard of preference for this study.

- **WebID**: WebID is the first real identity standard according to the above classification and uses SSL client certificates to authenticate its users. Each of them has a profile page in the machine-readable Friend Of A Friend (FOAF) syntax, where the public key of their certificates are published. Originally proposed at a W3C Workshop in 2009, it is now elaborated in a W3C Community Group but its adoption is quite limited so far. Its approach is still interesting though!

- **Virtual ID**: After having developed the main concepts of Virtual ID in 2010, I worked out its cryptographic protocol in my bachelor thesis. During the Distributed Systems Lab at ETH Zurich, I have built a first prototype together with Dominik Blunschy. Virtual ID belongs also to the class of identity standards and is this thesis’s actual motivation.

Rejection
Due to limited time, many standards that would have been interesting to study had to be omitted. The following list of such standards indicates some reasons for their exclusion:

- **Kerberos**: Developed in 1983 as an authentication solution for the Massachusetts Institute of Technology (MIT), Kerberos became an IETF standard ten years later. It uses symmetric key cryptography to distribute keys to users and services for mutual authentication and confidential communication. As a trusted third party is required, it does not scale to the size of the Internet and is just another federation standard.

- **OpenPGP**: Pretty Good Privacy (PGP) had been created by Phil Zimmermann in 1991 and standardized as OpenPGP by the Internet Engineering Task Force (IETF), see [RFC4880]. It is mainly used to encrypt and sign e-mails among peers without relying on central authorities for key certificates (thanks to its web of trust). To my knowledge, OpenPGP has never been used to authenticate users at services so far.

- **WS-Federation**: This standard belongs to the Web Services protocol suite and enables the federation of identities very similar to SAML. Its main proponents are Microsoft and IBM, which use it as part of their Identity Metasystem (see 2.4.) in the Higgins Project or by the notion of Information Cards.

- **BrowserID**: This protocol (also known as Mozilla Persona) was initiated in July 2011 and is from a user’s perspective quite close to OpenID. The main differences are that it uses email addresses instead of URLs as identifiers, improves on privacy by solving the calling home problem and is meant to be fully integrated into the next generation of browsers.

- **SuisseID**: This is the first digital identity whose signatures are legally approved in Switzerland and this initiative was launched by the Swiss government in May 2010. Users get a certificate issued by an accredited private organization on a smart card or USB token to authenticate themselves and sign. It is, therefore, only an authentication standard.
5.2. Scenario

File Sharing
As we have seen in the classification of standards (see 4.7.), identity management is all about access control to internal and external resources. A very basic but quite generic form of resources are files. As the sharing of files is a common use case of the Global Information Systems Group at ETH Zurich, I have also adopted it as the scenario for my study. The goal is to implement a distributed file service based on the chosen standards in order to provide a decentralized alternative to platforms like Dropbox, Google Drive and Microsoft's SkyDrive.

Requirements
The beauty of this scenario is that only a few characteristics (see 4.) are essential but many aspects of the standards like attributes and contacts affect the criteria described below.

The minimal set of features that need to be supported are:

- **Internal Files**: Users have to be able to upload, download and delete their own files from the file service provider of their choice. Additionally, they may specify for each file an access policy that determines its visibility towards others.
- **Contacts**: For a simplified access to the files of their friends, users add and remove contacts that they can click to visit.
- **External Files**: When visiting the files of a friend, users can see and download the ones they are indeed authorized for.

User Interface
For the first three standards SAML, OpenID and WebID, I have implemented a single Web application and protected it with the various authentication mechanisms. Each requirement is covered by a dedicated page, which are printed below.

The prototypes are available on www.fileservice.ch and on the separate host www.xdf.ch. (XDF is Virtual ID’s data format and the domain is just reused for this new purpose.) Please do not rely on this file service! It is only a proof of concept and the database may be reset at any time! For this reason, no support will be provided to the users of this platform.

The intention of this implementation is to demonstrate the advantages and disadvantages of different approaches to access control. In particular, usability and security were of no concern and could easily be improved! For example, all users share the same table for their identities and, therefore, hijacking another name is trivial, especially when searching:

![Search box for contacts.](image)

List of my files with the options to upload, download or delete a file:

![File list](image)

List of my contacts with the options to add, visit or remove a contact:

![Contact list](image)
5.3. Criteria

Categories
For being able to compare the chosen standards based on the presented scenario (see 5.1. and 5.2.), we need a set of objective criteria. From the numerous characteristics that were discussed earlier (see 4.), I have selected those which are really relevant for decentralized file sharing and have grouped them into the following four categories:

- **Suitability**: Is the standard appropriate for the scenario?
- **Usability**: How well does the solution support the user?
- **Security**: How vulnerable is the application to attacks?
- **Privacy**: Is the dissemination of information restricted?

Focus
Most of the criteria described below concentrate on aspects of the standard and not their respective frameworks or usual practices. As an example, the ease of deployment is not part of the study as it is difficult to assess objectively and tells us more about the available tools than the inherent concepts. If a standard is not so clear about the right practice, however, it is the mainstream that counts (also in case of divergence).

Grading
Each category consists of four aspects on which a standard can score. Points are either awarded completely or not at all, with four points being the maximum and zero the minimum. The following ranking is used: --- (0), – (1), = (2), + (3), ++ (4).

Exclusion
Covering only sixteen characteristics of identity management systems means that many features were not considered. This includes most facets of identity administration, performance, attribute certification, caching, liability and regulation, which were not regarded as being crucial for the outlined scenario.

Suitability
- **Scope of Identity**: If everyone should be able to host their files themselves, it is essential that identities are accepted globally without requiring a central registration in advance.
- **Attribute Access**: In order to look up the name and host of other users (see the screenshot on the previous page), it is desirable to be able to retrieve attributes asynchronously. (Attribute transmission during authentication is deficient.)
- **Authorization**: Especially when dealing with files, you are interested in giving native clients access to your resources but also to the ones of your friends. If the procedures can be automated, such a client is able to import external files.

Security
- **Requirements**: Does the usage of a standard demand any additional hardware or software (being bad for adoption)?
- **Attribute-Based Access Control (ABAC)**: Many times, it is more convenient to restrict the admission to resources on the basis of trusted attributes instead of listing identifiers.
- **Contacts**: Automatically synchronizing his or her contacts with a new service improves the user’s efficiency notably.
- **Authentication**: If each contact uses a different host, the authentication at every service provider is cumbersome. Either trusting your contacts or all SPs does simplify a lot!

Privacy
- **Calling Home**: If an identity provider learns about every authentication, it can track its users across the Internet.
- **Wrong Consent**: Similar to phishing, not only the identity provider can be forged, but also a service provider. Such a situation might lead to an involuntary leakage of identity.
- **Attribute Selection**: Although a lot of standards allow the transmission of attributes during authentication, it is not always up to the user to select respectively reject them. (In distributed services, users no longer choose all SPs)
- **Pseudonymity**: Allowing users to mask their real identity for attribute-based access control improves their privacy.
5.4. SAML

Execution
In order to reuse the credentials of users at ETH Zurich (or any other Swiss university), I have chosen the Authentication and Authorization Infrastructure of SWITCH (short SWITCHaai) for the implementation of the first standard. SWITCHaai runs on the open source software Shibboleth, which uses the Security Assertion Markup Language to provide single sign-on among federation partners. (See www.switch.ch/aai/demo/ for how Shibboleth works and appendix C. for all the references).

On www.switch.ch/aai/support/serviceproviders/, SWITCH has excellent guides for installing and configuring Shibboleth in the SWITCHaai federation. Having the file service realized with Java Server Pages running on Tomcat (see 5.2.), I needed to switch to Apache for being able to install the Shibboleth module (called mod_shib) that communicates with a special process named shibd. Only three directives were required to protect a location with Shibboleth in the configuration files of Apache. The requested attributes of users (see below) are passed through the Apache JServ Protocol (AJP) to the login script, which establishes a cookie-based user session. (This step is not necessary as Shibboleth would handle the session for you, but I kept it in conformity with the other standards.)

The server setup (chart taken from www.switch.ch).

After installation and configuration, you need to register as a service provider at the AAI Resource Registry (rr.aai.switch.ch):

Completing your data at the resource registry.

All technical information is directly taken from the metadata, you still have to enter many details manually though. Before you are done, you also specify the attributes that you require from the identity providers as well as the intended audience:

Selecting the required or desired attributes.

Once submitted, your application has to be approved by the Resource Registration Authority of your organization, which was in my case the IT Services of ETH Zurich. As a last step, you confirm the fingerprint of the self-issued certificate used by Shibboleth to encrypt and authenticate SAML messages on a second channel like e-mail. Afterwards, users can select their home organization and authenticate themselves to log in:

Redirect to the so-called where-are-you-from page.

User authentication at and by ETH Zurich.
Deploying

Overall, the deployment process was relatively smooth as a lot of things happen under the hood. However, if the default configuration is no longer sufficient because, e.g., you want to activate a second domain (as in my case with www.xal.ch), the hassle begins and Shibboleth becomes overly complex.

Suitability
- **Scope of Identity**: Considering the on both sides largely manual registration procedure for service providers, self-hosting is not practical for most users in this federation.
- **Attribute Access**: Shibboleth only allows the transmission of attributes during authentication. If you want to add an external user as a contact, no data lookups can be made.
- **Authorization**: SAML does not know the notion of a client as presented here and thus no authorizations are possible. Since the authentication towards the identity provider is not further specified, file access cannot be automated.
- **Accountability**: Users are not able to sign their requests.

Usability
- **Requirements**: Shibboleth uses standard technologies of the Web and therefore functions in all available browsers. It relies on cookies to store the user session and, without JavaScript, one more click is needed after authentication.
- **Attribute-Based Access Control**: The big advantage of an identity federation is that you know all identity providers. As they guarantee the quality of its users’ attributes, you can rely on these for access control. The only problem is that you need to know the desired attributes in advance, as they are already specified in the registration procedure.

5.5. OpenID

**Execution**

Deploying OpenID for user authentication is fairly simple: Import the libraries from code.google.com/p/openid4java/ and add a few lines to your code. Users can then log in:

[Example URL]

Identification at the service provider.

- **Contacts**: The only information you can get about a user’s social environment is his or her organizational unit. When combined with the Lightweight Directory Access Protocol to get useful contact data (separately for each organization), the search functionality can still significantly be improved.
- **Authentication**: Since the service providers of a federation are manually approved, all of them are trusted to respect the privacy of users, who are thus implicitly signed on.

**Security**
- **Phishing**: The fact that unsuspecting users can be sent to an arbitrary page for selecting their organization and then another one for authenticating themselves is a very severe issue of Shibboleth and knowing all IPs does not solve this!
- **Evidence**: How users authenticate themselves at their IPs is not prescribed by the standard but, as you can certainly guess from the screenshots, most IPs employ passwords.
- **Compromise**: Since such passwords usually allow you to control the whole identity, which in case of SWITCHaai is often a very critical one, attacks can be totally disastrous.
- **Logout**: What probably most users are unaware of is the circumstance that they will remain logged in for a specific service provider until they quit their browser. Just logging out at a service provider and closing the open windows is not sufficient (though for example myStudies tells you so!)

**Privacy**
- **Calling Home**: Your home organization learns about the time and place of every authentication that you demand.
- **Wrong Consent**: If users tick the checkbox so that SWITCH remembers their selection of home organization, they will no longer be notified about future authentication requests during the same browser session! This means that as soon as you are approved as a service provider, you can identify visitors on your site without their knowledge or consent.
- **Attribute Selection**: Another drawback of SWITCHaai is the fact that users are never informed about which attributes are transmitted to a service provider (see the screenshots above)! (A list of the requested attributes by each service provider is available on www.switch.ch/aai/participants/)!
- **Pseudonymity**: There is a dedicated attribute to identify users pseudonymously (in order to confuse developers it is both called targeted ID and persistent ID) but as they are unlikely to learn about it, such privacy is totally voluntary.
the part after the question mark in a URL), where they enter their credentials to authenticate themselves the first time:

![Image](https://via.placeholder.com/150)

**Authentication** at the identity provider.

In a final step, users need to approve that they indeed want to disclose their identity and possibly some more attributes to the stated service provider. Certain OpenID Provider allow their users to choose between various identifiers and related attributes (a feature which is often called personas) to return to service providers. The specification calls this functionality **OpenID Provider driven identifier selection** (section 10 of spec):

![Image](https://via.placeholder.com/150)

**Authorization** of the SP at the IP with ID selection.

In order to protect their users’ privacy, Google goes even one step further and generates automatically a distinct identifier for every service provider. This concept is known as **directed identity** (see 2.4.) and can to my knowledge not be turned off.

**Suitability**

- **Scope of Identity**: OpenIDs are accepted globally but, due to the above-mentioned feature, users are often not aware of their true but opaque (non human-readable) identifier.
- **Attribute Access**: An extension to the core protocol which is called OpenID Attribute Exchange allows service providers to read or store personal information during authentication. However, this does not enable service providers which are not involved in the authentication to look up attributes of contacts. As the big players Yahoo! and Google do have no public profile for their users, it is also hard to use the URL.
- **Authorization**: OpenID is a standard to authenticate users that interact with a browser in the **World Wide Web**. Since giving clients or third parties access to one’s resources is not incorporated, a complementary framework evolved under the name **OAuth**, providing a standardized method to authorize clients for **internal** (but not **external**) access.

- **Accountability**: Though OpenID has been designed with the aim of allowing people to comment on blog posts by others, it provides no way to check a statement’s validity.

**Usability**

- **Requirements**: None, and you do not even need to have root access to a Web server to run your own SP or also IP!
- **Attribute-Based Access Control (ABAC)**: OpenID states explicitly that it is not a trust system and that you cannot rely on identity providers in order to prevent spamming.
- **Contacts**: OpenID does not support exchanging contacts.
- **Authentication**: For limiting the risk of accidental identity disclosure, service providers have to be approved initially.

**Security**

- **Phishing**: User can be spoofed easily by redirecting them to a fake copy of their identity provider or performing so-called cross-site scripting if no appropriate measures are in place. The most reasonable way to prevent this is to use client certificates for the authentication of users at identity providers, but in that case you could as well rely on WebID.
- **Evidence**: It is the responsibility of every identity provider to choose an adequate authentication mechanism, but as most of them use passwords, no point can be given here.
- **Compromise**: Your OpenID is your single point of failure. If your credentials get stolen, the attacker can access all SPs.
- **Logout**: OpenID is just about authenticating users towards service providers and supports no session management. As a consequence, there is no single log-out functionality.

**Privacy**

- **Calling Home**: Being redirected to your identity provider for each authentication means that it can totally track you.
- **Wrong Consent**: Since you need to approve each service provider the first time you sign on, you should recognize an unsolicited attempt to establish your identity. For being notified every time you log in at a certain service provider, you can usually just uncheck a corresponding checkbox.
- **Attribute Selection**: Though the OpenID Attribute Exchange specification explicitly states that requirements should not be enforced by the OpenID Provider, a lot of providers fail to provide a reasonable user experience for deselecting a few attributes. This is not a problem of OpenID, however.
- **Pseudonymity**: By allowing the issuance of random but persistent identifiers per service provider (also known as directed identities), pseudonymity can be achieved but the original purpose of OpenID – to identify users – is defeated.

### 5.6. WebID

**Execution**

The beauty of WebID is its simplicity: Users create a certificate in their browser for client-side **authentication** in the secured Web protocol (known as **HTTPS**) and publish their public key on their **profile page**, which can be hosted anywhere. When a server demands a certificate, users are asked to select one:
Selecting the desired client certificate.

These certificates do not have to be signed by a well-known certification authority, the software on the server just needs to verify that the public key is indeed published on the page stated as a Subject Alternative Name (see image on the right).

The only difficulty in deployment was to configure a server in such a way that users were indeed prompted to provide a client certificate. With the little information that is available on the Web about WebID, we did not manage to set up our Tomcat server correctly. In case of Apache, however, a single directive ("SSLVerifyClient optional_no_ca") did the trick.

Suitability

– **Scope of Identity**: Based on URLs, identifiers are global.
– **Attribute Access**: Using vocabularies such as FOAF (Friend of a Friend), users can add personal details to their profile. As long as these are public, everyone can retrieve them.
– **Authorization**: The certificates can also be used by other clients than browsers (and even for other protocols than HTTPS), allowing the automated import of external files.
– **Accountability**: Transport Layer Security (TLS), on which WebID builds, provides authenticity and confidentiality but no non-repudiation among the communication partners.

Usability

– **Requirements**: WebID builds on common Web standards and works in most browsers but its usability varies widely.
– **Attribute-Based Access Control**: The various statements on a user’s profile can generally not be trusted and are not intended to be certified, but thanks to the Semantic Web (respectively the Resource Description Framework (RDF)), claims can be verified by consulting the primary source.
– **Contacts**: As the name FOAF suggests, its goal is to link people on the Web and SPs can easily consume this data.
– **Authentication**: Depending on your browser, you can set it to present a client certificate without previously asking you, but this is usually not what you want. Consequently, you need to select a certificate for every service provider.

Security

– **Phishing**: As no redirections are used and your private key is never revealed (not even to your IP), this is not an issue.
– **Evidence**: Since the corresponding private key is required to misuse certificates, your ID is protected with possession.

– **Compromise**: WebID does not specify any restrictions of authorization, so unless your identity provider does anything special, you risk to lose control over your entire ID!
– **Logout**: As soon as browser manufacturers start to offer better support for WebID, a single logout is no problem.

Privacy

– **Calling Home**: Since service providers could fetch profile data anonymously, identity providers cannot track users.
– **Wrong Consent**: With current browser implementations, it could easily happen that you approve identification to undesired SPs, since these are not stored across sessions.
– **Attribute Selection**: Though WebID does not support the transmission of attributes during authentication, a user can still configure its IP to deliver them only selectively.
– **Pseudonymity**: Since the identifier in a certificate cannot be modified, the user is always identified (and creating a separate certificate per SP renders WebID totally useless).

Certificate with the identifier in Subject Alternative Name.
5.7. Virtual ID

Execution

A big part of this master thesis consisted in bringing the not fully existing implementation of Virtual ID to a level that can be used for a decentralized file service as described above. The current version builds on a prototype that I have written together with Dominik Blunschy in the Distributed Systems Lab at ETH Zurich last spring. Besides general improvements, the main advancements have been in managing clients with the granular permissions and restrictions as outlined in a thesis for my bachelor’s degree (client authorization has just been binary before), in adding support for contacts and enabling access policies for attributes and other resources. Moreover, certified attributes are now also supported, which was mainly needed to verify the public key of hosts. (Clients are delivered with the public key of virtualid.ch and can therewith validate the public key of xdf.ch.) Unfortunately, a general mechanism to issue certificates is not yet in place and therefore attribute-based access control is not possible so far. The cryptography required for anonymous credentials (see A.3.), however, is fully implemented and clients use it to authenticate themselves at other hosts (and can thereby no longer be distinguished from each other). This lack of certification is also the reason why it is not yet possible to run one’s own hosts, since clients would not be able to verify their authenticity. (The public key of the host xdf.ch has been signed with an internal procedure.)

Thanks to the fact that Virtual ID and its type system, which is called Extensible Data Format or short XDF, are so simple to extend, the development of the desired file service required only relatively little effort. The functionality that is related to the actual sharing of files was realized with just one database table and four methods on the client- and the server-side to issue respectively handle the necessary requests. A little bit more work was to write the thread that loops every second through the synchronized files to check if anyone of them has changed and needs to be uploaded or downloaded.

Unlike the other standards, Virtual ID synchronizes the files directly in your file system. On startup, the client creates the folder File Service in your home directory with two subfolders called Internal and External for your own files respectively the ones of your friends. The file structure should look like this:

![Image of file structure]

All the files stored in Internal are actively synchronized with the host which you have specified when starting a client for the first time. The folder External though just imports all the files that your contacts have shared with you to folders that are labelled with their respective names. These files are only to read: Whatever you change there will not be reflected on any server! Furthermore, the synchronization process does not keep track of changes, it just mirrors added or modified files for now. As a consequence, a file that you delete will be immediately added back again (unless you take the option dedicated for this in the client’s command line interface). If you want to see external files synchronization, you can add kaspar.etter@virtualid.ch as a contact to get my public files.

The visibility of your files can be specified in the implicitly created and automatically updated file Access.txt. The syntax for each line is first the file name and a colon followed by a so-called passive expression that determines the access policy. Basically, you can separate several identifiers with a plus sign, use the keyword “everybody” to make a file public or enter a zero to grant access only to your contacts. As expressions are not yet checked on the client-side, you will receive ugly error messages if you make a mistake. (Just delete that line then.)

In order to execute the client, you need to have access to a (preferably local) MySQL installation. On initial startup, the client guides you through the configuration of the database and the creation of your virtual identity (abbreviated as VID).

The client creates a hidden folder named VirtualID in your home directory to store the database configuration and the client’s secret, which is used for authentication. If you delete this folder, you will no longer be able to access your VID! You can just create a new one though. The subfolder Files contains the log of the file service as well as the client’s name, which is important in case you want to authorize a second client on a different machine. (This setup synchronizes writable files!)

The other folders and files in VirtualID are only needed if the code is run as a server, which will create a private and a public key for each host and log all incoming requests in the file Log.txt. As services are developed independently of the core server, their implementations can be placed as a Java Archive (JAR) in the Services folder, from where they will be loaded dynamically, i.e. during the runtime of the server.

This hidden folder has the following content, where normal users do not have the files with the black and brownish icons:

![Image of file structure]
5.8. Evaluation

Comparison

The above analysis of the four standards based on the criteria presented in 5.3. resulted in the following table:

<table>
<thead>
<tr>
<th>Name</th>
<th>SAML</th>
<th>OpenID</th>
<th>WebID</th>
<th>Virtual ID</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Suitability</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>– Scope of Identity</td>
<td>–</td>
<td>–</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>– Attribute Access</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>– Authorization</td>
<td>–</td>
<td>–</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>– Accountability</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td><strong>Usability</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>– Requirements</td>
<td>+</td>
<td>–</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>– ABAC</td>
<td>–</td>
<td>+</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>– Contacts</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>– Authentication</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td><strong>Security</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>– Phishing</td>
<td>–</td>
<td>–</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>– Evidence</td>
<td>–</td>
<td>–</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>– Compromise</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>– Logout</td>
<td>–</td>
<td>–</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td><strong>Privacy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>– Calling Home</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>++</td>
</tr>
<tr>
<td>– Wrong Consent</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>– Attribute Selection</td>
<td>–</td>
<td>–</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>– Pseudonymity</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
</tbody>
</table>

The differences between the four standards are remarkable. The next section gives some advice on how to best use them.
6. Conclusions

6.1. Contributions

Characterization
For people not familiar with identity management systems, it is tough to get an accurate picture of the numerous standards and even more difficult to compare them in a thorough way. The presented characterization is the first holistic attempt to systematically identify all conceptually important aspects of single sign-on and identity standards. Its primary purpose is to facilitate and standardize the creation of standard profiles that enable the reader to grasp and classify existing and new proposals in the identity landscape in a short amount of time.

Although many of the characteristics can be combined in arbitrary ways, there seem to be some sweet spots around which standards cluster. The major two distinctions concern whether they focus on the users or their clients and whether access is granted to internal or external resources. Based on this, I suggest the following classification of standards (4.7.):

<table>
<thead>
<tr>
<th>Standard</th>
<th>User</th>
<th>Client</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal</td>
<td>(1) Auth</td>
<td>(2) Authorization</td>
</tr>
<tr>
<td>External</td>
<td>(3) Feder</td>
<td>(4) Identity</td>
</tr>
</tbody>
</table>

Comparative Study
In order to show the practical relevance of this classification, I designed a study in which I compared four standards on the basis of a concrete scenario. Each standard was employed to implement a decentralized file service, where users can select a provider of their choice and are still able to share content with their friends and co-workers utilizing other hosts.

The four standards were selected by means of the outlined classification with a representative from each class which has support for external access control plus my own standard.

The criteria were derived from the characterization as well. Grouped into four categories, they result in the grades (5.8.):

<table>
<thead>
<tr>
<th>Name</th>
<th>SAML</th>
<th>OpenID</th>
<th>WebID</th>
<th>Virtual ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suitability</td>
<td>—</td>
<td>—</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Usability</td>
<td>+</td>
<td>—</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Security</td>
<td>—</td>
<td>—</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Privacy</td>
<td>—</td>
<td>==</td>
<td>==</td>
<td>++</td>
</tr>
</tbody>
</table>

The given scenario clearly demands a real identity standard!

6.2. Future Work

Characterization
The list of characteristics is not fixed but should evolve with new insights and requirements. Though I was first skeptical about the benefits of an actual implementation, I learned a lot during the deployment of the four standards. This would certainly affect the characterization if I started anew with my master thesis. Among the things I would do differently are:
- better conceptualization of the authentication mechanism (e.g. whether the messages are relayed through the client);
- split privacy and security concerns according to the study;
- determine who controls the submission of the evidence (with proper challenge-response techniques on the client-side, phishing is no issue (but man-in-the-middle attacks));
- and depict partial and directed identities more accurately.

Comparative Study
In my opinion, the criteria of the study are adequate and also quite informative. The implementation could be significantly improved from a usability perspective, but the standards are likely to profit equally from a better user interface. Moreover, a native application for WebID could demonstrate its ability to span both the Web and the desktop. A desirable extension of the scenario would be to allow modifications to external files and thereby highlight the importance of accountability. This feature is not supported in the current version since it would complicate the user experience (also of Virtual ID) too much.

It is always possible, however, to evaluate more standards and show their respective strengths and weaknesses. Some potential candidates can be found in the chapter 5.1.
6.3. Semantic Web

Vision
The term Semantic Web was coined by Tim Berners-Lee, who is known as the inventor of the World Wide Web, in an article from 2001, where he outlined his vision of a Web that is also understandable by machines and not just humans [BHL01]. Until now, browsers can only display the content of Websites to users and wait for their reactions but have a hard time to find relevant information on their own. Once computers can process semantic data on behalf of their users, the dream of having a personal digital assistant finally comes true.

Requirements
The promise of the Semantic Web requires two ingredients:
– **Identities**: In order to trust some information, you need to know its source. On the other hand, whenever your device orders something for you, it enters a contract between two legal entities. Furthermore, most data is not meant to be public but still contains a lot of semantics, so you would like to have a way to disclose resources only selectively.
– **Automation**: For being able to assist you with your tasks, clients need to be authorized with the proper permissions, which includes the capability to act on your behalf towards others. Only if no more human interaction is required, it is feasible to automate the procedures for digital agents.

Realization
What I tried to demonstrate with the present master thesis, is that federation and sign-on standards do not meet the two requirements for the realization of the Semantic Web as they neither allow the user to make trustworthy statements nor to authorize clients for automated exchange of information. They just allow service providers to recognize the same user.

To the best of my knowledge, there exist currently only two general-purpose proposals that are technically qualified to enable the Semantic Web: WebID and Virtual ID. Considering the enormous efforts that are needed to accomplish such a big transition, it is probably worth to rely on the technically and conceptually more mature of the two: Virtual ID.

Laying the foundation for the realization of the Semantic Web:

![Diagram showing the evolution from Web 1.0 to Web 2.0 and Identity 1.0 to Identity 2.0 with Virtual ID as the Semantic Web]

Virtual ID is a protocol that constitutes an open identity layer for the Internet and a semantic alternative to the World Wide Web. It allows you to prove your identity towards others and to look up attributes of others in a decentralized manner. Being freely extensible with services, Virtual ID aims to supersede proprietary platforms by establishing a framework of open standards.
A. Technologies

A.1. Internet

Internet Protocol (IP)
The Internet originates from the ARPANET (Advanced Research Projects Agency). In 1974, different networking methods were unified by an internetwork protocol, which became ten years later the only approved protocol on the ARPANET. The goal of this Internet Protocol (better known as IP) is to route packets between any two devices that are connected to the Internet. Each end point is denoted by an IP address, a 32-bit number that reflects the hierarchical organization of the Internet.

Transmission Control Protocol (TCP)
As the Internet Protocol provides no reliability, the Transmission Control Protocol (TCP) is used to transport packets between processes (a process is an instantiation of a program), where so-called port numbers designate the process on each of the communicating devices. When a packet is received, it is the task of the Operating System to deliver it to the right process. Additionally, TCP recognizes lost packets and such which are out of order to provide reliable and in-order data transfer.

Secure Sockets Layer (SSL)
The Secure Sockets Layer (SSL) respectively its successor called Transport Layer Security (TLS) are cryptographic protocols that provide confidentiality and integrity for secure communication over the Internet. They use public-key cryptography (see A.3.) to authenticate the opposite party and symmetric encryption to ensure that nobody can decipher a transmitted message.

Domain Name System (DNS)
Instead of referencing machines by their IP addresses, a more human-friendly solution was introduced in 1983: the Domain Name System (DNS). It acts as a distributed “phone book” to look up the IP addresses of domain names. A domain name is a sequence of labels separated by dots, e.g. www.ethz.ch.

Uniform Resource Locator (URL)
A Uniform Resource Identifier (URL) is a special string (a string is a sequence of characters) that uniquely identifies a resource. A Uniform Resource Locator (URL) is a URI that specifies where and how a resource can be accessed on the Internet. URLs are written as scheme://domain:port/path?query_string#fragment.

A.2. World Wide Web

Hypertext Transfer Protocol (HTTP)
The Hypertext Transfer Protocol (HTTP), which you know from the scheme of URLs, is the so-called Application Layer protocol of the World Wide Web. A client, usually known as a browser, initiates a TCP connection to a server on port 80 to retrieve the document as specified by the path and the query string of the URL. Since HTTP is a stateless protocol, user sessions are most commonly maintained by cookies, which are sent by the browser in every request. As TCP provides neither confidentiality nor authenticity, HTTP is often used over SSL/TLS, which results in the well-known HTTPS scheme.

Extensible Markup Language (XML)
The Extensible Markup Language (XML) defines a set of rules to encode information in a machine-readable format. It can be seen as a generalization of HTML that is widely used to transfer data between programs and machines. All these standards are specified by the WWW Consortium (W3C).

JavaScript (JS)
JavaScript (JS) is a scripting language that enables dynamic Web Pages and was introduced by Netscape in 1995. Unlike other scripting languages, it is executed on the client-side by the browser and can modify a page’s content and layout.

Hypertext Markup Language (HTML)
The Hypertext Markup Language (HTML) describes the content and structure of Web pages. It is text-based and uses tags like <p> (for opening) and </p> (for closing) to mark its content. Browsers interpret these tags and display pages accordingly.

Resource Description Framework (RDF)
The Resource Description Framework (RDF) is a W3C standard to describe Web resources using a variety of notations and formats. It consists of subject-predicate-object expressions.
A.3. Cryptography

Symmetric-Key Cryptography
In symmetric-key cryptography, the communicating parties share the same key for encryption and decryption. This was the only encryption method publicly known before the year 1976, when Whitfield Diffie and Martin Hellman proposed to use different but related keys for encryption and decryption.

Public Key Cryptography
The main problem with symmetric-key cryptography is the management of keys since each pair of parties must share a different key or rely on a trusted third party to distribute one on demand. By using a pair of related but distinct keys, it is possible to share the one for encryption while keeping the one for decryption secret. The former is known as the public key, the latter as the private key. For confidentiality, it has to be hard to compute the private key from the public key.

Digital Signatures
The essential feature of signatures is that they are easy for the author to produce but hard for others to forge. This is achieved by using the private key for signing and the public key for the verification of a signature, which anyone can do.

Public Key Infrastructure
Since it is not possible to authenticate someone you have never met before, you need to trust a third party to confirm their identity. This service is usually provided by certification authorities (CAs) that issue certificates on the public key of registered users and thereby making them accountable.

Anonymous Credentials
By signing only the hash, classical public-key cryptography requires the complete message for the verification of digital signatures. In order to protect one’s privacy, it is desirable to reveal the content of a certificate more selectively and prove nevertheless certain facts about hidden statements. This can be used to show certificates anonymously as credentials and still provide evidence that they were issued to the same user.

The Onion Router (Tor)
As we have seen in the previous section, computers on the Internet are uniquely identified by their IP address. In order to still achieve anonymity on the Network Layer, you can join the free volunteer network of nodes that relay each other packets to prevent network surveillance and traffic analysis: Tor [Tor].

A.4. Vulnerabilities

Protocol
A first family of vulnerabilities that an attacker might exploit concern the design of a protocol itself. If not properly done, the evil party can eavesdrop on the communication channel to learn confidential information, drop, insert and replay any message or be the man-in-the-middle that impersonates the respective other party. If randomness is not taken from a big enough range (e.g. by relying on passwords), an attacker can also run a brute force attack by simply trying all possible keys or letter combinations. A further option is to trick the victim into voluntarily releasing its secret to a fake Web page, which is called phishing and is currently the biggest security threat.

Implementation
Many of the vulnerabilities in practice, however, are not due to flawed specifications but due to careless implementations. An attacker can do some cross-site scripting (XSS) by injecting malicious code that is executed on the client-side (usually in JavaScript) or make cross-site request forgery (XSRF) by posting harmful form data and actions to a Website at which the user is currently logged in. If sessions are not handled properly, an attacker could also fixate the session of a victim (which was an issue in OAuth.) The major problem though is that negligent identity providers can also damage the reputation of service providers, which can deter a company from using a protocol.

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1 This section uses material from a previous paper of mine, which can be found on www.virtualid.ch.
# B. Standards

## B.1. Comparison

The following table compares the standards SAML, OpenID, WebID and Virtual ID according to the characterization of chapter 4.

<table>
<thead>
<tr>
<th>Name</th>
<th>SAML</th>
<th>OpenID</th>
<th>WebID</th>
<th>Virtual ID</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Logo</td>
<td><img src="saml.png" alt="saml.png" /></td>
<td><img src="OpenID.png" alt="OpenID.png" /></td>
<td><img src="WebID.png" alt="WebID.png" /></td>
<td>![Virtual ID.png](Virtual ID.png)</td>
</tr>
<tr>
<td>- Website</td>
<td>saml.xml.org</td>
<td>openid.net</td>
<td>webid.info</td>
<td><a href="http://www.virtualid.ch">www.virtualid.ch</a></td>
</tr>
<tr>
<td>- Proponent</td>
<td>SSTC of OASIS</td>
<td>OpenID Foundation</td>
<td>WebID Community Group</td>
<td>Virtual ID Foundation</td>
</tr>
<tr>
<td>- Intention</td>
<td>Have an open standard for authentication data</td>
<td>Provide a safe, fast and easier login to Websites</td>
<td>Replace the traditional, weak login on the Web</td>
<td>Supersede proprietary platforms of the Web</td>
</tr>
<tr>
<td>- Target</td>
<td>Mainly used as SSO in commerce/academia</td>
<td>All users of Websites</td>
<td>All users of Websites</td>
<td>All natural and artificial persons in any services</td>
</tr>
<tr>
<td><strong>History</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Development</td>
<td>Active</td>
<td>Active</td>
<td>Active</td>
<td>Active</td>
</tr>
<tr>
<td>- Adoption</td>
<td>Industry standard</td>
<td>Decreasing popularity</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>- Support</td>
<td>Excellent (SWITCHaai)</td>
<td>Many online forums</td>
<td>Mailing list</td>
<td>Limited</td>
</tr>
<tr>
<td>- Specification</td>
<td>Overly complex</td>
<td>Many options but clear</td>
<td>Incomplete but clear</td>
<td>Incomplete but clear</td>
</tr>
<tr>
<td>- Community</td>
<td>Big</td>
<td>Huge</td>
<td>Small</td>
<td>None</td>
</tr>
<tr>
<td>- Libraries</td>
<td>Apache (Shibboleth)</td>
<td>Many modules/plugins</td>
<td>PHP and Java (?)</td>
<td>Java (not yet available)</td>
</tr>
<tr>
<td>- Protocol</td>
<td>Client-server</td>
<td>Client-server</td>
<td>Client-server</td>
<td>Client-server</td>
</tr>
<tr>
<td>- Version</td>
<td>2.0</td>
<td>2.0</td>
<td>Unfinished</td>
<td>Unfinished</td>
</tr>
<tr>
<td>- Patents</td>
<td>No licenses required</td>
<td>Non-assertion covenants</td>
<td>Disclosure obligations</td>
<td>Guaranteed by IBM</td>
</tr>
<tr>
<td>- Extensions</td>
<td>Many proprietary ones</td>
<td>Attribute Exchange, etc.</td>
<td>–</td>
<td>Various services</td>
</tr>
<tr>
<td>Name</td>
<td>SAML</td>
<td>OpenID</td>
<td>WebID</td>
<td>Virtual ID</td>
</tr>
<tr>
<td>------</td>
<td>------</td>
<td>--------</td>
<td>-------</td>
<td>------------</td>
</tr>
<tr>
<td><strong>Identity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>– Identity</td>
<td>Unique (if ensured)</td>
<td>Arbitrary</td>
<td>Arbitrary</td>
<td>Arbitrary</td>
</tr>
<tr>
<td>– Scope</td>
<td>Federated</td>
<td>Global</td>
<td>Global</td>
<td>Global</td>
</tr>
<tr>
<td>– Creation</td>
<td>Authority</td>
<td>User</td>
<td>User</td>
<td>Client</td>
</tr>
<tr>
<td>– Deletion</td>
<td>Supported</td>
<td>Identifier remains</td>
<td>Identifier remains</td>
<td>–</td>
</tr>
<tr>
<td>– Merging</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Supported for persons</td>
</tr>
<tr>
<td>– Identifier</td>
<td>Unique ID (opaque)</td>
<td>URL or XRI</td>
<td>Any URI</td>
<td>Identifier like e-mail</td>
</tr>
<tr>
<td>– Relocation</td>
<td>–</td>
<td>Delegated or redirected</td>
<td>Possible: HTTP Redirect</td>
<td>Approved redirects</td>
</tr>
<tr>
<td>– Reusability</td>
<td>–</td>
<td>Allowed with fragments</td>
<td>Unspecified</td>
<td>Forbidden</td>
</tr>
<tr>
<td>– Interaction</td>
<td>Implicit (at ID provider)</td>
<td>Unspecified (manually)</td>
<td>Explicit (prompt)</td>
<td>Implicit</td>
</tr>
<tr>
<td>– Frequency</td>
<td>Once per browser session</td>
<td>Per SP and brows. session</td>
<td>Per SP and brows. session</td>
<td>Once per client</td>
</tr>
<tr>
<td>– Submission</td>
<td>SAML assertion</td>
<td>Unspecified (form field)</td>
<td>SSL client certificate</td>
<td>Request signature</td>
</tr>
<tr>
<td>– Attributes</td>
<td>Implicit by SP (static)</td>
<td>Explicit by the SP (dyn.)</td>
<td>–</td>
<td>Implicit by user (static)</td>
</tr>
<tr>
<td>– Linkability</td>
<td>Anonymous (pseudo.)</td>
<td>Identifiable (or pseudo.)</td>
<td>–</td>
<td>Anonymous</td>
</tr>
<tr>
<td>– Revocation</td>
<td>? (by identity provider)</td>
<td>(By identity provider)</td>
<td>–</td>
<td>By certifying authority</td>
</tr>
<tr>
<td><strong>Authentication</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>– Mechanism</td>
<td>Redirections with crypto</td>
<td>Redirections with secret</td>
<td>Cryptographic certificate</td>
<td>Cryptographic signature</td>
</tr>
<tr>
<td>– Performance</td>
<td>15 mess. with signatures</td>
<td>11/13 mess. with hashes</td>
<td>SSL handshake (5 mess.)</td>
<td>TCP with crypto (1 mess.)</td>
</tr>
<tr>
<td>– Compatibility</td>
<td>Any user authentication</td>
<td>Any user authentication</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>– Requirements</td>
<td>Web server module</td>
<td>–</td>
<td>SSL certificate on server</td>
<td>New clients and servers</td>
</tr>
<tr>
<td>– Vulnerabilities</td>
<td>Phishing, no logout</td>
<td>Phishing, DNS and XSS</td>
<td>Wrong X.509 certificate</td>
<td>DoS, single root in PKI</td>
</tr>
<tr>
<td>– Privacy Issues</td>
<td>Calling home, consent</td>
<td>Calling home problem</td>
<td>ID leaked to wrong SP</td>
<td>–</td>
</tr>
<tr>
<td>– Identity Provider</td>
<td>Online</td>
<td>Online</td>
<td>Online</td>
<td>Offline (key cached; &lt; 1 h)</td>
</tr>
<tr>
<td>– Discovery</td>
<td>Central page (WAYF)</td>
<td>IP referenced in Meta</td>
<td>Alternative Name in X.509</td>
<td>Part of the identifier</td>
</tr>
<tr>
<td>– Relocation</td>
<td>– (not even initial choice)</td>
<td>Delegate to the new IP</td>
<td>Possible: HTTP Redirect</td>
<td>Supported</td>
</tr>
<tr>
<td>– Verification</td>
<td>Known list of providers</td>
<td>– (X.509 Certificates)</td>
<td>X.509 Certificates</td>
<td>Centralized PKI</td>
</tr>
<tr>
<td>– Rotation</td>
<td>3 years</td>
<td>–</td>
<td>Validity of certificate</td>
<td>2 years</td>
</tr>
<tr>
<td>– Regulation</td>
<td>Central registration</td>
<td>–</td>
<td>–</td>
<td>By Virtual ID Foundation</td>
</tr>
<tr>
<td>– Service Provider</td>
<td>Central registration</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>– Evidence</td>
<td>Unspecified (password)</td>
<td>Unspecified (password)</td>
<td>Cryptographic key</td>
<td>Cryptographic key</td>
</tr>
<tr>
<td>– Factor</td>
<td>Unspecified (knowledge)</td>
<td>Unspecified (knowledge)</td>
<td>Possession</td>
<td>Possession</td>
</tr>
<tr>
<td>– Control</td>
<td>Unspecified (user)</td>
<td>Unspecified (user)</td>
<td>Client</td>
<td>Client</td>
</tr>
<tr>
<td>– Rotation</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>2 years</td>
</tr>
<tr>
<td>– Interaction</td>
<td>Unspecified (manually)</td>
<td>Unspecified (manually)</td>
<td>– (during identification)</td>
<td>–</td>
</tr>
<tr>
<td>– Frequency</td>
<td>Once per browser session</td>
<td>Once to IP (per session)</td>
<td>– (once per SP and session)</td>
<td>–</td>
</tr>
<tr>
<td>– Submission</td>
<td>Unspecified (form field)</td>
<td>Unspecified (form field)</td>
<td>SSL certificate</td>
<td>Request signature</td>
</tr>
<tr>
<td>– Compromise</td>
<td>Unspecified (identity)</td>
<td>Unspecified (identity)</td>
<td>Unspecified (identity)</td>
<td>Client</td>
</tr>
<tr>
<td>– Revocation</td>
<td>Unspecified (change pw.)</td>
<td>Unspecified (change pw.)</td>
<td>Remove public key</td>
<td>Deaccreditation</td>
</tr>
<tr>
<td>– Session</td>
<td>Shibboleth Daemon</td>
<td>By SP (cookies)</td>
<td>SSL Connection</td>
<td>Signatures</td>
</tr>
<tr>
<td>– Logout</td>
<td>– (in case of SWITCHaai)</td>
<td>At the IP and all SPs</td>
<td>Browser dependent</td>
<td>Unspecified (client-side)</td>
</tr>
<tr>
<td>– Encryption</td>
<td>At least setup encrypted</td>
<td>–</td>
<td>Recommended</td>
<td>Mandatory</td>
</tr>
<tr>
<td>– Forward Secrecy</td>
<td>–</td>
<td>–</td>
<td>– (optional in SSL)</td>
<td>–</td>
</tr>
<tr>
<td>Name</td>
<td>SAML</td>
<td>OpenID</td>
<td>WebID</td>
<td>Virtual ID</td>
</tr>
<tr>
<td>---------------------</td>
<td>------</td>
<td>--------</td>
<td>----------------</td>
<td>--------------------</td>
</tr>
<tr>
<td><strong>Authorization</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>– Clients</td>
<td>–</td>
<td>–</td>
<td>Supported</td>
<td>Supported</td>
</tr>
<tr>
<td>– Rights</td>
<td>–</td>
<td>–</td>
<td>Unspecified (all)</td>
<td>Attributes and contacts</td>
</tr>
<tr>
<td>– Permissions</td>
<td>–</td>
<td>–</td>
<td>Unspecified (all)</td>
<td>Attributes and services</td>
</tr>
<tr>
<td>– Restrictions</td>
<td>–</td>
<td>–</td>
<td>Unspecified (none)</td>
<td>Attr., contacts, history</td>
</tr>
<tr>
<td>– Management</td>
<td>–</td>
<td>–</td>
<td>Unspecified (Web UI)</td>
<td>Trust-based client order</td>
</tr>
<tr>
<td>– Accreditation</td>
<td>–</td>
<td>–</td>
<td>Unspecified</td>
<td>Commit to secret value</td>
</tr>
<tr>
<td>– Deaccreditation</td>
<td>–</td>
<td>–</td>
<td>Removal from profile</td>
<td>Remove (&lt; 1 h effective)</td>
</tr>
<tr>
<td>– Users</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Supported (with roles)</td>
</tr>
<tr>
<td><strong>Accountability</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>– Signatures</td>
<td>–</td>
<td>–</td>
<td>Nowhere</td>
<td>Requests and responses</td>
</tr>
<tr>
<td>– Liability</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Oral (written intended)</td>
</tr>
<tr>
<td>– Duration</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1 year</td>
</tr>
<tr>
<td>– Revocation</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>– Framing</td>
<td>Possible</td>
<td>Possible</td>
<td>Possible</td>
<td>Prevented by auditing</td>
</tr>
<tr>
<td><strong>Attributes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>– Storage</td>
<td>Predefined</td>
<td>– (Attribute Exchange)</td>
<td>Extensible</td>
<td>Extensible</td>
</tr>
<tr>
<td>– Format</td>
<td>String (XML)</td>
<td>– (UTF-8 string, id. by URI)</td>
<td>String (RDF)</td>
<td>Arbitrary (XDF)</td>
</tr>
<tr>
<td>– Regulation</td>
<td>By the federation</td>
<td>–</td>
<td>–</td>
<td>By attribute author</td>
</tr>
<tr>
<td>– Transmission</td>
<td>Supported (all attributes)</td>
<td>Supported (all attributes)</td>
<td>–</td>
<td>Only certified attributes</td>
</tr>
<tr>
<td>– Access</td>
<td>–</td>
<td>–</td>
<td>Unspecified (possible)</td>
<td>Specified per attribute</td>
</tr>
<tr>
<td>– Policy</td>
<td>–</td>
<td>–</td>
<td>Unspecified (possible)</td>
<td>Passive expressions with contexts and attributes</td>
</tr>
<tr>
<td>– Caching</td>
<td>–</td>
<td>–</td>
<td>Unspecified (possible)</td>
<td>Specified per attribute</td>
</tr>
<tr>
<td>– Certification</td>
<td>(Trusted identity providers)</td>
<td>–</td>
<td>–</td>
<td>Specified per attribute</td>
</tr>
<tr>
<td>– Authority</td>
<td>(Identity providers)</td>
<td>–</td>
<td>–</td>
<td>Hierarchical (single root)</td>
</tr>
<tr>
<td>– Revocation</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>– Liability</td>
<td>?</td>
<td>–</td>
<td>–</td>
<td>Given (only trust in root)</td>
</tr>
<tr>
<td><strong>Contacts</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>– Format</td>
<td>–</td>
<td>–</td>
<td>Friend of a Friend (FOAF)</td>
<td>Identifiers in XDF</td>
</tr>
<tr>
<td>– Structure</td>
<td>–</td>
<td>–</td>
<td>Unspecified</td>
<td>Hierarchical contexts</td>
</tr>
<tr>
<td>– Disclosure</td>
<td>–</td>
<td>–</td>
<td>Public by default</td>
<td>Designated attributes</td>
</tr>
<tr>
<td>– Notification</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Knock with preferences</td>
</tr>
<tr>
<td><strong>Conclusion</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>– Classification</td>
<td>Federation Standard</td>
<td>Sign-On Standard</td>
<td>Identity Standard</td>
<td>Identity Standard</td>
</tr>
<tr>
<td>– Suitability</td>
<td>Among organizations</td>
<td>Primarily for the Web</td>
<td>Web and Apps</td>
<td>Distributed services</td>
</tr>
<tr>
<td>– Summary</td>
<td>Mature standard for businesses/universities</td>
<td>Simple to authenticate millions of Web users</td>
<td>Badly supported by browsers, nice idea</td>
<td>Clean concepts and state-of-the-art cryptography</td>
</tr>
</tbody>
</table>
C. References

Standards and Initiatives

- ABC4Trust: www.abc4trust.net
- BrowserID: www.persona.org
- CardSpace: (discontinued)
- FIDIS: www.fidis.net
- FOAF: www.foaf-project.org
- Higgins Project: www.eclipse.org/higgins/
- Kerberos: web.mit.edu/kerberos/
- Liberty Alliance: www.projectliberty.org
- NSTIC: www.nist.gov/nstic/
- OAuth: oauth.net
- OpenID: openid.net
- OpenPGP: www.openpgp.org
- PICOS: www.picos-project.eu
- PRIME: www.prime-project.eu
- PrimeLife: www.prime-life.eu
- SAML: saml.xml.org
- Shibboleth: shibboleth.net
- SuisseID: www.suisseid.ch
- Tor: www.torproject.org
- Virtual ID: www.virtua1id.ch
- WebID: webid.info
- WS-Federation: docs.oasis-open.org/wsfed/federation/

Request for Comments (RFCs)

- RFC2616: www.ietf.org/rfc/rfc2616 (HTTP/1.1)
- RFC2617: www.ietf.org/rfc/rfc2617 (HTTP Authentication)
- RFC4880: www.ietf.org/rfc/rfc4880 (OpenPGP)


[Cam05] Kim Cameron; The Laws of Identity; Microsoft Corporation, 2005.


