IT University of Copenhagen

Bachelor Project

Verifiable Secure Open Source Alternative to NemID

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Abstract

Your abstract goes here...

Contents

Chapter 1

Introduction

...

We're extending the work done by Jacob Hjgaard in his Masters Thesis 'Securing Single Sign-On Systems With Executable Models'. Jacobs research has focused on the current implementation of NemID and therefore describes, outlines and models the current system used in Denmark as of May 2013.

1.1 Objectives

Some explaining text here

1. Describe and outline the OpenNemID protocol, including but not limited to registration and login.
2. Formalize the specification of OpenNemID in F* to the extent possible.

1.2 Scope

This project has had it focus towards specifying a new protocol that could replace NemID. The intent of this project is therefore not to develop a complete system, but to make the specification for a system that could then later be developed based on the specification.

1.3 Background

...

Chapter 2

Technical Background

2.1 SAML Protocol

2.2 Static Analysis

2.3 Selection of verification tool

F* - formal specification language that is also executable

2.4 N Factor Authentication

Videreudvikling af two factor authentication

Chapter 3

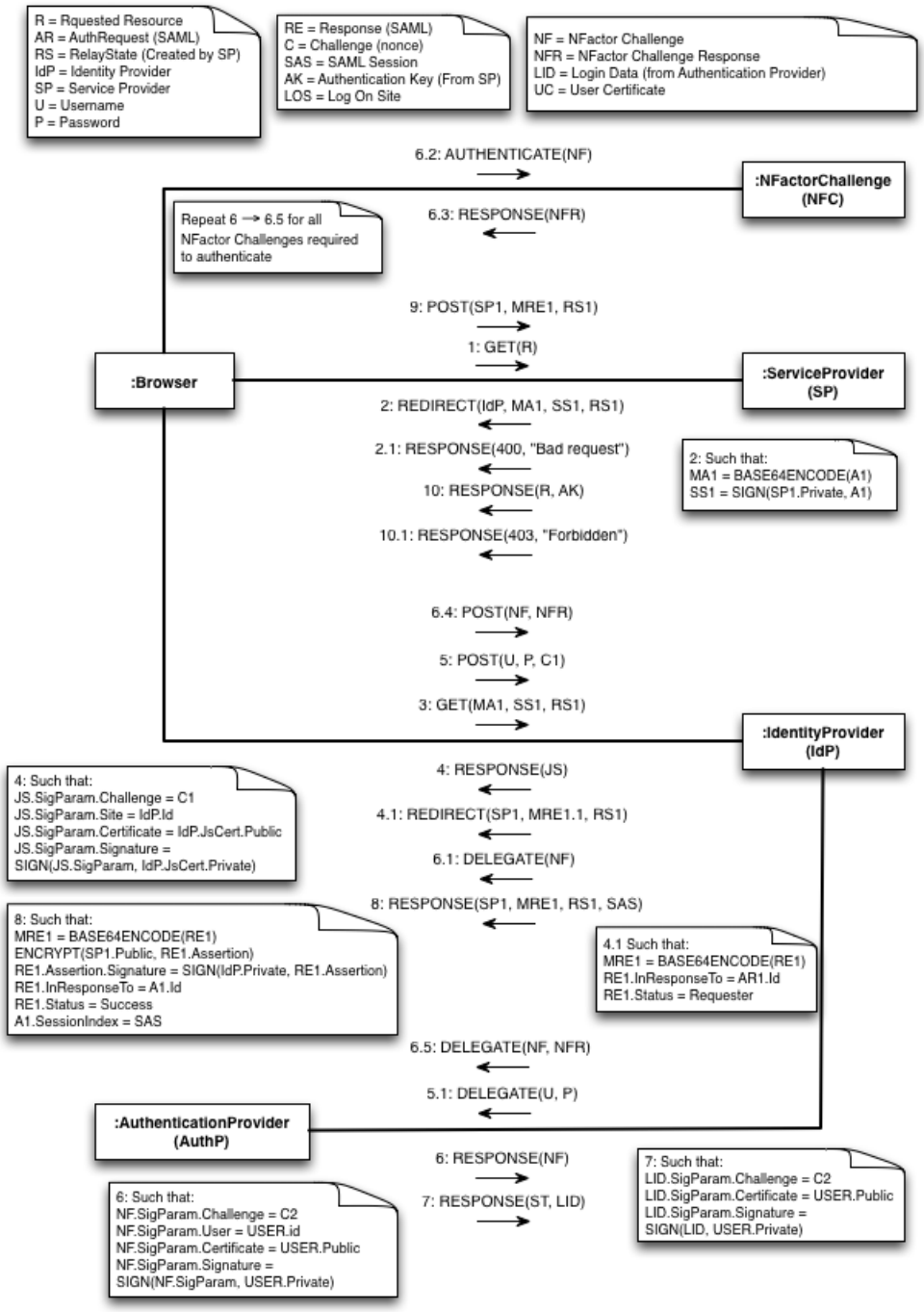
Remodelling the protocol

3.1 How It Is Today

3.2 How It Could Be

3.3 Communication Model

The communication model displays a graphical overview of how data should be communicated between the involved parties.



TEXT DESCRIBING ALGORITHM 1

Algorithm 1 Process 1

Require: GET is well-formed **and** IdP.Public **and** SP.Private
  if R exists **then**
    AR ← CreateAuthnRequest()
    SAR ← SIGN(AR, SP.Private)
    MA ← UrlEnc(Base64Enc(DeflateCompress(AR)))
    RS ← UrlEnc(Base64Enc(R))
    return REDIRECT(IdP, MA, SAR, RS)
  else
    return RESPONSE(400, BadRequest)
  end if

TEXT DESCRIBING ALGORITHM 2

Algorithm 2 Process 3

Require: GET is well-formed **and** IdP.Private **and** SP.Public **and** IdPJsCert.Public **and** IdP has JavaScript from AuthP
  AR ← DeflateDecompress(Base64Dec(UrlDec(MA)))
  if VERIFY(AR, SAR, SP.Public) **then**
    C1 ← GenChallenge()
    JS ← StoredJavaScript()
    JS.SigParams.Challenge ← C1
    JS.SigParams.Certificate ← IdPJsCert.Public
    JS.SigParams.Signature ← SIGN(JS.SigParams, IdPJsCert.Private)
    return RESPONSE(JS)
  else
    RE ← CreateResponse()
    RE.InResponseTo ← AR
    RE.Status ← Requester
    MRE ← Base64Enc(RE)
    return REDIRECT(SP, MRE, RS)
  end if

TEXT DESCRIBING ALGORITHM 3

Algorithm 3 Process 4

Require: U **and** P **and** Browser allows JavaScript
  SigParams ← Js.SigParams
  if VERIFY(SigParams, SigParams.Signature, SigParams.Certificate) **then**
    C1 ← SigParams.Challenge
    return POST(U, P, C1)
  else
    print ERROR
  end if

TEXT DESCRIBING ALGORITHM 4

Algorithm 4 Process 5

Require: POST is well formed
  if C1 matches challenge issued by IdP **then**
    Delegate U **and** P **to** AuthP
  else
    return RESPONSE(ERROR)
  end if
Require: C1 matches challenge issued by IdP

TEXT DESCRIBING ALGORITHM 5

Algorithm 5 Process 5.1

  USER ← GetUser(U, P)
  if USER is valid **then**
    C2 ← GenChallenge()
    NF ← GetNextNFactorChallenge(USER)
    NF.SigParam.User ← USER
    NF.SigParam.Challenge ← C2
    NF.SigParam.Certificate ← USER.Public
    NF.SigParam.Signature ← SIGN(NF.SigParam, USER.Private)
    return RESPONSE(NF)
  else
    return RESPONSE(ERROR)
  end if

TEXT DESCRIBING ALGORITHM 6

Algorithm 6 Process 6

  SigParams ← NF.SigParams
  if VERIFY(SigParams, SigParams.Signature, SigParams.Certificate) **then**
    RELATE(SigParams.User, SigParams.Challenge)
    Delegate NF **to** Browser
  else
    Delegate ERROR **to** Browser
  end if

TEXT DESCRIBING ALGORITHM 7

Algorithm 7 Process 6.1

```
SigParams ← NF.SigParams
if VERIFY(SigParams, SigParams.Signature, SigParams.Certificate) then
  AUTHENTICATE(NF)
else
  print ERROR
end if
```

TEXT DESCRIBING ALGORITHM 8

Algorithm 8 Process 6.2

```
NFR ← NFactorResult(NF)
return RESPONSE(NFR)
```

TEXT DESCRIBING ALGORITHM 9

Algorithm 9 Process 6.5

```
Require: Stored relation for (NF.SigParams.USER, NF.SigParams.Certificate)
SigParams ← NF.SigParams
if VERIFY(SigParams, SigParams.Signature, SigParams.Certificate) then
  if NFR is acceptable result of NF then
    USER ← GetUser(SigParams.USER, SigParams.Certificate)
    C2 ← GenChallenge()
    if USER.HasNextChallenge then
      NF ← GetNextNFactorChallenge(USER)
      NF.SigParams.User ← USER
      NF.SigParams.Challenge ← C2
      NF.SigParams.Certificate ← USER.Public
      NF.SigParams.Signature ← SIGN(NF.SigParams, USER.Private)
      return RESPONSE(NF)
    else
      LID ← CreateLogInData()
      ST ← OK
      return RESPONSE(ST, LID)
    end if
  else
    return RESPONSE(ERROR)
  end if
else
  return RESPONSE(ERROR)
end if
```

TEXT DESCRIBING ALGORITHM 10

Algorithm 10 Process 7

```
Require: SP.Public and LID is well-formed and stored AuthRequest for
  (LID.User, LID.Challenge)
  if ST = "OK" then
    ARC ← GetAuthRequest(LID.User, LID.Challenge)
    MA ← ARC.AR
    SAR ← ARC.SAR
    RS ← ARC.RS
    AR ← DeflateDecompress(Base64Dec(UrlDec(MA)))
    if VERIFY(AR, SAR, SP.Public) then
      A ← BuildAssertion(LID.Certificate)
      SI ← GenerateSessionIndex()
      A.InResponseTo ← AR
      A.Issuer ← IdP
      A.Audience ← SP
      A.SessionIndex ← SI
      A.Signature ← SIGN(A, IdP.Private)
      EA ← ENCRYPT(A, SP.Public)
      RE ← CreateResponse()
      RE.Assertion ← EA
      RE.InResponseTo ← AR
      RE.Status ← "Success"
      MRE ← DeflateCompress(Base64Enc(UrlEnc(RE)))
      SAS ← CreateSAMLSession(SI, SP, LID.CertificateSubject)
      return REDIRECT(SP, MRE, RS, SAS)
    else
      RE ← CreateResponse()
      RE.InResponseTo ← AR
      RE.Status ← "Requester"
      MRE ← DeflateCompress(Base64Enc(UrlEnc(RE)))
      return REDIRECT(SP, MRE, RS)
    end if
  else
    return RESPONSE(ST)
  end if
```

TEXT DESCRIBING ALGORITHM 11

Algorithm 11 Process 9

Require: POST is well.formed **and** SP.Private **and** IdP.Public
  RE ← UrlDec(Base64Dec(DeflateDecompress(MRE)))
  A ← DECRYPT(RE.Assertion, SP.Private)
  if VERIFY(A, A.Signature, IdP.Public) **then**
    AK ← GenAuthKey()
    R ← Base64Dec(UrlDec(RS))
    RES ← GetResource(R)
    return RESPONSE(RES, AK)
  else
    return RESPONSE(403, Forbidden)
  end if

Chapter 4

Modelling with F*

This chapter will introduce the language F* that can be used to model a security protocol. Despite being a formal specification language F* is also executable. F* is described as a *A Verifying Compiler for Distributed Programming*. This chapter will describe how we have used F* to build a formal specification of our protocol shown in the previous chapter.

4.1 Introducing F*

F* is a research language from Microsoft Research. F* primarily subsumes two research languages from Microsoft Research, F7[1] and Fine[2]. F* is at this time considered to be an α-release.The purpose of designing F* is to enable the construction and communication of proofs of program properties and of properties of a program's environment in a verifiable secure way. F* is a dialect of ML and compiles to .NET bytecode in type-preserving style. This means that it can interop with other .NET languages and the types defined in F* can be used by other .NET lanuages without loosing type information. Furthermore there also exists a fully abstract compiler from F* to JavaScript. This makes it possible to deploy F* programs on web pages as JavaScript meanwhile there is a formal guarantee that the program still behaves just as they would according to F* semantics. The compiling and type-checking of F* code utilizes the Z3[3] SMT solver for proving assumptions made with refinement types. F* has been formalized and verified using Coq[4].

[1] http://research.microsoft.com/en-us/projects/f7/
[2] http://research.microsoft.com/en-us/projects/fine/
[3] http://z3.codeplex.com/
[4] Coq is an interactive theorem prover written in OCaml

4.2 Syntax and semantics

F* inherits syntax and semantics from ML. F* is a functional language which means that it has features like immutability by default, polymorphic types and type inference. In Listing 4.1 we have shown the classic Hello World example in F*.

```
module HelloWorld

let _ = print "Hello world!"
```

Listing 4.1: Hello World example in F*

4.3 Refinement types

4.4 Protocol specification in F*

hello world

4.4.1 Specification of the type functionality module

```
module TypeFunc

type Authentication =
  | Facebook: id:int -> Authentication
  | SMS: generated:int -> Authentication
 | Google: id:int -> Authentication
 | OpenId: id:int -> Authentication
```

Listing 4.2: TypeFunc module

4.4.2 Specification of the SAML Protocol

```
module SamlProtocol

open Crypto
open TypeFunc

type assertiontoken = string (*Add refinements*)
type signedtoken = string (*Add refinements*)
type id = string
type endpoint = string
type uri = string


type AuthnRequest =
  | MkAuthnRequest: IssueInstant:string ->
      Destination:endpoint -> Issuer:prin ->
      message:string -> sig:dsig ->
      AuthnRequest
```

```
18
19 type LoginData =
20   | MkLoginData:  user:prin -> signature:dsig ->
21     cert:pubkey user -> challenge:nonce ->
22     site:string -> data:string ->
23     LoginData
24
25 type LoginInfo =
26   | UserLogin:  userid:string -> password:string ->
27   LoginInfo
28
29 type AuthInfo =
30   | UserAuth:   userid:string -> authmethod:Authentication ->
31   authresponse:Authentication -> AuthInfo
32
33 type Assertion =
34   | SignedAssertion: assertiontoken -> dsig -> Assertion
35   | EncryptedAssertion: cypher -> Assertion
36
37 type SamlStatus =
38   | Success: SamlStatus
39   | Requester: SamlStatus
40   | Responder: SamlStatus
41   | User: SamlStatus
42
43 type SamlMessage =
44   | SPLogin: uri -> SamlMessage
45   | Login: loginInfo:LoginInfo -> challenge:nonce ->
       SamlMessage
46   | LoginResponse: string -> SamlMessage
47   | AuthnRequestMessage: issuer:prin ->  destination:endpoint
       -> message:string -> dsig -> SamlMessage
48   | LoginRequestMessage: issuer:prin ->  destination:endpoint
       -> loginInfo:LoginInfo -> SamlMessage
49   | NfactAuthRequest: issuer:prin -> destination:endpoint ->
       authInfo:AuthInfo -> challenge:nonce -> dsig ->
       SamlMessage
50   | AuthResponseMessage: issuer:prin -> destination:endpoint ->
        Assertion -> SamlMessage
51   | LoginResponseMessage: issuer:prin -> destination:endpoint
       -> auth:Authentication -> challenge:nonce -> dsig ->
       SamlMessage
52   | UserAuthenticated: status:string -> logindata:LoginData ->
       authnReq:AuthnRequest -> SamlMessage
53   | UserCredRequest: javascript:string -> challenge:nonce ->
       dsig -> SamlMessage
54   | UserAuthRequest: authmethod:Authentication -> challenge:
       nonce -> dsig -> SamlMessage
55   | UserAuthResponse: authInfo:AuthInfo -> challenge:nonce ->
       dsig -> SamlMessage
56   | LoginSuccess: status:string -> issuer:prin -> destination:
       endpoint -> SamlMessage
57   | Failed: SamlStatus -> SamlMessage
58   | DisplayError: int -> SamlMessage
59
60
61 val SendSaml: prin -> SamlMessage -> unit
```

```
val ReceiveSaml: prin -> SamlMessage

val CreateAuthnRequestMessage: issuer:prin -> destination:prin
    -> string
val CreateLoginRequestMessage: issuer:prin -> destination:prin
    -> string
val CreateNfactAuthReqMessage: issuer:prin -> destination:prin
    -> string
val IssueAssertion: issuer:prin -> subject:prin -> audience:
    prin -> inresto:AuthnRequest -> assertiontoken
val MakeAssertion: issuer:prin -> subject:prin -> audience:prin
     -> assertiontoken
val AddSignatureToAssertion: assertiontoken -> dsig ->
    signedtoken
val EncryptAssertion: receiver:prin -> pubkey receiver ->
    signedtoken -> Assertion
val DecryptAssertion: receiver:prin -> privkey receiver ->
    Assertion -> (signedtoken * dsig)
```

Listing 4.3: SAML Protocol module

4.4.3 Specification of cryptographic elements

```
module Crypto

open Protocol
open TypeFunc

type prin = string
type pubkey :: prin => *
type privkey :: prin => *
type dsig
type nonce = string
type cypher

(*Verification*)
type Log :: prin => string => E

type LogAuth :: prin => Authentication => E

val Keygen: p:prin
   -> (pubkey p * privkey p)

val Sign: p:prin
 -> privkey p
 -> msg:string{Log p msg}
 -> dsig

val SignAuth: p:prin
 -> privkey p
 -> msg:Authentication{LogAuth p msg}
 -> dsig

val VerifySignature: p:prin
 -> pubkey p
```

```
  -> msg:string
  -> dsig
  -> b:bool{b=true ==> Log p msg}

val VerifySignatureAuth: p:prin
  -> pubkey p
  -> msg:Authentication
  -> dsig
  -> b:bool{b=true ==> LogAuth p msg}

val Encrypt: p:prin
  -> pubkey p
  -> string
  -> cypher

val Decrypt: p:prin
  -> privkey p
  -> cypher
  -> string

val GenerateNonce: prin -> nonce (*Add refinement to ensure
    unqueness*)
```

Listing 4.4: Crypto module

4.4.4 Specification of certificate store module

```
module CertStore

open Crypto

val GetPublicKey: p:prin -> pubkey p
val GetJSPublicKey: p:prin -> pubkey p
(*Prin needs to be updated to include credentials*)
val GetPrivateKey: p:prin -> privkey p
val GetJSPrivateKey: p:prin -> privkey p
```

Listing 4.5: CertStore module

4.4.5 Specification of the messaging protocol

```
module Messaging

open Crypto
open TypeFunc

type Status =
  | Successful: Status
  | Unsuccessful: Status

type Message =
  | NewSiteRequest: idp:prin -> Message
  | ChallengeResponse: challenge:nonce -> Message
```

```
  | IdpChalResponse: challenge:nonce -> Message
  | AcceptedIdp: idp:prin -> pubkey:pubkey idp -> authp:prin ->
      authpubkey:pubkey authp -> signedjavascript:string ->
      Message
  | RequestForLogin: userid:string -> password:string -> Message
  | ReqLoginResponse: challenge:nonce -> Message
  | CreateLogin: generatedpassword:string -> challenge:nonce ->
      Message
  | ChangeUserId: userid:string -> newUserId:string -> password:
      string -> Message
  | ChangePassword: userid:string -> password:string ->
      newPassword:string -> Message
  | UserRevokeIdp: userid:string -> password:string -> idp:
      string -> Message
  | AddNfactor: userid:string -> password:string -> nfact:
      Authentication -> Message
  | RemoveNfactor: userid:string -> password:string -> nfact:
      Authentication -> Message
  | StatusMessage: Status -> Message


val SendMessage: prin -> Message -> unit
val ReceiveMessage: prin -> Message
```

Listing 4.6: Messaging module

4.4.6 Specification of the Service Provider

```
module Serviceprovider

open SamlProtocol
open Crypto

val serviceprovider:  me:prin -> client:prin -> idp:prin ->
    unit

let rec serviceprovider me client idp =
 let req = ReceiveSaml client in
 match req with
  | SPLogin (url) ->
    let authnReq = CreateAuthnRequestMessage me idp in
    assume(Log me authnReq);
    let myprivk = CertStore.GetPrivateKey me in
    let sigSP = Sign me myprivk authnReq in
    let resp = AuthnRequestMessage me idp authnReq sigSP in
    SendSaml client resp;
    serviceprovider me client idp
  | AuthResponseMessage (issuer, destination, encassertion) ->
    let myprivk = CertStore.GetPrivateKey me in
    let assertion = DecryptAssertion me myprivk encassertion in
    match assertion with
    | SignedAssertion (token,sigIDP) ->
      let pubkissuer = CertStore.GetPublicKey idp in
      if VerifySignature idp pubkissuer token sigIDP
      then
```

```
27          (assert(Log idp token);
28          let resp = LoginResponse "You are now logged in" in
29          SendSaml client resp)
30        else SendSaml client (DisplayError 403);
31        serviceprovider me client idp
32
33    | _ -> SendSaml client (DisplayError 400);
34          serviceprovider me client idp
```

Listing 4.7: ServiceProvider Module

4.4.7 Specification of the Identity Provider

```
1  module Identityprovider
2
3  open SamlProtocol
4  open Crypto
5  open TypeFunc
6  open Messaging
7
8  val userloggedin: user:prin -> bool
9  val getjavascript: string
10 val decodeMessage: message:string -> AuthnRequest
11 val getauthnrequest: user:prin -> challenge:nonce ->
       AuthnRequest
12 val getuserchallenge: user:prin -> nonce
13 val relatechallenge: user:prin -> challenge:nonce -> unit
14 val verifychallenge: user:prin -> challenge:nonce -> bool
15 val relate: user:prin -> challenge:nonce -> authnReq:
       AuthnRequest -> unit
16
17 val handleUserAuthenticated: me:prin -> user:prin -> authnReq:
       AuthnRequest -> unit
18
19 let handleUserAuthenticated me user authnReq =
20  match authnReq with
21  | MkAuthnRequest(issueinst,dest,sp,msg,sigSP) ->
22   let pubksp = CertStore.GetPublicKey sp in
23    if (VerifySignature sp pubksp msg sigSP) then
24   (assert (Log sp msg);
25   let assertion = IssueAssertion me user sp authnReq in
26   let myprivk = CertStore.GetPrivateKey me in
27   assume(Log me assertion);
28   let sigAs = Sign me myprivk assertion in
29   let signAssertion = AddSignatureToAssertion assertion sigAs
         in
30   let encryptedAssertion = EncryptAssertion sp pubksp
         signAssertion in
31   let resp = AuthResponseMessage me sp encryptedAssertion in
32   SendSaml user resp)
33       else
34  SendSaml user (Failed Requester)
35
36 val handleauthresponse: me:prin -> user:prin -> authp:prin ->
       unit
```

```
37
38 let handleauthresponse me user authp =
39  let resp = ReceiveSaml authp in
40  match resp with
41  | LoginResponseMessage(issuer, destination, authmethod,
       challenge, sigUser) ->
42   let pubkeyuser = CertStore.GetPublicKey user in
43   if VerifySignatureAuth user pubkeyuser authmethod sigUser
       then
44    (assert (LogAuth user authmethod);
45    relatechallenge user challenge;
46    let resp = UserAuthRequest authmethod challenge sigUser in
47    SendSaml user resp)
48   else
49    SendSaml user (DisplayError 403)
50  | LoginSuccess(status, issuer, destination) ->
51   if (status = "OK") then
52    let challenge = getuserchallenge user in
53    let authnReq = getauthnrequest user challenge in
54    handleUserAuthenticated me user authnReq
55   else
56    SendSaml user (DisplayError 403)
57  | _ -> SendSaml user (DisplayError 400)
58
59 val identityprovider: me:prin -> user:prin -> authp:prin ->
     unit
60
61 let rec identityprovider me user authp =
62  let request = ReceiveSaml user in
63  match request with
64  | AuthnRequestMessage(issuer, destination, message, sigSP) ->
65   let pubkissuer = CertStore.GetPublicKey issuer in
66  if (VerifySignature issuer pubkissuer message sigSP) then
67   (assert (Log issuer message);
68   let authnReq = decodeMessage message in
69   let myprivk = CertStore.GetPrivateKey me in
70   if not (userloggedin user) then
71    let challenge = GenerateNonce me in
72    relate user challenge authnReq;
73    relatechallenge user challenge;
74    let js = getjavascript in
75    assume(Log me js);
76    let myprivk = CertStore.GetJSPrivateKey me in
77    let sigIdP = Sign me myprivk js in
78    let resp = UserCredRequest js challenge sigIdP in
79    SendSaml user resp;
80    identityprovider me user authp
81   else
82    let assertion = IssueAssertion me user issuer authnReq in
83    assume(Log me assertion);
84    let myprivk = CertStore.GetPrivateKey me in
85    let pubksp = CertStore.GetPublicKey issuer in
86    let sigAs = Sign me myprivk assertion in
87    let signAssertion = AddSignatureToAssertion assertion sigAs
        in
88    let encryptedAssertion = EncryptAssertion issuer pubksp
        signAssertion in
```

```
89      let resp = AuthResponseMessage me issuer encryptedAssertion
            in
90      SendSaml user resp)
91    else
92     SendSaml user (Failed Requester);
93     identityprovider me user authp
94    | Login (loginInfo, challenge) ->
95     if (verifychallenge user challenge) then
96      let req = LoginRequestMessage me authp loginInfo in
97      SendSaml authp req;
98      handleauthresponse me user authp;
99      identityprovider me user authp
100    else
101     SendSaml user (DisplayError 400);
102     identityprovider me user authp
103   | UserAuthResponse(authInfo, challenge, sigAuth) ->
104    let req = NfactAuthRequest me authp authInfo challenge
           sigAuth in
105    SendSaml authp req;
106    handleauthresponse me user authp;
107    identityprovider me user authp
108   | _ -> SendSaml user (DisplayError 400);
109    identityprovider me user authp
110
111 val savejavascript: javascript:string -> unit
112 val savepublickey: owner:prin -> publickey:pubkey owner -> unit
113
114 val connectwithauthp: me:prin -> authp:prin -> unit
115
116 let connectwithauthp me authp =
117  let req = NewSiteRequest me in
118  let _ = SendMessage authp req in
119  let resp = ReceiveMessage authp in
120  match resp with
121  | ChallengeResponse(challenge) ->
122   let _ = SendMessage authp (IdpChalResponse challenge) in
123   let res = ReceiveMessage authp in
124   match res with
125   | AcceptedIdp(idp, idppubkey, authp, authppubkey, signedjs)
          ->
126    (*Established secure connection*)
127    savejavascript signedjs;
128    savepublickey authp authppubkey;
129    savepublickey idp idppubkey
130   | _ -> res; ()
131  | _ -> resp; ()
```

Listing 4.8: Identity Provider module

4.4.8 Specification of the Database Handler

```
1 module Database
2
3 open Crypto
4 open CertStore
```

```
open TypeFunc

(*Identity provider functionality*)
val whitelist: idp:prin -> unit
val blacklist: idp:prin -> unit
val addidp: idp:prin -> bool
val whitelisted: idp:prin -> bool

(*User functionality*)
val createuser: user:prin -> userid:string -> password:string
    -> bool
val usercreation: user:prin -> generatedPassword:string -> bool
val changeuserid: user:string -> newuser:string -> password:
    string -> bool
val changeuserpassword: user:string -> password:string ->
    newpassword:string -> bool

val addnfactor: user:string -> password:string -> nfactor:
    Authentication -> bool
val removenfactor: user:string -> password:string -> nfactor:
    Authentication -> bool

val getnfactor: user:string -> Authentication
val checknfactor: user:string -> Authentication -> bool
val allnfactauthed: user:string -> bool
val resetnfact: user:string -> unit

val checklogin: user:string -> password:string -> bool

val revokeidp: user:string -> password:string -> idp:string ->
    bool

val revokedidp: user:string -> idp:prin -> bool
```

Listing 4.9: Database module

4.4.9 Specification of the Authentication Provider

```
module Authenticationprovider

open SamlProtocol
open Crypto
open Database
open TypeFunc
open Messaging

val relatechallenge: user:prin -> challenge:nonce -> unit

val verifychallenge: user:prin -> challenge:nonce -> bool

val nfactauth: me:prin -> idp:prin -> user:prin -> userid:
    string -> unit

let nfactauth me idp user userid =
 if (allnfactauthed userid) then
```

```
17    resetnfact userid;
18    let status = "OK" in
19    let resp = LoginSuccess status me idp in
20    SendSaml idp resp
21   else
22    let challenge = GenerateNonce me in
23    let authmethod = getnfactor userid in
24    assume(LogAuth user authmethod);
25    let userprivkey = CertStore.GetPrivateKey user in
26    let sigUser = SignAuth user userprivkey authmethod in
27    let resp = LoginResponseMessage me idp authmethod challenge
          sigUser in
28    SendSaml idp resp
29
30  val authenticationprovider: me:prin -> idp:prin -> user:prin ->
        unit
31
32  let rec authenticationprovider me idp user =
33   let req = ReceiveSaml idp in
34   match req with
35   | LoginRequestMessage (issuer, destination, loginInfo) ->
36    if (whitelisted idp) then
37     match loginInfo with
38     | UserLogin(userid, password) ->
39      if not (revokedidp userid idp) && (checklogin userid
            password) then
40       let challenge = GenerateNonce me in
41       let authmethod = getnfactor userid in
42       assume(LogAuth user authmethod);
43       let userprivkey = CertStore.GetPrivateKey user in
44       let sigUser = SignAuth user userprivkey authmethod in
45       relatechallenge user challenge;
46       let resp = LoginResponseMessage me idp authmethod
             challenge sigUser in
47       SendSaml idp resp;
48       authenticationprovider me idp user
49      else
50       SendSaml idp (Failed User);
51       authenticationprovider me idp user
52     | _ -> SendSaml idp (Failed Requester);
53      authenticationprovider me idp user
54    else
55     SendSaml idp (Failed Requester);
56     authenticationprovider me idp user
57   | NfactAuthRequest(issuer, destination, authInfo, challenge,
        sigAuth) ->
58    if (whitelisted idp) then
59     match authInfo with
60     | UserAuth(userid, authmethod, authresponse) ->
61      let userpubkey = CertStore.GetPublicKey user in
62      if VerifySignatureAuth user userpubkey authmethod sigAuth
            && verifychallenge user challenge then
63       if not (revokedidp userid idp) && (checknfactor userid
             authresponse) then
64        nfactauth me idp user userid;
65        authenticationprovider me idp user
66       else
```

```
67        SendSaml idp (Failed User);
68        authenticationprovider me idp user
69      else
70       SendSaml idp (Failed User);
71       authenticationprovider me idp user
72     | _ -> SendSaml idp (Failed Requester);
73      authenticationprovider me idp user
74    else
75     SendSaml idp (Failed Requester);
76     authenticationprovider me idp user
77   | _ -> SendSaml idp (Failed Requester);
78    authenticationprovider me idp user
79
80
81 val usercommunication: me:prin -> user:prin -> unit
82
83 let rec usercommunication me user =
84  let req = ReceiveMessage user in
85  match req with
86  | RequestForLogin(userid, password) ->
87   if createuser user userid password then
88    let challenge = GenerateNonce me in
89    relatechallenge user challenge;
90    SendMessage user (ReqLoginResponse challenge);
91    usercommunication me user
92   else
93    SendMessage user (StatusMessage Unsuccessful);
94    usercommunication me user
95  | CreateLogin(generatedpassword, challenge) ->
96   if (verifychallenge user challenge) && (usercreation user
       generatedpassword) then
97    let challenge = GenerateNonce me in
98    relatechallenge user challenge;
99    SendMessage user (StatusMessage Successful);
100   usercommunication me user
101  else
102   SendMessage user (StatusMessage Unsuccessful);
103   usercommunication me user
104 | ChangePassword(userid, password, newPassword) ->
105  if changeuserpassword userid password newPassword then
106   SendMessage user (StatusMessage Successful);
107   usercommunication me user
108  else
109   SendMessage user (StatusMessage Unsuccessful);
110   usercommunication me user
111 | ChangeUserId(userid, newUserId, password) ->
112  if changeuserid userid newUserId password then
113   SendMessage user (StatusMessage Successful);
114   usercommunication me user
115  else
116   SendMessage user (StatusMessage Unsuccessful);
117   usercommunication me user
118 | UserRevokeIdp(userid, password, idp) ->
119  if revokeidp userid password idp then
120   SendMessage user (StatusMessage Successful);
121   usercommunication me user
122  else
```

```
    SendMessage user (StatusMessage Unsuccessful);
    usercommunication me user
  | AddNfactor(userid, password, nfact) ->
   if addnfactor userid password nfact then
    SendMessage user (StatusMessage Successful);
    usercommunication me user
   else
    SendMessage user (StatusMessage Unsuccessful);
    usercommunication me user
  | RemoveNfactor(userid, password, nfact) ->
   if removenfactor userid password nfact then
    SendMessage user (StatusMessage Successful);
    usercommunication me user
   else
    SendMessage user (StatusMessage Unsuccessful);
    usercommunication me user
  | _ -> SendMessage user (StatusMessage Unsuccessful);
   usercommunication me user

val getsignedjavascript: string

val establishidp: me:prin -> idp:prin -> unit

let rec establishidp me idp =
 let req = ReceiveMessage idp in
 match req with
 | NewSiteRequest(idp) ->
  let challenge = GenerateNonce me in
  relatechallenge idp challenge;
  SendMessage idp (ChallengeResponse challenge);
  establishidp me idp
 | IdpChalResponse(challenge) ->
  if (verifychallenge idp challenge) && (addidp idp) then
   let idppubkey = CertStore.GetPublicKey idp in
   let mypubk = CertStore.GetPublicKey me in
   let signedjs = getsignedjavascript in
   let resp = AcceptedIdp idp idppubkey me mypubk signedjs in
   SendMessage idp resp;
   establishidp me idp
  else
   SendMessage idp (StatusMessage Unsuccessful);
   establishidp me idp
 | _ -> SendMessage idp (StatusMessage Unsuccessful);
  establishidp me idp
```

Listing 4.10: Authentication Provider module

4.4.10 Specification of the Browser

```
module Browser

open SamlProtocol
open Crypto
open CertStore
open TypeFunc
```

```
7  open Messaging
8
9  val loginWithFb: Authentication
10 val loginWithGoogle: Authentication
11 val loginWithSMS: Authentication
12 val loginWithOpenId: Authentication
13 val userid: string
14 val password: string
15 val fakeprint: str:string -> unit
16 val newUserId: string
17 val newPassword: string
18 val idpToRevoke:string
19 val nfactToRemove: Authentication
20 val nfactToAdd: Authentication
21 (*Handle the two-factor authentication*)
22
23 val handleAuthMethod: auth:Authentication -> Authentication
24
25 let handleAuthMethod auth =
26  match auth with
27  | Facebook(fbid) -> loginWithFb
28  | Google(gid) -> loginWithGoogle
29  | SMS(gen) -> loginWithSMS
30  | OpenId(oid) -> loginWithOpenId
31
32 val loop: user:string -> idp:prin -> sp:prin -> unit
33
34 let rec loop userid idp sp =
35  let loginresp = ReceiveSaml idp in
36   match loginresp with
37   | UserAuthRequest(authmethod, challenge, sigAuth) ->
38    let authresponse = handleAuthMethod authmethod in
39    let authInfo = UserAuth userid authmethod authresponse in
40    let authresp = UserAuthResponse authInfo challenge sigAuth
         in
41    SendSaml idp authresp;
42    loop userid idp sp
43   | AuthResponseMessage(idenp, dest, assertion) ->
44    SendSaml sp loginresp
45   | _ -> loginresp; ()
46
47 val browser: sp:prin -> res:uri -> unit
48
49 let browser sp resource =
50  let req = SPLogin resource in
51  let _ = SendSaml sp req in
52   let res = ReceiveSaml sp in
53   match res with
54   | AuthnRequestMessage(sp, idp, message, sigSP) ->
55    let _ = SendSaml idp res in
56    let idpResp = ReceiveSaml idp in
57    match idpResp with
58    | UserCredRequest(javascript, challenge, sigIdP) ->
59     let pubkissuer = CertStore.GetJSPublicKey idp in
60     if VerifySignature idp pubkissuer javascript sigIdP then
61      (assert (Log idp javascript);
62      let loginInfo = UserLogin userid password in
```

```
63        let loginreq = Login loginInfo challenge in
64        SendSaml idp loginreq;
65        loop userid idp sp;
66        let spResp = ReceiveSaml sp in
67        match spResp with
68        | LoginResponse(str) ->
69          fakeprint str
70        | _ -> spResp; ())
71       else
72        fakeprint "Validation Error"
73     | _ -> idpResp; ()
74    | _ -> res; ()
75
76  val retrieveGeneratedPassword: string
77
78  val createUser: authp:prin -> unit
79
80  let createUser authp =
81   let name = userid in
82   let pw = password in
83   let req = RequestForLogin name pw in
84   let _ = SendMessage authp req in
85    let resp = ReceiveMessage authp in
86    match resp with
87    | ReqLoginResponse(challenge) ->
88     let reqlresp = CreateLogin retrieveGeneratedPassword
           challenge in
89     let _ = SendMessage authp reqlresp in
90     let createloginresp = ReceiveMessage authp in
91     match createloginresp with
92     | StatusMessage(status) ->
93      match status with
94      | Successful -> fakeprint "You have created an account"
95      | Unsuccessful -> fakeprint "Something went wrong. No
           account has been created"
96     | _ -> createloginresp; ()
97    | _ -> resp; ()
98
99  val changeUserPassword: authp:prin -> unit
100
101 let changeUserPassword authp =
102  let name = userid in
103  let pw = password in
104  let newpw = newPassword in
105  let req = ChangePassword name pw newpw in
106  let _ = SendMessage authp req in
107   let resp = ReceiveMessage authp in
108   match resp with
109    | StatusMessage(status) ->
110     match status with
111     | Successful -> fakeprint "You have change your password"
112     | Unsuccessful -> fakeprint "Something went wrong. You have
           not changed your password"
113    | _ -> resp; ()
114
115 val changeUserUserId: authp:prin -> unit
116
```

```
117 let changeUserUserId authp =
118  let name = userid in
119  let pw = password in
120  let newid = newUserId in
121  let req = ChangeUserId name newid pw in
122  let _ = SendMessage authp req in
123  let resp = ReceiveMessage authp in
124   match resp with
125    | StatusMessage(status) ->
126      match status with
127      | Successful -> fakeprint "You have change your userid"
128      | Unsuccessful -> fakeprint "Something went wrong. You have
             not changed your userid"
129    | _ -> resp; ()
130
131 val identityrevoke: authp:prin -> unit
132
133 let identityrevoke authp =
134  let name = userid in
135  let pw = password in
136  let idp = idpToRevoke in
137  let req = UserRevokeIdp name pw idp in
138  let _ = SendMessage authp req in
139  let resp = ReceiveMessage authp in
140   match resp with
141    | StatusMessage(status) ->
142      match status with
143      | Successful -> fakeprint "You have revoked the
           identityprovider"
144      | Unsuccessful -> fakeprint "Something went wrong. You have
             not revoked the identityprovider"
145    | _ -> resp; ()
146
147 val addNfact: authp:prin -> unit
148
149 let addNfact authp =
150  let name = userid in
151  let pw = password in
152  let nfact = nfactToAdd in
153  let req = AddNfactor name pw nfact in
154  let _ = SendMessage authp req in
155  let resp = ReceiveMessage authp in
156   match resp with
157    | StatusMessage(status) ->
158      match status with
159      | Successful -> fakeprint "You have added this
           authentication method"
160      | Unsuccessful -> fakeprint "Something went wrong. You have
             not added this authentication method"
161    | _ -> resp; ()
162
163 val removeNfact: authp:prin -> unit
164
165 let removeNfact authp =
166  let name = userid in
167  let pw = password in
168  let nfact = nfactToRemove in
```

```
169   let req = RemoveNfactor name pw nfact in
170   let _ = SendMessage authp req in
171   let resp = ReceiveMessage authp in
172    match resp with
173    | StatusMessage(status) ->
174      match status with
175      | Successful -> fakeprint "You have removed this
           authentication method"
176      | Unsuccessful -> fakeprint "Something went wrong. You have
           not removed this authentication method"
177    | _ -> resp; ()
```

Listing 4.11: Browser module

4.5 Introducing adversaries

```
1  module Main
2
3  open SamlProtocol
4  open Crypto
5  open Serviceprovider
6  open Identityprovider
7  open Authenticationprovider
8
9  val Fork: list (unit -> unit) -> unit
10
11 let main attacker =
12  Fork [ attacker;
13    (fun () -> serviceprovider "serviceprovider.org" "browser" "
        identityprovider.org");
14    (fun () -> identityprovider "identityprovider.org" "browser"
        "authenticationprovider.org");
15    (fun () -> authenticationprovider "authenticationprovider.org
        " "identityprovider.org" "browser")]
```

Listing 4.12: Main module for introducing adversaries

Chapter 5

Evaluation

Bibliography

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