Forensic Analysis of Communication Records of Web-based Messaging Applications from Physical Memory

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Abstract: Inspection of physical memory allows digital investigators to retrieve evidence otherwise inaccessible when analyzing other storage media. In this paper, we analyze in-memory communication records produced by web-based instant messaging and email applications. Our results show that, in spite of the heterogeneity of data formats specific to each application, communication records can be represented in a common application-independent format. This format can then be used as a common representation to allow for general analysis of digital artifacts across various applications, even when executed in different browsers. Then, we introduce RAMAS, an extensible forensic tool which aims to ease the process of analyzing communication records left behind in physical memory by instant-messaging and email web clients.

1 INTRODUCTION

Instant-messaging (IM) and email applications such as Facebook's chat and Gmail clients, respectively, are widely used communication services that allow individuals to exchange messages over the Internet. Given the nature of the exchanged data, digital artifacts left by such applications may hold highly relevant forensic value. This is particularly true if, from such artifacts, it is possible to recover communication records of past conversations providing information about the content of exchanged messages, identity of communicating parties, or time-related information.

To assist forensic analysts in recovering such artifacts, we aim to develop a forensic tool for extraction of conversation records left by *web-based messaging applications* in *physical memory dumps*. As opposed to their native counterparts, web-based applications run inside a browser and are becoming increasingly popular because users do not need to install them on their computers; all they need to do is to open a browser and visit a URL. By focusing on physical memory analysis, our goal is to complement the functionality of existing forensic tools which focus on the analysis of persistent state, e.g., local logs (Yang et al., 2016; Al Mutawa et al., 2011), and to address a latent need for the analysis of high-level data present in such memory dumps (Simon and Slay, 2009).

Although some prior work employs memory forensic techniques on messaging applications, existing tools tend to be highly application-dependent. For example, Wong et al. present techniques that allow for the recovery of digital artifacts for the Facebook messaging service (Wong et al., 2011). However, the proposed techniques cannot directly be applied to multiple other applications due to the heterogeneity of data formats implemented by each application. Furthermore, the fact that web-based applications run inside a browser may interfere with the durability of applications' artifacts in memory, for example due to the memory management policy implemented by the browser. Existing works on browser forensics concentrate only on the extraction of browser-specific artifacts (e.g., browsing history, web cache) leaving aside the recovery of application-specific artifacts (Ohana and Shashidhar, 2013).

In this paper we make three key contributions. First, we present a *digital forensics study* aimed to systematically analyze the digital artifacts left in memory by several popular IM and email web-applications when executed on various browsers. We successfully identified and retrieved IM communication records from web-applications such as Facebook, Twitter and Skype, as well as email records from Outlook and a generic Roundcube email web-client. Our study helps to characterize how the communication records of web-based messaging applications are typically represented and to identify how browser-specific mechanisms may affect the durability of such records in memory (Section 2).

Second, we introduce the design and implementation of a *forensic tool* called RAMAS, which consists of a collaborative and extensible framework for analysis of communication records from volatile memory. RAMAS is able to extract such records from multiple web-based messaging applications and display the extracted records on a user-friendly timeline. RAMAS is designed in a modular fashion so as to accommodate an ever-growing number of applications and allow collaborative development and maintenance of the system by independent forensic analysts. This goal is achieved through the implementation of extraction modules: each module contains a set of (simple) rules that allow RAMAS to extract the records of a specific application and represent them on a common application-independent format (Section 3).

Lastly, we present an *experimental evaluation* of our framework. To this end, we used RAMAS for conducting analysis over the data extracted from memory chips with sizes typically found in commodity hardware. Our evaluation shows that RAMAS is efficient, e.g., it can process communication records spawning from six different applications, in an 8 GB memory dump, in roughly about three minutes. We also enact a use case for demonstrating the usefulness of our framework's evidence presentation capabilities which may help digital investigators in uncovering sophisticated correlations among evidence from several applications or across memory images (Section 4).

2 DIGITAL FORENSICS STUDY

This section presents the digital forensics study that we carried out in order to assess the existence of communication records in physical memory produced by web-based messaging applications. This study lays the ground for the subsequent development of a forensic tool for automatic extraction of such records.

2.1 Goals of the Forensics Study

More concretely, the goal of this study is to check whether and in which conditions communication records can be obtained from memory dumps. In particular, our research is driven by two key questions:

How are messages represented in memory? The programmers of web-based messaging applications are free to implement them using a range of different technologies. Some design decisions comprise the choice of front-end and back-end programming languages (ex. Javascript, PHP), others involve selecting the data representation format of communication records (ex. JSON, XML, binary). This heterogeneity in data representation and platforms may impact the way communication records are loaded into memory and contribute for the absence of a common model of the structure of communication records among different implementations of browsers and operating systems. This implies that a tool developed for analyzing this kind of evidence would exhibit the additional complexity of having to take into account such differences between record structures, even when analyzing a single application. We aim to assess whether there is a common model which allows for the interpretation of textual web-application data lingering in memory.

How long do messages persist in memory? The persistence of in-memory data structures may be affected by the browser where the web-based messaging application runs. First, we must ascertain whether the *browser runtime environment* imposes limitations on the ability to recover communication records from physical memory. In particular, to provide the interaction with web-applications, web-browsers rely on different layout engines (ex. Blink, Gecko) which affect the way a browser hosts, renders or executes web content. Similarly, several implementations of operating systems target different platforms (ex. workstation, mobile) and are expected to apply disparate low-level mechanisms for performing memory management. Furthermore, different *user interactions* may trigger the erasure or replacement of potential evidence in volatile memory. For instance, data pertaining to a given web-application may be evicted shall a user navigate to a different browser tab or terminate her browsing session. Finally, modern browsers implement *private browsing* execution modes which enables users to browse the web while disabling both the browsing history and web cache. This feature is implemented by popular browser vendors and is known under different aliases, such as Incognito, InPrivate or PrivateBrowsing. We must evaluate whether the use of private browsing may compromise the existence of digital artifacts lingering in memory.

2.2 Experimental Methodology

To investigate whether and in which conditions messages can be obtained from memory, we performed an experimental study of several web-based messaging applications. In particular, we analyzed digital artifacts concerning IM records for Facebook's chat, Facebook Messenger's chat, Skype, Twitter's Direct Messages, Google Hangouts, WhatsApp, Telegram, and Trillian. We also analyzed communication records of three email web-clients: Outlook, a generic Roundcube email client, and Gmail.

These applications were tested on different

Table 1: Feasibility of recovering web-based messaging application records from different browsers.

Web-Application	Browser			
	Google Chrome v55.0	Mozilla Firefox v50.0.1	Opera v42.0	Microsoft Edge v38.14393.0.0
Facebook	✓	✓	✓	✓
Messenger	✓	✓	✓	✓
Skype	✓	-	✓	✓
Twitter	✓	✓	✓	✓
Hangouts	-	-	-	-
WhatsApp	-	-	-	-
Telegram	-	-	-	-
Trillian	-	-	-	-
Outlook	✓	-	✓	✓
Roundcube	✓	✓	✓	✓
Gmail	-	-	-	-

browsers: Google Chrome, Mozilla Firefox, Opera, and also Microsoft Edge. Tests for each browser were conducted for both private and non-private browsing sessions. For our tests, every web-application was used in a freshly generated browser tab. We have conducted our experiments in two widely used desktop operating systems: Windows 10 and Ubuntu 16.04. Both operating systems were deployed in VirtualBox 5.1.8 virtual machines with 1GB of RAM. Memory dumps of both systems are acquired through atomic virtualization-aided methods. Each virtual machine was restarted between separate test runs.

For each individual test, we conducted a predefined set of actions that capture real world usage of each web-application:

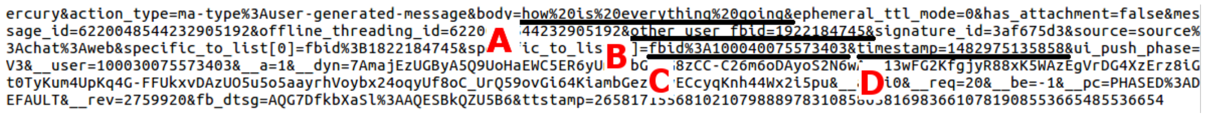
- *Instant-Messaging test run:* A user performs login in an IM web-application and sends two messages to a given recipient. The user also browses through existing contacts and inspects the current conversation, as well as past conversations (by navigating back and forth between conversations or by opening different chat windows inside the same browser tab). The aim of this set of actions is to retain relevant data in memory, while simulating a typical use of this kind of applications.
- *Email test run:* A user performs login in her webmail client and browses her inbox and outbox. This allows us to simulate a common use-case for these applications and later check which digital artifacts were retained in memory.

Simulated user interactions: Investigators may miss out the opportunity to get access to the target machine while a suspect is still logged in a given account. We assess four different sequences of actions a user may perform after concluding a session within the web-application, before we have the opportunity of acquiring a memory dump of the system. We consider the following sequences of actions, sorted in an increasing fashion according to their expected *intrusiveness level* (IL) with the artifacts we are concerned with:

- *(IL1)* Logout;
- *(IL2)* Logout and navigate to a webpage in a different browser tab;
- *(IL3)* Logout and navigate to a webpage in the same browser tab;
- *(IL4)* Logout and close the tab/browser.

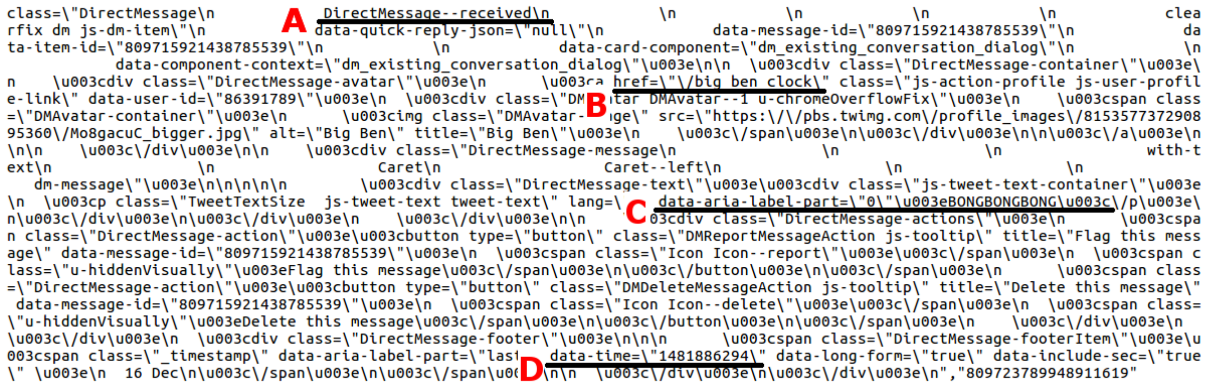
We contemplate these degrees of *intrusiveness* according to the inner architecture of existing browsers. In all tested browsers, each tab runs in a separate process which is responsible for rendering a page's content. As an example, we refer to the recent Mozilla's Electrolysis project (Mozilla, 2015). In this setting, the browser's parent process manages tabs and the core browser functionality. This architecture brings several advantages, such as providing inter-tab data security, isolate crashes in individual tabs, and maintaining the overall browser's responsiveness (Charlie Reis, 2008). According to this description, we expect *IL1* and *IL2* sequences to be the least intrusive ones, since the tab state after logout is expected to be preserved. In contrast, the *IL3* sequence may affect the content of the memory allocated to the tab where the messaging service was used, possibly causing the eradication of evidence. Lastly, we expect the *IL4* sequence to be the most intrusive one, since the OS shall reclaim the memory associated to the tab/browser process, possibly wiping out any artifact that could have been left behind by the application.

Extraction methodology: To assess whether a given communication record was retained in memory and to pinpoint metadata structures surrounding it, the messages sent in each test run act like keywords for enabling posterior search. To look for these keywords, we begin by extracting the strings contained in the memory dump with the `strings` command-line utility, followed by a `grep` search to match the strings



```
ercury&action_type=ma-type%3Auser-generated-message&body=how%20is%20everything%20going&ephemeral_ttl_mode=0&has_attachment=false&mes
sage_id=6220048544232905192&offline_threading_id=6220   44232905192&other_user_fbid=1922184745&signature_id=3af675d3&source=source%
3Achat%3Aweb&specific_to_list[0]=fbid%3B1822184745&sp  ic_to_lis  ]=fbid%3A100040075573403&timestamp=1482975135858&ui_push_phase=
V3&__user=100030075573403&__a=1&__dyn=7AmajEzUGByA5Q9UoHaEWC5ER6yU  bG  8zCC-C26m6oDAyoS2N6w   13wFG2KfgjyR88xK5WAzEgVrDG4XzErz8iG
t0TyKum4UpKq4G-FFUkxvDAzUO5u5o5aayrhVoybx24oqyUf8oC_UrQ59ovGi64KiambGez  ECcyqKnh44Wx2i5pu&__  i0&__req=20&__be=-1&__pc=PHASED%3AD
EFAULT&__rev=2759920&fb_dtsg=AQG7DfkbXaSl%3AAQESBkQZU5B6&ttstamp=265817  68102107988897831085  816983661078190855366548553665
```

Figure 1: Facebook recently sent message data fields.



```
class=\"DirectMessage\n          DirectMessage--received\n               \n              \n              \n              \n           clea
rfix dm js-dm-item\"\n            data-quick-reply-json=\"null\"\n            data-message-id=\"809715921438785539\"\n               da
ta-item-id=\"809715921438785539\"\n              \n              data-card-component=\"dm_existing_conversation_dialog\"\n              \n
           data-component-context=\"dm_existing_conversation_dialog\"\u003e\n\n  \u003cdiv class=\"DirectMessage-container\"\u003e\
n    \u003cdiv class=\"DirectMessage-avatar\"\u003e\n       \u003ca href=\"\/big ben clock\" class=\"js-action-profile js-user-profil
e-link\" data-user-id=\"86391789\"\u003e\n  \u003cdiv class=\"DM  tar DMAvatar--1 u-chromeOverflowFix\"\u003e\n     \u003cspan class
=\"DMAvatar-container\"\u003e\n      \u003cimg class=\"DMAvatar-  ge\" src=\"https:\/\/pbs.twimg.com\/profile_images\/8153577372908
95360\/Mo8gacuC_bigger.jpg\" alt=\"Big Ben\" title=\"Big Ben\"\u003e\n    \u003c\/span\u003e\n\u003c\/div\u003e\n\n\u003c\/a\u003e\n
\n\n    \u003c\/div\u003e\n\n    \u003cdiv class=\"DirectMessage-message\n              \n              \n              with-t
ext\n              \n              Caret\n              Caret--left\n              \n              \n
   dm-message\"\u003e\n\n\n\n\n       \u003cdiv class=\"DirectMessage-text\"\u003e\u003cdiv class=\"js-tweet-text-container\"\u003e
\n  \u003cp class=\"TweetTextSize  js-tweet-text tweet-text\" lang=\  data-aria-label-part=\"0\"\u003eBONGBONGBONG\u003c\/p\u003e\
n\u003c\/div\u003e\n\u003c\/div\u003e\n    \u003c\/div\u003e\n\n   03cdiv class=\"DirectMessage-actions\"\u003e\n       \u003cspa
n class=\"DirectMessage-action\"\u003e\u003cbutton type=\"button\" class=\"DMReportMessageAction js-tooltip\" title=\"Flag this mess
age\" data-message-id=\"809715921438785539\"\u003e\n  \u003cspan class=\"Icon Icon--report\"\u003e\u003c\/span\u003e\n  \u003cspan c
lass=\"u-hiddenVisually\"\u003eFlag this message\u003c\/span\u003e\n\u003c\/button\u003e\n\u003c\/span\u003e\n       \u003cspan class
=\"DirectMessage-action\"\u003e\u003cbutton type=\"button\" class=\"DMDeleteMessageAction js-tooltip\" title=\"Delete this message\"
 data-message-id=\"809715921438785539\"\u003e\n  \u003cspan class=\"Icon Icon--delete\"\u003e\u003c\/span\u003e\n  \u003cspan class=
\"u-hiddenVisually\"\u003eDelete this message\u003c\/span\u003e\n\u003c\/button\u003e\n\u003c\/span\u003e\n    \u003c\/div\u003e\n
\u003c\/div\u003e\n  \u003cdiv class=\"DirectMessage-footer\"\u003e\n\n\n      \u003cspan class=\"DirectMessage-footerItem\"\u003e\u
003cspan class=\"_timestamp\" data-aria-label-part=\"last  data-time=\"1481886294\" data-long-form=\"true\" data-include-sec=\"true
\" \u003e\n  16 Dec\n\u003c\/span\u003e\n\u003c\/span\u00  \n\n  \u003c\/div\u003e\n\u003c\/div\u003e\n","809723789948911619"
```

Figure 2: Twitter received message data fields.

which contain a chosen keyword. Similarly, we attempt to match email records by searching email addresses known to be present in the client's inbox/outbox. A communication record is retrieved if the identified metadata enables for the collection of the tuple ⟨*Timestamp, Author, Recipient, Message*⟩, at least.

Below, we present our main findings of our study.

2.3 Message Representation

Table 1 depicts a summary of our analysis for several popular web-applications and web-browsers. Results show that it was not possible to retrieve any structured communication record from Gmail, Hangouts, WhatsApp and Telegram, which leads us to conjecture that these applications may make use of a binary data representation format which can not be directly recovered in the form of strings.

For all the remaining applications under test we were able to find messages with accompanying high-level metadata structures in the form of strings. For instance, we can observe in Figure 1 and Figure 2 two digital artifacts left in memory by Facebook chat and Twitter Direct Messages. In these cases, enclosing metadata was found either in the form of JSON or HTML, respectively. Albeit the metadata structures lingering in memory use a different data format and exhibit different fields, both follow a similar model which may be used to reconstruct the tuple ⟨*Timestamp, Author, Recipient, Message*⟩ which we consider a communication record. In the case of Facebook chat, the metadata fields present in Figure 1 allow us to easily reconstruct the full ⟨*Timestamp, Author, Recipient, Message*⟩ tuple, where 1.A corresponds to *Message*, 1.B to *Author*, 1.C to *Recipient* and 1.D to the message *Timestamp*.

The example in Figure 2 helps to identify an edge-case on the reconstruction of communication records. While 2.C can be easily matched with *Message* field and 2.D to the message *Timestamp*, 2.B does not provide enough information to state whether the identified Twitter alias corresponds to either *Author* or *Recipient*. However, 2.A clearly specifies the direction of the message. Thus, the record in Figure 2 suggests it refers to a message where 2.B specifies its *Author*. The message *Receiver* would then consist of the account which the suspect has logged-in to and which can be known either by previously gathered intel or other data structures residing in memory. We experimentally verified that, for outbound messages, the 2.A field would mark the Twitter Direct Message as *sent*.

Additionally, we found that the structure of obtained communication records remains the same for each web-application even across different browsers and operating systems. This observation reinforces our conjecture that the leakage of high-level data into memory is caused by the way web-applications are built, as the structure of high-level records present in memory is not tied to the particular implementation of a browser or an operating system's inner workings.

2.4 Message Durability

We now ascertain how the use of different browsers and operating systems, as well as the execution of intrusive actions affects the recovery of communication records. As shown in Table 1, we were able to retrieve communication logs with all tested browsers. However, we note that, for experiment *IL1*, we collected a smaller amount of messages when using Firefox or Edge rather than when using Chrome or Opera. A possible explanation for this fact is that both Chrome and Opera are based on Chromium's codebase and may share implementation details which favour the preservation of a tab's resources in memory.

Browsers may implement different mechanisms for refreshing the contents of volatile memory, evicting the resources of background tabs and favouring those of the foreground tab. To check whether this fact affects the recovery of communication records, we conducted experiment *IL2*. Our results show that Chrome and Opera still retain communication records in memory while Firefox and Edge have eliminated all remnants of communication records belonging to the tab where the web-application test run has occurred. These results are congruent with experiment *IL1*, where Firefox and Edge were also less amenable to retain artifacts in memory.

Since modern browsers spawn a process for managing each tab, our intuition was that by closing a tab or by killing the browser, the opportunity to gather communication records would cease to exist. As it stands, for experiment *IL4*, we were not able to retrieve any communication record when testing over Windows 10. Upon closing a tab or killing the browser process, the operating system swiftly reclaimed the process memory back, thwarting our high-level data inspection. Interestingly, when conducting the same experiments over Ubuntu 16.04, we were able to retrieve communication records from memory after executing such intrusive actions.

Opposed to our initial expectations, navigating to different webpages in a given tab has triggered the most changes on volatile memory contents. Albeit we were able to recover a small number of high-level records in Ubuntu 16.04, no records were recovered when conducting experiment *IL3* in Windows 10. In fact, the sequence of actions performed in experiment *IL3* fosters the replacement of older resources kept in memory in favour of more recent data. Thus, possibly useful evidence is discarded more promptly. Taking into account the outcomes of experiments *IL3* and *IL4*, Linux Ubuntu's memory management thus seems more favourable to conduct memory analysis in the context of our work rather than Windows 10.

Additionally, we experimentally verified that the use of private browsing in all tested browsers does not affect the collection of targeted high-level data. No visible changes have been observed either in the structure or the overall amount of communication records recovered in each test. Hence, our findings suggest that some privacy preserving properties of private browsing can be nullified through memory forensics.

Lastly, results show that the existence of communication records in memory appears to be loosely dependent on the browser/operating system in use, which leads us to infer that our results arise from the technologies and programming methodologies used by application/browser developers with respect to the loading and presentation of data. Two concrete cases are those comprising the recovery of Skype and Outlook logs, which can be performed for all browsers tested except Firefox when run over Windows 10.

2.5 Summary

The results of our study indicate that the recovery of communication records from physical memory is a viable path for uncovering otherwise ephemeral evidence. We were able to retrieve high-level data from some of the most popular web-applications used today, which motivates the need to develop specialized tools to recover evidence for the unfolding of digital investigation cases. In particular, given the heterogeneity of data structures found in memory, digital investigators would be burdened with the task to build and maintain a wealth of pattern matching expressions so as to be able to automatically extract available evidence from memory dumps.

3 RAMAS FRAMEWORK

This section presents RAMAS, a forensic tool for the extraction of communication records from memory dumps of web-based messaging applications[1].

3.1 Design Goals

We built RAMAS according to four design goals:

Simple design of extraction modules: The design of new extraction modules (composed of string matching patterns) should be easy to perform. Practitioners should be able to contribute to the RAMAS framework without the need of being familiar with a particular programming language.

Simple sharing/update of extraction modules: Developed modules should be easily upgradable, without the need to change RAMAS' core functionality. It should be straightforward for practitioners to share and advertise newly developed modules.

Organized case management: The number of seized machines in computer forensics cases may scale to

[1]RAMAS stands for "RAM Analysis System"

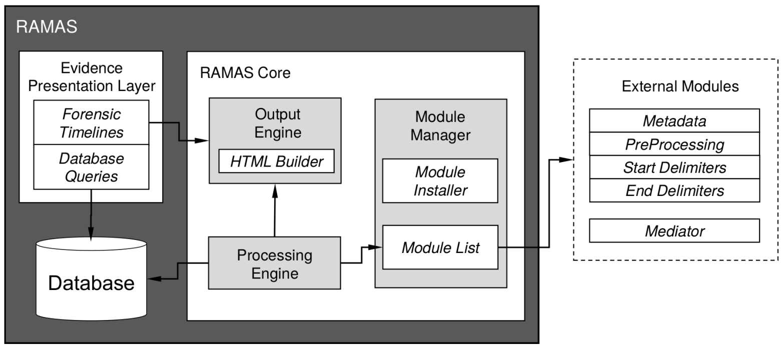
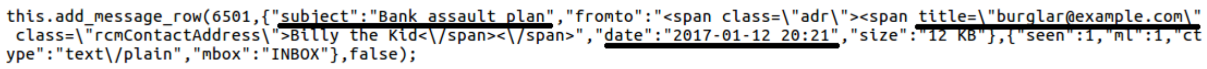


Figure 3: RAMAS architecture.



```
this.add_message_row(6501,{"subject":"Bank assault plan","fromto":"<span class=\"adr\"><span title=\"burglar@example.com\"
 class=\"rcmContactAddress\">Billy the Kid<\/span><\/span>","date":"2017-01-12 20:21","size":"12 KB"},{"seen":1,"ml":1,"ct
ype":"text\/plain","mbox":"INBOX"},false);
```

Figure 4: Roundcube inbox entry data fields.

large numbers. To avoid extra work in managing data pertaining to several cases, RAMAS should provide an integrated way to organize the collected memory images and store the retrieved high-level data.

Simple inspection of results: RAMAS should provide a simple interface to visualize extracted communication records, support queries on the recovered data, and aid investigators in disclosing more complex correlations among different pieces of evidence.

3.2 Architecture

We implemented a RAMAS prototype for Linux. Our prototype was written in Python and leverages a SQLitev3 database for holding memory analysis results. Figure 3 shows the several components that implement the core functionality of the system, the management of extraction modules, and the evidence presentation layer. Additionally, we deployed RAMAS as a GUI desktop application as a further effort in making the system attractive to users without compromising any of its functionality.

Our framework is based on a carving approach to retrieve matching records present in memory images. RAMAS matches communication records by exploring their structure, retrieving all meaningful data held between well defined delimiters. Upon the collection of digital artifacts containing communication records, RAMAS processes the metadata associated to these artifacts to isolate the sole components which convey useful evidence to the investigator. This allows for the discard of application dependent fields which are useless for high-level inspection of records, such as application versions. Furthermore, other kinds of data forming the structure of a record can also be discarded. A relevant example comprises verbose HTML wrapper artifacts that compose the structure of the communication record but offer no value from the point of view of the analysis (see Figure 2).

Analysis in RAMAS is conducted by running a selection of the available extraction modules over the strings obtained from a given memory dump. After analysis, RAMAS stores the recovered data in a database and offers a simplified visualization of the recovered records, organized by modules.

3.3 Extraction Modules

The forensic study conducted in Section 2 suggests that the internal representation of messaging web clients is different for each application. Considering the ever-growing number of web applications, there is not an obvious number of extraction modules that should be integrated into RAMAS before-hand. Thus, users should be able to develop and install new extraction modules without the need for changing the system's core or to be familiar with a specific programming language. We used Python's `ConfigParser` configuration files for implementing extraction modules. These easily allow us to define groups of named values which suffice for delimiting an existing record, as well as individual fields within the record.

Listing 1 provides the extraction module for recovering Roundcube's inbox email records, depicted in Figure 4. The first section of a module is named `Info` and contains general information about the module, namely its name and a short description. The second section of a module is called `PreProcess` and contains a single `Keyword` parameter, the content of which shall be used to restrict the pool of strings upon which record matching will be applied. In our example, we retain all strings which contain the sub-string `add_message_row`, since this keyword appears in the metadata structure of the records we aim to extract. The two next sections declare the start and end delimiters of the whole record as well as the individual fields that should be extracted and recorded in RAMAS' database. As RAMAS attempts to sequentially match the declared record fields, the corresponding delimiters must be declared in the order they appear within the record. We note that this restriction must be enforced by the module developer. Lastly, the `Mediator` section contains a hint on how to interpret the date representation so as to convert it to a common date representation shared among all modules.

Listing 1: Extraction Module for Roundcube inbox records.

```
[Info]
Name: roundcubeInbox
Description: Roundcube's inbox record fetcher.

[PreProcess]
Keyword: add_message_row

[StartDelimiter]
Record: this.add_message_row
Content: {"subject":"
Author: title="
Date: date":"

[EndDelimiter]
Record:;
Content: ","from"
Author: " class
Date: ",

[Mediator]
Date: yyyy-mm-dd hh:mm
```

Module update: Application providers are free to update the internal representation of data. To ensure the retrieval of communication records, investigators must update extraction modules accordingly. Hence, the update of extraction modules should be straightforward. Due to the modular design of RAMAS, the task of updating a module only comprises changes on the module itself, not affecting any other component of RAMAS' core functionality. Similarly to the development of new modules, updates are performed by changing the required fields on the configuration file. This process may encompass the addition/removal of some metadata field that has became available/deprecated, or it may just involve the minor updates in fields already declared in the configuration file.

Module sharing: To avoid repeated work due to concurrent endeavours by digital investigators, we envision the creation of a centralized repository for helping a module's creator and other practitioners to update existing modules while keeping track of changes. Additionally, RAMAS can check the repository on start-up and update installed modules to their most recent version. While the implementation of such a repository is deferred to future work, the codebase resulting from our work already allows for the manual install and update of extraction modules.

3.4 Dealing with Heterogeneous Data

Due to the heterogeneity between applications, building a database of all recovered records represents a challenge. We refer to classical problems in data integration. Firstly, we encounter a *schema-matching* problem, where the same concept may be identified in different applications by differently named fields. Secondly, we may encounter a *semantic-matching* problem, where even fields with the same name can refer to data with distinct underlying meanings. Moreover, the metadata available in some application may be richer than that available in others. Thus, the identification of the minimal set of fields that can be successfully used for unveiling correlations between collected evidence is crucial for allowing RAMAS to execute data integration routines for providing better query support.

The fields extracted by each module can represent semantically equivalent metadata, although it is named differently in distinct applications, e.g., a message timestamp may be identified by fields with different names (*date* vs *time*). To offer a single database schema which supports queries over records extracted with different modules, RAMAS performs data integration to provide users a unified view of the communication records coming from different sources. Each configuration file declares the mapping between the heterogeneous schema of different modules and the global RAMAS database schema.

RAMAS still faces a semantic integration problem where, for different modules, the same concept may express different meanings. As an example, for any two different modules, *author* may be a user's name in some application and an application-dependent identifier on another. Even with such a limitation, RAMAS can still maintain a global timeline of all application activity conducted by a suspect. When ordering records which use different representations for time, the configuration file can contain a hint on how to convert a particular timestamp representation to a common representation such as UNIX time.

3.5 Memory Dump Processing Pipeline

The strategy we followed in the creation of modules ensures a flexible independence between these and the core functionality of RAMAS. We now describe how

RAMAS processes a memory dump with base in such modules. We assume that RAMAS receives as input a file containing strings, instead of the raw memory image acquired by first responders. To produce such a file, investigators may resort to the standard command-line utility `strings` which finds and prints text strings embedded in binary files.

The strings file obtained from the raw memory image can be analyzed simultaneously by a set of modules. To this end, RAMAS dispatches a batch of modules to a pool of threads. Threads filter the initial list of strings obtained from the memory image, generate regular expressions by gluing together the delimiters of the fields declared in each module, and perform the actual evidence extraction work.

The initial pre-processing of the strings file with a keyword is justified by performance reasons. We discuss in Section 4 the advantages of this preliminary filtering step. After filtering the strings dump, the backend of RAMAS applies a regular expression over the remaining strings, further restricting the existing digital artifacts to the strings comprising a full communication record. In this second processing stage, RAMAS introduces a countermeasure against the injection of delimiters in the content of messages. If RAMAS allowed for such an injection, a miscreant would be able to inject an end-delimiter of a message among the written text and hide incriminating messages after this artificial delimiter. To thwart this attack on the inner workings of our system, RAMAS applies a find-and-replace method on each individual record. RAMAS searches for the start delimiter of the message field of a record starting from the far left and scans the end delimiter of the same field from the far right. When found, these delimiters are replaced by a pseudo-random nonce which will now act as start/end delimiter for the message field. Thus, the only way an attacker would have to interfere with the correct recovery of the message content would be to guess this nonce and place it before his incriminating message.

In the third processing stage, RAMAS builds a second regular expression which scans every remaining record and retains data according to each of the declared fields in the module configuration file. Lastly, RAMAS saves the obtained records in a database for further analysis. Details over the evidence presentation layer are detailed next.

3.6 Evidence Presentation Layer

Upon completing the analysis of the high-level data contained in a selected memory dump, RAMAS builds a set of simple forensic timelines for presenting the extracted communication records. A timeline is built for each of the modules used for analysis. Timelines are rendered by RAMAS GUI.

Raw Memory	Strings File Size	Time Elapsed
1 GB	82 MB	27.205s
2 GB	157 MB	53.148s
4 GB	255 MB	108.459s
8 GB	233 MB	193.539s

Table 2: Time elapsed (in seconds) in extracting printable characters out of differently sized memory images.

Apart from analyzing the results for each memory image in an isolated fashion, RAMAS updates its global database schema, adding the newly discovered ⟨*Timestamp, Author, Recipient, Message*⟩ tuples. This global schema allows investigators to pose queries at the database of recovered records, enabling the correlation of evidence obtained from the use of several modules over a single memory image, or across different memory images pertaining to a case. An example of this scenario is presented in Section 4.2.

4 EVALUATION

We evaluated the performance of RAMAS by conducting several experiments over the time it takes to complete a forensic analysis. Particularly, we tested the impact of the number of extraction modules applied, as well as the impact of the memory image size on the forensic analysis performance.

In our experiments, we have exchanged messages on four web-applications in order to conduct forensic analysis: Facebook chat, Skype, Twitter and Roundcube. Each web-application was operated in a different tab of Google Chrome running over a Windows 10 virtual machine. For the experiments reported in this section, we have used the sequence of user actions with intrusiveness level *IL1*.

The analysis of communication records using RAMAS was conducted on a 64-bit Ubuntu 16.04 LTS virtual machine equipped with four 2.6GHz Intel i7-6700HQ virtual CPUs, and 4GB of RAM.

4.1 Measuring Analysis Time

Finding printable characters: The strings file used as input for RAMAS is indeed smaller than the total size of the raw memory image under analysis. Table 2 depicts the time spent in reducing a raw memory dump to its printable characters in a default execution of the `strings` utility. We note that `strings` can be further instructed to ignore sequences of characters

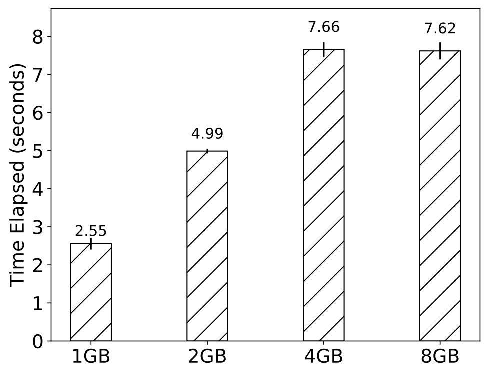


Figure 5: Time elapsed on the forensic analysis of differently sized memory images with Facebook recent messages module - no pre-processing.

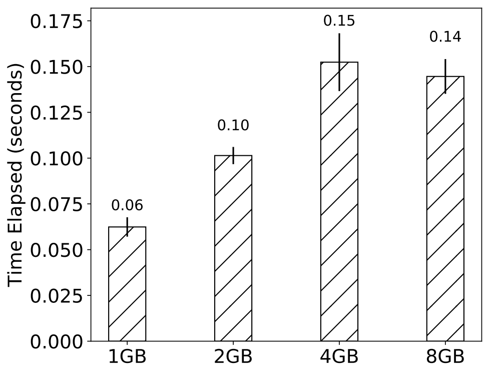


Figure 6: Time elapsed on the forensic analysis of differently sized memory images with Facebook recent messages module - with pre-processing.

less than a given size constant, which may further reduce the time elapsed during the pre-processing step.

Table 2 also shows us a counter-intuitive result comprising the amount of printable characters found in 4GB and 8GB raw memory images. Interestingly, the size of the strings file obtained from the 4GB memory image (255MB) was larger than that obtained from saving the strings contained in the 8GB memory image (233MB). We verified our results by acquiring six new memory images using the same procedure. For all the acquisitions, the amount of printable characters found in a 4GB memory image was larger than that found in an 8GB memory image.

Varying memory image size: We studied the impact of the memory image size on the elapsed time to complete a forensic analysis with RAMAS. In this test, we fixed the use of a single module while we vary the size of the memory dump (respectively, the size of the produced strings file). Without loss of generality, we selected a module for identifying Facebook communication records depicted in Figure 1 and extract the full ⟨*Timestamp, Author, Recipient, Message*⟩ tuple.

Figure 5 presents the elapsed time for five executions of our test without employing the pre-processing stage described in Section 3.5. Conversely, Figure 6 presents the elapsed time for a similar experiment in which we employ the pre-processing stage.

In a general way, our results suggest that the size of the memory image negatively affects the time it takes to complete a forensic analysis. The results depicted in Figure 5 show that omitting a pre-processing step over the initial high-level data artifacts slows down the analysis time considerably. For an 8GB memory dump, scanning for evidence lasts for about eight seconds, threefold the time it takes for analyzing the strings contained in a 1GB raw memory dump.

Figure 6 shows that pre-processing the initial strings file brings a whole lot of improvement to the performance of the forensic analysis conducted by RAMAS. Indeed, reducing the set of strings that a module must be matched against to the data related to the search domain drastically decreases the analysis elapsed time. This performance improvement is of several orders of magnitude, being noticeable when analyzing the biggest memory images under test.

The attentive reader may notice the similarity in the time spent while analyzing a 4GB and an 8GB memory image, either applying pre-processing or not. In fact, the analysis performed over the strings collected from the 4GB memory image is slower than the analysis for the strings of an 8GB memory image. This is due to the fact that, albeit the 4GB raw image is smaller than the 8GB raw image, we were able to find a larger amount of strings in the former.

Varying the number of modules: A different experiment aims to understand the impact of the number of applied modules on the elapsed time to complete a RAMAS analysis. In this test, we fixed the size of the memory dump in 8GB, a reasonable amount of RAM widely deployed in commodity hardware. For conducting this experiment, we attempted the extraction of communication records from all of the different Facebook, Skype and Roundcube Inbox artifacts we identified in our forensic study in Section 2. Accordingly, we developed the corresponding extraction modules for each of the corresponding web-application's digital artifacts, spawning a total of six modules. Figure 7 presents the elapsed time for five executions of our test.

The results of our experiments show that running several modules in parallel results in a sub-linear time for the completion of the forensic analysis. In fact, an analysis comprised of six modules has completed in nearly double the time of the time spent conducting an analysis with a single module. Our study suggests that the most expensive operation consists in the extraction of high-level data in the form of strings. When compared to this preliminary effort, the actual forensic analysis of the obtained data is several orders of magnitude smaller, even when applying multiple extraction modules. This suggests that RAMAS can be deemed a practical tool for aiding digital investigators as its performance allows for evidence to be quickly obtained, raging from seconds to a few minutes, depending on the size of each memory image.

In this experiment, we have recovered 17 Roundcube Inbox, 1 Skype and 26 Facebook records, where 5 of the latter were duplicates and 3 were corrupted (application-level data was included beyond a partial message itself). We discuss possible causes for the corruption of recovered records in Section 4.3.

4.2 Use Case

We enacted a use case for showing the benefits of maintaining a global database schema which investigators can query in order to unveil more sophisticated correlations among data fetched from different modules/memory images.

An example of such a scenario is the identification of a chain of command in a criminal organization. Let us assume that law-enforcement suspects one individual (S_1) to be involved in a criminal organization. While investigating this case, law-enforcement storms through S_1's household and acquires the volatile memory of the hardware operated by the suspect. Upon analyzing the memory image in search of ⟨*Timestamp, Author, Recipient, Message*⟩ message tuples, investigators recover the chat records depicted in Listing 2.

Listing 2: Records extracted by several modules.

```
#Records recovered with Twitter Direct
    Messages module
1482949701, S_3, S_1, I have revised the plan,
     lets do it at 4pm.
1482949712, S_3, S_1, Ok boss, I'll tell
    Pinkman.

#Records recovered with Skype messages module
1482949730, S_1, S_2, Hey, Heisenberg has
    revised the plan, lets rob the bank at 4pm

#Global Timeline
-------------------------------------------
1482949701, S_3, S_1, Twitter, I have revised
    the plan, lets do it at 4pm.
1482949712, S_3, S_1, Twitter, Ok boss, I'll
    tell Pinkman.
1482949730, S_1, S_2, Hey, Heisenberg has
    revised it, we strike at 4pm.
```

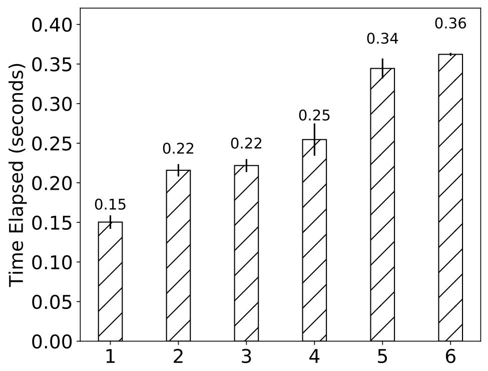


Figure 7: Time elapsed on the forensic analysis of an 8GB memory image with increasing number of modules.

This example sequence of messages allows investigators to draw the following conclusions:

- S_1 was a surrogate in the organization. Investigators now have digital evidence about the fact.
- S_2 represents a person in the organization that authorities were not aware of. He was not the head of the criminal organization, but authorities now have a new lead to follow.
- S_3 seems to be the organization's mastermind. Moreover, Heisenberg appears to be his name.

Although we present a simple example, we expect the number of records to be recovered in actual settings to be much larger and harder to digest. By analyzing modules' output in an isolated fashion, investigators could not be able to directly reach the conclusion presented in the last bullet. The connection between the name and organization rank can only be established by joining and contextualizing the evidence recovered from both modules. Albeit this example suffices to show the need for a global timeline for correlating data across modules, the benefits of maintaining a single global timeline can be further noticeable when attempting to correlate data obtained from several different memory images, collected in the scope of a single case.

4.3 Limitations and Future Work

Due to the nature of volatile memory, metadata structures may be only partially available when scanning for evidence. If RAMAS is unable to find the start/end delimiters of a record, it will either ignore a partial record or capture data beyond the expected limits, respectively. To overcome this limitation, an improved version of RAMAS may attempt to match the end of a record and backtrace to fetch existing metadata, as well as use heuristics for the record expected size and limit overruns in adjacent artifacts.

Additionally, miscreants with knowledge about RAMAS' analysis procedure may refresh the browser tabs used to conduct illegal activity often. This behavior may cause communication records to be replaced/evicted, eliminating traces of criminal activity.

5 RELATED WORK

This section describes related literature regarding memory collection procedures and the analysis of high-level data present in physical memory.

5.1 Memory Acquisition

The proper collection of evidence is a crucial step in any computer forensics investigation. Typical computer investigations targeted the hard drive of a suspect's machine, ignoring all of the data kept in volatile memory. Today, the analysis of both static media and physical memory allows digital investigators to have a better picture of the original state of the system and recover otherwise ephemeral data (Vömel and Freiling, 2012). Although the choice of a memory acquisition procedure should take into account the particularities of the case at hand, there are three main memory acquisition methods used by first responders, which are based on hardware, software and virtualization (Vömel and Freiling, 2011).

Hardware-based methods take advantage of DMA (Direct Memory Access) requests through hardware cards and allow for the collection of memory content while having little impact in the system. However, the target system must be equipped with specialized hardware, and this technique may lead to system crashes which poses reliability issues in memory collection.

Virtualization-based methods allow for a sound extraction of memory by either collecting a file where the physical memory of the virtual machine is kept or by dumping it with the virtualization software. Clearly, this is only interesting if malicious activity is being conducted on top of a virtual machine. Nonetheless, the growing importance of Internet-hosted services is expected to impose a partial shift on the focus of digital investigations to virtual machines.

Software-based methods for dumping physical memory are widely available. Still, some of these tools require special access privileges and cannot generally offer a full copy of the memory at a given time. Kernel level acquisition tools overcome some of the limitations imposed by user level collection tools, but are still unable to provide a completely atomic memory image due to the activity of concurrent processes. Despite this shortcoming, software-based collection is often applicable in practice since it does not require a specific system configuration to be set in advance nor does it rely on specialized hardware.

5.2 Memory Analysis

Contrary to the analysis of static media, the analysis of physical memory typically presents a harder challenge due to the lack of a completely deterministic organization. It should be noted that many of the efforts dedicated to the analysis of physical memory focus on the recognition and inspection of OS-dependent low-level memory structures (Simon and Slay, 2009; Vömel and Freiling, 2011). Conversely, high-level memory inspection strategies are typically bound to the search of strings in the acquired dump.

Analysis approaches based on the search of strings containing pertinent keywords related to a case exhibits several drawbacks. In the one hand, investigators may be presented with thousands of matching records when analyzing large amounts of data (Beebe and Dietrich, 2007). To make it worse, only few of those records may be directly related to the case itself. In the other hand, if the terms contained in memory slightly deviate from the keyword list used by the investigator, some evidence will fail to be recognized.

A previous approach (Beebe et al., 2011) has addressed some of these drawbacks by improving string searching through neural networks which learn a list of terms related to the case beforehand. Analysis results are ordered according to their relevance, allowing the investigator to inspect the most pertinent data first. Although the prototype yields good results with respect to the obtained recall, the neural network takes a non-negligible time to learn the terms and is not able to provide any context about the matched keywords.

A different technique based on the use of regular expressions has been successfully applied in order to extract evidence from strings accompanied by syntactically structured metadata (Simon and Slay, 2010; Wong et al., 2011; Yang et al., 2016). This metadata provides context about a given artifact, allowing digital investigators to reason about the contextual relevance of the data (Raghavan, 2013). For instance, providing that the metadata contains a timestamp, investigators can build a timeline and reconstruct a sequence of actions took forth by a suspect.

However, this line of research has some drawbacks. Firstly, prototypes are developed independently without enabling regular expression sharing or providing evidence visualization interfaces; extraction capabilities are merely seen as proofs-of-concept. Secondly, string matching works only as long as regular expressions match the syntax of the application ar-

Table 3: Comparison of RAMAS with different memory forensic tools. * Tool requires plugins to provide the functionality.

Forensic Tool	Memory Acquisition	Multiple OS Target	Live Analysis	Extensibility	Investigation Workflow	Open-Source	High-Level Analysis
RAMAS	-	✓	-	✓	✓	✓	✓
Volatility	-	✓	-	✓	-	✓	-
Redline	-	-	-	-	✓	-	✓
Memoryze	✓	-	✓	-	-	-	-
FATkit	-	✓	-	✓	-	-	-
VAD Tools	-	-	-	-	-	✓	-
EnCase	✓	✓*	-	✓	✓	-	✓
Rekall	✓	✓	✓	✓	-	✓	-
IEF	✓	✓	-	-	✓	-	✓

tifacts left in memory. Since the artifact structure may change due to application implementation decisions, investigators must take the burden of updating regular expressions accordingly. RAMAS aims to tackle the aforementioned issues by fostering the collaboration of digital investigators on maintaining a platform for the analysis of high-level data residing in memory.

To better lay RAMAS in the space of existing memory forensic analysis tools, Table 3 depicts a comparison of several properties exhibited by our system with those of well-known memory forensic analysis software. We can observe that RAMAS presents itself as the only open-source tool that provides an investigation workflow (including case management and evidence visualization) and is extensible, while focusing on the recovery of high-level data. Comparatively, although EnCase can be extended through plugins, it remains a proprietary and expensive forensic tool, while Rekall focuses on low-level analysis and fails to provide a proper investigation workflow.

6 CONCLUSION

This paper described a forensic study over the digital artifacts left behind in memory by popular web-applications. Our study concludes that it is possible to retrieve communication records from IM/email applications, in various settings and system configurations.

Motivated by the findings above, we have introduced RAMAS, a framework for the extraction of instant-messaging and email client data from volatile memory. Our evaluation suggests that RAMAS can efficiently extract and report the existence of communication records. RAMAS code is publicly available and has been released as an open-source tool[2].

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[2]RAMAS repository - https://tiagolb.github.io/CSF/

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