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The OAKLEY Key Determination Protocol

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Abstract

This document describes a protocol, named OAKLEY, by which two authenticated parties can agree on secure and secret keying material. The basic mechanism is the Diffie-Hellman key exchange algorithm.

The OAKLEY protocol supports Perfect Forward Secrecy, compatibility with the ISAKMP protocol for managing security associations, user-defined abstract group structures for use with the Diffie-Hellman algorithm, key updates, and incorporation of keys distributed via out-of-band mechanisms.

1. INTRODUCTION

Key establishment is the heart of data protection that relies on cryptography, and it is an essential component of the packet protection mechanisms described in [RFC2401], for example. A scalable and secure key distribution mechanism for the Internet is a necessity. The goal of this protocol is to provide that mechanism, coupled with a great deal of cryptographic strength.

The Diffie-Hellman key exchange algorithm provides such a mechanism. It allows two parties to agree on a shared value without requiring encryption. The shared value is immediately available for use in encrypting subsequent conversation, e.g. data transmission and/or authentication. The STS protocol [STS] provides a demonstration of how to embed the algorithm in a secure protocol, one that ensures that in addition to securely sharing a secret, the two parties can be sure of each other’s identities, even when an active attacker exists.

Because OAKLEY is a generic key exchange protocol, and because the keys that it generates might be used for encrypting data with a long privacy lifetime, 20 years or more, it is important that the algorithms underlying the protocol be able to ensure the security of the keys for that period of time, based on the best prediction capabilities available for seeing into the mathematical future. The protocol therefore has two options for adding to the difficulties faced by an attacker who has a large amount of recorded key exchange traffic at his disposal (a passive attacker). These options are useful for deriving keys which will be used for encryption.

The OAKLEY protocol is related to STS, sharing the similarity of authenticating the Diffie-Hellman exponentials and using them for determining a shared key, and also of achieving Perfect Forward Secrecy for the shared key, but it differs from the STS protocol in several ways.

The first is the addition of a weak address validation mechanism ("cookies", described by Phil Karn in the Photuris key exchange protocol work in progress) to help avoid denial of service attacks.

The second extension is to allow the two parties to select mutually agreeable supporting algorithms for the protocol: the encryption method, the key derivation method, and the authentication method.

Thirdly, the authentication does not depend on encryption using the Diffie-Hellman exponentials; instead, the authentication validates the binding of the exponentials to the identities of the parties.

The protocol does not require the two parties compute the shared exponentials prior to authentication.

This protocol adds additional security to the derivation of keys meant for use with encryption (as opposed to authentication) by including a dependence on an additional algorithm. The derivation of keys for encryption is made to depend not only on the Diffie-Hellman algorithm, but also on the cryptographic method used to securely authenticate the communicating parties to each other.

Finally, this protocol explicitly defines how the two parties can select the mathematical structures (group representation and operation) for performing the Diffie-Hellman algorithm; they can use standard groups or define their own. User-defined groups provide an additional degree of long-term security.

OAKLEY has several options for distributing keys. In addition to the classic Diffie-Hellman exchange, this protocol can be used to derive a new key from an existing key and to distribute an externally derived key by encrypting it.

The protocol allows two parties to use all or some of the anti-clogging and perfect forward secrecy features. It also permits the use of authentication based on symmetric encryption or non-encryption algorithms. This flexibility is included in order to allow the parties to use the features that are best suited to their security and performance requirements.

This document draws extensively in spirit and approach from the Photuris work in progress by Karn and Simpson (and from discussions with the authors), specifics of the ISAKMP document by Schertler et al. the ISAKMP protocol document, and it was also influenced by papers by Paul van Oorschot and Hugo Krawcyzk.

2. The Protocol Outline

2.1 General Remarks

The OAKLEY protocol is used to establish a shared key with an assigned identifier and associated authenticated identities for the two parties. The name of the key can be used later to derive security associations for the RFC 2402 and RFC 2406 protocols (AH and ESP) or to achieve other network security goals.

Each key is associated with algorithms that are used for authentication, privacy, and one-way functions. These are ancillary algorithms for OAKLEY; their appearance in subsequent security association definitions derived with other protocols is neither required nor prohibited.

The specification of the details of how to apply an algorithm to data is called a transform. This document does not supply the transform definitions; they will be in separate RFC’s.

The anti-clogging tokens, or "cookies", provide a weak form of source address identification for both parties; the cookie exchange can be completed before they perform the computationally expensive part of the protocol (large integer exponentiations).

It is important to note that OAKLEY uses the cookies for two purposes: anti-clogging and key naming. The two parties to the protocol each contribute one cookie at the initiation of key establishment; the pair of cookies becomes the key identifier (KEYID), a reusable name for the keying material. Because of this

dual role, we will use the notation for the concatenation of the cookies ("COOKIE-I, COOKIE-R") interchangeably with the symbol "KEYID".

OAKLEY is designed to be a compatible component of the ISAKMP protocol [ISAKMP], which runs over the UDP protocol using a well-known port (see the RFC on port assignments, STD02-RFC-1700). The only technical requirement for the protocol environment is that the underlying protocol stack must be able to supply the Internet address of the remote party for each message. Thus, OAKLEY could, in theory, be used directly over the IP protocol or over UDP, if suitable protocol or port number assignments were available.

The machine running OAKLEY must provide a good random number generator, as described in [RANDOM], as the source of random numbers required in this protocol description. Any mention of a "nonce" implies that the nonce value is generated by such a generator. The same is true for "pseudorandom" values.

2.2 Notation

The section describes the notation used in this document for message sequences and content.

2.2.1 Message descriptions

The protocol exchanges below are written in an abbreviated notation that is intended to convey the essential elements of the exchange in a clear manner. A brief guide to the notation follows. The detailed formats and assigned values are given in the appendices.

In order to represent message exchanges succinctly, this document uses an abbreviated notation that describes each message in terms of its source and destination and relevant fields.

Arrows ("->") indicate whether the message is sent from the initiator to the responder, or vice versa ("<-").

The fields in the message are named and comma separated. The protocol uses the convention that the first several fields constitute a fixed header format for all messages.

For example, consider a HYPOTHETICAL exchange of messages involving a fixed format message, the four fixed fields being two "cookies", the third field being a message type name, the fourth field being a multi-precision integer representing a power of a number:

```
      Initiator                                          Responder
          ->    Cookie-I, 0, OK_KEYX, g^x                    ->
          <-    Cookie-R, Cookie-I, OK_KEYX, g^y             <-
```

The notation describes a two message sequence. The initiator begins by sending a message with 4 fields to the responder; the first field has the unspecified value "Cookie-I", second field has the numeric value 0, the third field indicates the message type is OK_KEYX, the fourth value is an abstract group element g to the x'th power.

The second line indicates that the responder replies with value "Cookie-R" in the first field, a copy of the "Cookie-I" value in the second field, message type OK_KEYX, and the number g raised to the y'th power.

The value OK_KEYX is in capitals to indicate that it is a unique constant (constants are defined in the appendices).

Variable precision integers with length zero are null values for the protocol.

Sometimes the protocol will indicate that an entire payload (usually the Key Exchange Payload) has null values. The payload is still present in the message, for the purpose of simplifying parsing.

2.2.2 Guide to symbols

Cookie-I and Cookie-R (or CKY-I and CKY-R) are 64-bit pseudo-random numbers. The generation method must ensure with high probability that the numbers used for each IP remote address are unique over some time period, such as one hour.

KEYID is the concatenation of the initiator and responder cookies and the domain of interpretation; it is the name of keying material.

sKEYID is used to denote the keying material named by the KEYID. It is never transmitted, but it is used in various calculations performed by the two parties.

OK_KEYX and OK_NEWGRP are distinct message types.

IDP is a bit indicating whether or not material after the encryption boundary (see appendix B), is encrypted. NIDP means not encrypted.

g^x and g^y are encodings of group elements, where g is a special group element indicated in the group description (see Appendix A) and g^x indicates that element raised to the x'th power. The type of the encoding is either a variable precision integer or a pair of such

integers, as indicated in the group operation in the group description. Note that we will write g^xy as a short-hand for g^(xy). See Appendix F for references that describe implementing large integer computations and the relationship between various group definitions and basic arithmetic operations.

EHAO is a list of encryption/hash/authentication choices. Each item is a pair of values: a class name and an algorithm name.

EHAS is a set of three items selected from the EHAO list, one from each of the classes for encryption, hash, authentication.

GRP is a name (32-bit value) for the group and its relevant parameters: the size of the integers, the arithmetic operation, and the generator element. There are a few pre-defined GRP's (for 768 bit modular exponentiation groups, 1024 bit modexp, 2048 bit modexp, 155-bit and 210-bit elliptic curves, see Appendix E), but participants can share other group descriptions in a later protocol stage (see the section NEW GROUP). It is important to separate notion of the GRP from the group descriptor (Appendix A); the former is a name for the latter.

The symbol vertical bar "|" is used to denote concatenation of bit strings. Fields are concatenated using their encoded form as they appear in their payload.

Ni and Nr are nonces selected by the initiator and responder, respectively.

ID(I) and ID(R) are the identities to be used in authenticating the initiator and responder respectively.

E{x}Ki indicates the encryption of x using the public key of the initiator. Encryption is done using the algorithm associated with the authentication method; usually this will be RSA.

S{x}Ki indicates the signature over x using the private key (signing key) of the initiator. Signing is done using the algorithm associated with the authentication method; usually this will be RSA or DSS.

prf(a, b) denotes the result of applying pseudo-random function "a" to data "b". One may think of "a" as a key or as a value that characterizes the function prf; in the latter case it is the index into a family of functions. Each function in the family provides a "hash" or one-way mixing of the input.

prf(0, b) denotes the application of a one-way function to data "b".

The similarity with the previous notation is deliberate and indicates that a single algorithm, e.g. MD5, might will used for both purposes. In the first case a "keyed" MD5 transform would be used with key "a"; in the second case the transform would have the fixed key value zero, resulting in a one-way function.

The term "transform" is used to refer to functions defined in auxiliary RFC's. The transform RFC's will be drawn from those defined for IPSEC AH and ESP (see RFC 2401 for the overall architecture encompassing these protocols).

2.3 The Key Exchange Message Overview

The goal of key exchange processing is the secure establishment of common keying information state in the two parties. This state information is a key name, secret keying material, the identification of the two parties, and three algorithms for use during authentication: encryption (for privacy of the identities of the two parties), hashing (a pseudorandom function for protecting the integrity of the messages and for authenticating message fields), and authentication (the algorithm on which the mutual authentication of the two parties is based). The encodings and meanings for these choices are presented in Appendix B.

The main mode exchange has five optional features: stateless cookie exchange, perfect forward secrecy for the keying material, secrecy for the identities, perfect forward secrecy for identity secrecy, use of signatures (for non-repudiation). The two parties can use any combination of these features.

The general outline of processing is that the Initiator of the exchange begins by specifying as much information as he wishes in his first message. The Responder replies, supplying as much information as he wishes. The two sides exchange messages, supplying more information each time, until their requirements are satisfied.

The choice of how much information to include in each message depends on which options are desirable. For example, if stateless cookies are not a requirement, and identity secrecy and perfect forward secrecy for the keying material are not requirements, and if non-repudiatable signatures are acceptable, then the exchange can be completed in three messages.

Additional features may increase the number of roundtrips needed for the keying material determination.

ISAKMP provides fields for specifying the security association parameters for use with the AH and ESP protocols. These security

association payload types are specified in the ISAKMP memo; the payload types can be protected with OAKLEY keying material and algorithms, but this document does not discuss their use.

2.3.1 The Essential Key Exchange Message Fields

There are 12 fields in an OAKLEY key exchange message. Not all the fields are relevant in every message; if a field is not relevant it can have a null value or not be present (no payload).

CKY-I	originator cookie.
CKY-R	responder cookie.
MSGTYPE	for key exchange, will be ISA_KE&AUTH_REQ or ISA_KE&AUTH_REP; for new group definitions, will be ISA_NEW_GROUP_REQ or ISA_NEW_GROUP_REP
GRP	the name of the Diffie-Hellman group used for the exchange
g^x (or g^y)	variable length integer representing a power of group generator
EHAO or EHAS	encryption, hash, authentication functions, offered and selectedj, respectively
IDP	an indicator as to whether or not encryption with g^xy follows (perfect forward secrecy for ID's)
ID(I)	the identity for the Initiator
ID(R)	the identity for the Responder
Ni	nonce supplied by the Initiator
Nr	nonce supplied by the Responder

The construction of the cookies is implementation dependent. Phil Karn has recommended making them the result of a one-way function applied to a secret value (changed periodically), the local and remote IP address, and the local and remote UDP port. In this way, the cookies remain stateless and expire periodically. Note that with OAKLEY, this would cause the KEYID's derived from the secret value to also expire, necessitating the removal of any state information associated with it.

In order to support pre-distributed keys, we recommend that implementations reserve some portion of their cookie space to permanent keys. The encoding of these depends only on the local implementation.

The encryption functions used with OAKLEY must be cryptographic transforms which guarantee privacy and integrity for the message data. Merely using DES in CBC mode is not permissible. The MANDATORY and OPTIONAL transforms will include any that satisfy this criteria and are defined for use with RFC 2406 (ESP).

The one-way (hash) functions used with OAKLEY must be cryptographic transforms which can be used as either keyed hash (pseudo-random) or non-keyed transforms. The MANDATORY and OPTIONAL transforms will include any that are defined for use with RFC 2406 (AH).

Where nonces are indicated, they will be variable precision integers with an entropy value that matches the "strength" attribute of the GRP used with the exchange. If no GRP is indicated, the nonces must be at least 90 bits long. The pseudo-random generator for the nonce material should start with initial data that has at least 90 bits of entropy; see RFC 1750.

2.3.1.1 Exponent Advice

Ideally, the exponents will have at least 180 bits of entropy for every key exchange. This ensures complete independence of keying material between two exchanges (note that this applies if only one of the parties chooses a random exponent). In practice, implementors may wish to base several key exchanges on a single base value with 180 bits of entropy and use one-way hash functions to guarantee that exposure of one key will not compromise others. In this case, a good recommendation is to keep the base values for nonces and cookies separate from the base value for exponents, and to replace the base value with a full 180 bits of entropy as frequently as possible.

The values 0 and p-1 should not be used as exponent values; implementors should be sure to check for these values, and they should also refuse to accept the values 1 and p-1 from remote parties (where p is the prime used to define a modular exponentiation group).

2.3.2 Mapping to ISAKMP Message Structures

All the OAKLEY message fields correspond to ISAKMP message payloads or payload components. The relevant payload fields are the SA payload, the AUTH payload, the Certificate Payload, the Key Exchange Payload. The ISAKMP protocol framwork is a work in progress at this time, and the exact mapping of Oakley message fields to ISAKMP payloads is also in progress (to be known as the Resolution document).

Some of the ISAKMP header and payload fields will have constant values when used with OAKLEY. The exact values to be used will be published in a Domain of Interpretation document accompanying the Resolution document.

In the following we indicate where each OAKLEY field appears in the ISAKMP message structure. These are recommended only; the Resolution document will be the final authority on this mapping.

CKY-I	ISAKMP header
CKY-R	ISAKMP header
MSGTYPE	Message Type in ISAKMP header
GRP	SA payload, Proposal section
g^x (or g^y)	Key Exchange Payload, encoded as a variable precision integer
EHAO and EHAS	SA payload, Proposal section
IDP	A bit in the RESERVED field in the AUTH header
ID(I)	AUTH payload, Identity field
ID(R)	AUTH payload, Identity field
Ni	AUTH payload, Nonce Field
Nr	AUTH payload, Nonce Field
S{...}Kx	AUTH payload, Data Field
prf{K,...}	AUTH payload, Data Field

2.4 The Key Exchange Protocol

The exact number and content of messages exchanged during an OAKLEY key exchange depends on which options the Initiator and Responder want to use. A key exchange can be completed with three or more messages, depending on those options.

The three components of the key determination protocol are the

1. cookie exchange (optionally stateless)
2. Diffie-Hellman half-key exchange (optional, but essential for perfect forward secrecy)
3. authentication (options: privacy for ID's, privacy for ID's with PFS, non-repudiatable)

The initiator can supply as little information as a bare exchange request, carrying no additional information. On the other hand the initiator can begin by supplying all of the information necessary for the responder to authenticate the request and complete the key determination quickly, if the responder chooses to accept this method. If not, the responder can reply with a minimal amount of information (at the minimum, a cookie).

The method of authentication can be digital signatures, public key encryption, or an out-of-band symmetric key. The three different methods lead to slight variations in the messages, and the variations are illustrated by examples in this section.

The Initiator is responsible for retransmitting messages if the protocol does not terminate in a timely fashion. The Responder must therefore avoid discarding reply information until it is acknowledged by Initiator in the course of continuing the protocol.

The remainder of this section contains examples demonstrating how to use OAKLEY options.

2.4.1 An Aggressive Example

The following example indicates how two parties can complete a key exchange in three messages. The identities are not secret, the derived keying material is protected by PFS.

By using digital signatures, the two parties will have a proof of communication that can be recorded and presented later to a third party.

The keying material implied by the group exponentials is not needed for completing the exchange. If it is desirable to defer the computation, the implementation can save the "x" and "g^y" values and mark the keying material as "uncomputed". It can be computed from this information later.

```
Initiator                                                  Responder
---------                                                  ---------
  -> CKY-I, 0,     OK_KEYX, GRP, g^x, EHAO, NIDP,              ->
     ID(I), ID(R), Ni, 0,
     S{ID(I) | ID(R) | Ni | 0 | GRP | g^x | 0 | EHAO}Ki
 <-  CKY-R, CKY-I, OK_KEYX, GRP, g^y, EHAS, NIDP,
     ID(R), ID(I), Nr, Ni,
     S{ID(R) | ID(I) | Nr | Ni | GRP | g^y | g^x | EHAS}Kr     <-
  -> CKY-I, CKY-R, OK_KEYX, GRP, g^x, EHAS, NIDP,              ->
     ID(I), ID(R), Ni, Nr,
     S{ID(I) | ID(R) | Ni | Nr | GRP | g^x | g^y | EHAS}Ki
```

NB "NIDP" means that the PFS option for hiding identities is not used.
i.e., the identities are not encrypted using a key based on g^xy

NB Fields are shown separated by commas in this document; they are concatenated in the actual protocol messages using their encoded forms as specified in the ISAKMP/Oakley Resolution document.

The result of this exchange is a key with KEYID = CKY-I|CKY-R and value

sKEYID = prf(Ni | Nr, g^xy | CKY-I | CKY-R).

The processing outline for this exchange is as follows:

Initiation

The Initiator generates a unique cookie and associates it with the expected IP address of the responder, and its chosen state information: GRP (the group identifier), a pseudo-randomly selected exponent x, g^x, EHAO list, nonce, identities. The first authentication choice in the EHAO list is an algorithm that supports digital signatures, and this is used to sign the ID's and the nonce and group id. The Initiator further

notes that the key is in the initial state of "unauthenticated", and

sets a timer for possible retransmission and/or termination of the request.

When the Responder receives the message, he may choose to ignore all the information and treat it as merely a request for a cookie, creating no state. If CKY-I is not already in use by the source address in the IP header, the responder generates a unique cookie, CKY-R. The next steps depend on the Responder's preferences. The minimal required response is to reply with the first cookie field set to zero and CKY-R in the second field. For this example we will assume that the responder is more aggressive (for the alternatives, see section 6) and accepts the following:

group with identifier GRP,
first authentication choice (which must be the digital signature method used to sign the Initiator message),
lack of perfect forward secrecy for protecting the identities,
identity ID(I) and identity ID(R)

In this example the Responder decides to accept all the information offered by the initiator. It validates the signature over the signed portion of the message, and associate the pair (CKY-I, CKY-R) with the following state information:

the source and destination network addresses of the message

key state of "unauthenticated"

the first algorithm from the authentication offer

group GRP, a "y" exponent value in group GRP, and g^x from the message

the nonce Ni and a pseudorandomly selected value Nr

a timer for possible destruction of the state.

The Responder computes g^y, forms the reply message, and then signs the ID and nonce information with the private key of ID(R) and sends it to the Initiator. In all exchanges, each party should make sure that he neither offers nor accepts 1 or g^(p-1) as an exponential.

In this example, to expedite the protocol, the Responder implicitly accepts the first algorithm in the Authentication class of the EHAO list. This because he cannot validate the Initiator signature without accepting the algorithm for doing the signature. The Responder's EHAS list will also reflect his acceptance.

The Initiator receives the reply message and
validates that CKY-I is a valid association for the network address of the incoming message,

adds the CKY-R value to the state for the pair (CKY-I, network address), and associates all state information with the pair (CKY-I, CKY-R),

validates the signature of the responder over the state information (should validation fail, the message is discarded)

adds g^y to its state information,

saves the EHA selections in the state,

optionally computes (g^y)^x (= g^xy) (this can be deferred until after sending the reply message),

sends the reply message, signed with the public key of ID(I),

marks the KEYID (CKY-I|CKY-R) as authenticated,

and composes the reply message and signature.

When the Responder receives the Initiator message, and if the signature is valid, it marks the key as being in the authenticated state. It should compute g^xy and associate it with the KEYID.

Note that although PFS for identity protection is not used, PFS for the derived keying material is still present because the Diffie-Hellman half-keys g^x and g^y are exchanged.

Even if the Responder only accepts some of the Initiator information, the Initiator will consider the protocol to be progressing. The Initiator should assume that fields that were not accepted by the

Responder were not recorded by the Responder.

If the Responder does not accept the aggressive exchange and selects another algorithm for the A function, then the protocol will not continue using the signature algorithm or the signature value from the first message.

2.4.1.1 Fields Not Present

If the Responder does not accept all the fields offered by the Initiator, he should include null values for those fields in his response. Section 6 has guidelines on how to select fields in a "left-to-right" manner. If a field is not accepted, then it and all following fields must have null values.

The Responder should not record any information that it does not accept. If the ID's and nonces have null values, there will not be a signature over these null values.

2.4.1.2 Signature via Pseudo-Random Functions

The aggressive example is written to suggest that public key technology is used for the signatures. However, a pseudorandom function can be used, if the parties have previously agreed to such a scheme and have a shared key.

If the first proposal in the EHAO list is an "existing key" method, then the KEYID named in that proposal will supply the keying material for the "signature" which is computed using the "H" algorithm associated with the KEYID.

Suppose the first proposal in EHAO is
EXISTING-KEY, 32
and the "H" algorithm for KEYID 32 is MD5-HMAC, by prior negotiation. The keying material is some string of bits, call it sK32. Then in the first message in the aggressive exchange, where the signature

S{ID(I), ID(R), Ni, 0, GRP, g^x, EHAO}Ki

is indicated, the signature computation would be performed by
MD5-HMAC_func(KEY=sK32, DATA = ID(I) | ID(R) | Ni | 0 | GRP | g^x | g^y | EHAO) (The exact definition of the algorithm corresponding to "MD5-HMAC- func" will appear in the RFC defining that transform).

The result of this computation appears in the Authentication payload.

2.4.2 An Aggressive Example With Hidden Identities

The following example indicates how two parties can complete a key exchange without using digital signatures. Public key cryptography hides the identities during authentication. The group exponentials are exchanged and authenticated, but the implied keying material (g^xy) is not needed during the exchange.

This exchange has an important difference from the previous signature scheme --- in the first message, an identity for the responder is indicated as cleartext: ID(R'). However, the identity hidden with the public key cryptography is different: ID(R). This happens because the Initiator must somehow tell the Responder which public/private key pair to use for the decryption, but at the same time, the identity is hidden by encryption with that public key.

The Initiator might elect to forgo secrecy of the Responder identity, but this is undesirable. Instead, if there is a well-known identity for the Responder node, the public key for that identity can be used to encrypt the actual Responder identity.

```
Initiator                                                  Responder
---------                                                  ---------
  -> CKY-I, 0,     OK_KEYX, GRP, g^x, EHAO, NIDP,                ->
     ID(R'), E{ID(I), ID(R), E{Ni}Kr}Kr'
 <-  CKY-R, CKY-I, OK_KEYX, GRP, g^y, EHAS, NIDP,
     E{ID(R), ID(I), Nr}Ki,
     prf(Kir, ID(R) | ID(I) | GRP | g^y | g^x | EHAS) <-
  -> CKY-I, CKY-R, OK_KEYX, GRP, 0, 0, NIDP,
     prf(Kir, ID(I) | ID(R) | GRP | g^x | g^y | EHAS)    ->
```

Kir = prf(0, Ni | Nr)

NB "NIDP" means that the PFS option for hiding identities is not used.

NB The ID(R') value is included in the Authentication payload as described in Appendix B.

The result of this exchange is a key with KEYID = CKY-I|CKY-R and value sKEYID = prf(Ni | Nr, g^xy | CKY-I | CKY-R).

The processing outline for this exchange is as follows:

Initiation

The Initiator generates a unique cookie and associates it with the expected IP address of the responder, and its chosen state information: GRP, g^x, EHAO list. The first authentication choice in the EHAO list is an algorithm that supports public key

encryption. The Initiator also names the two identities to be used for the connection and enters these into the state. A well-known identity for the responder machine is also chosen, and the public key for this identity is used to encrypt the nonce Ni and the two connection identities. The Initiator further

notes that the key is in the initial state of "unauthenticated", and

sets a timer for possible retransmission and/or termination of the request.

When the Responder receives the message, he may choose to ignore all the information and treat it as merely a request for a cookie, creating no state.

If CKY-I is not already in use by the source address in the IP header, the Responder generates a unique cookie, CKY-R. As before, the next steps depend on the responder's preferences. The minimal required response is a message with the first cookie field set to zero and CKY-R in the second field. For this example we will assume that responder is more aggressive and accepts the following:

group GRP, first authentication choice (which must be the public key encryption algorithm used to encrypt the payload), lack of perfect forward secrecy for protecting the identities, identity ID(I), identity ID(R)

The Responder must decrypt the ID and nonce information, using the private key for the R' ID. After this, the private key for the R ID will be used to decrypt the nonce field.

The Responder now associates the pair (CKY-I, CKY-R) with the following state information:

the source and destination network addresses of the message

key state of "unauthenticated"

the first algorithm from each class in the EHAO (encryption-hash-authentication algorithm offers) list

group GRP and a y and g^y value in group GRP

the nonce Ni and a pseudorandomly selected value Nr

a timer for possible destruction of the state.

The Responder then encrypts the state information with the public key of ID(I), forms the prf value, and sends it to the Initiator.

The Initiator receives the reply message and
validates that CKY-I is a valid association for the network address of the incoming message,

adds the CKY-R value to the state for the pair (CKY-I, network address), and associates all state information with the pair (CKY-I, CKY-R),

decrypts the ID and nonce information

checks the prf calculation (should this fail, the message is discarded)

adds g^y to its state information,

saves the EHA selections in the state,

optionally computes (g^x)^y (= g^xy) (this may be deferred), and

sends the reply message, encrypted with the public key of ID(R),

and marks the KEYID (CKY-I|CKY-R) as authenticated.

When the Responder receives this message, it marks the key as being in the authenticated state. If it has not already done so, it should compute g^xy and associate it with the KEYID.

The secret keying material sKEYID = prf(Ni | Nr, g^xy | CKY-I | CKY-R)

Note that although PFS for identity protection is not used, PFS for the derived keying material is still present because the Diffie-Hellman half-keys g^x and g^y are exchanged.

2.4.3 An Aggressive Example With Private Identities and Without Diffie-Hellman

Considerable computational expense can be avoided if perfect forward secrecy is not a requirement for the session key derivation. The two parties can exchange nonces and secret key parts to achieve the authentication and derive keying material. The long-term privacy of data protected with derived keying material is dependent on the private keys of each of the parties.

In this exchange, the GRP has the value 0 and the field for the group exponential is used to hold a nonce value instead.

As in the previous section, the first proposed algorithm must be a public key encryption system; by responding with a cookie and a non-zero exponential field, the Responder implicitly accepts the first proposal and the lack of perfect forward secrecy for the identities and derived keying material.

```
Initiator                                                  Responder
---------                                                  ---------
  -> CKY-I, 0,     OK_KEYX, 0, 0, EHAO, NIDP,                 ->
     ID(R'), E{ID(I), ID(R), sKi}Kr', Ni
 <-  CKY-R, CKY-I, OK_KEYX, 0, 0, EHAS, NIDP,
     E{ID(R), ID(I), sKr}Ki, Nr,
     prf(Kir, ID(R) | ID(I) | Nr | Ni | EHAS)                <-
  -> CKY-I, CKY-R, OK_KEYX, EHAS, NIDP,
     prf(Kir, ID(I) | ID(R) | Ni | Nr | EHAS)                 ->
```

Kir = prf(0, sKi | sKr)

NB The sKi and sKr values go into the nonce fields. The change in notation is meant to emphasize that their entropy is critical to setting the keying material.

NB "NIDP" means that the PFS option for hiding identities is not used.

The result of this exchange is a key with KEYID = CKY-I|CKY-R and value sKEYID = prf(Kir, CKY-I | CKY-R).

2.4.3 A Conservative Example

In this example the two parties are minimally aggressive; they use the cookie exchange to delay creation of state, and they use perfect forward secrecy to protect the identities. For this example, they use public key encryption for authentication; digital signatures or pre-shared keys can also be used, as illustrated previously. The conservative example here does not change the use of nonces, prf's, etc., but it does change how much information is transmitted in each message.

The responder considers the ability of the initiator to repeat CKY-R as weak evidence that the message originates from a "live" correspondent on the network and the correspondent is associated with the initiator's network address. The initiator makes similar assumptions when CKY-I is repeated to the initiator.

All messages must have either valid cookies or at least one zero cookie. If both cookies are zero, this indicates a request for a cookie; if only the initiator cookie is zero, it is a response to a cookie request.

Information in messages violating the cookie rules cannot be used for any OAKLEY operations.

Note that the Initiator and Responder must agree on one set of EHA algorithms; there is not one set for the Responder and one for the Initiator. The Initiator must include at least MD5 and DES in the initial offer.

Fields not indicated have null values.

```
Initiator                                                  Responder
---------                                                  ---------
  ->     0, 0, OK_KEYX                                        ->
 <-      0, CKY-R, OK_KEYX                                   <-
  ->     CKY-I, CKY-R, OK_KEYX, GRP, g^x, EHAO                ->
 <-      CKY-R, CKY-I, OK_KEYX, GRP, g^y, EHAS               <-
  ->     CKY-I, CKY-R, OK_KEYX, GRP, g^x, IDP*,
         ID(I), ID(R), E{Ni}Kr,                               ->
 <-      CKY-R, CKY-I, OK_KEYX, GRP, 0  , 0, IDP,            <-
         E{Nr, Ni}Ki, ID(R), ID(I),
         prf(Kir, ID(R) | ID(I) | GRP | g^y | g^x | EHAS )
  ->     CKY-I, CKY-R, OK_KEYX, GRP, 0  , 0, IDP,
         prf(Kir, ID(I) | ID(R) | GRP | g^x | g^y | EHAS ) ->
```

Kir = prf(0, Ni | Nr)

* when IDP is in effect, authentication payloads are encrypted with the selected encryption algorithm using the keying material prf(0, g^xy). (The transform defining the encryption algorithm will define how to select key bits from the keying material.) This encryption is in addition to and after any public key encryption. See Appendix B.

  Note that in the first messages, several fields are omitted from the description. These fields are present as null values.

The first exchange allows the Responder to use stateless cookies; if the responder generates cookies in a manner that allows him to validate them without saving them, as in Photuris, then this is possible. Even if the Initiator includes a cookie in his initial request, the responder can still use stateless cookies by merely omitting the CKY-I from his reply and by declining to record the Initiator cookie until it appears in a later message.

After the exchange is complete, both parties compute the shared key material sKEYID as prf(Ni | Nr, g^xy | CKY-I | CKY-R) where "prf" is the pseudo-random function in class "hash" selected in the EHA list.

As with the cookies, each party considers the ability of the remote side to repeat the Ni or Nr value as a proof that Ka, the public key of party a, speaks for the remote party and establishes its identity.

In analyzing this exchange, it is important to note that although the IDP option ensures that the identities are protected with an ephemeral key g^xy, the authentication itself does not depend on g^xy. It is essential that the authentication steps validate the g^x and g^y values, and it is thus imperative that the authentication not involve a circular dependency on them. A third party could intervene with a "man-in-middle" scheme to convince the initiator and responder to use different g^xy values; although such an attack might result in revealing the identities to the eavesdropper, the authentication would fail.

2.4.4 Extra Strength for Protection of Encryption Keys

The nonces Ni and Nr are used to provide an extra dimension of secrecy in deriving session keys. This makes the secrecy of the key depend on two different problems: the discrete logarithm problem in the group G, and the problem of breaking the nonce encryption scheme. If RSA encryption is used, then this second problem is roughly equivalent to factoring the RSA public keys of both the initiator and responder.

For authentication, the key type, the validation method, and the certification requirement must be indicated.

2.5 Identity and Authentication

2.5.1 Identity

In OAKLEY exchanges the Initiator offers Initiator and Responder ID’s -- the former is the claimed identity for the Initiator, and the latter is the requested ID for the Responder.

If neither ID is specified, the ID’s are taken from the IP header source and destination addresses.

If the Initiator doesn’t supply a responder ID, the Responder can reply by naming any identity that the local policy allows. The Initiator can refuse acceptance by terminating the exchange.

The Responder can also reply with a different ID than the Initiator suggested; the Initiator can accept this implicitly by continuing the exchange or refuse it by terminating (not replying).

2.5.2 Authentication

The authentication of principals to one another is at the heart of any key exchange scheme. The Internet community must decide on a scalable standard for solving this problem, and OAKLEY must make use of that standard. At the time of this writing, there is no such standard, though several are emerging. This document attempts to describe how a handful of standards could be incorporated into OAKLEY, without attempting to pick and choose among them.

The following methods can appear in OAKLEY offers:

a. Pre-shared Keys
   When two parties have arranged for a trusted method of distributing secret keys for their mutual authentication, they can be used for authentication. This has obvious scaling problems for large systems, but it is an acceptable interim solution for some situations. Support for pre-shared keys is REQUIRED.

   The encryption, hash, and authentication algorithm for use with a pre-shared key must be part of the state information distributed with the key itself.

   The pre-shared keys have a KEYID and keying material sKEYID; the KEYID is used in a pre-shared key authentication option offer. There can be more than one pre-shared key offer in a list.

   Because the KEYID persists over different invocations of OAKLEY (after a crash, etc.), it must occupy a reserved part of the KEYID space for the two parties. A few bits can be set aside in each party's "cookie space" to accommodate this.

   There is no certification authority for pre-shared keys. When a pre-shared key is used to generate an authentication payload, the certification authority is "None", the Authentication Type is "Preshared", and the payload contains

      the KEYID, encoded as two 64-bit quantities, and the result of applying the pseudorandom hash function to the message body with the sKEYID forming the key for the function

b. DNS public keys
Security extensions to the DNS protocol [DNSSEC] provide a convenient way to access public key information, especially for public keys associated with hosts. RSA keys are a requirement for secure DNS implementations; extensions to allow optional DSS keys are a near-term possibility.

DNS KEY records have associated SIG records that are signed by a zone authority, and a hierarchy of signatures back to the root server establishes a foundation for trust. The SIG records indicate the algorithm used for forming the signature.

OAKLEY implementations must support the use of DNS KEY and SIG records for authenticating with respect to IPv4 and IPv6 addresses and fully qualified domain names. However, implementations are not required to support any particular algorithm (RSA, DSS, etc.).

c. RSA public keys w/o certification authority signature PGP [Zimmerman] uses public keys with an informal method for establishing trust. The format of PGP public keys and naming methods will be described in a separate RFC. The RSA algorithm can be used with PGP keys for either signing or encryption; the authentication option should indicate either RSA-SIG or RSA-ENC, respectively. Support for this is OPTIONAL.

d.1 RSA public keys w/ certificates There are various formats and naming conventions for public keys that are signed by one or more certification authorities. The Public Key Interchange Protocol discusses X.509 encodings and validation. Support for this is OPTIONAL.

d.2 DSS keys w/ certificates Encoding for the Digital Signature Standard with X.509 is described in draft-ietf-ipsec-dss-cert-00.txt. Support for this is OPTIONAL; an ISAKMP Authentication Type will be assigned.

2.5.3 Validating Authentication Keys

The combination of the Authentication algorithm, the Authentication Authority, the Authentication Type, and a key (usually public) define how to validate the messages with respect to the claimed identity. The key information will be available either from a pre-shared key, or from some kind of certification authority.

Generally the certification authority produces a certificate binding the entity name to a public key. OAKLEY implementations must be prepared to fetch and validate certificates before using the public key for OAKLEY authentication purposes.

The ISAKMP Authentication Payload defines the Authentication Authority field for specifying the authority that must be apparent in the trust hierarchy for authentication.

Once an appropriate certificate is obtained (see 2.4.3), the validation method will depend on the Authentication Type; if it is PGP then the PGP signature validation routines can be called to satisfy the local web-of-trust predicates; if it is RSA with X.509 certificates, the certificate must be examined to see if the certification authority signature can be validated, and if the hierarchy is recognized by the local policy.

2.5.4 Fetching Identity Objects

In addition to interpreting the certificate or other data structure that contains an identity, users of OAKLEY must face the task of retrieving certificates that bind a public key to an identifier and also retrieving auxiliary certificates for certifying authorities or co-signers (as in the PGP web of trust).

The ISAKMP Credentials Payload can be used to attach useful certificates to OAKLEY messages. The Credentials Payload is defined in Appendix B.

Support for accessing and revoking public key certificates via the Secure DNS protocol [SECDNS] is MANDATORY for OAKLEY implementations. Other retrieval methods can be used when the AUTH class indicates a preference.

The Public Key Interchange Protocol discusses a full protocol that might be used with X.509 encoded certificates.

2.6 Interface to Cryptographic Transforms

The keying material computed by the key exchange should have at least 90 bits of entropy, which means that it must be at least 90 bits in length. This may be more or less than is required for keying the encryption and/or pseudorandom function transforms.

The transforms used with OAKLEY should have auxiliary algorithms which take a variable precision integer and turn it into keying material of the appropriate length. For example, a DES algorithm could take the low order 56 bits, a triple DES algorithm might use the following:

```
K1 = low 56 bits of md5(0|sKEYID)
K2 = low 56 bits of md5(1|sKEYID)
K3 = low 56 bits of md5(2|sKEYID)
```

The transforms will be called with the keying material encoded as a variable precision integer, the length of the data, and the block of memory with the data. Conversion of the keying material to a transform key is the responsibility of the transform.

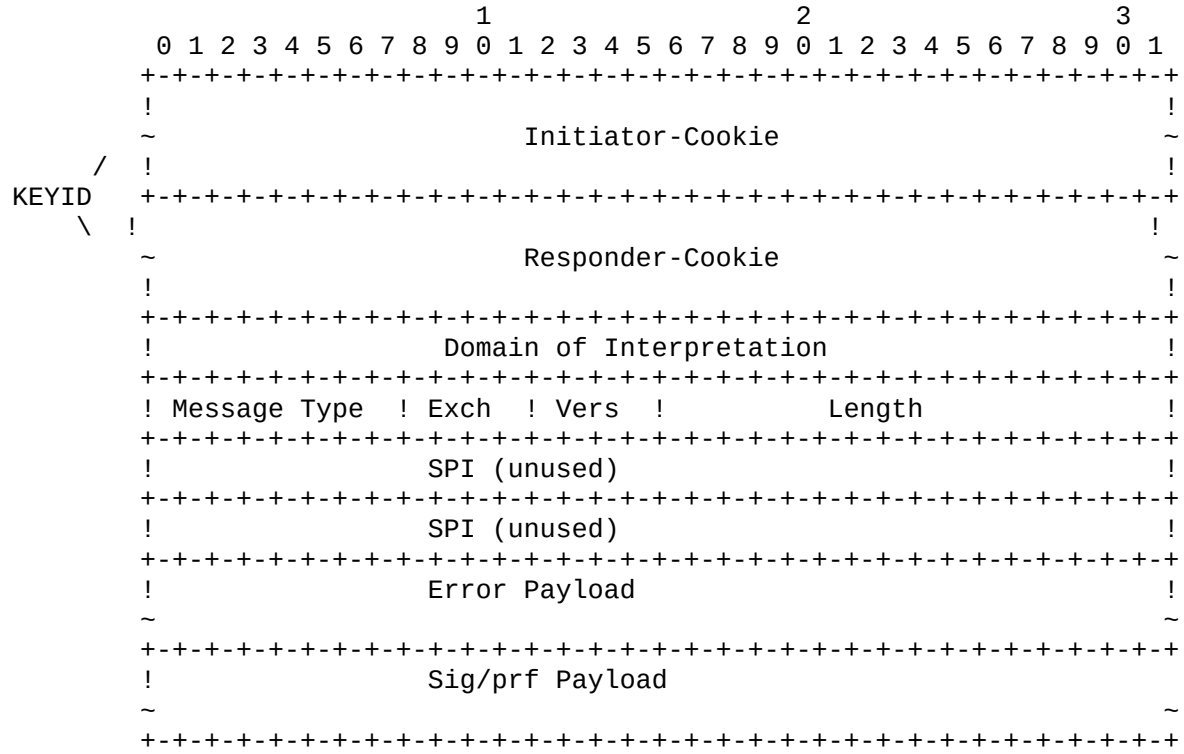
2.7 Retransmission, Timeouts, and Error Messages

If a response from the Responder is not elicited in an appropriate amount of time, the message should be retransmitted by the Initiator. These retransmissions must be handled gracefully by both parties; the Responder must retain information for retransmitting until the Initiator moves to the next message in the protocol or completes the exchange.

Informational error messages present a problem because they cannot be authenticated using only the information present in an incomplete exchange; for this reason, the parties may wish to establish a default key for OAKLEY error messages. A possible method for establishing such a key is described in Appendix B, under the use of ISA_INIT message types.

In the following the message type is OAKLEY Error, the KEYID supplies the H algorithm and key for authenticating the message contents; this value is carried in the Sig/Prf payload.

The Error payload contains the error code and the contents of the rejected message.



The error message will contain the cookies as presented in the offending message, the message type OAKLEY_ERROR, and the reason for the error, followed by the rejected message.

Error messages are informational only, and the correctness of the protocol does not depend on them.

Error reasons:

TIMEOUT	exchange has taken too long, state destroyed
AEH_ERROR	an unknown algorithm appears in an offer
GROUP_NOT_SUPPORTED	GRP named is not supported
EXPONENTIAL_UNACCEPTABLE	exponential too large/small or is +-1
SELECTION_NOT_OFFERED	selection does not occur in offer
NO_ACCEPTABLE_OFFERS	no offer meets host requirements
AUTHENTICATION_FAILURE	signature or hash function fails
RESOURCE_EXCEEDED	too many exchanges or too much state info
NO_EXCHANGE_IN_PROGRESS	a reply received with no request in progress

2.8 Additional Security for Privacy Keys: Private Groups

If the two parties have need to use a Diffie-Hellman key determination scheme that does not depend on the standard group definitions, they have the option of establishing a private group. The authentication need not be repeated, because this stage of the protocol will be protected by a pre-existing authentication key. As an extra security measure, the two parties will establish a private name for the shared keying material, so even if they use exactly the same group to communicate with other parties, the re-use will not be apparent to passive attackers.

Private groups have the advantage of making a widespread passive attack much harder by increasing the number of groups that would have to be exhaustively analyzed in order to recover a large number of session keys. This contrasts with the case when only one or two groups are ever used; in that case, one would expect that years and years of session keys would be compromised.

There are two technical challenges to face: how can a particular user create a unique and appropriate group, and how can a second party assure himself that the proposed group is reasonably secure?

The security of a modular exponentiation group depends on the largest prime factor of the group size. In order to maximize this, one can choose "strong" or Sophie Germaine primes, P = 2Q + 1, where P and Q are prime. However, if P = kQ + 1, where k is small, then the strength of the group is still considerable. These groups are known as Schnorr subgroups, and they can be found with much less computational effort than Sophie-Germaine primes.

Schnorr subgroups can also be validated efficiently by using probable prime tests.

It is also fairly easy to find P, k, and Q such that the largest prime factor can be easily proven to be Q.

We estimate that it would take about 10 minutes to find a new group of about 2^1024 elements, and this could be done once a day by a scheduled process; validating a group proposed by a remote party would take perhaps a minute on a 25 MHz RISC machine or a 66 MHz CISC machine.

We note that validation is done only between previously mutually authenticated parties, and that a new group definition always follows and is protected by a key established using a well-known group. There are five points to keep in mind:

a. The description and public identifier for the new group are protected by the well-known group.

b. The responder can reject the attempt to establish the new group, either because he is too busy or because he cannot validate the largest prime factor as being sufficiently large.

c. The new modulus and generator can be cached for long periods of time; they are not security critical and need not be associated with ongoing activity.

d. Generating a new g^x value periodically will be more expensive if there are many groups cached; however, the importance of frequently generating new g^x values is reduced, so the time period can be lengthened correspondingly.

e. All modular exponentiation groups have subgroups that are weaker than the main group. For Sophie Germain primes, if the generator is a square, then there are only two elements in the subgroup: 1 and g^(-1) (same as g^(p-1)) which we have already recommended avoiding. For Schnorr subgroups with k not equal to 2, the subgroup can be avoided by checking that the exponential is not a kth root of 1 (e^k != 1 mod p).

2.8.1 Defining a New Group

This section describes how to define a new group. The description of the group is hidden from eavesdroppers, and the identifier assigned to the group is unique to the two parties. Use of the new group for Diffie-Hellman key exchanges is described in the next section.

The secrecy of the description and the identifier increases the difficulty of a passive attack, because if the group descriptor is not known to the attacker, there is no straightforward and efficient way to gain information about keys calculated using the group.

Only the description of the new group need be encrypted in this exchange. The hash algorithm is implied by the OAKLEY session named by the group. The encryption is the encryption function of the OAKLEY session.

The descriptor of the new group is encoded in the new group payload. The nonces are encoded in the Authentication Payload.

Data beyond the encryption boundary is encrypted using the transform named by the KEYID.

The following messages use the ISAKMP Key Exchange Identifier OAKLEY New Group.

To define a new modular exponentiation group:

```
  Initiator                                          Responder
  ---------                                         ----------
   ->   KEYID,                                          ->
        INEWGRP,
        Desc(New Group), Na
        prf(sKEYID, Desc(New Group) | Na)

   <-   KEYID,
        INEWGRPRS,
        Na, Nb
        prf(sKEYID, Na | Nb | Desc(New Group))        <-

    ->  KEYID,
        INEWGRPACK
        prf(sKEYID, Nb | Na | Desc(New Group))         ->
```

These messages are encrypted at the encryption boundary using the key indicated. The hash value is placed in the "digital signature" field (see Appendix B).

New GRP identifier = trunc16(Na) | trunc16(Nb)

(trunc16 indicates truncation to 16 bits; the initiator and responder must use nonces that have distinct upper bits from any used for current GRPID's)

Desc(G) is the encoding of the descriptor for the group descriptor (see Appendix A for the format of a group descriptor)

The two parties must store the mapping between the new group identifier GRP and the group descriptor Desc(New Group). They must also note the identities used for the KEYID and copy these to the state for the new group.

Note that one could have the same group descriptor associated with several KEYID's. Pre-calculation of g^x values may be done based only on the group descriptor, not the private group name.

2.8.2 Deriving a Key Using a Private Group

Once a private group has been established, its group id can be used in the key exchange messages in the GRP position. No changes to the protocol are required.

2.9 Quick Mode: New Keys From Old,

When an authenticated KEYID and associated keying material sKEYID already exist, it is easy to derive additional KEYID's and keys sharing similar attributes (GRP, EHA, etc.) using only hashing functions. The KEYID might be one that was derived in Main Mode, for example.

On the other hand, the authenticated key may be a manually distributed key, one that is shared by the initiator and responder via some means external to OAKLEY. If the distribution method has formed the KEYID using appropriately unique values for the two halves (CKY-I and CKY-R), then this method is applicable.

In the following, the Key Exchange Identifier is OAKLEY Quick Mode. The nonces are carried in the Authentication Payload, and the prf value is carried in the Authentication Payload; the Authentication Authority is "None" and the type is "Pre-Shared".

The protocol is:

```
  Initiator                                              Responder
  ---------                                              ---------
  -> KEYID, INEWKRQ, Ni, prf(sKEYID, Ni)                   ->
 <-  KEYID, INEWKRS, Nr, prf(sKEYID, 1 | Nr | Ni)         <-
  -> KEYID, INEWKRP, 0, prf(sKEYID,  0 | Ni | Nr)          ->
```

The New KEYID, NKEYID, is Ni | Nr

sNKEYID = prf(sKEYID, Ni | Nr)

The identities and EHA values associated with NKEYID are the same as those associated with KEYID.

Each party must validate the hash values before using the new key for any purpose.

2.10 Defining and Using Pre-Distributed Keys

If a key and an associated key identifier and state information have been distributed manually, then the key can be used for any OAKLEY purpose. The key must be associated with the usual state information: ID's and EHA algorithms.

Local policy dictates when a manual key can be included in the OAKLEY database. For example, only privileged users would be permitted to introduce keys associated with privileged ID's, an unprivileged user could only introduce keys associated with her own ID.

2.11 Distribution of an External Key

Once an OAKLEY session key and ancillary algorithms are established, the keying material and the "H" algorithm can be used to distribute an externally generated key and to assign a KEYID to it.

In the following, KEYID represents an existing, authenticated OAKLEY session key, and sNEWKEYID represents the externally generated keying material.

In the following, the Key Exchange Identifier is OAKLEY External Mode. The Key Exchange Payload contains the new key, which is protected

```
  Initiator                                                    Responder
  ---------                                                    ---------
  -> KEYID, IEXTKEY, Ni, prf(sKEYID, Ni)                             ->
 <-  KEYID, IEXTKEY, Nr, prf(sKEYID, 1 | Nr | Ni)                  <-
  -> KEYID, IEXTKEY, Kir xor sNEWKEYID*, prf(Kir, sNEWKEYID | Ni | Nr) ->
```

Kir = prf(sKEYID, Ni | Nr)

* this field is carried in the Key Exchange Payload.

Each party must validate the hash values using the "H" function in the KEYID state before changing any key state information.

The new key is recovered by the Responder by calculating the xor of the field in the Authentication Payload with the Kir value.

The new key identifier, naming the keying material sNEWKEYID, is prf(sKEYID, 1 | Ni | Nr).

Note that this exchange does not require encryption. Hugo Krawcyzk suggested the method and noted its advantage.

2.11.1 Cryptographic Strength Considerations

The strength of the key used to distribute the external key must be at least equal to the strength of the external key. Generally, this means that the length of the sKEYID material must be greater than or equal to the length of the sNEWKEYID material.

The derivation of the external key, its strength or intended use are not addressed by this protocol; the parties using the key must have some other method for determining these properties.

As of early 1996, it appears that for 90 bits of cryptographic strength, one should use a modular exponentiation group modulus of 2000 bits. For 128 bits of strength, a 3000 bit modulus is required.

3. Specifying and Deriving Security Associations

When a security association is defined, only the KEYID need be given. The responder should be able to look up the state associated with the KEYID value and find the appropriate keying material, sKEYID.

Deriving keys for use with IPSEC protocols such as ESP or AH is a subject covered in the ISAKMP/Oakley Resolution document. That document also describes how to negotiate acceptable parameter sets and identifiers for ESP and AH, and how to exactly calculate the keying material for each instance of the protocols. Because the basic keying material defined here (g^xy) may be used to derive keys for several instances of ESP and AH, the exact mechanics of using one-way functions to turn g^xy into several unique keys is essential to correct usage.

4. ISAKMP Compatibility

OAKLEY uses ISAKMP header and payload formats, as described in the text and in Appendix B. There are particular noteworthy extensions beyond the version 4 draft.

4.1 Authentication with Existing Keys

In the case that two parties do not have suitable public key mechanisms in place for authenticating each other, they can use keys that were distributed manually. After establishment of these keys and their associated state in OAKLEY, they can be used for authentication modes that depend on signatures, e.g. Aggressive Mode.

When an existing key is to appear in an offer list, it should be indicated with an Authentication Algorithm of ISAKMP_EXISTING. This value will be assigned in the ISAKMP RFC.

When the authentication method is ISAKMP_EXISTING, the authentication authority will have the value ISAKMP_AUTH_EXISTING; the value for this field must not conflict with any authentication authority registered with IANA and is defined in the ISAKMP RFC.

The authentication payload will have two parts:

the KEYID for the pre-existing key

the identifier for the party to be authenticated by the pre-existing key.

The pseudo-random function "H" in the state information for that KEYID will be the signature algorithm, and it will use the keying material for that key (sKEYID) when generating or checking the validity of message data.

E.g. if the existing key has an KEYID denoted by KID and 128 bits of keying material denoted by sKID and "H" algorithm a transform named HMAC, then to generate a "signature" for a data block, the output of HMAC(sKID, data) will be the corresponding signature payload.

The KEYID state will have the identities of the local and remote parties for which the KEYID was assigned; it is up to the local policy implementation to decide when it is appropriate to use such a key for authenticating other parties. For example, a key distributed for use between two Internet hosts A and B may be suitable for authenticating all identities of the form "alice@A" and "bob@B".

4.2 Third Party Authentication

A local security policy might restrict key negotiation to trusted parties. For example, two OAKLEY daemons running with equal sensitivity labels on two machines might wish to be the sole arbiters of key exchanges between users with that same sensitivity label. In this case, some way of authenticating the provenance of key exchange requests is needed. I.e., the identities of the two daemons should be bound to a key, and that key will be used to form a "signature" for the key exchange messages.

The Signature Payload, in Appendix B, is for this purpose. This payload names a KEYID that is in existence before the start of the current exchange. The "H" transform for that KEYID is used to calculate an integrity/authentication value for all payloads preceding the signature.

Local policy can dictate which KEYID’s are appropriate for signing further exchanges.

4.3 New Group Mode

OAKLEY uses a new KEI for the exchange that defines a new group.

5. Security Implementation Notes

Timing attacks that are capable of recovering the exponent value used in Diffie-Hellman calculations have been described by Paul Kocher [Kocher]. In order to nullify the attack, implementors must take pains to obscure the sequence of operations involved in carrying out modular exponentiations.

A "blinding factor" can accomplish this goal. A group element, r, is chosen at random. When an exponent x is chosen, the value r^(-x) is also calculated. Then, when calculating (g^y)^x, the implementation will calculate this sequence:

```
A = (rg^y)
B = A^x = (rg^y)^x = (r^x)(g^(xy))
C = B*r^(-x) = (r^x)(r^-(x))(g^(xy)) = g^(xy)
```

The blinding factor is only necessary if the exponent x is used more than 100 times (estimate by Richard Schroeppel).

6. OAKLEY Parsing and State Machine

There are many pathways through OAKLEY, but they follow a left-to-right parsing pattern of the message fields.

The initiator decides on an initial message in the following order:

1. Offer a cookie. This is not necessary but it helps with aggressive exchanges.

2. Pick a group. The choices are the well-known groups or any private groups that may have been negotiated. The very first exchange between two Oakley daemons with no common state must involve a well-known group (0, meaning no group, is a well-known group). Note that the group identifier, not the group descriptor, is used in the message.

   If a non-null group will be used, it must be included with the first message specifying EHAO. It need not be specified until then.

3. If PFS will be used, pick an exponent x and present g^x.

4. Offer Encryption, Hash, and Authentication lists.

5. Use PFS for hiding the identities

If identity hiding is not used, then the initiator has this option:

6. Name the identities and include authentication information

The information in the authentication section depends on the first authentication offer. In this aggressive exchange, the Initiator hopes that the Responder will accept all the offered information and the first authentication method. The authentication method determines the authentication payload as follows:

1. Signing method. The signature will be applied to all the offered information.

2. A public key encryption method. The algorithm will be used to encrypt a nonce in the public key of the requested Responder identity. There are two cases possible, depending on whether or not identity hiding is used:

a. No identity hiding. The ID's will appear as plaintext.
b. Identity hiding. A well-known ID, call it R', will appear as plaintext in the authentication payload. It will be followed by two ID's and a nonce; these will be encrypted using the public key for R'.

3. A pre-existing key method. The pre-existing key will be used to encrypt a nonce. If identity hiding is used, the ID's will be encrypted in place in the payload, using the "E" algorithm associated with the pre-existing key.

The Responder can accept all, part or none of the initial message.

The Responder accepts as many of the fields as he wishes, using the same decision order as the initiator. At any step he can stop, implicitly rejecting further fields (which will have null values in his response message). The minimum response is a cookie and the GRP.

1. Accept cookie. The Responder may elect to record no state information until the Initiator successfully replies with a cookie chosen by the responder. If so, the Responder replies with a cookie, the GRP, and no other information.

2. Accept GRP. If the group is not acceptable, the Responder will not reply. The Responder may send an error message indicating the the group is not acceptable (modulus too small, unknown identifier, etc.) Note that "no group" has two meanings during

the protocol: it may mean the group is not yet specified, or it may mean that no group will be used (and thus PFS is not possible).

3. Accept the g^x value. The Responder indicates his acceptance of the g^x value by including his own g^y value in his reply. He can postpone this by ignoring g^x and putting a zero length g^y value in his reply. He can also reject the g^x value with an error message.

4. Accept one element from each of the EHA lists. The acceptance is indicated by a non-zero proposal.

5. If PFS for identity hiding is requested, then no further data will follow.

6. If the authentication payload is present, and if the first item in the offered authentication class is acceptable, then the Responder must validate/decrypt the information in the authentication payload and signature payload, if present. The Responder should choose a nonce and reply using the same authentication/hash algorithm as the Initiator used.

The Initiator notes which information the Responder has accepted, validates/decrypts any signed, hashed, or encrypted fields, and if the data is acceptable, replies in accordance to the EHA methods selected by the Responder. The Initiator replies are distinguished from his initial message by the presence of the non-zero value for the Responder cookie.

The output of the signature or prf function will be encoded as a variable precision integer as described in Appendix C. The KEYID will indicate KEYID that names keying material and the Hash or Signature function.

7. The Credential Payload

Useful certificates with public key information can be attached to OAKLEY messages using Credential Payloads as defined in the ISAKMP document. It should be noted that the identity protection option applies to the credentials as well as the identities.

Security Considerations

The focus of this document is security; hence security considerations permeate this memo.

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APPENDIX A Group Descriptors

Three distinct group representations can be used with OAKLEY. Each group is defined by its group operation and the kind of underlying field used to represent group elements. The three types are modular exponentiation groups (named MODP herein), elliptic curve groups over the field GF[2^N] (named EC2N herein), and elliptic curve groups over GF[P] (named ECP herein) For each representation, many distinct realizations are possible, depending on parameter selection.

With a few exceptions, all the parameters are transmitted as if they were non-negative multi-precision integers, using the format defined in this appendix (note, this is distinct from the encoding in Appendix C). Every multi-precision integer has a prefixed length field, even where this information is redundant.

For the group type EC2N, the parameters are more properly thought of as very long bit fields, but they are represented as multi-precision integers, (with length fields, and right-justified). This is the natural encoding.

MODP means the classical modular exponentiation group, where the operation is to calculate G^X (mod P). The group is defined by the numeric parameters P and G. P must be a prime. G is often 2, but may be a larger number. 2 <= G <= P-2.

ECP is an elliptic curve group, modulo a prime number P. The defining equation for this kind of group is
Y^2 = X^3 + AX + B The group operation is taking a multiple of an elliptic-curve point. The group is defined by 5 numeric parameters: The prime P, two curve parameters A and B, and a generator (X,Y). A,B,X,Y are all interpreted mod P, and must be (non-negative) integers less than P. They must satisfy the defining equation, modulo P.

EC2N is an elliptic curve group, over the finite field F[2^N]. The defining equation for this kind of group is
Y^2 + XY = X^3 + AX^2 + B (This equation differs slightly from the mod P case: it has an XY term, and an AX^2 term instead of an AX term.)

We must specify the field representation, and then the elliptic curve. The field is specified by giving an irreducible polynomial (mod 2) of degree N. This polynomial is represented as an integer of size between 2^N and 2^(N+1), as if the defining polynomial were evaluated at the value U=2.

For example, the field defined by the polynomial U^155 + U^62 + 1 is represented by the integer 2^155 + 2^62 + 1. The group is defined by 4 more parameters, A,B,X,Y. These parameters are elements of the field GF[2^N], and can be thought of as polynomials of degree < N, with (mod 2) coefficients. They fit in N-bit fields, and are represented as integers < 2^N, as if the polynomial were evaluated at U=2. For example, the field element U^2 + 1 would be represented by the integer 2^2+1, which is 5. The two parameters A and B define the curve. A is frequently 0. B must not be 0. The parameters X and Y select a point on the curve. The parameters A,B,X,Y must satisfy the defining equation, modulo the defining polynomial, and mod 2.

Group descriptor formats:

Type of group: A two-byte field,
assigned values for the types "MODP", "ECP", "EC2N"
will be defined (see ISAKMP-04).
Size of a field element, in bits. This is either Ceiling(log2 P)
or the degree of the irreducible polynomial: a 32-bit integer.
The prime P or the irreducible field polynomial: a multi-precision integer.
The generator: 1 or 2 values, multi-precision integers.
EC only: The parameters of the curve: 2 values, multi-precision integers.

The following parameters are Optional (each of these may appear independently):
a value of 0 may be used as a place-holder to represent an unspecified parameter; any number of the parameters may be sent, from 0 to 3.

The largest prime factor: the encoded value that is the LPF of the group size, a multi-precision integer.

EC only: The order of the group: multi-precision integer.
(The group size for MODP is always P-1.)

Strength of group: 32-bit integer.
The strength of the group is approximately the number of key-bits protected.
It is determined by the log2 of the effort to attack the group.
It may change as we learn more about cryptography.

This is a generic example for a "classic" modular exponentiation group:
Group type: "MODP"
Size of a field element in bits: Log2 (P) rounded *up*. A 32bit integer.
Defining prime P: a multi-precision integer.
Generator G: a multi-precision integer. 2 <= G <= P-2.

<optional>
Largest prime factor of P-1: the multi-precision integer Q
Strength of group: a 32-bit integer. We will specify a formula
for calculating this number (TBD).

This is a generic example for an elliptic curve group, mod P:
Group type: "ECP"
Size of a field element in bits: Log2 (P) rounded *up*,
a 32 bit integer.
Defining prime P: a multi-precision integer.
Generator (X,Y): 2 multi-precision integers, each < P.
Parameters of the curve A,B: 2 multi-precision integers, each < P.
<optional>
Largest prime factor of the group order: a multi-precision integer.
Order of the group: a multi-precision integer.
Strength of group: a 32-bit integer. Formula TBD.

This is a specific example for an elliptic curve group:
Group type: "EC2N"
Degree of the irreducible polynomial: 155
Irreducible polynomial: U^155 + U^62 + 1, represented as the
multi-precision integer 2^155 + 2^62 + 1.
Generator (X,Y) : represented as 2 multi-precision integers, each
< 2^155.
For our present curve, these are (decimal) 123 and 456. Each is
represented as a multi-precision integer.
Parameters of the curve A,B: represented as 2 multi-precision
integers, each < 2^155.
For our present curve these are 0 and (decimal) 471951, represented
as two multi-precision integers.

<optional>
Largest prime factor of the group order:

380599384721589301615546382619538626639743644 3,

represented as a multi-precision integer.
The order of the group:

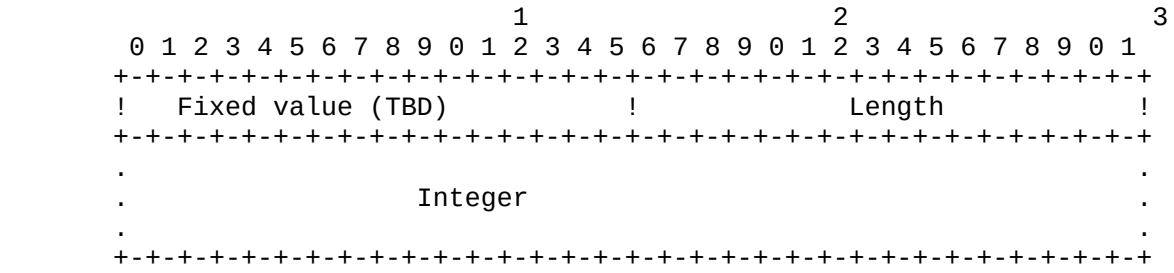
4567192616659071619386556591434463519676923 7316

represented as a multi-precision integer.

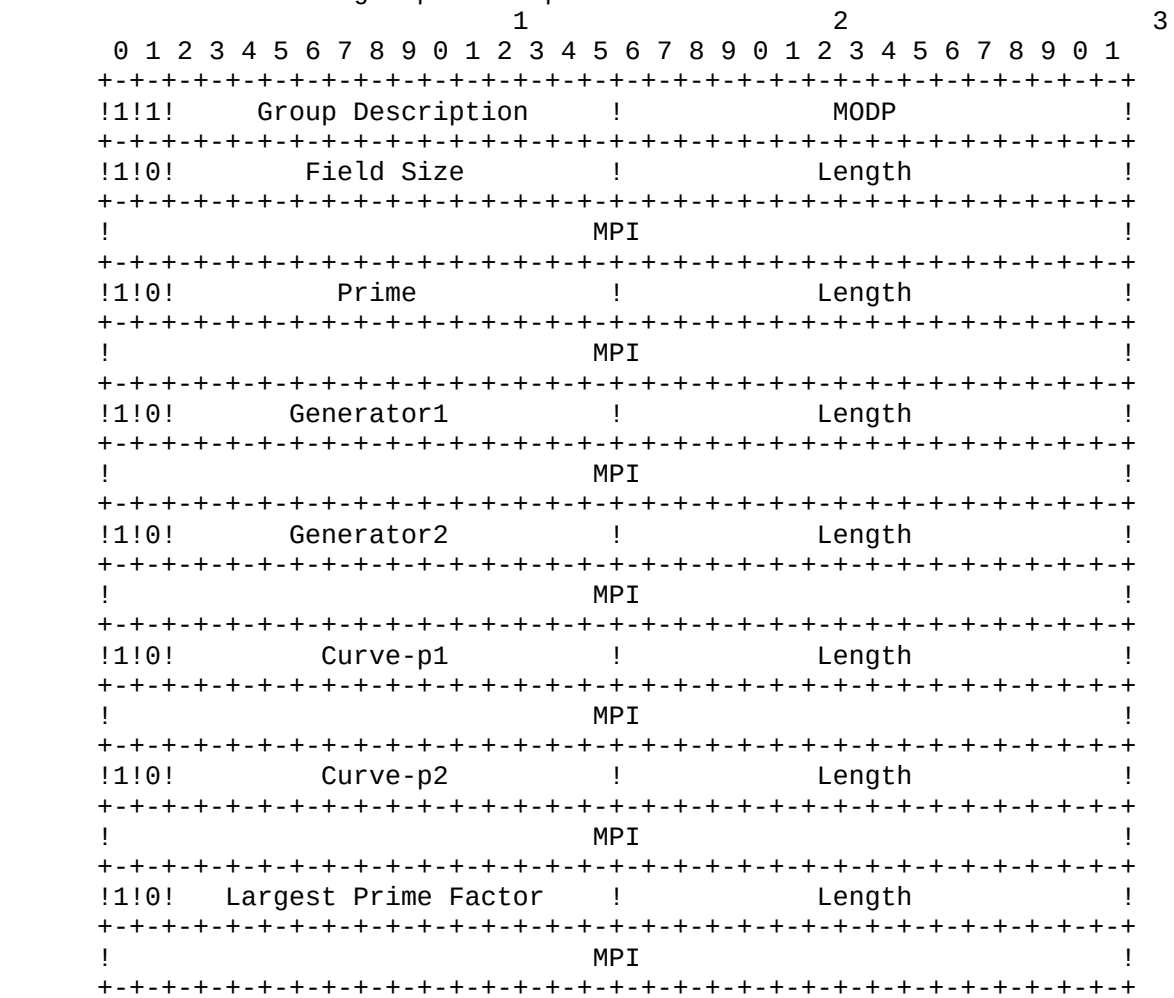
Strength of group: 76, represented as a 32-bit integer.

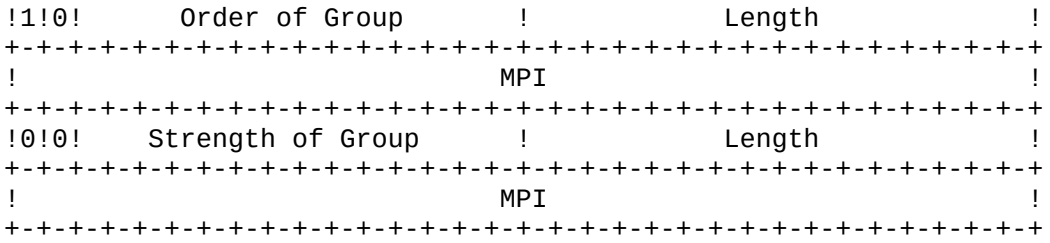
The variable precision integer encoding for group descriptor fields
is the following. This is a slight variation on the format defined
in Appendix C in that a fixed 16-bit value is used first, and the

length is limited to 16 bits. However, the interpretation is otherwise identical.



The format of a group descriptor is:



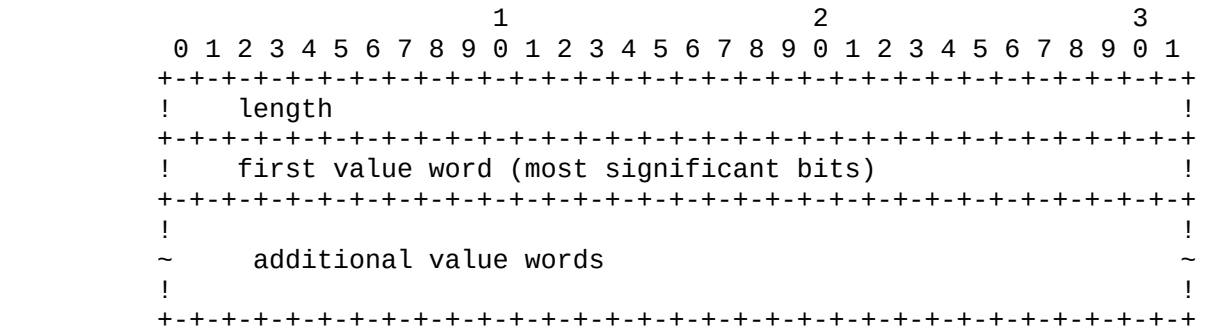

!1!0! Order of Group ! Length !
MPI
!0!0! Strength of Group ! Length !
MPI

APPENDIX B Message formats

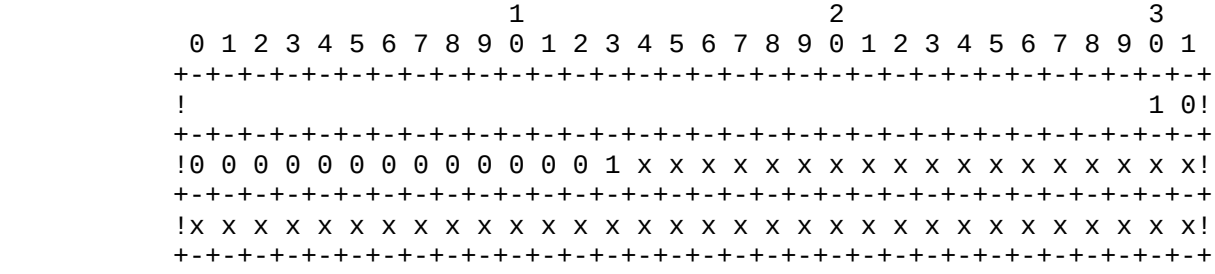
The encodings of Oakley messages into ISAKMP payloads is deferred to the ISAKMP/Oakley Resolution document.

APPENDIX C Encoding a variable precision integer.

Variable precision integers will be encoded as a 32-bit length field followed by one or more 32-bit quantities containing the representation of the integer, aligned with the most significant bit in the first 32-bit item.



An example of such an encoding is given below, for a number with 51 bits of significance. The length field indicates that 2 32-bit quantities follow. The most significant non-zero bit of the number is in bit 13 of the first 32-bit quantity, the low order bits are in the second 32-bit quantity.



APPENDIX D Cryptographic strengths

The Diffie-Hellman algorithm is used to compute keys that will be used with symmetric algorithms. It should be no easier to break the Diffie-Hellman computation than it is to do an exhaustive search over the symmetric key space. A recent recommendation by an group of cryptographers [Blaze] has recommended a symmetric key size of 75 bits for a practical level of security. For 20 year security, they recommend 90 bits.

Based on that report, a conservative strategy for OAKLEY users would be to ensure that their Diffie-Hellman computations were as secure as at least a 90-bit key space. In order to accomplish this for modular exponentiation groups, the size of the largest prime factor of the modulus should be at least 180 bits, and the size of the modulus should be at least 1400 bits. For elliptic curve groups, the LPF should be at least 180 bits.

If long-term secrecy of the encryption key is not an issue, then the following parameters may be used for the modular exponentiation group: 150 bits for the LPF, 980 bits for the modulus size.

The modulus size alone does not determine the strength of the Diffie-Hellman calculation; the size of the exponent used in computing powers within the group is also important. The size of the exponent in bits should be at least twice the size of any symmetric key that will be derived from it. We recommend that ISAKMP implementors use at least 180 bits of exponent (twice the size of a 20-year symmetric key).

The mathematical justification for these estimates can be found in texts that estimate the effort for solving the discrete log problem, a task that is strongly related to the efficiency of using the Number Field Sieve for factoring large integers. Readers are referred to [Stinson] and [Schneier].

APPENDIX E The Well-Known Groups

The group identifiers:

0	No group (used as a placeholder and for non-DH exchanges)
1	A modular exponentiation group with a 768 bit modulus
2	A modular exponentiation group with a 1024 bit modulus
3	A modular exponentiation group with a 1536 bit modulus (TBD)
4	An elliptic curve group over GF[2^155]
5	An elliptic curve group over GF[2^185]

values 2^31 and higher are used for private group identifiers

Richard Schroeppel performed all the mathematical and computational work for this appendix.

Classical Diffie-Hellman Modular Exponentiation Groups

The primes for groups 1 and 2 were selected to have certain properties. The high order 64 bits are forced to 1. This helps the classical remainder algorithm, because the trial quotient digit can always be taken as the high order word of the dividend, possibly +1. The low order 64 bits are forced to 1. This helps the Montgomery-style remainder algorithms, because the multiplier digit can always be taken to be the low order word of the dividend. The middle bits are taken from the binary expansion of pi. This guarantees that they are effectively random, while avoiding any suspicion that the primes have secretly been selected to be weak.

Because both primes are based on pi, there is a large section of overlap in the hexadecimal representations of the two primes. The primes are chosen to be Sophie Germain primes (i.e., (P-1)/2 is also prime), to have the maximum strength against the square-root attack on the discrete logarithm problem.

The starting trial numbers were repeatedly incremented by 2^64 until suitable primes were located.

Because these two primes are congruent to 7 (mod 8), 2 is a quadratic residue of each prime. All powers of 2 will also be quadratic residues. This prevents an opponent from learning the low order bit of the Diffie-Hellman exponent (AKA the subgroup confinement problem). Using 2 as a generator is efficient for some modular exponentiation algorithms. [Note that 2 is technically not a generator in the number theory sense, because it omits half of the possible residues mod P. From a cryptographic viewpoint, this is a virtue.]

E.1. Well-Known Group 1: A 768 bit prime

The prime is 2^768 - 2^704 - 1 + 2^64 * { [2^638 pi] + 149686 }. Its decimal value is

```
155251809230070893513091813125848175563133404943451431320235
119490296623994910210725866945387659164244291000768028886422
915080371891804634263272761303128298374438082089019628850917
069131659317536746955176311984337163722100721057791 9
```

This has been rigorously verified as a prime.

The representation of the group in OAKLEY is

```
Type of group:                    "MODP"
Size of field element (bits):      768
Prime modulus:                     21 (decimal)
   Length (32 bit words):          24
   Data (hex):
      FFFFFFFF FFFFFFFF C90FDAA2 2168C234 C4C6628B 80DC1CD1
      29024E08 8A67CC74 020BBEA6 3B139B22 514A0879 8E3404DD
      EF9519B3 CD3A431B 302B0A6D F25F1437 4FE1356D 6D51C245
      E485B576 625E7EC6 F44C42E9 A63A3620 FFFFFFFF FFFFFFFF
Generator:                         22 (decimal)
   Length (32 bit words):          1
   Data (hex):                     2

Optional Parameters:
Group order largest prime factor:  24 (decimal)
   Length (32 bit words):          24
   Data (hex):
      7FFFFFFF FFFFFFFF E487ED51 10B4611A 62633145 C06E0E68
      94812704 4533E63A 0105DF53 1D89CD91 28A5043C C71A026E
      F7CA8CD9 E69D218D 98158536 F92F8A1B A7F09AB6 B6A8E122
      F242DABB 312F3F63 7A262174 D31D1B10 7FFFFFFF FFFFFFFF
Strength of group:                 26 (decimal)
   Length (32 bit words)           1
   Data (hex):
      00000042
```

E.2. Well-Known Group 2: A 1024 bit prime

The prime is 2^1024 - 2^960 - 1 + 2^64 * { [2^894 pi] + 129093 }. Its decimal value is

```
179769313486231590770839156793787453197860296048756011706444
423684197180216158519368947833795864925541502180565485980503
646440548199239100050792877003355816639229553136239076508735
759914822574862575007425302077447712589550957937778424442426
617334727629299387668709205606050270810842907692932019128194
```

```
      467627007
```

The primality of the number has been rigorously proven.

The representation of the group in OAKLEY is

```
   Type of group:                    "MODP"
   Size of field element (bits):      1024
   Prime modulus:                     21 (decimal)
      Length (32 bit words):          32
      Data (hex):
         FFFFFFFF FFFFFFFF C90FDAA2 2168C234 C4C6628B 80DC1CD1
         29024E08 8A67CC74 020BBEA6 3B139B22 514A0879 8E3404DD
         EF9519B3 CD3A431B 302B0A6D F25F1437 4FE1356D 6D51C245
         E485B576 625E7EC6 F44C42E9 A637ED6B 0BFF5CB6 F406B7ED
         EE386BFB 5A899FA5 AE9F2411 7C4B1FE6 49286651 ECE65381
         FFFFFFFF FFFFFFFF
   Generator:                         22 (decimal)
      Length (32 bit words):          1
      Data (hex):                     2

   Optional Parameters:
   Group order largest prime factor:  24 (decimal)
      Length (32 bit words):          32
      Data (hex):
         7FFFFFFF FFFFFFFF E487ED51 10B4611A 62633145 C06E0E68
         94812704 4533E63A 0105DF53 1D89CD91 28A5043C C71A026E
         F7CA8CD9 E69D218D 98158536 F92F8A1B A7F09AB6 B6A8E122
         F242DABB 312F3F63 7A262174 D31BF6B5 85FFAE5B 7A035BF6
         F71C35FD AD44CFD2 D74F9208 BE258FF3 24943328 F67329C0
         FFFFFFFF FFFFFFFF
   Strength of group:                 26 (decimal)
      Length (32 bit words)           1
      Data (hex):
         0000004D
```

E.3. Well-Known Group 3: An Elliptic Curve Group Definition

The curve is based on the Galois field GF[2^155] with 2^155 field elements. The irreducible polynomial for the field is u^155 + u^62 + 1. The equation for the elliptic curve is

Y^2 + X Y = X^3 + A X + B

X, Y, A, B are elements of the field.

For the curve specified, A = 0 and

B = u^18 + u^17 + u^16 + u^13 + u^12 + u^9 + u^8 + u^7 + u^3 + u^2 +

u + 1.

B is represented in binary as the bit string 11100110011100011111; in decimal this is 471951, and in hex 7338F.

The generator is a point (X,Y) on the curve (satisfying the curve equation, mod 2 and modulo the field polynomial).

X = u^6 + u^5 + u^4 + u^3 + u + 1

and

Y = u^8 + u^7 + u^6 + u^3.

The binary bit strings for X and Y are 1111011 and 111001000; in decimal they are 123 and 456.

The group order (the number of curve points) is
456719261665907161938655659143446351967692373 16
which is 12 times the prime

380599384721589301615546382619538626639743644 3.
(This prime has been rigorously proven.) The generating point (X,Y) has order 4 times the prime; the generator is the triple of some curve point.

OAKLEY representation of this group:

```
   Type of group:                    "EC2N"
   Size of field element (bits):      155
   Irreducible field polynomial:      21 (decimal)
      Length (32 bit words):          5
      Data (hex):
         08000000 00000000 00000000 40000000 00000001
   Generator:
      X coordinate:                   22 (decimal)
          Length (32 bit words):      1
          Data (hex):                 7B
      Y coordinate:                   22 (decimal)
          Length (32 bit words):      1
          Data (hex):                 1C8
   Elliptic curve parameters:
      A parameter:                    23 (decimal)
          Length (32 bit words):      1
          Data (hex):                 0
      B parameter:                    23 (decimal)
          Length (32 bit words):      1
          Data (hex):                 7338F
```

```
      Optional Parameters:
      Group order largest prime factor:  24 (decimal)
         Length (32 bit words):          5
         Data (hex):
            00AAAAAA AAAAAAAA AAAAB1FC F1E206F4 21A3EA1B
      Group order:                       25 (decimal)
         Length (32 bit words):          5
         Data (hex):
            08000000 00000000 000057DB 56985371 93AEF944
      Strength of group:                 26 (decimal)
         Length (32 bit words)            1
         Data (hex):
            0000004C
```

E.4. Well-Known Group 4: A Large Elliptic Curve Group Definition

This curve is based on the Galois field GF[2^185] with 2^185 field elements. The irreducible polynomial for the field is

u^185 + u^69 + 1.

The equation for the elliptic curve is

Y^2 + X Y = X^3 + A X + B.

X, Y, A, B are elements of the field. For the curve specified, A = 0 and

B = u^12 + u^11 + u^10 + u^9 + u^7 + u^6 + u^5 + u^3 + 1.

B is represented in binary as the bit string 1111011101001; in decimal this is 7913, and in hex 1EE9.

The generator is a point (X,Y) on the curve (satisfying the curve equation, mod 2 and modulo the field polynomial);

X = u^4 + u^3 and Y = u^3 + u^2 + 1.

The binary bit strings for X and Y are 11000 and 1101; in decimal they are 24 and 13. The group order (the number of curve points) is

490398573077084434674671048576526822480523850010450531 16,

which is 4 times the prime

122599643269271108668667762144131705620130962502612632 79.

(This prime has been rigorously proven.)

The generating point (X,Y) has order 2 times the prime; the generator is the double of some curve point.

OAKLEY representation of this group:

```
Type of group:                    "EC2N"
Size of field element (bits):      185
Irreducible field polynomial:      21 (decimal)
   Length (32 bit words):          6
   Data (hex):
      02000000 00000000 00000000 00000020 00000000 00000001
Generator:
   X coordinate:                   22 (decimal)
       Length (32 bit words):      1
       Data (hex):                 18
   Y coordinate:                   22 (decimal)
       Length (32 bit words):      1
       Data (hex):                 D
Elliptic curve parameters:
   A parameter:                    23 (decimal)
       Length (32 bit words):      1
       Data (hex):                 0
   B parameter:                    23 (decimal)
       Length (32 bit words):      1
       Data (hex):                 1EE9

Optional parameters:
Group order largest prime factor:  24 (decimal)
   Length (32 bit words):          6
   Data (hex):
      007FFFFF FFFFFFFF FFFFFFFF F6FCBE22 6DCF9210 5D7E53AF
Group order:                       25 (decimal)
   Length (32 bit words):          6
   Data (hex):
      01FFFFFF FFFFFFFF FFFFFFFF DBF2F889 B73E4841 75F94EBC
Strength of group:                 26 (decimal)
   Length (32 bit words)            1
   Data (hex):
      0000005B
```

E.5. Well-Known Group 5: A 1536 bit prime

The prime is 2^1536 - 2^1472 - 1 + 2^64 * { [2^1406 pi] + 741804 }.

Its decimal value is

```
241031242692103258855207602219756607485695054850245994265411
694195810883168261222889009385826134161467322714147790401219
650364895705058263194273070680500922306273474534107340669624
```

```
      60145893616597740410271692494532003787294341703258437786591981437631937768598695240889401955773461198435453015470437472077499697637500843089263392955599688824578724129938101291302945929999479263652640592846472097303849472116814344647144384885209401274598442888593365268963209196339191
```

The primality of the number has been rigorously proven.

The representation of the group in OAKLEY is

```
   Type of group:                    "MODP"
   Size of field element (bits):      1536
   Prime modulus:                     21 (decimal)
      Length (32 bit words):          48
      Data (hex):
         FFFFFFFF FFFFFFFF C90FDAA2 2168C234 C4C6628B 80DC1CD1
         29024E08 8A67CC74 020BBEA6 3B139B22 514A0879 8E3404DD
         EF9519B3 CD3A431B 302B0A6D F25F1437 4FE1356D 6D51C245
         E485B576 625E7EC6 F44C42E9 A637ED6B 0BFF5CB6 F406B7ED
         EE386BFB 5A899FA5 AE9F2411 7C4B1FE6 49286651 ECE45B3D
         C2007CB8 A163BF05 98DA4836 1C55D39A 69163FA8 FD24CF5F
         83655D23 DCA3AD96 1C62F356 208552BB 9ED52907 7096966D
         670C354E 4ABC9804 F1746C08 CA237327 FFFFFFFF FFFFFFFF
   Generator:                         22 (decimal)
      Length (32 bit words):          1
      Data (hex):                     2

   Optional Parameters:
   Group order largest prime factor:  24 (decimal)
      Length (32 bit words):          48
      Data (hex):
         7FFFFFFF FFFFFFFF E487ED51 10B4611A 62633145 C06E0E68
         94812704 4533E63A 0105DF53 1D89CD91 28A5043C C71A026E
         F7CA8CD9 E69D218D 98158536 F92F8A1B A7F09AB6 B6A8E122
         F242DABB 312F3F63 7A262174 D31BF6B5 85FFAE5B 7A035BF6
         F71C35FD AD44CFD2 D74F9208 BE258FF3 24943328 F6722D9E
         E1003E5C 50B1DF82 CC6D241B 0E2AE9CD 348B1FD4 7E9267AF
         C1B2AE91 EE51D6CB 0E3179AB 1042A95D CF6A9483 B84B4B36
         B3861AA7 255E4C02 78BA3604 6511B993 FFFFFFFF FFFFFFFF
   Strength of group:                 26 (decimal)
      Length (32 bit words)           1
      Data (hex):
         0000005B
```

Appendix F Implementing Group Operations

The group operation must be implemented as a sequence of arithmetic operations; the exact operations depend on the type of group. For modular exponentiation groups, the operation is multi-precision integer multiplication and remainders by the group modulus. See Knuth Vol. 2 [Knuth] for a discussion of how to implement these for large integers. Implementation recommendations for elliptic curve group operations over GF[2^N] are described in [Schroeppel].

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