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D. Harkins
Aruba Networks
G. Zorn
Network Zen

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Extensible Authentication Protocol (EAP) Authentication Using Only a Password

Abstract

This memo describes an Extensible Authentication Protocol (EAP) method, EAP-pwd, which uses a shared password for authentication. The password may be a low-entropy one and may be drawn from some set of possible passwords, like a dictionary, which is available to an attacker. The underlying key exchange is resistant to active attack, passive attack, and dictionary attack.

Status of This Memo

This document is not an Internet Standards Track specification; it is published for informational purposes.

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1. Introduction

1.1. Background

The predominant access method for the Internet today is that of a human using a username and password to authenticate to a computer enforcing access control. Proof of knowledge of the password authenticates the human and computer.

Typically these passwords are not stored on a user's computer for security reasons and must be entered each time the human desires network access. Therefore, the passwords must be ones that can be repeatedly entered by a human with a low probability of error. They will likely not possess high-entropy, and it may be assumed that an adversary with access to a dictionary will have the ability to guess a user's password. It is therefore desirable to have a robust authentication method that is secure even when used with a weak password in the presence of a strong adversary.

EAP-pwd is an EAP method that addresses the problem of password-based authenticated key exchange -- using a possibly weak password for authentication to derive an authenticated and cryptographically strong shared secret. This problem was first described by Bellovin and Merritt in [BM92] and [BM93]. There have been a number of subsequent suggestions ([JAB96], [LUC97], [BMP00], and others) for password-based authenticated key exchanges.

1.2. Keyword Definitions

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC 2119 [RFC2119].

1.3. Requirements

Any protocol that claims to solve the problem of password-authenticated key exchange must be resistant to active, passive, and dictionary attack and have the quality of forward secrecy. These characteristics are discussed further in the following sections.

1.3.1. Resistance to Passive Attack

A passive, or benign, attacker is one that merely relays messages back and forth between the peer and server, faithfully, and without modification. The contents of the messages are available for inspection, but that is all. To achieve resistance to passive attack, such an attacker must not be able to obtain any information about the password or anything about the resulting shared secret from

watching repeated runs of the protocol. Even if a passive attacker is able to learn the password, she will not be able to determine any information about the resulting secret shared by the peer and server.

1.3.2. Resistance to Active Attack

An active attacker is able to modify, add, delete, and replay messages sent between protocol participants. For this protocol to be resistant to active attack, the attacker must not be able to obtain any information about the password or the shared secret by using any of its capabilities. In addition, the attacker must not be able to fool a protocol participant into thinking that the protocol completed successfully.

It is always possible for an active attacker to deny delivery of a message critical in completing the exchange. This is no different than dropping all messages and is not an attack against the protocol.

1.3.3. Resistance to Dictionary Attack

For this protocol to be resistant to dictionary attack, any advantage an adversary can gain must be directly related to the number of interactions she makes with an honest protocol participant and not through computation. The adversary will not be able to obtain any information about the password except whether a single guess from a single protocol run is correct or incorrect.

1.3.4. Forward Secrecy

Compromise of the password must not provide any information about the secrets generated by earlier runs of the protocol.

2. Specification of EAP-pwd

2.1. Notation

The following notation is used in this memo:

peer-ID
: The peer's identity, the peer NAI [RFC4282].

server-ID
: A string that identifies the server to the peer.

password
: The password shared between the peer and server.

y = H(x)
The binary string x is given to a function H, which produces a fixed-length output y.

a | b
The concatenation of string a with string b.

[a]b
A string consisting of the single bit "a" repeated "b" times.

x mod y
The remainder of division of x by y. The result will be between 0 and y.

g^x mod p
The multiplication of the value "g" with itself "x" times, modulo the value "p".

inv(Q)
The inverse of an element, Q, from a finite field.

len(x)
The length in bits of the string x.

chop(x, y)
The reduction of string x, being at least y bits in length, to y bits.

PRF(x,y)
A pseudo-random function that takes a key, x, and variable-length data, y, and produces a fixed-length output that cannot be distinguished (with a significant advantage) from a random source.

LSB(x)
Returns the least-significant bit of the bitstring "x".

Ciphersuite
An encoding of a group to use with EAP-pwd, the definition of function H, and a PRF, in that order.

MK
The Master Key is generated by EAP-pwd. This is a high-entropy secret whose length depends on the random function used.

MSK
: The Master Session Key exported by EAP-pwd. This is a high-entropy secret 512 bits in length.

EMSK
: The Extended Master Session Key exported by EAP-pwd. This is a high-entropy secret 512 bits in length.

2.2. Discrete Logarithm Cryptography

This protocol uses discrete logarithm cryptography to achieve authentication and key agreement (see [SP800-56A]). Each party to the exchange derives ephemeral keys with respect to a particular set of domain parameters (referred to here as a "group"). A group can be based on Finite Field Cryptography (FFC) or Elliptic Curve Cryptography (ECC).

2.2.1. Finite Field Cryptography

Domain parameters for the FFC groups used by EAP-pwd include:

- A prime, p, determining a prime field GF(p), the integers modulo p. The FFC group will be a subgroup of GF(p)*, the multiplicative group of non-zero elements in GF(p). The group operation for FFC groups is multiplication modulo p.

- An element, G, in GF(p)* which serves as a generator for the FFC group. G is chosen such that its multiplicative order is a sufficiently large prime divisor of ((p-1)/2).

- A prime, r, which is the multiplicative order of G, and thus also the size of the cryptographic subgroup of GF(p)* that is generated by G.

An integer scalar, x, acts on an FFC group element, Y, via exponentiation modulo p -- Y^x mod p.

The inverse function for an FFC group is defined such that the product of an element and its inverse modulo the group prime equals one (1). In other words,

```
(q * inv(q)) mod p = 1
```

EAP-pwd uses an IANA registry for the definition of groups. Some FFC groups in this registry are based on safe primes and the order is not included in the domain parameters. In this case only, the order, r, MUST be computed as the prime minus one divided by two -- (p-1)/2. If the definition of the group includes an order in its domain

parameters, that value MUST be used in this exchange when an order is called for. If an FFC group definition does not have an order in its domain parameters and it is not based on a safe prime, it MUST NOT be used with EAP-pwd.

2.2.2. Elliptic Curve Cryptography

Domain parameters for the ECC groups used by EAP-pwd include:

- A prime, p, determining a prime field GF(p). The cryptographic group will be a subgroup of the full elliptic curve group that consists of points on an elliptic curve -- elements from GF(p) that satisfy the curve's equation -- together with the "point at infinity" that serves as the identity element. The group operation for ECC groups is addition of points on the elliptic curve.

- Elements a and b from GF(p) that define the curve's equation. The point (x, y) in GF(p) x GF(p) is on the elliptic curve if and only if (y^2 - x^3 - a*x - b) mod p equals zero (0).

- A point, G, on the elliptic curve, which serves as a generator for the ECC group. G is chosen such that its order, with respect to elliptic curve addition, is a sufficiently large prime.

- A prime, r, which is the order of G, and thus is also the size of the cryptographic subgroup that is generated by G.

- A co-factor, f, defined by the requirement that the size of the full elliptic curve group (including the "point at infinity") is the product of f and r.

An integer scalar, x, acts on an ECC group element, Y, via repetitive addition (Y is added to itself x times), also called point multiplication -- x * Y.

The inverse function for an ECC group is defined such that the sum of an element and its inverse is the "point at infinity" (the identity for elliptic curve point addition). In other words,

```
Q + inv(Q) = "O"
```

Only ECC groups over GF(p) can be used by EAP-pwd. ECC groups over GF(2^m) SHALL NOT be used by EAP-pwd. While such groups exist in the IANA registry used by EAP-pwd, their use in EAP-pwd is not defined. In addition, ECC groups with a co-factor greater than one (1) SHALL NOT be used by EAP-pwd. At the time of publication, no such groups existed in the IANA registry used by EAP-pwd.

2.3. Assumptions

In order to see how the protocol addresses the requirements above (see Section 1.3), it is necessary to state some assumptions under which the protocol can be evaluated. They are:

1. Function H maps a binary string of indeterminate length onto a fixed binary string that is x bits in length.

   H: {0,1}^* --> {0,1}^x

2. Function H is a "random oracle" (see [RANDOR]). Given knowledge of the input to H, an adversary is unable to distinguish the output of H from a random data source.

3. Function H is a one-way function. Given the output of H, it is computationally infeasible for an adversary to determine the input.

4. For any given input to function H, each of the 2^x possible outputs are equally probable.

5. The discrete logarithm problem for the chosen group is hard. That is, given g, p, and y = g^x mod p, it is computationally infeasible to determine x. Similarly, for an ECC group given the curve definition, a generator G, and Y = x * G, it is computationally infeasible to determine x.

6. There exists a pool of passwords from which the password shared by the peer and server is drawn. This pool can consist of words from a dictionary, for example. Each password in this pool has an equal probability of being the shared password. All potential attackers have access to this pool of passwords.

2.4. Instantiating the Random Function

The protocol described in this memo uses a random function, H. As noted in Section 2.3, this is a "random oracle" as defined in [RANDOR]. At first glance, one may view this as a hash function. As noted in [RANDOR], though, hash functions are too structured to be used directly as a random oracle. But they can be used to instantiate the random oracle.

The random function, H, in this memo is instantiated by HMAC-SHA256 (see [RFC4634]) with a key whose length is 32 octets and whose value is zero. In other words,

H(x) = HMAC-SHA-256([0]32, x)

2.5. Key Derivation Function

The keys output by this protocol, MSK and EMSK, are each 512 bits in length. The shared secret that results from the successful termination of this protocol is only 256 bits. Therefore, it is necessary to stretch the shared secret using a key derivation function (KDF).

The KDF used in this protocol has a counter-mode with feedback construction using a generic pseudo-random function (PRF), according to [SP800-108]. The specific value of the PRF is specified along with the random function and group when the server sends the first EAP-pwd packet to the peer.

The KDF takes a key to stretch, a label to bind into the key, and an indication of the desired length of the output in bits. It uses two internal variables, i and L, each of which is 16 bits in length and is represented in network order. Algorithmically, it is:

```
KDF(key, label, length) {
  i = 1
  L = length
  K(1) = PRF(key, i | label | L)
  res = K(1)
  while (len(res) < length)
  do
    i = i + 1
    K(i) = PRF(key, K(i-1) | i | label | L)
    res = res | K(i)
  done
  return chop(res, length)
}
```

Figure 1: Key Derivation Function

2.6. Random Numbers

The security of EAP-pwd relies upon each side, the peer and server, producing quality secret random numbers. A poor random number chosen by either side in a single exchange can compromise the shared secret from that exchange and open up the possibility of dictionary attack.

Producing quality random numbers without specialized hardware entails using a cryptographic mixing function (like a strong hash function) to distill entropy from multiple, uncorrelated sources of information and events. A very good discussion of this can be found in [RFC4086].

2.7. Representation and Processing of Input Strings

2.7.1. Identity Strings

The strings representing the server identity and peer identity MUST follow the requirements of [RFC4282] for Network Access Identifiers. This ensures a canonical representation of identities by both ends of the conversation prior to their use in EAP-pwd.

2.7.2. Passwords

EAP-pwd requires passwords be input as binary strings. For the protocol to successfully terminate, each side must produce identical binary strings from the password. This imposes processing requirements on a password prior to its use.

Three techniques for password pre-processing exist for EAP-pwd:

- None: The input password string SHALL be treated as an ASCII string or a hexadecimal string with no treatment or normalization performed. The output SHALL be the binary representation of the input string.

- RFC 2759: The input password string SHALL be processed to produce the output PasswordHashHash, as defined in [RFC2759], including any approved errata to [RFC2759]. This technique is useful when the server does not have access to the plaintext password.

- SASLprep: The input password string is processed according to the rules of the [RFC4013] profile of [RFC3454]. A password SHALL be considered a "stored string" per [RFC3454], and unassigned code points are therefore prohibited. The output SHALL be the binary representation of the processed UTF-8 character string. Prohibited output and unassigned codepoints encountered in SASLprep pre-processing SHALL cause a failure of pre-processing, and the output SHALL NOT be used with EAP-pwd.

Changing a password is out of scope of EAP-pwd, but due to the ambiguities in the way internationalized character strings are handled, 1) it SHOULD be done using SASLprep to ensure a canonical representation of the new password is stored on the server, and 2) subsequent invocations of EAP-pwd SHOULD use SASLprep to ensure that the client generates an identical binary string from the input password.

2.8. Protocol

2.8.1. Overview

EAP is a two-party protocol spoken between an EAP peer and an authenticator. For scaling purposes, the functionality of the authenticator that speaks EAP is frequently broken out into a stand-alone EAP server. In this case, the EAP peer communicates with an EAP server through the authenticator, with the authenticator merely being a passthrough.

An EAP method defines the specific authentication protocol being used by EAP. This memo defines a particular method and therefore defines the messages sent between the EAP server (or the "EAP server" functionality in an authenticator if it is not broken out) and the EAP peer for the purposes of authentication and key derivation.

2.8.2. Message Flows

EAP-pwd defines three message exchanges: an Identity exchange, a Commit exchange, and a Confirm exchange. A successful authentication is shown in Figure 2.

The peer and server use the Identity exchange to discover each other's identities and to agree upon a Ciphersuite to use in the subsequent exchanges; in addition, the EAP Server uses the EAP-pwd-ID/Request message to inform the client of any password pre-processing that may be required. In the Commit exchange, the peer and server exchange information to generate a shared key and also to bind each other to a particular guess of the password. In the Confirm exchange, the peer and server prove liveness and knowledge of the password by generating and verifying verification data.

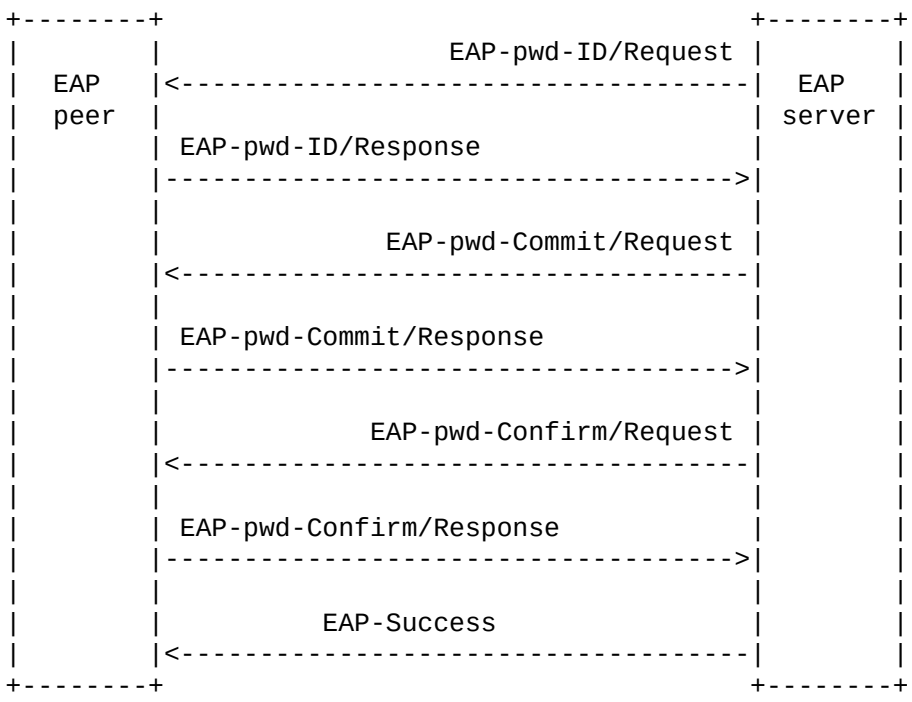

Figure 2: A Successful EAP-pwd Exchange

The components of the EAP-pwd-* messages are as follows:

EAP-pwd-ID/Request
    Ciphersuite, Token, Password Processing Method, Server_ID

EAP-pwd-ID/Response
    Ciphersuite, Token, Password Processing Method, Peer_ID

EAP-pwd-Commit/Request
    Scalar_S, Element_S

EAP-pwd-Commit/Response
    Scalar_P, Element_P

EAP-pwd-Confirm/Request
    Confirm_S

EAP-pwd-Confirm/Response
    Confirm_P

2.8.3. Fixing the Password Element

Once the EAP-pwd-ID exchange is completed, the peer and server use each other's identities and the agreed upon ciphersuite to fix an element in the negotiated group called the Password Element (PWE or pwe, for an element in an ECC group or an FFC group, respectively). The resulting element must be selected in a deterministic fashion using the password but must result in selection of an element that will not leak any information about the password to an attacker. From the point of view of an attacker who does not know the password, the Password Element will be a random element in the negotiated group.

To properly fix the Password Element, both parties must have a common view of the string "password". Therefore, if a password pre-processing algorithm was negotiated during the EAP-pwd-ID exchange, the client MUST perform the specified password pre-processing prior to fixing the Password Element.

Fixing the Password Element involves an iterative hunting-and-pecking technique using the prime from the negotiated group's domain parameter set and an ECC- or FFC-specific operation depending on the negotiated group.

First, an 8-bit counter is set to the value one (1). Then, the agreed-upon random function is used to generate a password seed from the identities and the anti-clogging token from the EAP-pwd-ID exchange (see Section 2.8.5.1):

```
pwd-seed = H(token | peer-ID | server-ID | password | counter)
```

Then, the pwd-seed is expanded using the KDF from the agreed-upon Ciphersuite out to the length of the prime:

```
pwd-value = KDF(pwd-seed, "EAP-pwd Hunting And Pecking", len(p))
```

If the pwd-value is greater than or equal to the prime, p, the counter is incremented, and a new pwd-seed is generated and the hunting-and-pecking continues. If pwd-value is less than the prime, p, it is passed to the group-specific operation which either returns the selected Password Element or fails. If the group-specific operation fails, the counter is incremented, a new pwd-seed is generated, and the hunting-and-pecking continues. This process continues until the group-specific operation returns the Password Element.

2.8.3.1. ECC Operation for PWE

The group-specific operation for ECC groups uses pwd-value, pwd-seed, and the equation for the curve to produce the Password Element. First, pwd-value is used directly as the x-coordinate, x, with the equation for the elliptic curve, with parameters a and b from the domain parameter set of the curve, to solve for a y-coordinate, y. If there is no solution to the quadratic equation, this operation fails and the hunting-and-pecking process continues. If a solution is found, then an ambiguity exists as there are technically two solutions to the equation and pwd-seed is used to unambiguously select one of them. If the low-order bit of pwd-seed is equal to the low-order bit of y, then a candidate PWE is defined as the point (x, y); if the low-order bit of pwd-seed differs from the low-order bit of y, then a candidate PWE is defined as the point (x, p - y), where p is the prime over which the curve is defined. The candidate PWE becomes PWE, and the hunting and pecking terminates successfully.

Algorithmically, the process looks like this:

```
found = 0
counter = 1
do {
  pwd-seed = H(token | peer-ID | server-ID | password | counter)
  pwd-value = KDF(pwd-seed, "EAP-pwd Hunting And Pecking", len(p))
  if (pwd-value < p)
  then
    x = pwd-value
    if ( (y = sqrt(x^3 + ax + b)) != FAIL)
    then
      if (LSB(y) == LSB(pwd-seed))
      then
        PWE = (x, y)
      else
        PWE = (x, p-y)
      fi
      found = 1
    fi
  fi
  counter = counter + 1
} while (found == 0)
```

Figure 3: Fixing PWE for ECC Groups

2.8.3.2. FFC Operation for pwe

The group-specific operation for FFC groups takes pwd-value, and the prime, p, and order, r, from the group's domain parameter set (see Section 2.2.1 when the order is not part of the defined domain parameter set) to directly produce a candidate Password Element, pwe, by exponentiating the pwd-value to the value ((p-1)/r) modulo the prime. If the result is greater than one (1), the candidate pwe becomes pwe, and the hunting and pecking terminates successfully.

Algorithmically, the process looks like this:

```
found = 0
counter = 1
do {
  pwd-seed = H(token | peer-ID | server-ID | password | counter)
  pwd-value = KDF(pwd-seed, "EAP-pwd Hunting And Pecking", len(p))
  if (pwd-value < p)
  then
    pwe = pwd-value ^ ((p-1)/r) mod p
    if (pwe > 1)
    then
      found = 1
    fi
  fi
  counter = counter + 1
} while (found == 0)
```

Figure 4: Fixing PWE for FFC Groups

2.8.4. Message Construction

After the EAP-pwd Identity exchange, the construction of the components of subsequent messages depends on the type of group from the ciphersuite (ECC or FFC). This section provides an overview of the authenticated key exchange. For a complete description of message generation and processing, see Sections 2.8.5.2 and 2.8.5.3.

2.8.4.1. ECC Groups

Using the mapping function F() defined in Section 2.2.2 and the group order r:

Server: EAP-pwd-Commit/Request
- choose two random numbers, 1 < s_rand, s_mask < r
- compute Scalar_S = (s_rand + s_mask) mod r
- compute Element_S = inv(s_mask * PWE)

```
    Element_S and Scalar_S are used to construct EAP-pwd-Commit/Request

   Peer: EAP-pwd-Commit/Response
      - choose two random numbers, 1 < p_rand, p_mask < r
      - compute Scalar_P = (p_rand + p_mask) mod r
      - compute Element_P = inv(p_mask * PWE)

    Element_P and Scalar_P are used to construct EAP-pwd-Commit/Response

   Server: EAP-pwd-Confirm/Request
      - compute KS = (s_rand * (Scalar_P * PWE + Element_P))
      - compute ks = F(KS)
      - compute Confirm_S = H(ks | Element_S | Scalar_S |
                              Element_P | Scalar_P | Ciphersuite)

    Confirm_S is used to construct EAP-pwd-Confirm/Request

   Peer: EAP-pwd-Confirm/Response
      - compute KP = (p_rand * (Scalar_S * PWE + Element_S)),
      - compute kp = F(KP)
      - compute Confirm_P = H(kp | Element_P | Scalar_P |
                              Element_S | Scalar_S | Ciphersuite)

    Confirm_P is used to construct EAP-pwd-Confirm/Response

   The EAP Server computes the shared secret as:
     MK = H(ks | Confirm_P | Confirm_S)

   The EAP Peer computes the shared secret as:
     MK = H(kp | Confirm_P | Confirm_S)


   The MSK and EMSK are derived from MK per Section 2.9.
```

2.8.4.2. FFC Groups

There is no mapping function, F(), required for an FFC group. Using the order, r, for the group (see Section 2.2.1 when the order is not part of the defined domain parameters):

```
   Server: EAP-pwd-Commit/Request
      - choose two random numbers, 1 < s_rand, s_mask < r
      - compute Scalar_S = (s_rand + s_mask) mod r
      - compute Element_S = inv(pwe^s_mask mod p)

    Element_S and Scalar_S are used to construct EAP-pwd-Commit/Request
```

```
Peer: EAP-pwd-Commit/Response
   - choose random two numbers, 1 < p_rand, p_mask < r
   - compute Scalar_P = (p_rand + p_mask) mod r
   - compute Element_P = inv(pwe^p_mask mod p)

 Element_P and Scalar_P are used to construct EAP-pwd-Commit/Response

Server: EAP-pwd-Confirm/Request
   - compute ks = ((pwe^Scalar_P mod p) * Element_P)^s_rand mod p
   - compute Confirm_S = H(ks | Element_S | Scalar_S |
                           Element_P | Scalar_P | Ciphersuite)

 Confirm_S is used to construct EAP-pwd-Confirm/Request

Peer: EAP-pwd-Confirm/Response
   - compute kp = ((pwe^Scalar_S mod p) * Element_S)^p_rand mod p
   - compute Confirm_P = H(kp | Element_P | Scalar_P |
                           Element_S | Scalar_S | Ciphersuite)

 Confirm_P is used to construct EAP-pwd-Confirm/Request

The EAP Server computes the shared secret as:
  MK = H(ks | Confirm_P | Confirm_S)

The EAP Peer computes the shared secret as:
  MK = H(kp | Confirm_P | Confirm_S)
```

The MSK and EMSK are derived from MK per Section 2.9.

2.8.5. Message Processing

2.8.5.1. EAP-pwd-ID Exchange

Although EAP provides an Identity method to determine the identity of the peer, the value in the Identity Response may have been truncated or obfuscated to provide privacy or decorated for routing purposes [RFC3748], making it inappropriate for usage by the EAP-pwd method. Therefore, the EAP-pwd-ID exchange is defined for the purpose of exchanging identities between the peer and server.

The EAP-pwd-ID/Request contains the following quantities:

- a ciphersuite
- a representation of the server's identity per Section 2.7.1

- an anti-clogging token
- a password pre-processing method

The ciphersuite specifies the finite cyclic group, random function, and PRF selected by the server for use in the subsequent authentication exchange.

The value of the anti-clogging token MUST be unpredictable and SHOULD NOT be from a source of random entropy. The purpose of the anti-clogging token is to provide the server an assurance that the peer constructing the EAP-pwd-ID/Response is genuine and not part of a flooding attack.

A password pre-processing method is communicated to ensure interoperability by producing a canonical representation of the password string between the peer and server (see Section 2.7.2).

The EAP-pwd-ID/Request is constructed according to Section 3.2.1 and is transmitted to the peer.

Upon receipt of an EAP-pwd-ID/Request, the peer determines whether the ciphersuite and pre-processing method are acceptable. If not, the peer MUST respond with an EAP-NAK. If acceptable, the peer responds to the EAP-pwd-ID/Request with an EAP-pwd-ID/Response, constructed according to Section 3.2.1, that acknowledges the Ciphersuite, token, and pre-processing method and then adds its identity. After sending the EAP-pwd-ID/Response, the peer has the identity of the server (from the Request), its own identity (it encoded in the Response), a password pre-processing algorithm, and it can compute the Password Element as specified in Section 2.8.3. The Password Element is stored in state allocated for this exchange.

The EAP-pwd-ID/Response acknowledges the Ciphersuite from the Request, acknowledges the anti-clogging token from the Request providing a demonstration of "liveness" on the part of the peer, and contains the identity of the peer. Upon receipt of the Response, the server verifies that the Ciphersuite acknowledged by the peer is the same as that sent in the Request and that the anti-clogging token added by the peer in the Response is the same as that sent in the Request. If Ciphersuites or anti-clogging tokens differ, the server MUST respond with an EAP-Failure message. If the anti-clogging tokens are the same, the server knows the peer is an active participant in the exchange. If the Ciphersuites are the same, the server now knows its own identity (it encoded in the Request) and the peer’s identity (from the Response) and can compute the Password

Element according to Section 2.8.3. The server stores the Password Element in state it has allocated for this exchange. The server then initiates an EAP-pwd-Commit exchange.

2.8.5.2. EAP-pwd-Commit Exchange

The server begins the EAP-pwd-Confirm exchange by choosing two random numbers, s_rand and s_mask, between 1 and r (where r is described in Section 2.1 according to the group established in Section 2.8.5.1) such that their sum modulo r is greater than one (1). It then computes Element_S and Scalar_S as defined in Section 2.8.4 and constructs an EAP-pwd-Commit/Request according to Section 3.2.2. Element_S and Scalar_S are added to the state allocated for this exchange, and the EAP-pwd-Commit/Request is transmitted to the peer.

Upon receipt of the EAP-pwd-Commit/Request, the peer validates the length of the entire payload based upon the expected lengths of Element_S and Scalar_S (which are fixed according to the length of the agreed-upon group). If the length is incorrect, the peer MUST terminate the exchange. If the length is correct, Element_S and Scalar_S are extracted from the EAP-pwd-Commit/Request. Scalar_S is then checked to ensure it is between 1 and r, exclusive. If it is not, the peer MUST terminate the exchange. If it is, Element_S MUST be validated depending on the type of group -- Element validation for FFC groups is described in Section 2.8.5.2.1, and Element validation for ECC groups is described in Section 2.8.5.2.2. If validation is successful, the peer chooses two random numbers, p_rand and p_mask, between 1 and r (where r is described in Section 2.1 according to the group established in Section 2.8.5.1) such that their sum modulo r is greater than one (1), and computes Element_P and Scalar_P. Next, the peer computes kp from p_rand, Element_S, Scalar_S, and the Password Element according to Section 2.8.4. If kp is the "identity element" -- the point at infinity for an ECC group or the value one (1) for an FFC group -- the peer MUST terminate the exchange. If not, the peer uses Element_P and Scalar_P to construct an EAP-pwd-Commit/Response according to Section 3.2.2 and transmits the EAP-pwd-Commit/Response to the server.

Upon receipt of the EAP-pwd-Commit/Response, the server validates the length of the entire payload based upon the expected lengths of Element_P and Scalar_P (which are fixed according to the agreed-upon group). If the length is incorrect, the server MUST respond with an EAP-Failure message, and it MUST terminate the exchange and free up any state allocated. If the length is correct, Scalar_P and Element_P are extracted from the EAP-pwd-Commit/Response and compared to Scalar_S and Element_S. If Scalar_P equals Scalar_S and Element_P equals Element_S, it indicates a reflection attack and the server MUST respond with an EAP-failure and terminate the exchange. If they

differ, Scalar_P is checked to ensure it is between 1 and r, exclusive. If not the server MUST respond with an EAP-failure and terminate the exchange. If it is, Element_P is verified depending on the type of group -- Element validation for FFC groups is described in Section 2.8.5.2.1, and Element validation for ECC groups is described in Section 2.8.5.2.2. If validation is successful, the server computes ks from s_rand, Element_P, Scalar_P, and the Password Element according to Section 2.8.4. If ks is the "identity element" -- the point at infinity for an ECC group or the value one (1) for an FFC group -- the server MUST respond with an EAP-failure and terminate the exchange. Otherwise, the server initiates an EAP-pwd-Confirm exchange.

2.8.5.2.1. Element Validation for FFC Groups

A received FFC Element is valid if: 1) it is between one (1) and the prime, p, exclusive; and 2) if modular exponentiation of the Element by the group order, r, equals one (1). If either of these conditions are not true the received Element is invalid.

2.8.5.2.2. Element Validation for ECC Groups

Validating a received ECC Element involves: 1) checking whether the two coordinates, x and y, are both greater than zero (0) and less than the prime defining the underlying field; and 2) checking whether the x- and y-coordinates satisfy the equation of the curve (that is, that they produce a valid point on the curve that is not the point at infinity). If either of these conditions are not met, the received Element is invalid; otherwise, the Element is valid.

2.8.5.3. EAP-pwd-Confirm Exchange

The server computes Confirm_S according to Section 2.8.4, constructs an EAP-pwd-Confirm/Request according to Section 3.2.3, and sends it to the peer.

Upon receipt of an EAP-pwd-Confirm/Request, the peer validates the length of the entire payload based upon the expected length of Confirm_S (whose length is fixed by the agreed-upon random function). If the length is incorrect, the peer MUST terminate the exchange and free up any state allocated. If the length is correct, the peer verifies that Confirm_S is the value it expects based on the value of kp. If the value of Confirm_S is incorrect, the peer MUST terminate the exchange and free up any state allocated. If the value of Confirm_S is correct, the peer computes Confirm_P, constructs an EAP-pwd-Confirm/Response according to Section 3.2.3, and sends it off to the server. The peer then computes MK (according to Section 2.8.4) and the MSK and EMSK (according to Section 2.9) and stores these keys

in state allocated for this exchange. The peer SHOULD export the MSK and EMSK at this time in anticipation of a secure association protocol by the lower layer to create session keys. Alternatively, the peer can wait until an EAP-Success message from the server before exporting the MSK and EMSK.

Upon receipt of an EAP-pwd-Confirm/Response, the server validates the length of the entire payload based upon the expected length of Confirm_P (whose length is fixed by the agreed-upon random function). If the length is incorrect, the server MUST respond with an EAP-Failure message, and it MUST terminate the exchange and free up any state allocated. If the length is correct, the server verifies that Confirm_P is the value it expects based on the value of ks. If the value of Confirm_P is incorrect, the server MUST respond with an EAP-Failure message. If the value of Confirm_P is correct, the server computes MK (according to Section 2.8.4) and the MSK and EMSK (according to Section 2.9). It exports the MSK and EMSK and responds with an EAP-Success message. The server SHOULD free up state allocated for this exchange.

2.9. Management of EAP-pwd Keys

[RFC5247] recommends each EAP method define how to construct a Method-ID and Session-ID to identify a particular EAP session between a peer and server. This information is constructed thusly:

```
Method-ID = H(Ciphersuite | Scalar_P | Scalar_S)

Session-ID = Type-Code | Method-ID
```

where Ciphersuite, Scalar_P, and Scalar_S are from the specific exchange being identified; H is the random function specified in the Ciphersuite; and, Type-Code is the code assigned for EAP-pwd, 52, represented as a single octet.

The authenticated key exchange of EAP-pwd generates a shared and authenticated key, MK. The size of MK is dependent on the random function, H, asserted in the Ciphersuite. EAP-pwd must export two 512-bit keys, MSK and EMSK. Regardless of the value of len(MK), implementations MUST invoke the KDF defined in Section 2.5 to construct the MSK and EMSK. The MSK and EMSK are derived thusly:

```
MSK | EMSK = KDF(MK, Session-ID, 1024)
```

[RFC4962] mentions the importance of naming keys, particularly when key caching is being used. To facilitate such an important optimization, names are assigned thusly:

- EMSK-name = Session-ID | 'E' | 'M'| 'S' | 'K'

- MSK-name = Session-ID | 'M'| 'S' | 'K'

where 'E' is a single octet of value 0x45, 'M' is a single octet of value 0x4d, 'S' is a single octet of value 0x53, and 'K' is a single octet of value 0x4b.

This naming scheme allows for key-management applications to quickly and accurately identify keys for a particular session or all keys of a particular type.

2.10. Mandatory-to-Implement Parameters

For the purposes of interoperability, compliant EAP-pwd implementations SHALL support the following parameters:

- Diffie-Hellman Group: group 19 defined in [RFC5114]

- Random Function: defined in Section 2.4

- PRF: HMAC-SHA256 defined in [RFC4634]

- Password Pre-Processing: none

3. Packet Formats

3.1. EAP-pwd Header

The EAP-pwd header has the following structure:

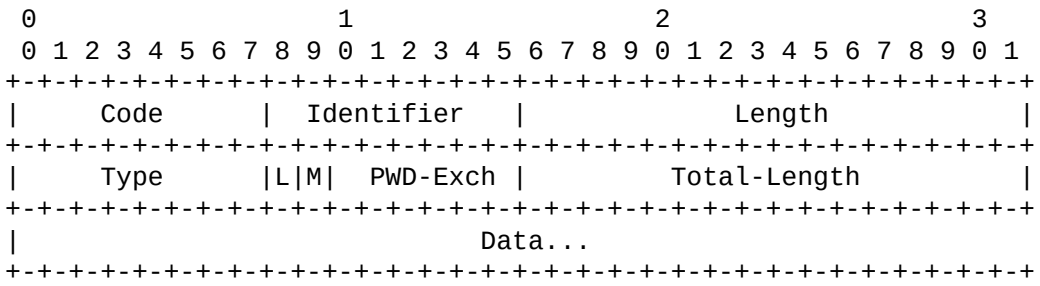

Figure 5: EAP-pwd Header

Code

Either 1 (for Request) or 2 (for Response); see [RFC3748].

Identifier

The Identifier field is one octet and aids in matching responses with requests. The Identifier field MUST be changed on each Request packet.

Length

The Length field is two octets and indicates the length of the EAP packet including the Code, Identifier, Length, Type, and Data fields. Octets outside the range of the Length field should be treated as Data Link Layer padding and MUST be ignored on reception.

Type

52 - EAP-pwd

L and M bits

The L bit (Length included) is set to indicate the presence of the two-octet Total-Length field, and MUST be set for the first fragment of a fragmented EAP-pwd message or set of messages.

The M bit (more fragments) is set on all but the last fragment.

PWD-Exch

The PWD-Exch field identifies the type of EAP-pwd payload encapsulated in the Data field. This document defines the following values for the PWD-Exch field:

* 0x00 : Reserved

* 0x01 : EAP-pwd-ID exchange

* 0x02 : EAP-pwd-Commit exchange

* 0x03 : EAP-pwd-Confirm exchange

All other values of the PWD-Exch field are unassigned.

Total-Length

The Total-Length field is two octets in length, and is present only if the L bit is set. This field provides the total length of the EAP-pwd message or set of messages that is being fragmented.

3.2. EAP-pwd Payloads

EAP-pwd payloads all contain the EAP-pwd header and encoded information. Encoded information is comprised of sequences of data. Payloads in the EAP-pwd-ID exchange also include a ciphersuite statement indicating what finite cyclic group to use, what cryptographic primitive to use for H, and what PRF to use for deriving keys.

3.2.1. EAP-pwd-ID

The Group Description, Random Function, and PRF together, and in that order, comprise the Ciphersuite included in the calculation of the peer's and server's confirm messages.

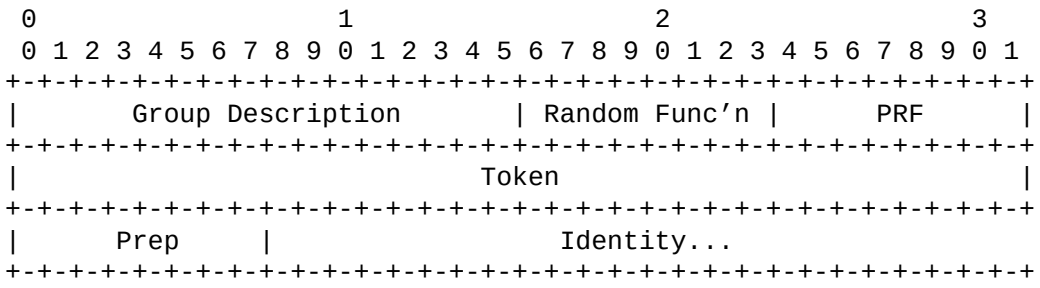

Figure 6: EAP-pwd-ID Payload

The Group Description field value is taken from the IANA registry for "Group Description" created by IKE [RFC2409].

This document defines the following value for the Random Function field:

o 0x01 : Function defined in this memo in Section 2.4

The value 0x00 is reserved for private use between mutually consenting parties. All other values of the Random Function field are unassigned.

The PRF field has the following value:

o 0x01 : HMAC-SHA256 [RFC4634]

The value 0x00 is reserved for private use between mutually consenting parties. All other values of the PRF field are unassigned.

The Token field contains an unpredictable value assigned by the server in an EAP-pwd-ID/Request and acknowledged by the peer in an EAP-pwd-ID/Response (see Section 2.8.5).

The Prep field represents the password pre-processing technique (see Section 2.7.2) to be used by the client prior to generating the password seed (see Section 2.8.3). This document defines the following values for the Prep field:

- 0x00 : None
- 0x01 : RFC2759
- 0x02 : SASLprep

All other values of the Prep field are unassigned.

The Identity field depends on the tuple of PWD-Exch/Code.

- EAP-pwd-ID/Request : Server_ID
- EAP-pwd-ID/Response : Peer_ID

The length of the identity is computed from the Length field in the EAP header.

3.2.2. EAP-pwd-Commit

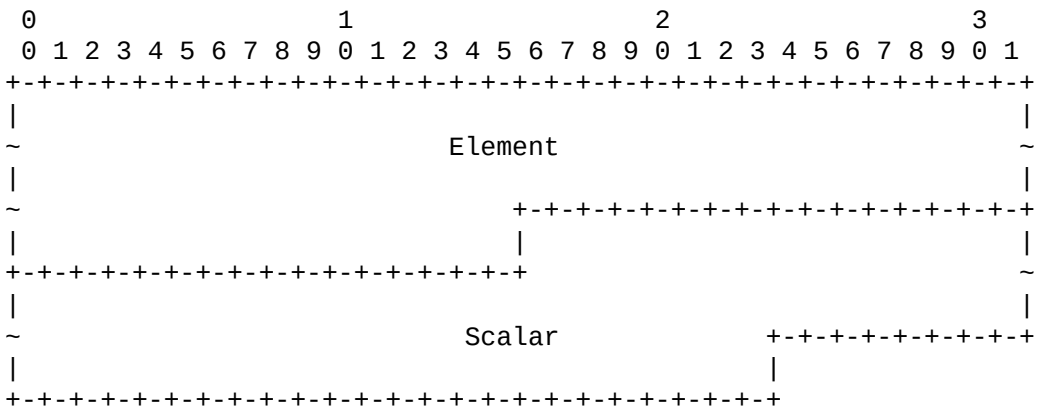

Figure 7: EAP-pwd-Commit Payload

The Element and Scalar fields depend on the tuple of PWD-Exch/Code.

o EAP-pwd-Commit/Request : Element_S, Scalar_S

o EAP-pwd-Commit/Response : Element_P, Scalar_P

The Element is encoded according to Section 3.3. The length of the Element is inferred by the finite cyclic group from the agreed-upon Ciphersuite. The length of the scalar can then be computed from the Length in the EAP header.

3.2.3. EAP-pwd-Confirm

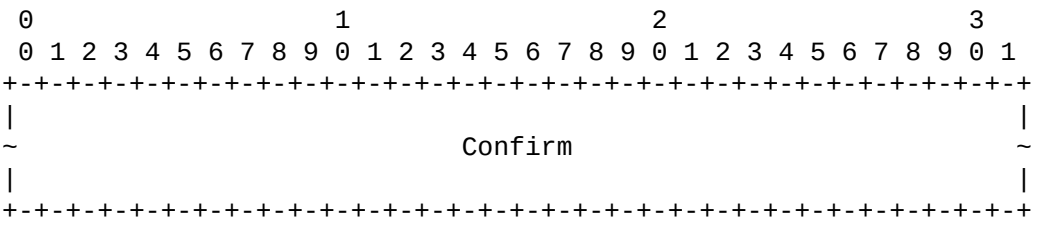

Figure 8: EAP-pwd-Confirm Payload

The Confirm field depends on the tuple of PWD-Exch/Code.

o EAP-pwd-Confirm/Request : Confirm_S

o EAP-pwd-Confirm/Response : Confirm_P

The length of the Confirm field computed from the Length in the EAP header.

3.3. Representation of Group Elements and Scalars

Payloads in the EAP-pwd-Commit exchange contain elements from the agreed-upon finite cyclic cryptographic group (either an FCC group or an ECC group). To ensure interoperability, field elements and scalars MUST be represented in payloads in accordance with the requirements described below.

3.3.1. Elements in FFC Groups

Elements in an FFC group MUST be represented (in binary form) as unsigned integers that are strictly less than the prime, p, from the group's domain parameter set. The binary representation of each group element MUST have a bit length equal to the bit length of the

binary representation of p. This length requirement is enforced, if necessary, by prepending the binary representation of the integer with zeros until the required length is achieved.

3.3.2. Elements in ECC Groups

Elements in an ECC group are points on the agreed-upon elliptic curve. Each such element MUST be represented by the concatenation of two components, an x-coordinate and a y-coordinate.

Each of the two components, the x-coordinate and the y-coordinate, MUST be represented (in binary form) as an unsigned integer that is strictly less than the prime, p, from the group's domain parameter set. The binary representation of each component MUST have a bit length equal to the bit length of the binary representation of p. This length requirement is enforced, if necessary, by prepending the binary representation of the integer with zeros until the required length is achieved.

Since the field element is represented in a payload by the x-coordinate followed by the y-coordinate, it follows that the length of the element in the payload MUST be twice the bit length of p. In other words, "compressed representation" is not used.

3.3.3. Scalars

Scalars MUST be represented (in binary form) as unsigned integers that are strictly less than r, the order of the generator of the agreed-upon cryptographic group. The binary representation of each scalar MUST have a bit length equal to the bit length of the binary representation of r. This requirement is enforced, if necessary, by prepending the binary representation of the integer with zeros until the required length is achieved.

4. Fragmentation

EAP [RFC3748] is a request-response protocol. The server sends requests and the peer responds. These request and response messages are assumed to be limited to at most 1020 bytes. Messages in EAP-pwd can be larger than 1020 bytes and therefore require support for fragmentation and reassembly.

Implementations MUST establish a fragmentation threshold that indicates the maximum size of an EAP-pwd payload. When an implementation knows the maximum transmission unit (MTU) of its lower layer, it SHOULD calculate the fragmentation threshold from that value. In lieu of knowledge of the lower layer's MTU, the fragmentation threshold MUST be set to 1020 bytes.

Since EAP is a simple ACK-NAK protocol, fragmentation support can be added in a simple manner. In EAP, fragments that are lost or damaged in transit will be retransmitted, and since sequencing information is provided by the Identifier field in EAP, there is no need for a fragment offset field as is provided in IPv4.

EAP-pwd fragmentation support is provided through the addition of flags within the EAP-Response and EAP-Request packets, as well as a Total-Length field of two octets. Flags include the Length included (L) and More fragments (M) bits. The L flag is set to indicate the presence of the two-octet Total-Length field, and MUST be set for the first fragment of a fragmented EAP-pwd message or set of messages. The M flag is set on all but the last fragment. The Total-Length field is two octets, and provides the total length of the EAP-pwd message or set of messages that is being fragmented; this simplifies buffer allocation.

When an EAP-pwd peer receives an EAP-Request packet with the M bit set, it MUST respond with an EAP-Response with EAP-Type=EAP-pwd and no data. This serves as a fragment ACK. The EAP server MUST wait until it receives the EAP-Response before sending another fragment. In order to prevent errors in processing of fragments, the EAP server MUST increment the Identifier field for each fragment contained within an EAP-Request, and the peer MUST include this Identifier value in the fragment ACK contained within the EAP-Response. Retransmitted fragments will contain the same Identifier value.

Similarly, when the EAP server receives an EAP-Response with the M bit set, it MUST respond with an EAP-Request with EAP-Type=EAP-pwd and no data. This serves as a fragment ACK. The EAP peer MUST wait until it receives the EAP-Request before sending another fragment. In order to prevent errors in the processing of fragments, the EAP server MUST increment the Identifier value for each fragment ACK contained within an EAP-Request, and the peer MUST include this Identifier value in the subsequent fragment contained within an EAP-Response.

5. IANA Considerations

This memo contains new numberspaces to be managed by IANA. The policies used to allocate numbers are described in [RFC5226]. IANA has allocated a new EAP method type for EAP-pwd (52).

IANA has created new registries for PWD-Exch messages, random functions, PRFs, and password pre-processing methods and has added the message numbers, random function, PRF, and pre-processing methods specified in this memo to those registries, respectively.

The following is the initial PWD-Exch message registry layout:

- 0x00 : Reserved
- 0x01 : EAP-pwd-ID exchange
- 0x02 : EAP-pwd-Commit exchange
- 0x03 : EAP-pwd-Confirm exchange

The PWD-Exch field is 6 bits long. The value 0x00 is reserved. All other values are available through assignment by IANA. IANA is instructed to assign values based on "IETF Review" (see [RFC5226]).

The following is the initial Random Function registry layout:

- 0x00 : Private Use
- 0x01 : Function defined in this memo, Section 2.4

The Random Function field is 8 bits long. The value 0x00 is for Private Use between mutually consenting parties. All other values are available through assignment by IANA. IANA is instructed to assign values based on "Specification Required" (see [RFC5226]). The Designated Expert performing the necessary review MUST ensure the random function has been cryptographically vetted.

The following is the initial PRF registry layout:

- 0x00 : Private Use
- 0x01 : HMAC-SHA256 as defined in [RFC4634]

The PRF field is 8 bits long. The value 0x00 is for Private Use between mutually consenting parties. All other values are available through assignment by IANA. IANA is instructed to assign values based on "IETF Review" (see [RFC5226]).

The following is the initial layout for the password pre-processing method registry:

- 0x00 : None
- 0x01 : RFC2759
- 0x02 : SASLprep

The Prep field is 8 bits long, and all other values are available through assignment by IANA. IANA is instructed to assign values based on "Specification Required" (see [RFC5226]).

6. Security Considerations

In Section 1.3, several security properties were presented that motivated the design of this protocol. This section will address how well they are met.

6.1. Resistance to Passive Attack

A passive attacker will see Scalar_P, Element_P, Scalar_S, and Element_S. She can guess at passwords to compute the password element but will not know s_rand or p_rand and therefore will not be able to compute MK.

The secret random value of the peer (server) is effectively hidden by adding p_mask (s_mask) to p_rand (s_rand) modulo the order of the group. If the order is "r", then there are approximately "r" distinct pairs of numbers that will sum to the value Scalar_P (Scalar_S). Attempting to guess the particular pair is just as difficult as guessing the secret random value p_rand (s_rand), the probability of a guess is 1/(r - i) after "i" guesses. For a large value of r, this exhaustive search technique is computationally infeasible. An attacker would do better by determining the discrete logarithm of Element_P (Element_S) using an algorithm like the baby-step giant-step algorithm (see [APPCRY]), which runs on the order of the square root of r group operations (e.g., a group with order 2^160 would require 2^80 exponentiations or point multiplications). Based on the assumptions made on the finite cyclic group in Section 2.3, that is also computationally infeasible.

6.2. Resistance to Active Attack

An active attacker can launch her attack after an honest server has sent EAP-pwd-Commit/Request to an honest peer. This would result in the peer sending EAP-pwd-Commit/Response. In this case, the active attack has been reduced to that of a passive attacker since p_rand and s_rand will remain unknown. The active attacker could forge a value of Confirm_P (Confirm_S) and send it to the EAP server (EAP peer) in the hope that it will be accepted, but due to the assumptions on H made in Section 2.3, that is computationally infeasible.

The active attacker can launch her attack by forging EAP-pwd-Commit/Request and sending it to the peer. This will result in the peer responding with EAP-pwd-Commit/Response. The attacker can then

attempt to compute ks, but since she doesn't know the password, this is infeasible. It can be shown that an attack by forging an EAP-pwd-Commit/Response is an identical attack with equal infeasibility.

6.3. Resistance to Dictionary Attack

An active attacker can wait until an honest server sends EAP-pwd-Commit/Request and then forge EAP-pwd-Commit/Response and send it to the server. The server will respond with EAP-pwd-Confirm/Request. Now the attacker can attempt to launch a dictionary attack. She can guess at potential passwords, compute the password element, and compute kp using her p_rand, Scalar_S, and Element_S from the EAP-pwd-Commit/Request and the candidate password element from her guess. She will know if her guess is correct when she is able to verify Confirm_S in EAP-pwd-Confirm/Request.

But the attacker committed to a password guess with her forged EAP-pwd-Commit/Response when she computed Element_P. That value was used by the server in his computation of ks that was used when he constructed Confirm_S in EAP-pwd-Confirm/Request. Any guess of the password that differs from the one used in the forged EAP-pwd-Commit/Response could not be verified as correct since the attacker has no way of knowing whether it is correct. She is able to make one guess and one guess only per attack. This means that any advantage she can gain -- guess a password, if it fails exclude it from the pool of possible passwords and try again -- is solely through interaction with an honest protocol peer.

The attacker can commit to the guess with the forged EAP-pwd-Commit/Response and then run through the dictionary, computing the password element and ks using her forged Scalar_P and Element_P. She will know she is correct if she can compute the same value for Confirm_S that the server produced in EAP-pwd-Confirm/Request. But this requires the attacker to know s_rand, which we noted above was not possible.

The password element PWE/pwe is chosen using a method described in Section 2.8.3. Since this is an element in the group, there exists a scalar value, q, such that:

PWE = q * G, for an ECC group

pwe = g^q mod p, for an FFC group

Knowledge of q can be used to launch a dictionary attack. For the sake of brevity, the attack will be demonstrated assuming an ECC group. The attack works thusly:

The attacker waits until an honest server sends an EAP-pwd-Commit/ Request. The attacker then generates a random Scalar_P and a random p_mask and computes Element_P = p_mask * G. The attacker sends the bogus Scalar_P and Element_P to the server and obtains Confirm_S in return. Note that the server is unable to detect that Element_P was calculated incorrectly.

The attacker now knows that:

KS = (Scalar_P * q + p_mask) * s_rand * G

and

s_rand * G = Scalar_P * G - ((1/q) mod r * -Element_P)

Since Scalar_P, p_mask, G, and Element_P are all known, the attacker can run through the dictionary, make a password guess, compute PWE using the technique in Section 2.8.3, determine q, and then use the equations above to compute KS and see if it can verify Confirm_S. But to determine q for a candidate PWE, the attacker needs to perform a discrete logarithm that was assumed to be computationally infeasible in Section 2.3. Therefore, this attack is also infeasible.

The best advantage an attacker can gain in a single active attack is to determine whether a single guess at the password was correct. Therefore, her advantage is solely through interaction and not computation, which is the definition for resistance to dictionary attack.

Resistance to dictionary attack means that the attacker must launch an active attack to make a single guess at the password. If the size of the dictionary from which the password was extracted was D, and each password in the dictionary has an equal probability of being chosen, then the probability of success after a single guess is 1/D. After X guesses, and removal of failed guesses from the pool of possible passwords, the probability becomes 1/(D-X). As X grows, so does the probability of success. Therefore, it is possible for an attacker to determine the password through repeated brute-force, active, guessing attacks. This protocol does not presume to be secure against this, and implementations SHOULD ensure the size of D is sufficiently large to prevent this attack. Implementations SHOULD also take countermeasures -- for instance, refusing authentication attempts for a certain amount of time, after the number of failed authentication attempts reaches a certain threshold. No such threshold or amount of time is recommended in this memo.

6.4. Forward Secrecy

The MSK and EMSK are extracted from MK, which is derived from doing group operations with s_rand, p_rand, and the password element. The peer and server choose random values with each run of the protocol. So even if an attacker is able to learn the password, she will not know the random values used by either the peer or server from an earlier run and will therefore be unable to determine MK, or the MSK or EMSK. This is the definition of Forward Secrecy.

6.5. Group Strength

The strength of the shared secret, MK, derived in Section 2.8.4 depends on the effort needed to solve the discrete logarithm problem in the chosen group. [RFC3766] has a good discussion on the strength estimates of symmetric keys derived from discrete logarithm cryptography.

The mandatory-to-implement group defined in this memo is group 19, a group from [RFC5114] based on Elliptic Curve Cryptography (see Section 2.2.2) with a prime bit length of 256. This group was chosen because the current best estimate of a symmetric key derived using this group is 128 bits, which is the typical length of a key for the Advanced Encryption Standard ([FIPS-197]). While it is possible to obtain a equivalent measure of strength using a group based on Finite Field Cryptography (see Section 2.2.1), it would require a much larger prime and be more memory and compute intensive.

6.6. Random Functions

The protocol described in this memo uses a function referred to as a "random oracle" (as defined in [RANDOR]). A significant amount of care must be taken to instantiate a random oracle out of handy cryptographic primitives. The random oracle used here is based on the notion of a "Randomness Extractor" from [RFC5869].

This protocol can use any properly instantiated random oracle. To ensure that any new value for H will use a properly instantiated random oracle, IANA has been instructed (in Section 5) to only allocate values from the Random Function registry after being vetted by an expert.

A few of the defined groups that can be used with this protocol have a security estimate (see Section 6.5) less than 128 bits, many do not though, and to prevent the random function from being the gating factor (or a target for attack), any new random function MUST map its input to a target of at least 128 bits and SHOULD map its input to a target of at least 256 bits.

7. Security Claims

[RFC3748] requires that documents describing new EAP methods clearly articulate the security properties of the method. In addition, for use with wireless LANs, [RFC4017] mandates and recommends several of these. The claims are:

a. mechanism: password.

b. claims:

* mutual authentication: the peer and server both authenticate each other by proving possession of a shared password. This is REQUIRED by [RFC4017].

* forward secrecy: compromise of the password does not reveal the secret keys -- MK, MSK, or EMSK -- from earlier runs of the protocol.

* replay protection: an attacker is unable to replay messages from a previous exchange to either learn the password or a key derived by the exchange. Similarly the attacker is unable to induce either the peer or server to believe the exchange has successfully completed when it hasn't. Reflection attacks are foiled because the server ensures that the scalar and element supplied by the peer do not equal its own.

* key derivation: keys are derived by performing a group operation in a finite cyclic group (e.g., exponentiation) using secret data contributed by both the peer and server. An MSK and EMSK are derived from that shared secret. This is REQUIRED by [RFC4017]

* dictionary attack resistance: this protocol is resistant to dictionary attack because an attacker can only make one password guess per active attack. The advantage gained by an attacker is through interaction not through computation. This is REQUIRED by [RFC4017].

* session independence: this protocol is resistant to active and passive attack and does not enable compromise of subsequent or prior MSKs or EMSKs from either passive or active attack.

* Denial-of-Service Resistance: it is possible for an attacker to cause a server to allocate state and consume CPU cycles generating Scalar_S and Element_S. Such an attack is gated,

though, by the requirement that the attacker first obtain connectivity through a lower-layer protocol (e.g. 802.11 authentication followed by 802.11 association, or 802.3 "link-up") and respond to two EAP messages --the EAP-ID/ Request and the EAP-pwd-ID/Request. The EAP-pwd-ID exchange further includes an anti-clogging token that provides a level of assurance to the server that the peer is, at least, performing a rudimentary amount of processing and not merely spraying packets. This prevents distributed denial-of-service attacks and also requires the attacker to announce, and commit to, a lower-layer identity, such as a MAC (Media Access Control) address.

* Man-in-the-Middle Attack Resistance: this exchange is resistant to active attack, which is a requirement for launching a man-in-the-middle attack. This is REQUIRED by [RFC4017].

* shared state equivalence: upon completion of EAP-pwd, the peer and server both agree on MK, MSK, EMSK, Method-ID, and Session-ID. The peer has authenticated the server based on the Server-ID, and the server has authenticated the peer based on the Peer-ID. This is due to the fact that Peer-ID, Server-ID, and the shared password are all combined to make the password element, which must be shared between the peer and server for the exchange to complete. This is REQUIRED by [RFC4017].

* fragmentation: this protocol defines a technique for fragmentation and reassembly in Section 4.

* resistance to "Denning-Sacco" attack: learning keys distributed from an earlier run of the protocol, such as the MSK or EMSK, will not help an adversary learn the password.

c. key strength: the strength of the resulting key depends on the finite cyclic group chosen. See Section 6.5. This is REQUIRED by [RFC4017].

d. key hierarchy: MSKs and EMSKs are derived from the MK using the KDF defined in Section 2.5 as described in Section 2.8.4.

e. vulnerabilities (note that none of these are REQUIRED by [RFC4017]):

* protected ciphersuite negotiation: the ciphersuite offer made by the server is not protected from tampering by an active attacker. Downgrade attacks are prevented, though, since

this is not a "negotiation" with a list of acceptable ciphersuites. If a Ciphersuite was modified by an active attacker it would result in a failure to confirm the message sent by the other party, since the Ciphersuite is bound by each side into its confirm message, and the protocol would fail as a result.

* confidentiality: none of the messages sent in this protocol are encrypted.

* integrity protection: messages in the EAP-pwd-Commit exchange are not integrity protected.

* channel binding: this protocol does not enable the exchange of integrity-protected channel information that can be compared with values communicated via out-of-band mechanisms.

* fast reconnect: this protocol does not provide a fast-reconnect capability.

* cryptographic binding: this protocol is not a tunneled EAP method and therefore has no cryptographic information to bind.

* identity protection: the EAP-pwd-ID exchange is not protected. An attacker will see the server's identity in the EAP-pwd-ID/Request and see the peer's identity in EAP-pwd-ID/Response.

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Authors' Addresses

Dan Harkins
Aruba Networks
1322 Crossman Avenue
Sunnyvale, CA 94089-1113
USA

EMail: dharkins@arubanetworks.com

Glen Zorn
Network Zen
1310 East Thomas Street
#306
Seattle, WA 98102
USA

Phone: +1 (206) 377-9035
EMail: gwz@net-zen.net