Negotiated Finite Field Diffie-Hellman Ephemeral Parameters
for Transport Layer Security (TLS)

Abstract

Traditional finite-field-based Diffie-Hellman (DH) key exchange during the Transport Layer Security (TLS) handshake suffers from a number of security, interoperability, and efficiency shortcomings. These shortcomings arise from lack of clarity about which DH group parameters TLS servers should offer and clients should accept. This document offers a solution to these shortcomings for compatible peers by using a section of the TLS "Supported Groups Registry" (renamed from "EC Named Curve Registry" by this document) to establish common finite field DH parameters with known structure and a mechanism for peers to negotiate support for these groups.

This document updates TLS versions 1.0 (RFC 2246), 1.1 (RFC 4346), and 1.2 (RFC 5246), as well as the TLS Elliptic Curve Cryptography (ECC) extensions (RFC 4492).

Status of This Memo

This is an Internet Standards Track document.

This document is a product of the Internet Engineering Task Force (IETF). It represents the consensus of the IETF community. It has received public review and has been approved for publication by the Internet Engineering Steering Group (IESG). Further information on Internet Standards is available in Section 2 of RFC 7841.

Information about the current status of this document, any errata, and how to provide feedback on it may be obtained at http://www.rfc-editor.org/info/rfc7919.
Table of Contents

1. Introduction ................................................. 4
   1.1. Requirements Language ................................. 5
   1.2. Vocabulary ........................................... 5
2. Named Group Overview ....................................... 5
3. Client Behavior ........................................... 6
   3.1. Client Local Policy on Custom Groups ................ 7
4. Server Behavior ........................................... 8
5. Optimizations ............................................... 9
   5.1. Checking the Peer’s Public Key ......................... 9
   5.2. Short Exponents ....................................... 9
   5.3. Table Acceleration .................................. 10
6. Operational Considerations .............................. 10
   6.1. Preference Ordering .................................. 10
7. IANA Considerations ..................................... 11
8. Security Considerations ................................ 12
   8.1. Negotiation Resistance to Active Attacks ........... 12
   8.2. Group Strength Considerations ....................... 13
   8.3. Finite Field DHE Only ................................ 13
   8.4. Deprecating Weak Groups .............................. 14
   8.5. Choice of Groups ..................................... 14
   8.6. Timing Attacks ........................................ 14
   8.7. Replay Attacks from Non-negotiated FFDHE ........... 15
   8.8. Forward Secrecy ....................................... 15
   8.9. False Start ........................................... 15
9. Privacy Considerations ................................ 16
   9.1. Client Fingerprinting ................................ 16
10. References ................................................ 16
   10.1. Normative References ................................ 16
   10.2. Informative References ............................... 17
Appendix A. Supported Groups Registry (Formerly "EC Named Curve Registry") .......... 19
   A.1. ffdhe2048 ............................................. 19
   A.2. ffdhe3072 ............................................. 20
   A.3. ffdhe4096 ............................................. 22
   A.4. ffdhe6144 ............................................. 23
   A.5. ffdhe8192 ............................................. 26
Acknowledgements ........................................... 29
Author’s Address ........................................... 29
1. Introduction

Traditional TLS [RFC5246] offers a Diffie-Hellman Ephemeral (DHE) key exchange mode that provides forward secrecy for the connection. The client offers a cipher suite in the ClientHello that includes DHE, and the server offers the client group parameters generator g and modulus p. If the client does not consider the group strong enough (e.g., p is too small, p is not prime, or there are small subgroups that cannot be easily avoided) or if it is unable to process the group for other reasons, the client has no recourse but to terminate the connection.

Conversely, when a TLS server receives a suggestion for a DHE cipher suite from a client, it has no way of knowing what kinds of DH groups the client is capable of handling or what the client’s security requirements are for this key exchange session. For example, some widely distributed TLS clients are not capable of DH groups where p > 1024 bits. Other TLS clients may, by policy, wish to use DHE only if the server can offer a stronger group (and are willing to use a non-PFS (Perfect Forward Secrecy) key exchange mechanism otherwise). The server has no way of knowing which type of client is connecting but must select DH parameters with insufficient knowledge.

Additionally, the DH parameters selected by the server may have a known structure that renders them secure against a small subgroup attack, but a client receiving an arbitrary p and g has no efficient way to verify that the structure of a new group is reasonable for use.

This modification to TLS solves these problems by using a section of the "Supported Groups Registry" (renamed from "EC Named Curve Registry" by this document) to select common DH groups with known structure and defining the use of the "elliptic_curves(10)" extension (described here as the Supported Groups extension) for clients advertising support for DHE with these groups. This document also provides guidance for compatible peers to take advantage of the additional security, availability, and efficiency offered.

The use of this mechanism by one compatible peer when interacting with a non-compatible peer should have no detrimental effects.

This document updates TLS versions 1.0 [RFC2246], 1.1 [RFC4346], and 1.2 [RFC5246], as well as the TLS ECC extensions [RFC4492].
1.1.  Requirements Language

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

1.2.  Vocabulary

The terms "DHE" or "FFDHE" are used in this document to refer to the finite-field-based Diffie-Hellman ephemeral key exchange mechanism in TLS. TLS also supports Elliptic Curve Diffie-Hellman Ephemeral (ECDHE) key exchanges [RFC4492], but this document does not document their use. A registry previously used only by ECDHE-capable implementations is expanded in this document to cover FFDHE groups as well. "FFDHE cipher suites" is used in this document to refer exclusively to cipher suites with FFDHE key exchange mechanisms, but note that these suites are typically labeled with a TLS_DHE_ prefix.

2.  Named Group Overview

We use previously unallocated codepoints within the extension currently known as "elliptic_curves" (Section 5.1.1. of [RFC4492]) to indicate known finite field groups. The extension’s semantics are expanded from "Supported Elliptic Curves" to "Supported Groups". The enum datatype used in the extension has been renamed from NamedCurve to NamedGroup. Its semantics are likewise expanded from "named curve" to "named group".

Additionally, we explicitly relax the requirement about when the Supported Groups extension can be sent. This extension MAY be sent by the client when either FFDHE or ECDHE cipher suites are listed.

Codepoints in the "Supported Groups Registry" with a high byte of 0x01 (that is, between 256 and 511, inclusive) are set aside for FFDHE groups, though only a small number of them are initially defined and we do not expect many other FFDHE groups to be added to this range. No codepoints outside of this range will be allocated to FFDHE groups. The new codepoints for the "Supported Groups Registry" are:

```c
enum {
    ffdhe2048(256), ffdhe3072(257), ffdhe4096(258),
    ffdhe6144(259), ffdhe8192(260),
    } NamedGroup;
```
These additions to the "Supported Groups Registry" are described in detail in Appendix A. They are all safe primes derived from the base of the natural logarithm ("e"), with the high and low 64 bits set to 1 for efficient Montgomery or Barrett reduction.

The use of the base of the natural logarithm here is as a "nothing-up-my-sleeve" number. The goal is to guarantee that the bits in the middle of the modulus are effectively random, while avoiding any suspicion that the primes have secretly been selected to be weak according to some secret criteria. [RFC3526] used pi for this value. See Section 8.5 for reasons that this document does not reuse pi.

3. Client Behavior

A TLS client that is capable of using strong finite field Diffie-Hellman groups can advertise its capabilities and its preferences for stronger key exchange by using this mechanism.

The compatible client that wants to be able to negotiate strong FFDHE sends a Supported Groups extension (identified by type elliptic_curves(10) in [RFC4492]) in the ClientHello and includes a list of known FFDHE groups in the extension data, ordered from most preferred to least preferred. If the client also supports and wants to offer ECDHE key exchange, it MUST use a single Supported Groups extension to include all supported groups (both ECDHE and FFDHE groups). The ordering SHOULD be based on client preference, but see Section 6.1 for more nuance.

A client that offers a Supported Groups extension containing an FFDHE group SHOULD also include at least one FFDHE cipher suite in the ClientHello.

A client that offers a group MUST be able and willing to perform a DH key exchange using that group.

A client that offers one or more FFDHE groups in the Supported Groups extension and an FFDHE cipher suite and that receives an FFDHE cipher suite from the server SHOULD take the following steps upon receiving the ServerKeyExchange:

- For non-anonymous cipher suites where the offered certificate is valid and appropriate for the peer, validate the signature over the ServerDHParams. If not valid, terminate the connection.
o If the signature over ServerDHParams is valid, compare the
   selected dh_p and dh_g with the FFDHE groups offered by the
   client. If none of the offered groups match, the server is not
   compatible with this document. The client MAY decide to continue
   the connection if the selected group is acceptable under local
   policy, or it MAY decide to terminate the connection with a fatal
   insufficient_security(71) alert.

o If the client continues (either because the server offered a
   matching group or because local policy permits the offered custom
   group), the client MUST verify that dh_Ys is in the range 1 <
   dh_Ys < dh_p - 1. If dh_Ys is not in this range, the client MUST
   terminate the connection with a fatal handshake_failure(40) alert.

o If dh_Ys is in range, then the client SHOULD continue with the
   connection as usual.

3.1. Client Local Policy on Custom Groups

Compatible clients that are willing to accept FFDHE cipher suites
from non-compatible servers may have local policy about what custom
FFDHE groups they are willing to accept. This local policy presents
a risk to clients, who may accept weakly protected communications
from misconfigured servers.

This document cannot enumerate all possible safe local policy (the
safest may be to simply reject all custom groups), but compatible
clients that accept some custom groups from the server MUST do at
least cursory checks on group size and may take other properties into
consideration as well.

A compatible client that accepts FFDHE cipher suites using custom
groups from non-compatible servers MUST reject any group with |dh_p|
< 768 bits and SHOULD reject any group with |dh_p| < 1024 bits.

A compatible client that rejects a non-compatible server’s custom
group may decide to retry the connection while omitting all FFDHE
cipher suites from the ClientHello. A client SHOULD only use this
approach if it successfully verified the server’s expected signature
over the ServerDHParams, to avoid being forced by an active attacker
into a non-preferred cipher suite.
4. Server Behavior

If a compatible TLS server receives a Supported Groups extension from a client that includes any FFDHE group (i.e., any codepoint between 256 and 511, inclusive, even if unknown to the server), and if none of the client-proposed FFDHE groups are known and acceptable to the server, then the server MUST NOT select an FFDHE cipher suite. In this case, the server SHOULD select an acceptable non-FFDHE cipher suite from the client’s offered list. If the extension is present with FFDHE groups, none of the client’s offered groups are acceptable by the server, and none of the client’s proposed non-FFDHE cipher suites are acceptable to the server, the server MUST end the connection with a fatal TLS alert of type insufficient_security(71).

If at least one FFDHE cipher suite is present in the client cipher suite list and the Supported Groups extension is either absent from the ClientHello entirely or contains no FFDHE groups (i.e., no codepoints between 256 and 511, inclusive), then the server knows that the client is not compatible with this document. In this scenario, a server MAY select a non-FFDHE cipher suite, or it MAY select an FFDHE cipher suite and offer an FFDHE group of its choice to the client as part of a traditional ServerKeyExchange.

A compatible TLS server that receives the Supported Groups extension with FFDHE codepoints in it and that selects an FFDHE cipher suite MUST select one of the client’s offered groups. The server indicates the choice of group to the client by sending the group’s parameters as usual in the ServerKeyExchange as described in Section 7.4.3 of [RFC5246].

A TLS server MUST NOT select a named FFDHE group that was not offered by a compatible client.

A TLS server MUST NOT select an FFDHE cipher suite if the client did not offer one, even if the client offered an FFDHE group in the Supported Groups extension.

If a non-anonymous FFDHE cipher suite is selected and the TLS client has used this extension to offer an FFDHE group of comparable or greater strength than the server’s public key, the server SHOULD select an FFDHE group at least as strong as the server’s public key. For example, if the server has a 3072-bit RSA key and the client offers only ffdhe2048 and ffdhe4096, the server SHOULD select ffdhe4096.
When an FFDHE cipher suite is selected and the client sends a ClientKeyExchange, the server MUST verify that 1 < dh_Yc < dh_p - 1. If dh_Yc is out of range, the server MUST terminate the connection with a fatal handshake_failure(40) alert.

5. Optimizations

In a key exchange with a successfully negotiated known FFDHE group, both peers know that the group in question uses a safe prime as a modulus and that the group in use is of size p-1 or (p-1)/2. This allows at least three optimizations that can be used to improve performance.

5.1. Checking the Peer’s Public Key

Peers MUST validate each other’s public key Y (dh_Ys offered by the server or dh_Yc offered by the client) by ensuring that 1 < Y < p-1. This simple check ensures that the remote peer is properly behaved and isn’t forcing the local system into the 2-element subgroup.

To reach the same assurance with an unknown group, the client would need to verify the primality of the modulus, learn the factors of p-1, and test both the generator g and Y against each factor to avoid small subgroup attacks.

5.2. Short Exponents

Traditional finite field Diffie-Hellman has each peer choose their secret exponent from the range [2, p-2]. Using exponentiation by squaring, this means each peer must do roughly 2*\log_2(p) multiplications, twice (once for the generator and once for the peer’s public key).

Peers concerned with performance may also prefer to choose their secret exponent from a smaller range, doing fewer multiplications, while retaining the same level of overall security. Each named group indicates its approximate security level and provides a lower bound on the range of secret exponents that should preserve it. For example, rather than doing 2*2*3072 multiplications for an ffdhe3072 handshake, each peer can choose to do 2*2*275 multiplications by choosing their secret exponent from the range [2^274, 2^275] (that is, an m-bit integer where m is at least 275) and still keep the same approximate security level.

A similar short-exponent approach is suggested in a Secure SHell (SSH) Diffie-Hellman key exchange (see Section 6.2 of [RFC4419]).
5.3. Table Acceleration

Peers wishing to further accelerate FFDHE key exchange can also pre-compute a table of powers of the generator of a known group. This is a memory vs. time trade-off, and it only accelerates the first exponentiation of the ephemeral DH exchange (the fixed-base exponentiation). The variable-base exponentiation (using the peer’s public exponent as a base) still needs to be calculated as normal.

6. Operational Considerations

6.1. Preference Ordering

The ordering of named groups in the Supported Groups extension may contain some ECDHE groups and some FFDHE groups. These SHOULD be ranked in the order preferred by the client.

However, the ClientHello also contains a list of desired cipher suites, also ranked in preference order. This presents the possibility of conflicted preferences. For example, if the ClientHello contains a cipher_suite field with two choices in order <TLS_DHE_RSA_WITH_AES_128_CBC_SHA, TLS_ECDHE_RSA_WITH_AES_128_CBC_SHA> and the Supported Groups extension contains two choices in order <secp256r1, ffdhe3072>, then there is a clear contradiction. Clients SHOULD NOT present such a contradiction since it does not represent a sensible ordering. A server that encounters such a contradiction when selecting between an ECDHE or FFDHE key exchange mechanism while trying to respect client preferences SHOULD give priority to the Supported Groups extension (in the example case, it should select TLS_ECDHE_RSA_WITH_AES_128_CBC_SHA with secp256r1) but MAY resolve the contradiction any way it sees fit.

More subtly, clients MAY interleave preferences between ECDHE and FFDHE groups; for example, if stronger groups are preferred regardless of cost, but weaker groups are acceptable, the Supported Groups extension could consist of <ffdhe8192, secp384p1, ffdhe3072, secp256r1>. In this example, with the same cipher_suite field offered as the previous example, a server configured to respect client preferences and with support for all listed groups SHOULD select TLS_DHE_RSA_WITH_AES_128_CBC_SHA with ffdhe8192. A server configured to respect client preferences and with support for only secp384p1 and ffdhe3072 SHOULD select TLS_ECDHE_RSA_WITH_AES_128_CBC_SHA with secp384p1.
7. IANA Considerations

This document renames the "EC Named Curve Registry" (originally defined in [RFC4492] and updated by [RFC7027]) to the "Supported Groups Registry". See <https://www.iana.org/assignments/tls-parameters>.

This document expands the semantics of this registry to include groups based on finite fields in addition to groups based on elliptic curves. IANA has added a range designation to the registry, indicating that values from 256-511 (inclusive) are set aside for "Finite Field Diffie-Hellman groups" and that all other entries in the registry are "Elliptic curve groups".

This document allocates five well-defined codepoints in the registry for specific finite field Diffie-Hellman groups defined in Appendix A.

In addition, the four highest codepoints in the range 508-511, inclusive, are designated for Private Use [RFC5226] by peers who have privately developed finite field Diffie-Hellman groups that they wish to signal internally.

The updated registry section is as follows:

<table>
<thead>
<tr>
<th>Value</th>
<th>Description</th>
<th>DTLS-OK</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>256</td>
<td>ffdhe2048</td>
<td>Y</td>
<td>RFC 7919</td>
</tr>
<tr>
<td>257</td>
<td>ffdhe3072</td>
<td>Y</td>
<td>RFC 7919</td>
</tr>
<tr>
<td>258</td>
<td>ffdhe4096</td>
<td>Y</td>
<td>RFC 7919</td>
</tr>
<tr>
<td>259</td>
<td>ffdhe6144</td>
<td>Y</td>
<td>RFC 7919</td>
</tr>
<tr>
<td>260</td>
<td>ffdhe8192</td>
<td>Y</td>
<td>RFC 7919</td>
</tr>
<tr>
<td>508-511</td>
<td>Private Use</td>
<td>-</td>
<td>RFC 7919</td>
</tr>
</tbody>
</table>

IANA has also renamed the "elliptic_curves" extension as "supported_groups" and added a reference to this document in the "ExtensionType Values" registry. See <http://www.iana.org/assignments/tls-extensiontype-values>.
8. Security Considerations

8.1. Negotiation Resistance to Active Attacks

Because the contents of the Supported Groups extension are hashed in the Finished message, an active Man in the Middle (MITM) that tries to filter or omit groups will cause the handshake to fail, but possibly not before getting the peer to do something it would not otherwise have done.

An attacker who impersonates the server can try to do any of the following:

- Pretend that a non-compatible server is actually capable of this extension and select a group from the client’s list, causing the client to select a group it is willing to negotiate. It is unclear how this would be an effective attack.

- Pretend that a compatible server is actually non-compatible by negotiating a non-FFDHE cipher suite. This is no different than MITM cipher suite filtering.

- Pretend that a compatible server is actually non-compatible by negotiating a DHE cipher suite with a custom (perhaps weak) group selected by the attacker. This is no worse than the current scenario and would require the attacker to be able to sign the ServerDHParams, which should not be possible without access to the server’s secret key.

An attacker who impersonates the client can try to do the following:

- Pretend that a compatible client is not compatible (e.g., by not offering the Supported Groups extension or by replacing the Supported Groups extension with one that includes no FFDHE groups). This could cause the server to negotiate a weaker DHE group during the handshake or to select a non-FFDHE cipher suite, but it would fail to complete during the final check of the Finished message.

- Pretend that a non-compatible client is compatible (e.g., by adding the Supported Groups extension or by adding FFDHE groups to the extension). This could cause the server to select a particular named group in the ServerKeyExchange or to avoid selecting an FFDHE cipher suite. The peers would fail to compute the final check of the Finished message.
- Change the list of groups offered by the client (e.g., by removing the stronger of the set of groups offered). This could cause the server to negotiate a weaker group than desired, but again, should be caught by the check in the Finished message.

8.2. Group Strength Considerations

TLS implementations using FFDHE key exchange should consider the strength of the group they negotiate. The strength of the selected group is one of the factors that define the connection's resilience against attacks on the session's confidentiality and integrity, since the session keys are derived from the DHE handshake.

While attacks on integrity must generally happen while the session is in progress, attacks against session confidentiality can happen significantly later if the entire TLS session is stored for offline analysis. Therefore, FFDHE groups should be selected by clients and servers based on confidentiality guarantees they need. Sessions that need extremely long-term confidentiality should prefer stronger groups.

[ENISA] provides rough estimates of group resistance to attack and recommends that forward-looking implementations ("future systems") should use FFDHE group sizes of at least 3072 bits. ffdhe3072 is intended for use in these implementations.

Other sources (e.g., [NIST]) estimate the security levels of the Discrete Log (DLOG) problem to be slightly more difficult than [ENISA]. This document’s suggested minimum exponent sizes in Appendix A for implementations that use the short-exponent optimization (Section 5.2) are deliberately conservative to account for the range of these estimates.

8.3. Finite Field DHE Only

Note that this document specifically targets only finite field Diffie-Hellman ephemeral key exchange mechanisms. It does not cover the non-ephemeral DH key exchange mechanisms, nor does it address ECDHE key exchange, which is defined in [RFC4492].

Measured by computational cost to the TLS peers, ECDHE appears today to offer a much stronger key exchange mechanism than FFDHE.
8.4. Deprecating Weak Groups

Advances in hardware or in finite field cryptanalysis may cause some of the negotiated groups to not provide the desired security margins, as indicated by the estimated work factor of an adversary to discover the premaster secret (and may therefore compromise the confidentiality and integrity of the TLS session).

Revisions of this document should mark known weak groups as explicitly deprecated for use in TLS and should update the estimated work factor needed to break the group if the cryptanalysis has changed. Implementations that require strong confidentiality and integrity guarantees should avoid using deprecated groups and should be updated when the estimated security margins are updated.

8.5. Choice of Groups

Other lists of named finite field Diffie-Hellman groups [STRONGSWAN-IKE] exist. This document chooses to not reuse them for several reasons:

- Using the same groups in multiple protocols increases the value for an attacker with the resources to crack any single group.
- The Internet Key Exchange Protocol (IKE) groups include weak groups like MODP768 that are unacceptable for secure TLS traffic.
- Mixing group parameters across multiple implementations leaves open the possibility of some sort of cross-protocol attack. This shouldn’t be relevant for ephemeral scenarios, and even with non-ephemeral keying, services shouldn’t share keys; however, using different groups avoids these failure modes entirely.

8.6. Timing Attacks

Any implementation of finite field Diffie-Hellman key exchange should use constant-time modular-exponentiation implementations. This is particularly true for those implementations that ever reuse DHE secret keys (so-called "semi-static" ephemeral keying) or share DHE secret keys across a multiple machines (e.g., in a load-balancer situation).
8.7. Replay Attacks from Non-negotiated FFDHE

[SECURE-RESUMPTION], [CROSS-PROTOCOL], and [SSL3-ANALYSIS] all show a malicious peer using a bad FFDHE group to maneuver a client into selecting a premaster secret of the peer’s choice, which can be replayed to another server using a non-FFDHE key exchange and can then be bootstrapped to replay client authentication.

To prevent this attack (barring the session hash fix documented in [RFC7627]), a client would need not only to implement this document, but also to reject non-negotiated FFDHE cipher suites whose group structure it cannot afford to verify. Such a client would need to abort the initial handshake and reconnect to the server in question without listing any FFDHE cipher suites on the subsequent connection.

This trade-off may be too costly for most TLS clients today but may be a reasonable choice for clients performing client certificate authentication or for clients who have other reasons to be concerned about server-controlled premaster secrets.

8.8. Forward Secrecy

One of the main reasons to prefer FFDHE ciphersuites is forward secrecy, the ability to resist decryption even if the endpoint’s long-term secret key (usually RSA) is revealed in the future.

This property depends on both sides of the connection discarding their ephemeral keys promptly. Implementations should wipe their FFDHE secret key material from memory as soon as it is no longer needed and should never store it in persistent storage.

Forward secrecy also depends on the strength of the Diffie-Hellman group; using a very strong symmetric cipher like AES256 with a forward-secret cipher suite but generating the keys with a much weaker group like dhe2048 simply moves the adversary’s cost from attacking the symmetric cipher to attacking the dh_Ys or dh_Yc ephemeral key shares.

If the goal is to provide forward secrecy, attention should be paid to all parts of the cipher suite selection process, both key exchange and symmetric cipher choice.

8.9. False Start

Clients capable of TLS False Start [RFC7918] may receive a proposed FFDHE group from a server that is attacker controlled. In particular, the attacker can modify the ClientHello to strip the proposed FFDHE groups, which may cause the server to offer a weaker
FFDHE group than it should, and this will not be detected until receipt of the server’s Finished message. This could cause a client using the False Start protocol modification to send data encrypted under a weak key agreement.

Clients should have their own classification of FFDHE groups that are "cryptographically strong" in the same sense described in the description of symmetric ciphers in [RFC7918] and SHOULD offer at least one of these in the initial handshake if they contemplate using the False Start protocol modification with an FFDHE cipher suite.

Compatible clients performing a full handshake MUST NOT use the False Start protocol modification if the server selects an FFDHE cipher suite but sends a group that is not cryptographically strong from the client’s perspective.

9. Privacy Considerations

9.1. Client Fingerprinting

This extension provides a few additional bits of information to distinguish between classes of TLS clients (e.g., see [PANOPTICCLICK]). To minimize this sort of fingerprinting, clients SHOULD support all named groups at or above their minimum security threshold. New groups SHOULD NOT be added to the "Supported Groups Registry" without consideration of the cost of browser fingerprinting.

10. References

10.1. Normative References


10.2. Informative References

[CROSS-PROTOCO L]

[ECRYPTII]

[ENISA]

[NIST]

[PANOPTICL ICK]


Appendix A.  Supported Groups Registry (Formerly "EC Named Curve Registry")

Each description below indicates the group itself, its derivation, its expected strength (estimated roughly from guidelines in [ECRYPTII]), and whether it is recommended for use in TLS key exchange at the given security level. It is not recommended to add further finite field groups to the "Supported Groups Registry"; any attempt to do so should consider Section 9.1.

The primes in these finite field groups are all safe primes; that is, a prime p is a safe prime when q = (p-1)/2 is also prime. Where e is the base of the natural logarithm and square brackets denote the floor operation, the groups that initially populate this registry are derived for a given bit length b by finding the lowest positive integer X that creates a safe prime p where:

\[ p = 2^b - 2^{b-64} + \left\lfloor 2^{b-130} e \right\rfloor + X \right) \times 2^{64} - 1 \]

New additions of FFDHE groups to this registry may use this same derivation (e.g., with different bit lengths) or may choose their parameters in a different way, but they must be clear about how the parameters were derived.

New additions of FFDHE groups MUST use a safe prime as the modulus to enable the inexpensive peer verification described in Section 5.1.

A.1.  ffdhe2048

The 2048-bit group has registry value 256 and is calculated from the following formula:

The modulus is:

\[ p = 2^{2048} - 2^{1984} + \left\lfloor 2^{1918} e \right\rfloor + 560316 \right) \times 2^{64} - 1 \]
The hexadecimal representation of $p$ is:

```
FFFFFFFF FFFFFFFF ADF85458 A2BB4A9A AFDC5620 273D3CF1
D899C5B3 CE2D3695 A9E13641 146433FB CC939DCE 249B3E9F
7D2FE363 630C75D8 F681B202 AEC4617A D3DF1ED5 D5FD6591
2433F51F 5F066ED0 85636555 3D61AF3 B557135E 7F57C93F
984F0C70 E0E68B77 E2A689DA F3EEFE872 1DF158A1 36ADE735
30ACCA4F 483A797A BC0AB1B2 B324FB61 D108A94B B2C8E3FB
B96ADAB7 60DF6468 1D4F42A3 DE39DF4 AE56DE7 6372BB13
0B077A7C8 EE0A6D70 9E02F7CE1 CDF7E2EC C03A04CD 28342F61
9172E9C9 E985B3FF 8E4F12D2 EEF28183 C3E3B1B 4C6FAD7B
3BB5F6BC 2EC22005 C58F1B3 7D163B2C F34A26 C1B2EFA
886B4238 61285C97 FFFFFFFF FFFFFFFF
```

The generator is: $g = 2$

The group size is: $(p-1)/2$

The hexadecimal representation of $q$ is:

```
7FFFFFFFF FFFFFFFF D6FC2A2C 515DA54D 57EE2B10 139E9E78
EC5CE2C1 E7169B4A D4F09B20 8A3219FD E649CE7 124D9F7C
BE97F1B1 B18636E8 7B40D901 576230BD 69EF8F6A EAFEB2B0
9219FABF AF33768 42B1B2A9 9EF68D79 DAA89F 3FAB4E9A
CC278638 707345BB F1534ED 79F7F439 0EF8ACF0 9B56F3A9
95865277 A41D3CB5 D5E05B0C 59927DB0 E8845A45 D96471FD
DCB56D5B B06BFA34 0E9A7151 EF1C6A6F 572B76F3 B1B95D8C
8583D347 770536B8 4F017E70 E6F7F176 601A0266 941A1B0
CB97F3E4 74C2C1FF C7278919 77740C1 E1FF1D8D A637DB7B
9DDAEF5E 17611002 BE2F778C1 BE8841D9 6739A513 60D977FD
4435A11C 30942E4B FFFFFFFF FFFFFFFF
```

The estimated symmetric-equivalent strength of this group is 103 bits.

Peers using ffdhe2048 that want to optimize their key exchange with a short exponent (Section 5.2) should choose a secret key of at least 225 bits.

A.2. ffdhe3072

The 3072-bit prime has registry value 257 and is calculated from the following formula:

The modulus is:

$$p = 2^{3072} - 2^{3008} + ([2^{2942} \times e] + 2625351) \times 2^{64} - 1$$
The hexadecimal representation of p is:

```
FFFFFFFF FFFFFFFF ADF85458 A2BB4A9B AFDC5620 273D3CF1
D8B9C583 CE2D3695 A9E13641 146433FB C099DFCE 249B3EF9
7D2FE363 630C75D8 F681B202 AEC4617A D3DF1ED5 5FD6561
2433F51F 5F066ED0 85636555 3DED1AF3 B557135E 7F57C935
984F0C70 E0E8B777 E2A689DA F3EE8721 1DF158A1 36ADE735
30ACCA4F 483A797A BC0AB182 B324FB61 D108A94B B2C8E3FB
B96DAB87 6D7F4E68 1D4F42A3 DE394DF4 AE56DEE7 6372BB19
0B07A7C8 EE0A6D70 9E02FCE1 CDF7E2EC C03404CD 28342F61
9172FE9C E98536FF 8E4F1232 EEF28183 C3FE3B1B 4C6FAD73
3BB5FCBA 2EC22005 C58EF1B3 7D16B3B2 6F3A26C6 1CB2E4FA
886B4238 611FCDFC DE355B3B 6519035B BC34F4DE F99C0238
61B46FC9 D6E6C907 7AD91D26 91F7F7EE 598C0BFA C186DF1C
AEFE1309 8519327D B4130C93 BC437944 F4DF4522 E2D79D33
64F2E2B1 71F548BF 5CAE82AB 9C9DF69E E86D2BC5 22363A0D
ABC52197 9B0DEADA 1DBF9A42 D5C4484E 0ABCD06B FA53DEFE
3C1B20EE 3FD59D7C 25E412B6 66C6E37 7F57C935 273D3CF1
```

The generator is: \( g = 2 \)

The group size is: \( q = (p-1)/2 \)

The hexadecimal representation of q is:

```
7FFFFFFF FFFFFFFF D6FC2A2C A515DA54D 57EE2B10 139E9E78
EC5D2E2C1 E7169B4A D4F09B20 A3219FDE E649CEE7 124D9F7C
BE97F1B1 B1863AE3 7B4D901 576230BD 69EF8F6A EAEF2B0
9219FA8F AF833768 42B1B2AA 9EF68D79 DAA89AF 3FABE49A
CC276B38 7073458B F15344ED 79F7F439 0E8AC50 9B56F39A
98566527 A413D3CB 5E0558C1 59927DB0 E88454A5 D96471FD
DDB56D5B B06BFA34 0EA7A151 EF1CA6FA 572876F3 B189D8C
85F3D3E4 77053688 4F017E70 E6FBF176 601A0266 941A17B0
CBB97F4E 74C2C1FF C7287919 777F940C 11FF1D8D A637DB9
9DDA8F5E 17611002 E2C778C1 B0EB41D9 6379A513 60D977FD
4435A1C 308F77EE 6F1AADD9 B28C81AD DE1A7A6F 7CCE011C
30DA37E4 EB736843 BD6CE93 48FBBF7 2CC6587D 60C36C8E
577F9084 C289C93B 5A098B49 DE21BCA2 7A7EA229 7162AE9
B279710F 38F9A5FF AE574155 CE4EFB4F 743695E2 911B1D06
D5E290CB CD86F56D 0EDFCD21 6AE22427 055E6835 FD29E4F7
9E0D9077 1FEACEBE 12F20E95 B363171B FFFFFFFF FFFFFFFF
```

The estimated symmetric-equivalent strength of this group is 125 bits.

Peers using ffdhe3072 that want to optimize their key exchange with a short exponent (Section 5.2) should choose a secret key of at least 275 bits.
A.3.  ffdhe4096

The 4096-bit group has registry value 258 and is calculated from the following formula:

The modulus is:

\[ p = 2^{4096} - 2^{4032} + \lfloor 2^{3966} \cdot e \rfloor + 5736041 \cdot 2^{64} - 1 \]

The hexadecimal representation of \( p \) is:

```
FFFFFFFF FFFFFFFF ADF85458 A2BB4A9A AFDC5620 273D3CF1
D8B9C583 CE2D3695 A9E13641 146433FB CC939DCE 249B3EF9
7D2FE363 630C75DB F681B202 AEC4617A D3DF1ED5 D5FD6561
2433F51F 5F066ED0 85636555 3DED1AF3 B557135E 7F57C935
984F0C70 E0E68B77 E2A689DA F3FE872 1DF158A1 36ADE735
30ACCA4F 4B3A979A BC0AB1B2 B324FB61 D108A94B 228E3FB
B96ADA87 60D7F468 1D4F42A3 DE394DF4 AE56ED87 6372BB19
0B07A7C8 EE0A6D70 9E02FCE1 CDF7E2EC C03404CD 28342F61
9172FE9C E98583FF 8E4F1232 EEF28183 C3FE31B1 4C6FAD73
3BB5FCBC 2ECC2205 C58EF183 7D1683B2 C6F3A26C C1B2E2EF
886B4238 611FCFDC DE355B3B 6519035B BC34F2ED F99C0238
61B46FC9 D6E6C907 7AD91D26 91F7F7EE 598CB0FA C186D91C
AEFE1309 85139270 B4130C93 BC437944 F4FD4452 E2D74DD3
64F2E21E 71F54BFF 5CAE82AB 9C9DF69E E86D2BC5 22363A0D
ABC52197 9B0DEADA 1DBF9A42 D5C4484E 0ABC0D6B FA53D2EF
3C1B20EE 3FD59D7C 25E41D2B 669E1E91 6E6F52C3 16DF4FB
7930E9E4 E5857B76 AC7D5F42 D69F6D18 7763CF1D 55034004
87F55BA5 7E31CC7A 7135C886 EFB4318A ED6A1E01 2D9E6832
A907600A 918130C4 6DC778F9 71ADB038 0929999A 33CB8B7A
1A1DB93D 7140003C 2A4ECEA9 F98D0ACC 0A8291CD CEC97DCF
8EC9B55A 7F88A46B 4D85A851 F44182E1 C68A07E 5B655F6A
FFFFFFFF FFFFFFFF
```

The generator is: \( g = 2 \)

The group size is: \( q = (p-1)/2 \)
The hexadecimal representation of q is:

7FFFFFFF FFFFFFFF D6FC2A2C 515DA54D 57EE2B10 139E9E78
EC5CE2C1 E7169B4A D4F09B20 8A3219FD E649CEE7 12D9F7C
BE97F1B1 B1863AEC 7B40D901 576230BD 69EF8F6A EAFeB2B0
9219FA8F A833768 42B1B2AA 9EF68D79 DAAB89AF 3FABE49A
CC278638 707345BB F15344ED 79F7F439 0EF8AC50 9B56F39A
98566527 A41D3CBD 5E0558C1 59927DB0 E88454A5 D96471FD
DC856D5B B06BFA34 0EA7A151 EF1CA6FA 572B76F3 B1B95D8C
8583D3E4 770536B8 4F017E70 E6F8F176 601A0266 941A17B0
C8B97F4E 74C2C1FF C7278919 777940C1 E1FF1D8D A637D6B9
9DADFE5E 17611002 E2C778C1 BE8B41D9 6379A513 60D977FD
4435A11C 308FE7EE 6F1A9D9D B28C81AD DE1A7A6F 7CCE011C
30DA37E4 EB736483 BD6C8E93 48FBF87F 2CC6587D 60C36C8E
577F0984 C289C938 5A098649 DE21BCA2 7A7EA229 716BA6E9
B279710F 38FAA5FF AE574155 CE4E684F 743965E2 911B1D06
D5E290CB CD86F56D 0EDFCD21 6AE22427 0556E683 FD29E8E7
9E0D9077 1FEA9E6E 12F0E995 B34F0F78 B737A961 8B26FA7D
BC9874F2 72C42BDB 563EAF1 6B4FB68C 3BB1E78E AA81A002
43FAADD2 BF18E63D 389AE443 77DA18C5 76B550F0 96CF3419
5483B005 48C09862 36E3BC7C B8D6801C 0494CDD1 99E5C5BD
0D8ECD9E B8A0001E 15276754 FCB65866 0541686 764BE7E7
C764DAAD 3FC45235 A6DAD428 FA20C170 E345003F 2F32AFB5
7FFFFFFF FFFFFFFF

The estimated symmetric-equivalent strength of this group is 150 bits.

Peers using ffdhe4096 that want to optimize their key exchange with a short exponent (Section 5.2) should choose a secret key of at least 325 bits.

A.4. ffdhe6144

The 6144-bit group has registry value 259 and is calculated from the following formula:

The modulus is:

\[ p = 2^{6144} - 2^{6080} + \{2^{6014} \times e\} + 15705020 \times 2^{64} - 1 \]
The hexadecimal representation of p is:

```
FFFFFFFF FFFFFFFF ADF85458 A2BB4A9A AFDC5620 273D3CF1
D8BC95C8 CE2D3695 A9E13641 146433FB CC939DCE 249B3EF9
7D2FE363 630C75D8 F681B202 AECC617A D3FD1E55 D5FD6561
2433F51F 5F066ED0 85636555 3DED1AF3 B557135E 7F57C935
984F0C70 E0E68B77 E2A689DA F3EFE872 1DF158A1 36ADE735
30ACCA4F 483A797A BC0AB182 B324FB61 D108A94B B2C8E3FB
B96DAB87 60D7F468 1D4F42A3 DE394DF4 AE56EDDF 6372BB19
0B07A7C8 EE0A6D70 9E02FCE1 CDF7E2EC C03404CD 28342F61
9172FE9C E98583FF 8E4F1232 EEF28183 C3FE3B1B 4C6FAD73
3B5FCB3 2EC22005 C58EF183 7D1683B2 C6F3A26C 1B2E7FF9
886B4238 611FCFDC DE35B33B 6519035B BC34F4DE F99C0238
61B46FC9 D6EC907 7AD91D26 917F7FE8 598CB0FA C186D91C
AE5E1309 85139270 B4130C93 BC437944 F4FD4452 E2D74DD3
64F2E21E 71F54BFF 5CAB82AB 9C9DF69E E86D2BC5 22363A0D
ABC52197 9B0DEADA 1DBF94A2 D5C4484E 0ABC6D56 FA53D9EF
3C1B20EE 3FD59D7C 25E41D2B 669E1E91 6E6F52C3 164DF4FB
7930E9E4 E58857B6 AC75DF42 D69F6D18 7763CF1D 55034004
87F55BA5 7E31CC7A 7135C88E EFB4318A ED6A1E01 298E632E
A907600A 918130C4 6DC778F9 714D0038 92999A3 33CB8B7A
1A1DB93D 71D4003C 2A4ECE9A F980DACC 08291CDE CEC97DCE
8EC9855A 7F88A46B 4DB5A851 F44182E1 C68A007E 5BBDD902
0BFD64B6 4503C794 A4677D2C 3B53A2A3 23B4A442 CAF53E6A
3B985B3 9B7624C8 917BDD64 B1C0FD4C B38E8C33 4C7013CA
CDAD065F FCC8EC57 9BL1F5C3E 4E46041F 3681A7FB 4C5B2747
A52471F7 A9A96910 B855322E DB6340D8 A00EF92 350511E3
0ABEC1FF F9E3A26E 7F8B29F8C 183023C3 587E38DA 0077D9B4
763E4EB4 94B2BBBC 94C6651E 77CAF992 EEEAC023 2A281BF6
B3A739C1 22611682 0AEBDB5B 47A67CBE F9C9991B 462D538C
D72B0374 6AE77F5E 62292C31 1562A846 505DC82D B854338A
E49F5235 C95B9117 8CCF2D05 CACEF403 EC9D1B810 C6272B04
5B3B71F9 DC6B9D63 3FDD4A8E 9ADBB169 62A69526 D43161C1
A41D570D 79385DA44 A40E329C D0E40E65 FFFFFF FFFFFFFF
```

The generator is: \( g = 2 \)

The group size is: \( q = (p-1)/2 \)
The hexadecimal representation of q is:

```
7FFFFFFF FFFFFFFF D6FC2A2C 515DA54D 57EE2B10 139E9E78
EC5CE2C1 E7169B4A D4F09B20 8A3219FD E649CE57 124D9F7C
BE97F1B1 B1863AEC 7B4D0901 576230BD 69E8F6EA EAFEB2B0
9219FA8F AF833768 42B1B2AA 9EF68D79 DAAB89AF 3FABE49A
CC278638 707345BB F15344ED 79F7F439 0EF8AC50 9B56F939
98565627 A41D3CBD 5E0558C1 59927DB0 E88454A5 D96471FD
DCB565DB B06BFA34 0EA7A151 EF1CA6FA 572B76F3 1B195D8C
858D3D84 770536B8 4F017E70 6E6FBF17 601A0266 941A17B0
C8B97F4E 74C2C1FE C7278919 777940C1 E1FF1D8D A6376DB9
9DDA8E5E 17611002 E2C77C81 CE8B41D9 6379A513 60D9F7FD
4435A11C 308FE7EE 6F1A9D99 B28C81AD DE1A7A6F 7CCE011C
30DA37E4 EB736483 BD6C8E93 48FBBF72 2CC6587D 60C36CE8
577F0984 C289C388 5A098494 DE21BACA 7A7B0229 716B6E9
B279710F 38F0A5EF AE574155 CE4EFB4F 743695E2 911B1D06
D5E290CB CD86F56D 0EDFCD21 6AEB2247 056E6835 FD29EE7F
9ED90777 1F9EACEBE 12F20E39 B34F0F78 B73A961 8B26FA7D
BC9B74EF 70C42BDD 563E1FA1 6B4F6B8C 3BB17E8E AA81A002
43FAADD2 BF18E63D 389AE443 77DA18C5 76B50F00 96CF3419
5483B005 48C09862 36E3BC7C B8D6801C 0494CD1 99E5C5BD
0D6E990D B8A0001E 15276754 FCC68566 054148E6 E764BEE7
C764DAAD 3FC45235 A6DAD428 FA20C170 E345003F 2F06EC51
05FEB25B 2281B63D 2733BE86 1C29951D 11DD2221 657A9F53
1DDA2A19 4DDB1264 48BDDEB2 58E07EA6 59C74619 A630E1D
66D6832B FE676F38 CD8FAE1F 2723020F 940A3F3D A67EADA3
D29238FB D4DB488 95A29A97 6DB1A06C 50077849 1A8288F1
855F60BF FCF1D137 3FD94FC6 0C1811E1 AC3F1C6D 003BECDA
3B1F2725 CA595DE0 CA63328F 3BE57CC9 77556011 9514DDBF
59D39C6E 91308B41 05746DAC 23D33E5F 7CE4848D A316A9C6
6B9581BA 3573BFAF 31149618 8AB15423 282EE416 DC2A19C5
724FA91A E4ADC88B C66796EA E5677A01 F64E8C08 63139582
2D9DB8FC EE35C06B 1FE8A547 40D68F34 B1534A93 6A18B0E0
D20EABB6 BC9C6D6A 5207194E 68720732 FFFFFFFF FFFFFFFF
```

The estimated symmetric-equivalent strength of this group is 175 bits.

Peers using ffdhe6144 that want to optimize their key exchange with a short exponent (Section 5.2) should choose a secret key of at least 375 bits.
A.5.  ffdhe8192

The 8192-bit group has registry value 260 and is calculated from the following formula:

The modulus is:

\[ p = 2^{8192} - 2^{8128} + ([2^{8062} \times e] + 10965728) \times 2^{64} - 1 \]
The hexadecimal representation of p is:

```
FFFFFFFF FFFFFFFF ADF85458 A2BB4A9A AFDC5620 273D3CF1
D8B9C583 CE2D3695 A9E13641 146433FB CC939DCE 249B3EF9
7D2FE363 630C75D8 F681B202 AE4C617A D3F1E0D5 5FD6561
2433F51F 5F066ED0 85636555 3DED1AF3 B557135E 7F57C935
984FOC70 E0E86B77 E2A89DA F3EFE872 1DF158A1 36ADE735
30ACCA4F 483A797A BC0AB182 B324FB61 D108A94B B2C8E3FB
B96A8AD8 60DF4F68 1DF42A3 6E394DF4 AE56ADE7 6372BB19
0B07A7C8 EE0A6D70 9E02FCE1 CDF7E2EC C0340CD5 28342F61
9179E2C 9E85B3FF 84EF1232 EEF28183 C3FE3B1B 4C6FAF73
3BB5F2BC 2EC22D05 C58E1B83 7D1683B2 6F3A426 C1B2E1FA
886B4238 611FCFCD DE35B3B 6519035B BC34F4DE F99C0238
61B46FC9 D66C907 7AD91D26 91F7F7EE 59C8B0FA C186D91C
AEFE1309 85139270 B4130C93 BC437944 F4FD4452 E2D74DD3
6F2E2E17 71F54BF6 5CAE82AB 9C9DF69E E86D2BC5 22363A0D
ABC52197 9B08E4AD 1DBF9A42 D5C447EB 0ABC0D6B FA53DEEF
3C1B02EE 3FD59D7C 25E41D2B 669E1EE1 6E6F52C3 164DF4FB
7930E9E4 E58857B6 AC7D5F42 D69F6D18 7763CF1D 55034004
87F55BAA 7E311CC7 7135C886 EFB4318A ED6A1E01 209E6B32
A907600A 918130C4 6DC778F9 71AD0038 92999A3 33CB8B7A
1AAD8939 7140003C 2A4ECEA9 F98D0ACC 0A8291CD CEC9DCF
8EC9B55A 7F88A45B 4DB5A851 F44182E1 C68A007E 5BDD902
0BF6D4B6 45036C7A 4E6772DC 3853A3A2 23BA442C CAF54EA6
3BB45432 9B7624C8 917DD664 B1C0F4D4 B38E8C33 4C701C3A
CDAD0657 FCCFEC71 9B1F5C3E 4E46041F 388147FB 4CFDB477
A52471FE 889763E1 D63D40D8 0A0E0F92 350511E3 0ABEC1FF 9FEE3A6E 7EB2F98C 183023C3 587E38DA 0077DB94
763E4EAB 94B2B448 94C6651E 77CA9F92 EEAAC023 2A281BF6
B3A739C1 226116B2 0AEBD5B8 47A67CBE F9C9091B 462D538C
D72B0374 6AE7F5E 62292C31 1562A846 505DC82D B854338A
E49F5235 C959B117 8CCF2DD5 CACEF043 EC9D1810 C627B054
5B3B71F9 DC68B0D6 3FDD4AEB 9ADB1E69 62A69526 D43161C1
A41D570D 7938DA44 A40E329C CFF46AAA 36AD004C F600C838
1E425A31 D951A6E4 FDB23FCE C9509D43 687FEB69 EDD1CC5E
B5C8C3BD E64B10EF 86B3142D A3AB8829 555B2F74 7C932665
CB2C0F1C C01BD70 29388839 D2AF05E4 54504AC7 8B7582B2
2846C0BA 35C35F5C 59160CC0 46FD8251 541FC68C 9C86B022
BB709987 6A460E74 51A8A931 90730FEE 1C2176EC 3826E52C
51A6A91E 0E423CFD 99E9E316 50C121B7 624816CD AD9A559F
D5B80194 88D9C0A0 A1F30757 A577E231 83F81D4A 3F2FA457
1EC8C8E0 BA84FEE8 B6855DFE 72B0A66E DED2FAB F8E5BA30
FAFAE1BC 5D71A87E 2F741EF8 C1FE86FE A6B6FDE5 3067FF0D
97D11D49 F7A844D3 0822E506 A9F8614E 011E2A94 838FF88C
D68C8BB7 C5C6424C FFFFFFFFF FFFFFFFFF
```

The generator is: $g = 2$
The group size is: \( q = (p-1)/2 \)

The hexadecimal representation of \( q \) is:

```
7FFFFFFF FFFFFFFF D6FCA2A8 515DA545 57EE2B10 139E9E78
EC5ECE2C1 E7169B4A D4F09B20 8A3219FD E649CE7E 124DF97C
BE97F1B1 B1863AEC 7B40D901 576230BD 69EF8F6A EAFEB2B0
9219F2A9 F8337368 42B12A2A 9E6F68D7 9AAB89AF 3FABE49A
CC27B63C 707345BB F15344ED 79F7F439 0EF8AC50 B58F639A
9856D527 A41D3C0D 5E0558C1 59927DB0 E8454A54 D96471FD
DCB56D3A B60B4A3A E0A7A1A5 EF1CA6FA 572B76F3 B1B95D8C
8583D3E4 770536B8 4F0F17E7 0E6BF176 601A0266 941A17B0
CB9F7F4E 74C21C75 C7278919 777940C1 E1FF1D8D A63D67E9
9DAAEF5E 17611002 E2C77C81 BE08419D 6379A513 60D977FD
4345A11C 30F87E6E 6F1AAAD9 B28C81AD DE1A7A6F 7CCE011C
30DA37E4 EB736483 BD6CE9E3 48FBBF7C 2CC6567D 06C36C8E
577F09B4 C289C93E 5A098649 DE1B2CA2 7A7EA229 716BA6E9
B279710F 38F5AA56 AE574155 CE4E6F4F 743695E2 911B1D06
D5E290CB CD86F56D 0EDF0C21 6A2E2A27 055E6835 FD29E7FE
9E0D9071 1FEAC6BE 12F2E95B 34F0F78B 737A9611 8B26F7AD
BC9874F2 72C42B0B 563E3A1F 64BF6B0C 3BB1E78E AA8A0002
43FAADD2 BF18E63D 389AE443 77DA18C5 765B0F00 96CF3419
5485B005 48C09862 36E3BC7C BD68010C 0494CCD1 99E55C5D
0D0E0C99 B8A0001E 15276754 FCC68566 05414BEE E764FEB7
C764DAAD 3FC45235 A6DAD428 FA20C170 E345003F 2F06EC81
05FEB25B 2281B63D 2733B9E6 1C29951D 11D2D221 657A9F53
1DDAD919 4DBB1264 48BDEEB2 5E07EA65 59C74619 A638OE1D
66D8632B FE67F638 CD8F5AE1F 27B2D020 9C40A3FD A67EA3B
D29328FB D4D4B4C8 52CA29917 6DBA06C3 50077849 1A8288F1
85F60EF0 FCF1D137 3FD94F0C 0C1811E1 AC3F1C6D 003BECD5
3BF72725 CA595DE0 A633B28F 3B557CC9 77556011 95140DBF
59D39CE0 91308B41 05746DAC 23D3E5EF 7CE484BD A316A9C6
6B9581BA 3573BFAF 31496198 8AB15423 282EE416 DC2A19C5
724FA91A E4ADC88C C6679EAE E5677A01 F64E8C08 63139582
2D9DB88C EE35C06B 1FE6A547 4DBD8F34 B1534A93 6A18BE0E
D20EAB86 BC966D6A 5207194E 67FA3553 1B568026 7B00641C
0F212D18 ECA8D732 7ED91FE7 64A84EAE B43FF5B4 F6E8EE2F
05C661DE FB258777 C35B18A1 51D5CA14 AAAD07BA 3E493932
E59607BE 600DBB81 149C4C11 E9578F2B 2A282563 C5BAC14
12426305 1AE1AFAE 2CB8O660 237EC128 AA0F3E46 4E435811
52DB84CC B523073A 28DB4598 84B81FF7 0E10BF36 1C137296
2BD5348F 072111E7 4CF4F18B 286090BD B1240B66 6D6C4D9C
EADCC0CA 446CE205 50FF183A D2BB118 51FC0EA5 1F97D22B
8F7E4670 5D4527F4 5B42AEEF 39585337 6F697D55 FDF2C3A1
7D7D5F0E 2EBB84D3 17BA0F7C 60FF437F 53DFEF2F 983BF86
CBE88EA4 FBD4212E 84117283 54FA30A7 008F154A 41C7FC46
64B415DB E2E32126 7FFFFF FFFFFFFF
```
The estimated symmetric-equivalent strength of this group is 192 bits.

Peers using ffdhe8192 that want to optimize their key exchange with a short exponent (Section 5.2) should choose a secret key of at least 400 bits.

Acknowledgements

Thanks to Fedor Brunner, Dave Fergemann, Niels Ferguson, Sandy Harris, Tero Kivinen, Watson Ladd, Nikos Mavrogiannopolous, Niels Moeller, Bodo Moeller, Kenny Paterson, Eric Rescorla, Tom Ritter, Rene Struik, Martin Thomson, Sean Turner, and other members of the TLS Working Group for their comments and suggestions on this document. Any mistakes here are not theirs.

Author’s Address

Daniel Kahn Gillmor
ACLU
125 Broad Street, 18th Floor
New York, NY 10004
United States of America

Email: dkg@fifthhorseman.net