TLS hardening

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Abstract

This document presents TLS and how to make it secure enough as of 2014 Spring. Of course all the information given here will rot with time. Protocols known as secure will be cracked and will be replaced with better versions. Fortunately we will see that there are ways to assess the current security of your setup, but this explains why you may have to read further from this document to get the up to date knowledge on TLS security.

We will first introduce the TLS protocol and its underlying components: X.509 certificates, ciphers, and protocol versions. Next we will have a look at TLS hardening for web servers, and how to plug various vulnerabilities: CRIME, BREACH, BEAST, session renegotiation, Heartbleed, and others. We will finally see how the know-how acquired on hardening web servers can be used for other protocols and tools such as Dovecot, Sendmail, SquirrelMail, RoundCube, and OpenVPN.

We assume you already maintain services that use TLS, and have basic TCP/IP network knowledge. Some information will also be useful for the application developer.

1 An introduction to TLS

TLS stands for Transport Layer Security. It is an encryption and authentication layer that fits between transport and application level in the TCP/IP network stack. It got specified by IETF in 1999 as an enhancement over Netscape’s Secure Socket Layer (SSL), which is why we often see the SSL term used instead of TLS.

TLS is easy to add on top of any TCP service, and this is why it grown so popular, and it become available for many protocols. For instance, HTTP can be used over TLS, using well-known https:// URL. It works the same way for SMTP(S), IMAP(S), POP(S), LDAP(S), and so on.

1.1 X.509 certificates

The main goal of TLS is enforcing confidentiality and integrity. This cannot happen if the remote peer is not properly authenticated: who cares about having a secure channel if we do not know who we are speaking to? Attacks where an intruder slips between the two legitimate parties are known as Man In The Middle (MITM or MiM) attacks. In such a setup, a secure channel exists between one legitimate party and the intruder, and there is another secure channel between the intruder and the second legitimate party. The legitimate parties talk to each others, and the intruder sees all the traffic.

TLS attempts to authenticate the remote party using a Public Key Infrastructure (PKI). The idea is to use asymmetric cryptography, where each party has a private key capable of performing cryptographic signatures, and a public key, which can be used to verify a signature done by the associated private key. If a remote party is able to produce a public key validated signature for a nonce it was given, that proves it has the private key.
We are therefore able to authenticate a machine for which we already know a public key. That leaves a problem to solve: how can we learn the public key for a machine we never connected to?

Enter X.509 certificates, which are also known as SSL certificate. A X.509 certificate is a public key, with data such as the machine name attached, and signed by a private key which is known as a Certificate Authority (CA). When connecting to a server using TLS, the server sends its X.509 certificate. Provided we have the public key of the CA that signed it, we can check the signature and have a hint the public key is the right one for the host we want to connect to, and nobody attempted to perform a MITM attack. Of course if the software has bugs, this check can be incomplete, and this is what happened to Apple [1] and GnuTLS [2] recently.

But this mechanism relies on the following assumption: we have the public key of the CA. How do we have it? For Unix command-line tools such as `wget` or `curl`, you need to install it first. This means it cannot work out of the box, but it guarantees a level of security, as you can choose what CA you trust. Note that some distributions provide `curl` and `wget` configured with a system-wide CA repository, hence your mileage may vary. Try downloading a well known https:// to discover the behavior of your system.

At the other end of the spectrum, we have web browsers and mail clients, which are bundled with the public keys for hundreds of commercial CA. Since any CA can sign a certificate for any machine name, this means a web browser user trusts hundreds of CA, some of them running in oppressive jurisdictions where a government can compel the CA to sign a certificate for someone else’s machine. The CA can also be compromised by hackers [3], with the same result of having someone able to impersonate a machine during TLS authentication.

There are software to help defend against such attacks. For instance, Firefox has a Cert Patrol module that alerts you when the certificate of a web site is not the same as usual. That will let the user spot a MITM attack using a rogue certificate, except of course when connecting for the first time.

There is an even worse attack possible on X.509 certificates, when the cryptography used to build the certificate is too weak and can be cracked. For instance, a 512 bits RSA private key, which was once safe, is now vulnerable to factorization attacks [4], where the private key can be easily derived from the public key by computation. Once the private key is discovered, an attacker can just passively record TLS traffic and decipher it. We will see later that this can be avoided using Perfect Forward Secrecy (PFS), but even in that situation, an attacker can still decipher the traffic by running a MITM attack.

This leads us to the key length question: How long should it be? The longer it is, the longer it will take before it can be compromised. But a key too long means slower cryptographic operations, and perhaps software incompatibility. 1024 bits RSA is the next target, hence you should consider using 2048 bits RSA. 4096 bits RSA is even safer and will work most of the time, but there can be compatibility issues.

Huge key length is not always a guarantee for strong cryptography. Most cryptographic operations need a random source, and if an attacker can predict it, she may be able to decipher data or tamper with it. The private key generation step critically needs a good random generator. If your operating system warns you about low entropy for random source, make sure you fix it before generating private keys. Modern systems feed their random source from entropy gathered from various sources as they run. After a reboot, the entropy pool is low, but the system may be configured to save and restore that information across reboots. In virtualized setups, the virtual machine may be configured to grab entropy on start up from the hypervisor.

Sometimes you will learn about a random generator weakness in your operating System. This can be the result of an implementation bug, which happened for instance to Debian [5], or a design mistake, for instance in the Dual Elliptic Curve random number generator. In the later case, the mistake was made on purpose by the NSA, as a document leaked by former NSA contractor Edward Snowden taught us [6]. In both situation, you first need to fix the random number generation process, then regenerate keys, and finally think about what traffic may have been compromised.
While we are on the key factoring problem, it is worth mentioning the Shor algorithm, which allows quick factorization of decent sized keys. Fortunately this algorithm requires a quantum computer to operate, and as of today we are not aware of any implementation of such a system. But if it appears some day, asymmetric cryptography as it is used in TLS will become almost as useless as a Caesar’s code \(^7\) is today.

We talked about RSA keys. RSA is indeed the most used public key algorithm. It was invented by Rivest, Shamir and Adleman, hence the name. There are alternatives: DSA, and ECDSA. The latter is not yet widely supported, but it is interesting because it allows much faster operations, which is very valuable on embedded devices.

1.1.1 Key points

- Keep software up to date to avoid running known bugs in certificate validation and weak cryptography.
- Make sure your certificate are signed by a CA known by the client.
- Use certificate tracking software like Cert Patrol on the client.
- Make sure your system random generator is not predictable.
- Use RSA keys for compatibility, if possible, also use ECDSA keys.
- Use key length as long as possible considering performance and compatibility issues.

1.1.2 How-to

Create a 4096 bits RSA private key with appropriate file system permissions

```bash
( umask 077; openssl genrsa -out private.key 4096 )
```

Create a Certificate Signing Request (CSR, to be sent to a CA for signature)

```bash
openssl req -new -key private.key -out certificate.csr
```

Inspect a private key (beware the terminal will display private data)

```bash
openssl rsa -text -in private.key
```

Inspect a Certificate Signing Request

```bash
openssl req -text -in certificate.csr
```

Inspect a certificate (signed from the CSR by a CA)

```bash
openssl x509 -text -in certificate.crt
```

1.2 Ciphers

TLS uses various algorithms known as ciphers to check data integrity and encrypt it. The specifications make many ciphers available, and implementations do not have to implement them all. The high level of cipher choice means we will have to make sure the right ones are used. This is important, because among ciphers, some are secure for today’s standards, and some are trivial to crack. There are even null-ciphers, which perform no encryption at all. This is useful for debugging, but of course it should not be used for anything meant to be confidential.

The complete list of available ciphers for OpenSSL-based software can be obtained by running the following command:
openssl ciphers -v

| Cipher Name | Encryption Algorithm | Key Length | Authentication Algorithm | Mac Algorithm |
|-------------|----------------------|------------|-------------------------|---------------|
| ECDHE-RSA-DES-CBC3-SHA | SSLv3 Kx=ECDH Au=RSA Enc=3DES(168) Mac=SHA1 |
| ECDHE-ECDSA-DES-CBC3-SHA | SSLv3 Kx=ECDH Au=ECDSA Enc=3DES(168) Mac=SHA1 |
| SRP-DSS-3DES-DEDE-CBC-SHA | SSLv3 Kx=SRP Au=DSS Enc=3DES(168) Mac=SHA1 |
| SRP-RSA-3DES-DEDE-CBC-SHA | SSLv3 Kx=SRP Au=RSA Enc=3DES(168) Mac=SHA1 |
| EDH-RSA-DES-CBC3-SHA | SSLv3 Kx=DH Au=RSA Enc=3DES(168) Mac=SHA1 |
| EDH-DSS-DES-CBC3-SHA | SSLv3 Kx=DH Au=DSS Enc=3DES(168) Mac=SHA1 |
| ECDH-RSA-DES-CBC3-SHA | SSLv3 Kx=ECDH/RSA Au=RSA Enc=3DES(168) Mac=SHA1 |
| ECDH-ECDSA-DES-CBC3-SHA | SSLv3 Kx=ECDH/ECDSA Au=ECDH Enc=3DES(168) Mac=SHA1 |
| DES-CBC3-SHA | SSLv3 Kx=RSA Au=RSA Enc=3DES(168) Mac=SHA1 |
| PSK-3DES-DEDE-CBC-SHA | SSLv3 Kx=PSK Au=PSK Enc=3DES(168) Mac=SHA1 |

For the curious, each cipher has an IANA-registered number used in the TLS protocol. On recent versions of OpenSSL, that number can be displayed using openssl ciphers -V.

Cipher names, in the first column, contain hyphen-separated components. We find here the encryption algorithm, with optional key length. Here are a few examples:

**DES** The ancient Data Encryption Standard, with 56 bits keys

**3DES** Triple DES, which is equivalent to a 168 bit keys

**RC2** Ancient and insecure Rivest Cipher v2, with 40 bit keys

**AES128** Modern Advanced Encryption Standard, with 128 bit keys

**AES256** Modern Advanced Encryption Standard, with 256 bit keys

The key here is different from the private key used in X.509 certificate. The latter uses asymmetric cryptography, which uses a lot of CPU power, while the former uses symmetric cryptography, which costs much less processing. As the names suggests, symmetric cryptography uses a secret shared by both parties as the key, which may be renegotiated at regular interval in time. Because cipher keys are of different nature, their lengths are much shorter than X.509 certificates key lengths, but that does not means they are insecure.

Then we find the hash algorithm. Here are a few examples:

**MD5** Ancient and now insecure Message Digest v5

**SHA** Soon to be insecure Secure Hash Algorithm v1

**SHA384** Modern SHA v2 with 384 bits long hash

The cipher name can also specify the X.509 certificate private key flavor, if the cipher belongs to a specification recent enough to support something else than RSA:

**RSA** Well known Rivest, Shamir and Adleman

**DSS** Digital Signing Signature, used with DSA keys

**ECDSA** Elliptic Curve DSA

There are different family of ciphers, and within a family, a given cipher may have different modes of operation. This may or may not be reflected in the cipher name:

**Stream ciphers** whose last usable TLS cipher is RC4 (Rivest Cipher v4)

**Block ciphers** which can operate in various modes: ECB, CBC, CTR, GCM... The relevant modes for TLS block ciphers are:
CBC  Older Cipher block chain, which is quite common with TLS
GCM  More secure Galois/Counter Mode, introduced with TLSv1.2.

Within the block ciphers, CBC mode provides encryption without integrity. This means a CBC mode cipher always needs a helper Hash Message Authentication Code (HMAC) function to enable integrity. GCM mode do not have this requirement since it provides both encryption and integrity.

And finally, the cipher may negotiate its private keys using a Diffie-Hellman (DH) exchange:

EDH  Diffie-Hellman (DH) Exchange
DHE  Ephemeral EDH, which enables PFS (see below)
ECDH  Newer and faster Elliptic Curve Diffie-Hellman
ECDHE  Ephemeral ECDH, which enables PFS (see below)

DH exchange support is an optional but very valuable feature. It ensures that the symmetric cipher keys cannot be easily computed from stored TLS exchanges if the X.509 certificate private key is compromised in the future. That feature is called Perfect Forward Secrecy (PFS), or just Forward Secrecy (FS) since nothing is perfect. It is of no help for the ongoing TLS exchanges done after the X.509 certificate private key is compromised, but it protects stored communications, which is interesting since we know the NSA stores everything it can.

Some clients only implement ECDHE, hence it is desirable to support it although it may require quite recent versions of softwares, as we will see later for Sendmail. For Apache, latest 2.2.x will support it. And while we deal with Elliptic Curve cryptography, it is important to note that the algorithm may use different constants on which the administrator has no control, and some values may be less safe than others [1], although we do not know practical attacks on that front yet.

Client and server negotiate a common cipher, which should obviously be known by both implementations. On both side, the software may allow an ordered cipher suite to be configured. For instance, Apache does this through the SSLCipherSuite directive. The client setting usually prevail, unless the server requests otherwise. This is achieved on Apache using the SSLHonorCipherOrder directive.

In OpenSSL-based software the cipher suite syntax is a colon-separated list of cipher names, with some additional syntax explained in openssl_ciphers(1) man page. Here are a few examples:

ECDH  selects all ECDHE-enabled ciphers
HIGH  selects all high security ciphers (128 bit key length and beyond)
TLSv1  selects all TLSv1 ciphers
MD5  selects all ciphers using MD5

The openssl ciphers command can be used to see all the ciphers enabled by a particular cipher suite. Here is an example

```
openssl ciphers ECDH:!RC4:!MD5:!NULL
```

A good cipher suite specification favors the high security ciphers, forbids the insecure, and allows enough ciphers so that any client can connect. Here is a cipher suite specification that favors PFS and ciphers with 128 bit keys and beyond, while remaining compatible with all modern web browsers:

```
ECDH@STRENGTH:DH@STRENGTH:HIGH:!RC4:!MD5:!DES:!aNULL:!eNULL
```

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1.2.1 Key points

- Make sure server cipher setting prevails over the client’s one.
- Configure cipher suite server-side to disable insecure ciphers.
- For the sake of interoperability, do not restrict available ciphers too much.
- Favor ciphers that can do PFS, and cipher with longer keys.

1.2.2 How-to

Compare two cipher lists

```bash
openssl ciphers ALL:-NULL | tr ':' '
' > /tmp/1
openssl ciphers ALL:!aNULL:!eNULL | tr ':' '
' > /tmp/2
diff /tmp/1 /tmp/2|less
```

Dump all ciphers supported by a service (the SSLScan tool is an alternative)

```bash
for c in `openssl ciphers ALL|tr ':' '
'`; do
  echo ""| openssl s_client -cipher $c -connect www.example.net:443 2>/dev/null
done | awk '/Cipher.*:/{print $3}'
```

1.3 Protocols

There are now five versions of the protocol: SSLv2, SSLv3, TLSv1, TLSv1.1 and the latest TLSv1.2. SSLv2 is very well known to be insecure now and should not be used nowadays. Of course, using the latest version of the protocol is desirable, but it can only be used if both server and client support it. Most of the time it does not happen, which means that a server must support versions down to SSLv3 in order to avoid blocking older clients.

Newer versions of the protocol introduce support for stronger ciphers, and fix various vulnerabilities that existed in SSLv3 and TLSv1. In an ideal world, these two earlier versions of the protocol should be phased out, but unfortunately, support for TLSv1.1 and TLSv1.2 is still far from being universal in web browsers, therefore we need to support older SSLv3 and TLSv1, and work around their security flaws.

As an administrator, there are therefore very little to do with protocol versions. Disable SSLv2, and make sure your software is recent enough to use TLSv1.2. If you happen to develop software that uses TLS, there are a few things to know, though.

When using the OpenSSL library in the C language and initializing SSL contexts, a `SSL_METHOD` must be provided, and this `SSL_METHOD` is obtained by a set of functions that helps selecting the TLS version protocol. Here are the client side flavors (server side flavors look exactly the same):

- `SSLv23_client_method`
- `SSLv3_client_method`
- `TLSv1_client_method`
- `TLSv1_1_client_method`
- `TLSv1_2_client_method`

Using `TLSv1_2_client_method()` looks appealing, but unfortunately this function only enables TLSv1.2, which means that it will prevent from connecting to a server that does not support TLSv1.2. On the other hand, `SSLv23_client_method()` looks undesirable because it may enable insecure SSLv2. But as the function name does not suggest, `SSLv23_client_method()` is able to negotiate the highest protocol version available, up to latest TLSv1.2 if the server supports it. Using
SSLv23_client_method() while explicitly disabling SSLv2 (this is done using SSL_CTX_set_options() with SSL_OP_NO_SSLv2) will therefore bring you the best trade off between security and compatibility.

Another common issue is software that do not setup certificate validation. This should be done with the following functions:

- SSL_set_verify() or SSL_CTX_set_verify() : these functions take a mode, which should obviously not be SSL_VERIFY_NONE for a client that wants to authenticate a server.

- SSL_set_verify_depth() or SSL_CTX_set_verify_depth() : this sets the maximum certificate chain depth when validating the certification chain.

PHP programmers face the same problems. Various function accept a ssl:// or tls:// URL as an argument. Here again, tls:// looks more modern and more desirable, but in PHP 5.3.x it will translate into TLSv1_client_method(), which means only TLSv1. ssl:// will use SSLv23_client_method() and enable up to TLSv1.2 if possible. Using ssl:// instead of tls:// seems therefore better, but unfortunately, PHP 5.3.x does not configure OpenSSL so that SSLv23_client_method() is unable to use SSLv2, hence we have to be sure the server disabled it.

Another PHP 5.3.x issue is that by default, no certificate validation is done. It is possible to enable it using stream context options, and while there, ciphers can also be specified. Here is an example, with backward compatibility code for older PHP versions (where certificate validation will not be done):

```php
if (!function_exists('stream_socket_client')) {
    $remote = sprintf("ssl://%s:%d", $host, port);
    $opts = array(        'ssl' => array(            'verify_peer' => true,            'verify_depth' => 5,            'cfile' => '/path/to/ca_file',            'ciphers' => 'ECDH@STRENGTH:DH@STRENGTH:!RC4:!MD5:!DES:!aNULL:!eNULL',        ),    );
    $ctx = stream_context_create($opts);
    $timeout = ini_get("default_socket_timeout");
    $stream = @stream_socket_client($remote, $errorNumber, $errorString, $timeout, STREAM_CLIENT_CONNECT, $ctx);
} else { /*Backward compatible fallback without certificate validation */
    $stream = @fsockopen('ssl://' . $host, $port, $errorNumber, $errorString);
}
```

Other languages will often face the same kind of issues. Generally speaking, it is a good idea to check what happens when connecting to a server with a self signed certificate. If it works without an error, it means some specific code must be added to perform certificate validation. Disabling SSLv2 and using the best protocol version is also often a non trivial issue that should be inspected.

## 2 TLS Configuration hardening in practice: Apache

We will now look at how to harden TLS configuration for a few services: Apache, Sendmail, Dovecot, OpenVPN... Since we talk about examples, we will of course not cover every software available, but once you know what to look at, it is easy to do the same for another program. Our first target will be Apache.

First let us look at what we already covered:

- Make sure your Apache is recent enough to support TLSv1.2 and ECDH Latest Apache 2.2.x or Apache 2.4.x will do it.

- Generate a RSA private key at least 2048 bits long
• Make sure your certificate is signed by a CA known by browsers

• Use the following configuration for Apache

\begin{verbatim}
SSLProtocol all -SSLv2
SSLHonorCipherOrder On
SSLCipherSuite ECDH@STRENGTH:DH@STRENGTH:HIGH:!RC4:!MD5:!DES:!aNULL:!eNULL
\end{verbatim}

Removing SSLv3 (using `SSLProtocol all -SSLv2 -SSLv3`) and triple DES (using `!3DES` in `SSLCipherSuite`) would be desirable, but it may lock out some older clients. As older devices will get replaced, this will become possible without any drawback. Logging protocols and ciphers selected by your clients is the only way to know if time has come to phase out SSLv3 and triple DES.

Additionally, if you do not serve clear text content, let the client know it by using the Strict Transport Security HTTP header. Once it has been received by a browser, it will force HTTP over TLS even if the user follows a `http://` URL setup on a malicious site. This thwarts possible MITM attacks. Here is how to set it up on Apache:

\begin{verbatim}
Header set Strict-Transport-Security "max-age=15768000"
\end{verbatim}

There is also an older mechanism specific to cookie protection. Cookies are used to maintain sessions on web applications, and they are therefore authentication credentials that should not leak. When setting a cookie, one can set the `secure` flag, which means the cookie must be sent only over TLS protected connections. Although redundant for cookie protection, it does not hurt to setup both `secure` cookies and `Strict-Transport-Security`. Cookies can also have the `httpOnly` flag, which means the JavaScript environment cannot access them. It is a good idea to use it, as it reduces the attack surface on session cookies. Most of the time this requires modifying application code, but there are situations where it can be achieved by the administrator. For instance, applications using PHP sessions can get both `secure` and `httpOnly` cookies by setting `session.cookie_secure` and `session.cookie_httponly` to `On` in `php.ini`.

Next, test your setup. There is a very useful SSL server test \[10\] on the web for that, thanks to Qualys SSL Labs. Run the test and it will point most mistakes in your TLS configuration. If you used the configuration suggested in this paper, you will probably have a bad mark. Why? There can be two kind of issues.

First possible problem, you read this paper a long time after its publication, and the sample configuration is now insecure. You will have to adjust it with the help of Qualys SSL server test. If your certificate key length or hashing algorithm is now weak, improve it with better settings. If the tests says a TLS version is now insecure, adjust `SSLProtocol` to remove it. If you have problem with ciphers, look at the test results for browser handshake simulation. Check what cipher is picked by each browser, and adjust `SSLCipherSuite`.

Once you fixed certificate, protocol and cipher, you may still get a bad mark, despite the TLS configuration being pretty good. This is because the web is a quite complex environment, which makes some web-specific attacks against TLS possible, and hence we need to workaround them.

### 2.1 Mitigating the CRIME attack

The CRIME [11] attack belongs to the chosen plain text class of attacks. It allows the attacker to extract authentication cookies from the TLS-protected data stream, which allows session hijacking. The CRIME attack can happen if:

1. the browser is tricked into sending data controlled by the attacker
2. the attacker can observe the server response
3. TLS compression is enabled
The first two conditions can happen if the attacker controls content from the served pages, which can happen when the server has Cross Site Scripting (XSS) vulnerabilities. The other situation where it may happen are cross-site requests, where a malicious web site tricks the browser into sending data to the attacked web site.

The only CRIME workaround is to work on the third condition, and to disable TLS compression. this is the default in recent Apache releases, as in recent browsers. On earlier Apache releases, the following configuration directive lets you disable it:

```bash
SSLCompression off
```

Disabling TLS compression does not affect performance a lot, since on a well configured server, HTTP compression is enabled. But as we will see in the next section, it also brings problems.

### 2.2 Mitigating the BREACH attack

The BREACH [12] attack is similar to CRIME. Here the offending feature is not TLS compression but HTTP compression. A quick fix is to disable HTTP compression, but that could have a bad impact on performances.

A nice solution is to disable HTTP compression for requests coming from another web site. That will not help if the attacker uses a XSS vulnerability, but there are many other ways to attack your site in that scenario, hence we will assume you already fixed it.

On the other hand, that prevents an attacker from running a BREACH attack from another web site. This workaround can be implemented this way in Apache, assuming your server name is `www.example.net`:

```bash
# BREACH mitigation
SetEnvIfNoCase Referer .*self_referer=no
SetEnvIfNoCase Referer ^https://www\example\net/ self_referer=yes
SetEnvIf self_referer ^no$ no-gzip
```

### 2.3 Mitigating the BEAST attack

The BEAST attack works on SSLv3 and TLSv1, against a class of cipher known as block ciphers (most of the time they have CBC, like Cipher Block Chaining, in their names). The obvious fix is to disable block ciphers, but that leaves us with the following ciphers available:

**GCM** (Galois/Counter Mode) ciphers

**RC4** Rivest Cipher v4

GCM ciphers are only available with TLSv1.2, which means it does not help since we look for a mitigation against an attack on SSLv3 and TLSv1.

RC4 could help, and at some time it was advised to craft a `SSLCipherSuite` setting that favored GCM ciphers, then RC4, so that newer browsers could pick GCM and older would use RC4. Here is an example:

```bash
ECDH@STRENGTH:DH@STRENGTH:-SHA:ECDHE-RSA-RC4-SHA:HIGH:!MD5:!DES:!aNULL:!eNULL
```

Unfortunately, RC4 itself was discovered to be weaker than previously thought [13], leaving system administrators with the choice between two evils: be vulnerable to a RC4 attack that requires hours of exchanges, or be vulnerable to BEAST attacks.

The former alternative may look more desirable, but web browsers made progress at defending against BEAST, either by supporting TLSv1.1 or TLSv1.2, or by implementing a hack called the 1/n-1 split, that makes TLSv1 CBC ciphers not vulnerable to BEAST. On the other hand, there is no way to defend against attacks on RC4, and they are likely to get more efficient at times goes.
Favoring RC4 hence improves the security for browsers still vulnerable to BEAST, but it decreases it for browser that implemented BEAST workarounds and would be pushed to pick a weak RC4 cipher instead of for instance AES256.

This is the reason why today it makes sense to disable RC4 and favor BEAST-vulnerable, PFS-capable block ciphers. This is what we did in the suggested SSLCipherSuite in this paper, but there is no broad consensus on this: Some web site still prefer to favor RC4. This is the case for Google as of may of 2014. It makes some sense because today, an attack on RC4 still requires a lot of exchanges.

Despite BEAST mitigation being widely available, you may have clients that have not been updated and are still vulnerable. If you chose a server configuration that promotes strong ciphers but leaves older clients vulnerable to BEAST (i.e.: you did not favor RC4), you may want to detect vulnerable clients, and report the problem to the user in order to push for a browser update. The author of this paper wrote an Apache module for that [14]. Qualys SSL Labs also has a more feature-rich browser fingerprinting Apache module that can detect a BEAST vulnerable browser [15].

2.4 Session renegotiation

In 2009, a vulnerability was discovered in a feature called session renegotiation [16]. As the name suggests, it allows the change of TLS session parameters. For instance, you could have a part of a web site that wants the client to authenticate using an X.509 certificate, while the remaining of the site could be accessed without a certificate.

When the client connects to the web server and negotiate the TLS session, the server does not know the requested URL yet. In order to enforce a per-URL policy for requiring client certificate, the server needs to renegotiate the TLS session after the URL has been sent. This is that exact feature that has been under attack. The TLS renegotiation procedure has been updated in the TLS protocol to work around the problem.

The only reasonable fix here is to upgrade the server so that it support secure TLS session renegotiation. This will not be backward compatible with older browsers that have not been updated. If you need to support them, you will have to give up on per-URL policy, and use multiple virtual servers using different IP addresses. That way Apache knows what to do before the TLS handshake is done, and TLS renegotiation is not needed anymore.

2.5 Fixing Heartbleed

Heartbleed is the TLS attack that got the most press coverage, thanks to the communication efforts of the researchers that discovered it: a good name, a dedicated web site, and perhaps a first time for a computer vulnerability, a dedicated logo. And unfortunately, the vulnerability itself is extremely severe, making legitimate the efforts to get it picked up by mainstream press.

As opposed to protocol vulnerabilities like CRIME, BEAST and BREACH, Heartbleed is an implementation vulnerability: just a programming error in OpenSSL that introduces a vulnerability in a TLS extension called TLS Heartbeat. Other TLS implementations such as GnuTLS or Mozilla NSS are not vulnerable, neither are OpenSSL 0.9.x releases and earlier, which did not have the TLS Heartbeat functionality.

The bug is a buffer overflow that allows an attacker to read 64 kB of memory from the server, which can include various data recently used, like session cookies, passwords, database access credentials, and in the worst case, the server private key (the only case where the private key remains safe while the server is vulnerable is when it is stored in a hardware security module, because it never appears in memory).

Buffer overflow mitigation techniques such as Address Space Layout Randomization (ASLR) are not effective against Heartbleed because OpenSSL implemented its own memory management on top of libc’s one, for performance’s sake. That situation is controversial since it is not granted that
OpenSSL’s memory management layer is faster than libc’s one on any system. Even on systems where it is, this is a problem that should be fixed in libc itself, and not worked around in OpenSSL.

Even more unfortunate is the fact that TLS Heartbeat is an optional extension that is almost useless. It is used to keep connections alive in Datagram TLS (DTLS), which is TLS over UDP. When TLS runs on top of TCP, which is the case for HTTP over TLS, the problem solved by TLS Heartbeat does not exist.

Heartbleed is only an implementation vulnerability, which means it will be fixed by just upgrading OpenSSL to at least version 1.0.1g, or by rebuilding it without TLS Heartbeat enabled (that is, using --openssl_no_heartbeats option to the C compiler). Since the vulnerability may have allowed private keys to be extracted, they must be replaced, TLS certificates must be renewed and the older certificate should be revoked. Then all user passwords should be changed. All that work is painful, but probably necessary.

There have been some controversy on how easily the server private key could be extracted. The vulnerability only allows reading 64 kB of data, and most of the time the private key is out of reach, but it has been shown that it can be reliably obtained just after a server restart [17]. Reliable or not, a private key-leak vulnerability is still a major concern, as one leak is enough to compromise the private key forever. And moreover, the vulnerability has existed for two years before being disclosed and fixed, hence it cannot be excluded that someone knew it and used it during that time frame.

### 2.6 Ineffective certificate revocation vulnerabilities

There is a dark corner of Heartbleed recovery that has not been covered a lot: many web browsers never check for certificate revocation, and even if they do, there are situations where they fail to do it and still allow the connection to proceed (WiFi hotspot is a situation where it happens). As a result, if an attacker stole a private key, he is still able to use it with the revoked certificate to perform Man in the Middle attacks. This means an effort will have to be done to improve certificate revocation enforcement.

There are two widely supported methods to check for certificate revocation. The first one is Certificate Revocation List (CRL), a CA-signed list of revoked certificate serial numbers, which is published at a well known URL carved into the CA certificate. This method obviously does not scale, as the file length only increases as certificates are revoked. And it also requires a network connection.

The other major approach is Online Certificate Status Protocol (OCSP), a protocol that lets the browser ask for the revocation status of a particular certificate. It scales much better than CRL, but it still requires a network connection to be used.

Google introduced an offline mechanism in Chrome, which is called CRL sets. The idea is that Chrome gets CRL with its automatic updates, removing the need for a network connection when a certificate revocation status is checked. Unfortunately this mechanism suffers a scaling problem even worse than CRL, as CRL sets should list revoked certificate serial numbers for all the CA known to the browser. This would be huge, and as a result, Google only provide CRL sets for a subset of the installed CA [18], leaving the user vulnerable without any clue about which web site is protected by CRL sets and which one is not.

The problem could be addressed correctly by OCSP stapling, which is a TLS extension that enable the TLS server to acquire a certificate validity proof from the CA so that it can be presented to the client during the TLS handshake. In other words, the TLS server acts as an OCSP proxy for the client. This both solves scalability problem (except perhaps for the network bandwidth consumed by OCSP services) and the network access requirement: a not-yet-authenticated host on a WiFi hotspot is able to assess the authentication server’s certificate revocation status. But unfortunately, OCSP stapling requires client and server support, and it is not yet widely supported.
2.7 Other attacks

There are other attacks against TLS for which Qualys SSL server test will not warn you about. The padding oracle attack was discovered in 2002, and it was worked around for a long time by all implementations, but a new usable variant called Lucky 13 was published in 2013. Like BEAST, Lucky 13 targets CBC ciphers, which means it can be mitigated by using RC4 (but this trades a vulnerability for another one), or by using TLSv1.2, which brings GCM ciphers. There is also a Lucky 13 implementation workaround for CBC ciphers, obtained by introducing time variations in the algorithms. But both GCM and CBC with time variations are not implemented by all clients, and there is no way for the server to know if Lucky 13 mitigation for CBC is done on the client or not.

Fortunately, Lucky 13 needs the attacker to temper with TLS traffic, which means it must be in a position to act as a Man in the Middle (MITM). And since it is a timing dependent attack, it requires a network connexion with low jitter (jitter is the variation of latency), and a lot of requests to succeed and recover a session cookie. The risk is hence low for now. It can be lowered by limiting session cookie lifetime, or even better, by binding it to the number of requests done.

2.8 Client vulnerabilities

As noted earlier, some TLS vulnerabilities require client fixes. This is the case for TLS session renegotiation, and BEAST, thought the 1/n-1 split workaround in CBC ciphers. Lucky 13 can also be spared by implementing timing variation for CBC ciphers. If we assume the client has not been updated, we can have server-side mitigation, by avoiding TLS session renegotiation, or by using RC4 (but as already said it is a controversial choice, since RC4 is vulnerable to other attacks), or GCM ciphers available in TLS 1.2 (which is still not supported by many clients). However there are other threats against clients, for which no server-side mitigation is available.

The Apple TLS stack suffered a security failure because of a duplicate "goto fail" statement in the source code. It allowed easy hijacking of TLS session for TLS up to TLSv1.1 and ciphers using ECDHE or DHE (these are the ciphers required to support Perfect Forward Secrecy). This caused a widespread vulnerability on iOS, and vulnerabilities in Safari and Apple Mail on MacOS X. The only decent workaround is to upgrade the OS. On MacOS X, software that bring their own TLS implementation, such as Firefox and Thunderbird, remained safe.

As for the BEAST vulnerability, identifying the browsers vulnerable to the "Apple goto fail" vulnerability is a good idea, since it allows users to be notified. This can be done by running a dedicated Apache linked with a patched OpenSSL, as described by Qualys SSL labs’ Ivan Ristic [19].

If you have a corporate intranet start page, it is a good place to run Multiple browsers vulnerabilities tests. This can easily be achieved by including &lt;img&gt; tags for 1x1 images on a test server. If a vulnerability is identified, a site-wide cookie can be be set, and the corporate intranet start page can use it to warn the user.

While there, you can also test if the browser accepts self-signed certificates, which would allow anyone to perform easy Man in the Middle attacks. Some mobile browser fail to perform this basic check, which means their TLS implementation does not bring much more security than clear text communications.

Key Points

• Use up to date server software
• Test your TLS-enabled web server with Qualys SSL server test
• Make sure TLS compression is disabled
• Disable HTTP compression for requests incoming from other sites
• Until the day TLSv1.2 support becomes widespread, choose between dangers of RC4 and CBC ciphers.
• Assess browser vulnerabilities and notify users so that they know they need an upgrade
• Protect session cookies with the secure and httpOnly flags

3 Hardening other protocols

Once your web servers are secure, it is time to look at other protocols: here are a few obvious examples: POP, IMAP, SMTP, LDAP, OpenVPN.

The good news is that many attacks possible on HTTP over TLS cannot be transposed to other protocols. This is because there is no way to trick the client into sending chosen data. POP requests cannot bounce from an external server to yours, and no JavaScript can inject data into a SMTP session.

This is true for all above mentioned protocols. It means attacks on CBC ciphers such as BREACH, CRIME or BEAST cannot happen here. The only thing we will have to worry beyond certificates, protocols and ciphers are Lucky 13 and RC4 vulnerabilities.

Dealing with RC4 vulnerability is simple, we can just disable it. This is an easy choice here since we do not choose between RC4 attacks and BEAST. On the other hand, protecting against Lucky 13 is not easy. We cannot enforce the use of TLS 1.2 GCM ciphers, as many clients do not support them, and we do not want to use RC4. We may assume timing variant workarounds to be implemented in the client, we we have no way to assess it is the case. Unfortunately, this client workaround, and the difficulty to run a Lucky 13 attack, are our only solutions against Lucky 13 until the day TLS 1.2 is universally supported.

3.1 Dovecot

Here is a sample dovecot TLS settings:

```plaintext
ssl = yes
ssl_ca = /etc/openssl/certs/ca-chain.crt
ssl_key = /etc/openssl/private/server.key
# Server certificate with CA chain included
ssl_cert = /etc/openssl/certs/server-bundle.crt
# No need to disable SSLv2, it is done by default
ssl_prefer_server_ciphers = yes
ssl_cipher_list = ECDH@STRENGTH:DH@STRENGTH:HIGH:!RC4:!MD5:!DES:!aNULL:!eNULL
disable_plaintext_auth = yes
```

Note that ECDHE is available starting with Dovecot 2.2.6. As for web server, supporting it is important because it will increase the amount of Perfect Forward Secrecy capable clients.

SSLv2 is supposed to be disabled by default, but it does not hurt to check that:

```
openssl s_client -ssl2 -connect server:993
```

3.2 Sendmail

Many TLS features in Sendmail need to be enabled at compile time. This is achieved by filling the site.config.m4 before the build:

```plaintext
# enable STARTTLS
APPENDDEF('conf_sendmail_ENVDEF', '-DSTARTTLS')
APPENDDEF('conf_sendmail_LIBS', '-lssl -lcrypto')
# enable _FFR_TLS_1, for CipherList directive
APPENDDEF('conf_sendmail_ENVDEF', '-D_FFR_TLS_1')
# enable _FFR_TLS_EC, for ECDH support, requires sendmail 8.14.8 or higher
APPENDDEF('conf_sendmail_ENVDEF', '-D_FFR_TLS_EC')
```
If your Sendmail was obtained as a binary package, the following command let you know what is built inside (look for _FFR_TLS_ and _FFR_TLS_EC_):

```
sendmail -d0.13 < /dev/null
```

_­FFR_TLS_EC_ was contributed by the author of this paper. It is really new and is not likely to be built in a binary package in the months following the publication of this article. Also note that FFR stands for 'For Future Release', which suggests that the feature may become default in future.

Once you have the correct options, either because you already had them, or because you made a custom Sendmail build, you can use the following options in `sendmail.cf`:

```
O CACertPath=/etc/openssl/certs/
O CACertFile=/etc/openssl/certs/ca-chain.crt
O ServerCertFile=/etc/openssl/certs/server.crt
O ServerKeyFile=/etc/openssl/private/server.key
O DHParameters=/etc/openssl/certs/dh.pem
O CipherList=ECDH@STRENGTH:DH@STRENGTH:HIGH:!RC4:!MD5:!DES:!aNULL:!eNULL
O ServerSSLOptions=+SSL_OP_NO_SSLv2 +SSL_OP_CIPHER_SERVER_PREFERENCE
O ClientSSLOptions=+SSL_OP_NO_SSLv2
```

Recent Sendmail will not need the DHParameters option, but it is worth a few words. ECDHE and DHE ciphers need DH parameters to operate. Some softwares are able to auto-generate them internally, while others will require the administrator to generate a DH parameter file and specify it in the configuration. The file can be obtained by running the following command:

```
openssl dhparam 2048 > /etc/openssl/certs/dh.pem
```

### 3.3 OpenLDAP

TLS support in OpenLDAP has been good for a long time, hence you are not likely to have missing features.

There are two cases here: the TLS service available to clients, and the TLS connections between master server and replicas. The former needs to be permissive enough so that any client can connect, but the latter is a good candidate for hardening since it only needs to support connections from replicas using recent OpenLDAP releases.

Here is a hardened configuration for an OpenLDAP master:

```
TLSCertificateFile /etc/openssl/certs/server.crt
TLSCertificateKeyFile /etc/openssl/private/server.key
TLSCACertificateFile /etc/openssl/certs/ca-chain.crt
TLDHParamFile /etc/openssl/certs/dh2048.pem
TLSCipherSuite ECDH:DH:!RC4:!SHA:!MD5:!DES:!aNULL:!eNULL
TLSVerifyClient allow
TLSCACertificatePath /etc/openssl/certs
TLSCRLCheck all
```

TLSCACertificateFile, TLSVerifyClient, TLSCACertificatePath and TLSCRLCheck are useful if you allow clients to authenticate using certificates, which is a good idea for LDAP replicas connecting to a LDAP master (more on that later).

Note that `!SHA:!MD5` in the CipherSuite will disable all ciphers from TLSv1.1 and earlier: SHA in a cipher specification stands for SHA1, and only TLSv1.2 brings ciphers using hash algorithm using SHA2.

The specification may be odd, but it is just because it is an evolution from the previous cipher suite we used before. The same result could be achieved with something perhaps more easy to understand such as:

```
ECDH:DH:!TLSv1:!SSLv3:!aNULL:!eNULL
```
On the replica side, the cipher suite needs to allow more clients to connect. You can reuse the cipher suite we used for the web, or if your LDAP clients are good enough, you can force PFS usage:

```
TLSCertificateFile /etc/openssl/certs/server.crt
TLSCertificateKeyFile /etc/openssl/private/server.key
TLSCACertificateFile /etc/openssl/certs/ca-chain.crt
TLS DHParamFile /etc/openssl/certs/dh2048.pem
TLSCipherSuite ECDH@STRENGTH:DH@STRENGTH:!RC4:!MD5:!DES:!aNULL:!eNULL
TLSVerifyClient allow
TLSCACertificatePath /etc/openssl/certs
TLS CRLCheck all
```

OpenLDAP replicas can also have a TLS setup for their client-side, in chain overlay and syncrepl configuration. Here is a configuration sample:

```
syncrepl rid=17
  provider=ldap://ldap-master.example.net
  type=refreshAndPersist
  searchable="dc=example,dc=net"
  starttls=critical
  schemachecking=off
  sizelimit=unlimited
  retry="3 1 10 2 60 +*
  bindmethod=sasl
  saslmech=EXTERNAL
  tls_cert=/etc/openssl/certs/server.crt
  tls_key=/etc/openssl/private/server.key
  tls_cacert=/etc/openssl/certs/ca-chain.crt
  tls_reqcert=demand
  tls_cipher_suite=ECDH:DH:!RC4:!SHA:!MD5:!DES:!aNULL:!eNULL
  tls_cacertdir=/etc/openssl/certs
  tls_crlcheck=all
```

Both the master and replica configuration here include directives to enforce CRL checking. OpenSSL is a bit odd here and deserves some explanations. If CRL checking is enabled using TLSCRLCheck (tls_crlcheck in syncrepl configuration), then OpenSSL will look for a CRL file in the directory specified by TLSCACertificatePath (tls_cacertdir in syncrepl configuration). The name of the CRL file is of the form $hash.r0, where $hash is obtained by the openssl crl command:

```
openssl crl -hash -noout -in ca.crl
```

This means that once you obtained the ca.crl file, you must install it in the directory specified by TLSCACertificatePath (tls_cacertdir), and run the following command:

```
ln -s ca.crl "openssl crl -hash -noout -in ca.crl".r0
```

If you manage your own internal CA, which is a good idea for LDAP certificates, the CRL file can be obtained from the CA key and certificate by using this command:

```
openssl ca -keyfile ca.key -cert ca.crt -gencrl -out ca.crl
```

### 3.4 Webmail software

We dealt with web and mail servers, but not in the middleware that can sit between them, which is known as webmail. Many software are available, but a close inspection of a few of them (SquirrelMail, RoundCube, ImapProxy) has shown a few deficiencies: no certificate validation was done, no effort was done to push TLSv1.2 usage if available, and cipher suites were not configurable.

While the two latter issues can be acceptable, the lack of certificate validation can be a real problem, as it allows easy Man in the Middle attacks. Often the risk is neglected because mail and web servers sit close to each other in the same data center, but that may not always be the case.
Patches have been submitted and accepted in the three above mentioned software to improve the situation but as of today formal releases including the patches have not been done. Here are the minimum version requirement and configuration snippet to get support up to TLSv1.2, ECDHE ciphers, CA validation, and configurable cipher suites:

**ImapProxy > 1.2.7**  (Use SVN version)

```bash
tls_ca_file /etc/openssl/certs/tcs-chain.crt
tls_ciphers ECDH:DH:!RC4:!SHA:!MD5:!DES:!aNULL:!eNULL
tls_verify_server true
force_tls true
```

**Squirrelmail > 1.4.22**  (Use 1.4.23-svn or 1.5.2-svn versions)

```bash
$use_smtp_tls = true;
$smtpOptions['ssl']['verify_peer'] = true;
$smtpOptions['ssl']['verify_depth'] = 3;
$smtpOptions['ssl']['cafile'] = '/etc/openssl/certs/ca-chain.crt';
$smtpOptions['ssl']['ciphers'] = 'ECDH:DH:!RC4:!SHA:!MD5:!DES:!aNULL:!eNULL';
$smtp_stream_options = $smtpOptions;
```

**Roundcube ≥ 1.0rc**

```bash
$rcmail_config['smtp_conn_options'] = array(
    'ssl' => array(
        'verify_peer' => TRUE,
        'verify_depth' => 3,
        'cafile' => '/etc/openssl/certs/ca-chain.crt',
        'ciphers' => 'ECDH:DH:!RC4:!SHA:!MD5:!DES:!aNULL:!eNULL';
    ),
);
```

There are a few points to note:

- SquirrelMail and RoundCube certificate validation and cipher specification use PHP context options, which are only available in PHP 5.
- We assume ImapProxy usage here: IMAP configuration for SquirrelMail and Roundcube is therefore not using TLS.
- We assume the mail server TLS setup is under our control and that we can enforce a restrictive cipher suite, with only PFS-enabled TLSv1.2.

### 3.5 OpenVPN

The case of OpenVPN could be straightforward: it enjoyed very good TLS support for a long time, and we could assume clients are up to date. This would let us enforce the use of TLSv1.2 GCM ciphers. Here are the TLS related options in server configuration:

```bash
cs /etc/openssl/certs/ca-chain.crt
cert /etc/openssl/certs/server.crt
key /etc/openssl/private/server.key
dh /etc/openssl/certs/dh2048.pem
tls-cipher ECDH:DH:!RC4:!SHA:!MD5:!DES:!aNULL:!eNULL
client-cert-not-required
```

But unfortunately there are many outdated clients that will not support such a setup. TLSv1.2 is not available in OpenVPN up to 2.3.2, and MacOS X’s package GUI for OpenVPN, which is known as Tunnelblick, is bundled with various versions of OpenVPN (as of may 2014, latest Tunnelblick ships with OpenVPN version 2.2.1, 2.3.2, and 2.3.4). The preference panel lets the
user choose the OpenVPN version, and if it is not set to 2.3.4, or if Tunnelblick is too old to include 2.3.4, the client will not work with a TLSv1.2 only configuration. The setup below is more compatible by allowing CBC ciphers from protocols versions prior to TLSv1.2:

```
cs /etc/openssl/certs/ca-chain.crt
cert /etc/openssl/certs/server.crt
key /etc/openssl/private/server.key
dh /etc/openssl/certs/dh2048.pem
tls-cipher ECDH:DH:!RC4:!MD5:!DES:!aNULL:!eNULL
client-cert-not-required
```

### 3.6 More protocols

There may be other protocols to look at. To name a few, RADIUS configuration for EAP-TTLS in 802.1x authentications, SIP, or any TCP service wrapped into Stunnel.

This latter utility is worth mentioning, as it allows any TCP stream to be protected by TLS. If you encounter a software with broken TLS that cannot be fixed, disabling its TLS support and replacing it with Stunnel is a good idea: the broken software listens for plain text traffic on localhost, and Stunnel offers the TLS-protected service over the network, and relays it to the broken software. The Stunnel configuration will looks like this:

```
chroot = /var/chroot/stunnel/
setuid = stunnel
setgid = stunnel
pid = /stunnel.pid
debug = 0
CAfile = /etc/openssl/certs/ca-chain.crt
sslVersion = TLSv1
ciphers = ECDH@STRENGTH:DH@STRENGTH:HIGH:!RC4:!MD5:!DES:!aNULL:!eNULL

[https]
# contains CA chain and certificate
cert = /etc/openssl/private/cert-bundle.crt
key = /etc/openssl/private/server.key
accept = 443
# protected service is told to listen on port 127.0.0.1:8080
connect = localhost:8080
```

Note that such a setup is also useful for debugging TLS-protected protocols. Network sniffers such as tcpdump are of little interest when facing TLS protected streams. But if you install a Stunnel relay, it is possible to capture the clear text protocol by listening on the local interface:

```
tcpdump -ni lo0 -s0 -X 'port 8080'
```

### Conclusions

We had a look at TLS and how to harden it against the usual attacks against it for various open source software. The method is always the same: make sure software is up to date, disable SSLv2, choose a strong cipher suite that still allow older clients to connect, and test the result.

Server testing should make sure that insecure protocols versions and ciphers are disabled. Proper certificate validation should also be checked, as this step is sometimes missing in some software. It should be done for clients, and for servers that perform client authentication using X.509 certificates. Tests may spot broken software. If it cannot be fixed, using an up-to-date Stunnel as a relay is an option to obtain a properly hardened TLS service.

The final words could be an emphasis over the TLS flaws that cannot be worked around. Only TLSv1.2 with recent ciphers is safe from any known attack, and since some clients do not support it, the administrator often needs to choose between two kind of troubles: on one hand, using CBC ciphers that are subjects to various attacks that may be fixed in the client (BEAST, Lucky 13), and/or difficult to perform (Lucky 13). On the other hand, adopt the weak RC4, which is
vulnerable to attacks difficult to perform, but with no fix available, whether on client or server. No consensus exists here, and as various actors made different choices, the author of this paper chose CBC.

Unfixed TLS flaws also exist in older clients and servers, and will certainly happen again in the future. Even TLS-unrelated flaws can have an impact on TLS, for instance when a server private key is compromised because a cracker got root access on a server, or managed to derive it from the public key. In such a scenario, all TLS traffic that has been captured and stored in the past can be deciphered, except if a PFS cipher was used.

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