ABSTRACT
A digital forensic investigation aims to collect and analyse the evidence necessary to demonstrate a potential hypothesis of a digital crime. Despite the availability of several digital forensics tools, investigators still approach each crime case from scratch, postulating potential hypotheses and analysing large volumes of data. This paper proposes to explicitly model forensic requirements in order to engineer software systems that are forensic-ready and guide the activities of a digital investigation. Forensic requirements relate some speculative hypotheses of a crime to the evidence that should be collected and analysed in a crime scene. In contrast to existing approaches, we propose to perform proactive activities to preserve important - potentially ephemeral - evidence, depending on the risk of a crime to take place. Once an investigation starts, the evidence collected proactively is analysed to assess if some of the speculative hypotheses of a crime hold and what further evidence is necessary to support them. For each hypothesis that is satisfied, a structured argument is generated to demonstrate how the evidence collected supports that hypothesis. Our evaluation results suggest that the approach provides correct investigative findings and reduces significantly the amount of evidence to be collected and the hypotheses to be analysed.

Categories and Subject Descriptors
D.2.1 [Software Engineering]: Requirements; K.6.5 [Management of Information Systems]: Security and Protection

General Terms
Design, Security

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Keyswors
Digital forensics, forensic requirements, adaptation, arguments

1. INTRODUCTION
A digital forensic investigation [31] aims to collect and analyse the evidence necessary to demonstrate a potential hypothesis of a digital crime, which explains how that crime was committed, what harm was done, and who was responsible. A number of processes [7, 34, 28] and several digital forensics tools [25, 1, 20, 6, 1, 25, 10] can be used to conduct a digital investigation. However, digital investigations remain highly human-intensive, and investigators usually approach each crime case from scratch, by postulating potential hypotheses and manually analysing large volumes of - often irrelevant - data. Existing tools do not provide any investigative direction to suggest the potential hypotheses, including the evidence they require to be demonstrated, their likelihood of being true, or the evidence necessary to demonstrate them. Some evidence can also be ephemeral, as it can be concealed by an attacker or it can come from volatile sources. Indeed this evidence might be lost if it is not preserved before an investigation starts.

A software engineering challenge in digital forensics is to build systems that are forensic-ready [36], which maximises the potential to use digital evidence whilst minimising the costs of an investigation. Such systems not only should preserve all necessary evidence, but they should also help investigators assess the likelihood of potential hypotheses, and link the evidence collected to the findings of an investigation. To address this challenge, this paper proposes to explicitly model forensic requirements that relate some speculative hypotheses of a crime to the evidence to be collected in the crime scene. The hypotheses express how a crime can be committed and are formalised as logic expressions. The crime scene represents a bounded environment where a crime can be perpetrated. Forensic requirements also capture patterns of “suspicious events” that indicate that a crime may be taking place and for which all necessary evidence should be collected for some time.

Forensic requirements are used to configure a digital forensics process that includes proactive and reactive activities. Proactive activities – evidence collection and analysis – are performed during the normal system operation. Proactive collection preserves important – potentially ephemeral – evidence, which might otherwise be lost, before an investigation starts. Proactive analysis detects “suspicious events” and therefore enables the collection of additional evidence.
for some time. Once an investigation starts, some reactive activities are performed. First, forensics requirements are used to identify all potential hypotheses of a crime. Hypotheses are formalised in the Event Calculus [27] and are examined using Decreasoner [28], an Event Calculus analyser. The findings of this preliminary analysis are presented to the investigator, suggesting which hypotheses should be investigated (because they are likely) or ignored (because they have been formally refuted). For each hypothesis that may hold, our process suggests the remaining evidence that needs to be collected, and reactively re-analyses the crime in light of the new evidence. When a hypothesis is fully satisfied, our process automatically generates a structured argument [43] that demonstrates how the evidence collected formally supports that hypothesis.

This paper is a first step towards engineering forensic-ready systems and it builds on the assumption that all potential crimes are known and can be specified in advance. The paper provides three main contributions. First, it proposes a novel adaptive digital forensics process - initially sketched in [33] - to systematically perform the activities to be conducted before and during a digital investigation. The process performs proactive activities to preserve important evidence and suggests immediate investigative directions. Second, the paper introduces the notion of forensic requirements to systematically configure the activities of the proposed digital forensics process depending on a specific crime scene and on the potential hypotheses of a crime. Finally, the paper explains how structured arguments can be used to present the findings of an investigation. We illustrate our approach on a criminal case of confidentiality infringement and evaluate it on a realistic digital forensic scenario [16]. Our results suggest that the approach provides correct investigative findings and reduces significantly the amount of evidence to be collected and the number of hypotheses to be analysed compared to traditional digital investigations.

The rest of the paper is organised as follows. Section II presents the background and related research, while Section III illustrates a working example. Section IV provides an overview of our proposed digital forensics process. Sections V, VI and VII use our example to illustrate forensics requirements, and the proactive and reactive activities of our digital forensics process, respectively. Section VIII discusses our evaluation results, Section IX reviews related work, and Section X concludes.

2. PRELIMinARIES

This Section clarifies the differences of our approach with intrusion detection systems (IDS), illustrates the use of arguments, and introduces the Event Calculus.

2.1 Intrusion Detection Systems

Our approach augments traditional digital investigations with proactive activities, which are similar to the operations of IDS [5]. These detect and diagnose different kinds of attacks, such as intrusions, DDoS, and application-level attacks, by collecting and analysing data (network traffic) in real time. IDS perform proactive collection and analysis to recognize specific patterns in data that may suggest that an attack is taking place, discover new attacks, and re-configure firewall rules to counteract the attacks. However, IDS are not primarily designed to gather forensically meaningful evidence necessary to explain a crime. In contrast, the objective of this work is to engineer systems that are forensic-ready and are able to perform proactive evidence collection and analysis respectively to identify suspicious events and preserve additional evidence necessary to reconstruct a crime after it has been committed.

2.2 Argumentation

To explain the findings of an investigation we use a form of argument inspired by the work of Toulmin [43]. Toulmin-style arguments capture relationships between a claim and domain properties (grounds and facts), the assumptions that eventually support the grounds (warrants), and the reasons why the argument might not be valid (rebuttals). Arguments have been applied successfully to model and analyse privacy and security requirements. Haley et al. [21], have used Toulmin arguments to recursively represent the rebuttals and mitigations when reasoning about the satisfaction of security requirements. In their approach, security requirements are expressed as claims that are supported by grounds and warrants. Rebuttals show evidence that contradicts other arguments, whilst mitigations describe how rebuttals may be avoided or tolerated. Franqueira et al. [13] combine security arguments with risk assessment exploiting publicly available security catalogues. Privacy arguments [44] have been used to analyse selective disclosure requirements allowing reasoning about the satisfaction of personal non-disclosure requirements when context changes. Our work uses arguments to link the hypotheses of a crime (claims) to the evidence to be collected (facts), and the properties (grounds) and the assumptions (warrants) that hold in the crime scene. Since all these elements are represented explicitly in advance as forensic requirements, when a hypothesis is satisfied, it is possible to build an argument systematically to explain how a crime took place depending on the evidence collected. The derived argument structure can help provide robust evidence to support a hypothesis.

2.3 Event Calculus

To facilitate formal reasoning, the hypotheses of a crime are expressed in the Event Calculus, a language based on first-order predicate calculus. The Event Calculus is well suited to describing and reasoning about event-based temporal systems [17]. The calculus relates event sequences to fluents that denote the states of a system. Fluents are initiated by an event and cease to hold when terminated by another event. Event calculus also includes non-temporal predicates and functions that return a non-boolean result. Table [15] gives the meanings of the elementary predicates and quantifiers of the subset of the calculus we use in this paper. The Event Calculus supports both deductive and abductive reasoning. Deduction uses the description of the system behaviour together with the history of events occurring in the system to derive the events fluents that occur/hold at a particular point in time. Abduction determines the sequence of events that must have occurred to allow a set of events/fluents to hold/occur.

The Event Calculus is a suitable formalism for digital investigations [15]. Events can represent the actions that occur in a crime scene, which can also be perpetrated by an offender. Fluents can represent the state of the elements modelled in the crime scene. Deductive reasoning can be used for proactive analysis to determine if a suspicious event
happened. Abductive reasoning can be used for reactive analysis to speculate on what sequence of events might have occurred, if any, to allow the system to satisfy the condition claimed in the hypothesis.

3. WORKING EXAMPLE

Although enterprises often invest significant resources to develop incident response plans, very little effort is devoted to the identification and preservation of digital evidence and the structuring of processes for possible prosecution. The need for enterprises to prepare themselves for a crime investigation has also been highlighted in ISO27001/2 [42]. This can be particularly useful for those crimes following a specific pattern and whose hypotheses can be modelled with little effort. For example, the FBI Financial Crimes Report of 2010–2011 [41] identifies the crime patterns in corporate and health care cases. Corporate fraud crimes often involve insider trading using confidential information. For example, in the Galleon Group case [30], insiders were charged for the insider trading using confidential information. For example, if a corporate regulation states that a confidentiality document should not exfiltrate from the PC where it is stored, a generic hypothesis can express that an employee is logged onto the PC where the document is stored, s/he is in the room where the PC is located, and copies the document onto a USB storage.

For each generic hypothesis of a crime, a suspicious event is also represented. This expresses a condition in the crime scene that might indicate that the corresponding hypothesis of a crime is likely to be satisfied, and all the necessary evidence to prove it must be collected in advance until the suspicious event condition no longer holds. An example of suspicious event may indicate that a user is logged onto the machine in which the machine is in the crime scene that might be stored and mounts a USB storage.

2) Configuration. Forensic requirements are used to configure the proactive and reactive activities of a digital forensic process. Suspicious events are used to configure the conditions that will be checked by the Proactive Analysis to start/stop the full evidence collection (collection of all possible and necessary evidence to satisfy a hypothesis). Forensic requirements are also used to generate the potential hypotheses given as input to the Reactive Analysis. Potential hypotheses are defined by instantiating the generic hypotheses on the concrete elements of the crime scene. For our example, a number of hypotheses ($3^2 = 27$) will be generated depending on who can be in T225, who can log on M1, and who can own the storage device which should be mounted on M1 (Alice only, Bob only, or both Alice and Bob).

3) Proactive Collection. If no start condition is satisfied, the Proactive Collection only gathers all the events necessary to verify whether any of the start conditions holds. Otherwise, it will additionally gather all possible and necessary events to demonstrate the hypotheses associated with the start conditions that hold at that time. The Proactive Collection stores all monitored events securely and sends to the Proactive Analysis only those events necessary to verify the start and stop conditions.

4) Proactive Analysis. When new evidence is available, the Event Calculus Analyzer (Analyzer) checks if the conditions to start/stop the full evidence collection are satisfied. In case a start condition is satisfied, the Proactive Analysis signals the Proactive Collection to enable the full evidence collection for the hypothesis associated with the satisfied start condition. When a stop condition is satisfied, the Proactive Analysis signals the Proactive Collection to gather only the evidence necessary to verify the corresponding start condition.

5) Investigation Set-up. Once an investigation has started, the Reactive Analysis retrieves the data collected proactively from the Secure Storage.

6) Reactive Analysis. The Event Calculus Analyzer...
and a concrete domain model and a set of domain assumptions.

1) A General Domain Model represents the “type” of the entities and evidence sources in the crime scene. The general domain model of our example is shown in Figure 2. Entities can be employees, files, storage devices, and locations, while evidence sources can be computers, cameras, and card readers. Entities and evidence sources can be associated with some states, represented as attributes in Figure 2. For example, an employee can be In a location and Logged on a computer. S/he can also Possess a storage device, and be authorized to log on a computer (HasPermission) or to access a location (HasBadge). A file and a storage device can be respectively Stored and Mounted on a computer. A reader and a camera can monitor the access to a location (states AccessControl and Monitor, respectively), and a computer can be in a location (PlacedIn). The general domain model also includes general events. An event must have a source (arrow’s tail) and an observer (arrow’s head). Events can initiate or terminate one of the states of their source, and also have additional parameters. For example, Login and Logout respectively initiate and terminate state Logged of an employee for the computer on which the login/logout operation was performed.

2) A Concrete Domain Model instantiates the entities and the evidence sources specified in the general model depending on the concrete elements that are present in the crime scene. As shown in Figure 3, the concrete domain model of our example includes a location (room T225), three computers (M1, M2, M3), two employees (Alice and Bob), a camera (CCTV), a NFC reader (NFC reader), and a confidential file (Doc). The concrete domain model also devises the initial states for some elements of the crime scene. For example, Doc is stored on M1, which in turn is located in T225. CCTV and NFC control accesses to T225. Alice and Bob are authorized to access T225, and have permission to log on M1 and their own corporate computers (M3 and M2, respectively).

The concrete domain model also represents monitored events
identifying the concrete evidence that can be collected from a crime scene. The first and the last parameter of a monitored event identify respectively its source and observer – the evidence source from which an event must be collected. For example, Sys_Login and Sys_Logout respectively identify login and logout operations performed by an employee (source) on a computer (observer). Swipe_Card and HighMountCounts signal respectively that an employee swiped her/his card on a reader and a storage device was mounted several times (e.g., more than 3 times) on a computer. Any other middle parameter of an event – if present – identifies additional information. For example, Sys_Copy signals that a file was copied onto a directory (file'). The data coming from the sources of evidence represented with dashed lines cannot be collected proactively, because they cannot be gathered automatically; such as the evidence from a CCTV (CCTV_Access and CCTV.Exit), or because it is illegal to do so without a search warrant, such as evidence from an employee’s corporate computer (e.g., HighMountCounts from M2 or M3).

Figure 3: The Concrete Domain Model of our example.

3) Domain Assumptions are inference rules that link monitored events to the events and the states represented in the general domain model. Figure 2 shows some domain assumptions of our example. They are represented as implications or equivalences among Event Calculus predicates expressions. The first domain assumption states that an employee logs in on a computer (Login) if and only if s/he has the necessary permission, a monitored event Sys_Login signals that s/he performed the login, and no user is already logged on that computer. Note that the Login event initiates state Logged of the aforementioned employee. The second domain assumption states that a storage device is mounted at a specific mount point (file) in a computer, if and only if the storage is not already mounted, the mount point exists on that computer (StoredIn), and an attempt to mount a storage device was performed (Sys_Mount).

5.2 Hypotheses and Suspicious Events

The generic hypothesis of a crime and the suspicious event of our example are represented in Figure 4. They are formalized as an Event Calculus expression on the events and the states of the elements in the crime scene. Our hypothesis states that at least an employee is in T225; one of the employees is logged on M1 and copies the Doc on his/her USB pen which is mounted on M1. A suspicious event indicates that an employee is logged on M1 and mounts a USB pen. Note also that suspicious event conditions can only be expressed on those events that can be collected automatically (i.e., proactively). A hypothesis of a crime (H) must always imply its corresponding suspicious event condition (SE), but not vice-versa: H → SE ∧ ¬(SE → H).

Since proactive analysis is performed during the normal system operations, we aim to reduce its complexity by keeping a suspicious event condition simple (i.e., with a smaller number of predicates compared to those included in its corresponding hypothesis). However, on the other hand, the choice of a suspicious event condition should still allow reducing the amount of evidence collected proactively, and indeed it cannot be too simple and must still indicate if there is the risk of a crime to happen. Note that a suspicious event condition can only be specified if a hypothesis of a crime is composed of at least two predicates.

6. PROACTIVE ACTIVITIES

Proactive activities aim to collect evidence necessary to explain a crime. Full evidence collection is performed only when a suspicious event condition suggests that a crime is taking place, and is terminated after such condition no longer holds.

The Proactive Analysis is initially configured to check the start conditions necessary to activate the full evidence collection. In particular, the Event Calculus Analyzer (Analyzer) receives as input an Event Calculus specification, shown in Figure 5, which is obtained from the forensic requirements. The first part of the specification is static and is necessary to define a set of built-in types (sort), such as boolean, integer, time, predicate, event, and fluent. The general domain model is used to derive the second part of the specification. In particular, entities and evidence sources are translated into a set of Event Calculus types (sorts), while events are translated into Event Calculus events. Source, additional parameters – if present – and observer of each event are also encoded as event parameters. For each state an entity/evidence source can assume, a corresponding fluent is created, having the state’s subject and object as parameters. An Initiates/Terminates predicate is generated for each state initiated/terminated by an event. For example, Figure 5 shows how events Login and Logout respectively initiate and terminate state Logged.

The concrete domain model is used to generate the third part of the Event Calculus specification. The initial states are used to identify the initial predicates, which hold at time 0 for some of the Event Calculus constants. For all the other possible states that do not hold at time 0, a negated predicate is created. Monitored events are translated into Event Calculus events. Concrete entities and evidence sources are translated into Event Calculus constants. The fourth part of the Event Calculus specification is generated from the evidence gathered during the Proactive Collection. The fifth and the sixth parts include respectively the domain assumptions and the condition characterising a suspicious event. The last part also indicates the time interval that should be considered during the analysis (range), which in turn depends on the number of time instants in which the Proactive
Domain Assumptions

\[
\text{Happens(Sys\_Login(employee,computer),time) \& } (\text{employee}1 : \text{HoldsAt(Logged(employee1,computer),time)) \& \text{HasPermission(employee,computer),time)} \leftrightarrow \text{Happens(Login(employee,computer),time).}
\]

\[
\text{Happens(Sys\_Mount(storage,computer),time) \& } (\text{HasAt(Mounted(storage,computer),time) \& \text{Possess(employee,storage),time1).}
\]

Generic Hypothesis

\[
(\text{storage,employee,file,time,}time) \text{ HoldsAt(In(employee,T225),time) \& HoldsAt(Mounted(storage,file,computer),time) \&}
\]

\[
\text{HoldsAt(Logged(employee,M1),time) \& Happens(Copy(Doc,file,M1),time) \& HoldsAt(Possess(employee,storage),time1).}
\]

Suspicious Event

\[
(\text{employee,file,time}) \text{ HoldsAt(Logged(employee,M1),time) \& HoldsAt(Mounted(storage,file,M1),time).}
\]

Figure 4: Domain assumptions, generic hypothesis, and suspicious event of our example.

The Proactive Collection is initially configured to collect the monitored events necessary to check the suspicious event conditions. To this extent, it is necessary to identify the events and the entities' states a suspicious event condition predicates on. The suspicious event condition shown in Figure 4 is specified over state Logged and event Mount. Then, for each state, the initiating and terminating events are identified, from the general domain model. For example, events Login and Logout are identified from state Logged. Finally, the monitored events to be collected to detect these complex events are identified from the domain assumptions. For our example, the Proactive Collection is configured to collect events Sys_Login, Sys_Logout, Sys_Mount, and Sys_Unmount from M1 to detect respectively complex events Login, Logout, Mount, and Unmount.

When the Proactive Collection gathers some new events, these are sent to the Analyzer that updates the Event Calculus specification to be evaluated. In particular, it increments the time range and adds to the Collected Evidence (part 4 in Figure 5) a set of predicates representing the events that took place in the last time instant. For example, if event Sys_Login(Bob,M1) happened at instant 5, the Collected Evidence part is updated with predicate Happens(Sys_Login(Bob,M1), 5).

Furthermore, all other possible ways in which event Sys_Login can take place are negated (e.g., !Happens(Sys_Login(Alice, M1), 5)). When the start condition is satisfied, the Analyzer signals the Proactive Collection to enable the full evidence collection. In our example, the Proactive Collection will also gather all Sys_Copy from M1. In the meanwhile the Analyzer controls if the stop condition is satisfied, and, in that case, it signals the Proactive Collection to terminate the full evidence collection. The sequence of events - including their timestamps - collected during two consecutive times in which a stop condition holds will be grouped into a snapshot that is stored securely. Note that we assume that the stop condition initially holds.

7. REACTIVE ACTIVITIES

Reactive Analysis is configured with the potential hypotheses of a crime which will be evaluated for all the events snapshots preserved proactively. These are obtained by instantiating the generic hypotheses depending on the concrete elements present in a crime scene. As shown in Table 2 for our example, 27 hypotheses will be generated depending on who can be in T225, who can log on M1, and who can own the storage device that is mounted on M1. The potential hy-
hypotheses are formalised in the Event Calculus, as shown in Figure 6. In this case, the Monitored Events (part 4) will include one of the potential hypotheses of a crime. For example, the condition associated with H4 is shown in Figure 6 and expresses that Alice is in room T225, Bob is logged on M1 and copies the Doc on Alice's storage device, which is mounted on M1.

\[
\{\text{storage, time, time1}\} \text{ HoldsAt}\left(\text{In}(\text{Alice}, \text{T225}), \text{time}\right) \land \text{HoldsAt}(\text{Logged}(\text{Bob}, \text{M1}), \text{time}) \land \text{Happens}(\text{Copy}(\text{Doc}, \text{E}, \text{M1}), \text{time}) \land \text{HoldsAt}(\text{Possess}(\text{Alice}, \text{storage}), \text{time1})
\]

**Figure 6: Formalisation of Hypothesis H4.**

Once an investigation starts, the Analyzer retrieves all the events snapshots that have been collected proactively and, for each of them, it checks if the potential hypotheses are satisfied. Note that some of the events could not be monitored proactively, such as those that cannot be collected automatically (e.g. \(\text{CCTV\_Access} \) from CCTV). The Analyzer indeed performs abductive reasoning to verify if potential hypotheses can hold by speculating on the truth of these events. In other words, these events represent the missing evidence that must be collected to prove/refute the potential hypothesis. For our example, we assume that the events snapshot on which the analysis is performed is the one represented in Figure 6. This indicates that Bob was logged on M1 and copied the Doc on a USB pen that was mounted on M1. For this events snapshot, the Analyzer discovers that only some of the potential hypotheses can still hold (H4-H6, H13-H15, and H22-H24).

Analysis results are sent to the Presentation activity, which indicates the likelihood of each hypothesis depending on the proportion of predicates that have been demonstrated through the evidence collected (i.e., the predicates that have not been abduced [13] and indeed are known). For our example, the likelihood of hypotheses H4, H5, H13, and H14 is 60%, since the predicates specified on fluents \(\text{Logged}, \text{Copy}, \) and \(\text{Mounted}\) are satisfied by using monitored events, while the remaining predicates specified on fluents \(\text{In}\) and \(\text{Possess}\) leverage unknown events. The likelihood of H6, H15, H22, and H23 is 50%, as they include an additional predicate that verifies if Alice and Bob own the USB pen that was mounted on M1 (for H6 and H15) or are in room T225 (for H22 and H23). Finally the likelihood of H24 is about 42.86%, since it includes two additional predicates that state that both Bob and Alice were in T225 and own the USB pen that was mounted on M1. When an investigator selects a hypothesis s/he is willing to explore, the Presentation identifies additional evidence to be collected from the output of the Event Calculus analysis, by selecting those events that cannot be monitored automatically, as shown in Figure 8. In case an investigator selects one of the most likely hypotheses, such as H5, the Presentation suggests collecting additional evidence (events \(\text{Swipe\_Card}\) and \(\text{CCTV\_Access}\)) from the NFC and the CCTV that control room T225. Bob's corporate computer (M2) should also be inspected to verify whether he mounted the USB pen several times (event \(\text{HighMountCounts}\)).

**Figure 7: Events Snapshot Example.**

**Table 2: Potential Hypotheses**

<table>
<thead>
<tr>
<th>Name</th>
<th>In T225</th>
<th>Logged</th>
<th>USB Owner</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>Alice</td>
<td>Alice</td>
<td>Alice</td>
</tr>
<tr>
<td>H2</td>
<td>Alice</td>
<td>Alice</td>
<td>Bob</td>
</tr>
<tr>
<td>H3</td>
<td>Alice</td>
<td>Alice</td>
<td>Bob, Bob</td>
</tr>
<tr>
<td>H4</td>
<td>Bob</td>
<td>Bob</td>
<td>Alice</td>
</tr>
<tr>
<td>H5</td>
<td>Alice</td>
<td>Bob</td>
<td>Bob</td>
</tr>
<tr>
<td>H6</td>
<td>Alice</td>
<td>Bob</td>
<td>Alice, Bob</td>
</tr>
<tr>
<td>H13</td>
<td>Bob</td>
<td>Bob</td>
<td>Alice</td>
</tr>
<tr>
<td>H14</td>
<td>Bob</td>
<td>Bob</td>
<td>Bob</td>
</tr>
<tr>
<td>H15</td>
<td>Bob</td>
<td>Bob</td>
<td>Alice, Bob</td>
</tr>
<tr>
<td>H22</td>
<td>Alice, Bob</td>
<td>Bob</td>
<td>Alice</td>
</tr>
<tr>
<td>H23</td>
<td>Alice, Bob</td>
<td>Bob</td>
<td>Bob</td>
</tr>
<tr>
<td>H24</td>
<td>Alice, Bob</td>
<td>Bob</td>
<td>Alice, Bob</td>
</tr>
<tr>
<td>H27</td>
<td>Alice, Bob</td>
<td>Alice, Bob</td>
<td>Alice, Bob</td>
</tr>
</tbody>
</table>

If an investigator collects events \(\text{Happens}(\text{CCTV\_Access}(-\text{Alice}, \text{T225}), 1)\) and \(\text{Happens}(\text{Swipe\_Card}(\text{Alice}, \text{NFC}), 1)\), it means that only Alice was in T225 when Bob logged in. After the Reactive Analysis is re-performed, only 3 of the remaining hypotheses can still hold (H4-H6) with 80% of likelihood for H4 and H5 and about 67% of likelihood for H6. In case an investigator decides to explore H4, the Presentation suggests him/her to collect event \(\text{HighMountCounts}(\text{USB1}, \text{M3})\) to justify that Alice owns the USB storage. In case the investigator collects this evidence, only H4, and H6 can still hold as they will be respectively 100% and 83% likely. At this stage, the investigator can continue to explore H6 that is still not completely satisfied.

Once a hypothesis is fully satisfied, the Presentation uses the analysis results and the representation of the forensic requirements to build a structured argument that explains how collected evidence demonstrates the claim made by that hypothesis. An argument is decomposed into grounds (sub-
arguments) associated with a predicate defined on an event or a fluent in the claim (hypothesis definition). A sketch of the argument generated for H4 is shown in Figure9. This is decomposed into 5 grounds associated with each predicate of the claim. The predicate included in each grounds is further decomposed into lower-level grounds until only monitored events are identified (facts representing collected evidence). Facts and grounds in a sub-argument are related to their parent argument through domain assumptions (warrants). These explain how facts and grounds imply their parent argument. In Figure9 ground G1 is associated with the predicate defined on the fluent In. This ground is decomposed into facts that represent the monitored events that demonstrate that Alice entered in T225 at instant 1 (F1-F7) and did not exit from the room till instant 8 (F8). The domain assumptions that relate monitored events to state In are DK1 and DK2. DK1 relates state In to the event that initiates it (Enter), while DK2 relates event Enter to facts F1-F8 that trigger it.

8. EVALUATION

Our evaluation was conducted on a public digital forensic case [15] where a confidential document of a startup company was posted in the technical support forum of a competitor’s website. The document came from the computer of the CFO (Jean). The data-set provides a copy of Jean’s computer hard drive and a copy the document. The data-set is big enough to be realistic (~1.46GB), but it is small enough to allow performing an investigation on a desktop computer.

Our evaluation assessed the correctness and effectiveness of our approach compared to traditional digital investigations aided by digital forensics tools. In particular, we verify if, under the assumptions that modeled hypotheses of a crime are correct, our approach leads to the same - or even more accurate - conclusions. Effectiveness is estimated in terms of the amount of evidence an investigator has to analyze that also affects the number of hypotheses to be evaluated. We conducted the same investigation by using available digital forensics tools (Section 8.1), our approach without proactive activities (Section 8.2), and our approach with proactive activities (Section 8.3). The interested reader can find a detailed description of the evaluation results in [32].

8.1 Traditional Digital Investigation

We acquired the image of the computer hard drive by using the Sleuthkit & Autopsy tool [6] and we discovered that the installed operating system is Windows XP Service Pack 3. We also used PSTViewer [8] to analyze sent/received emails and RegRipper [8] to analyze Windows Registry hives and WinMD5 [10] to compute file hashes. By searching for one of the strings contained in the confidential document ($1,009,000), the keyword search functionality of Autopsy only gave one result (C:.../m57biz.xls). This document was created on 2008-06-16T16:13:51 and was last accessed on 2008-07-20T01:28:03 by Jean. All the hypotheses we formulated for this case are shown in Figure10 and the amount of evidence inspected (coming from search results) and operations performed for each hypothesis is shown in Figure11.

Figure 9: Structured Argument that Explains Hypothesis H4.

Figure 10: Investigative hypotheses

1. m57biz.xls is sent via email from a computer user to an internal employee
2. m57biz.xls is sent via email from a computer user to an external recipient
   a. An internal employee was impersonating the external recipient
   b. The credential of the user were stolen
3. m57biz.xls is copied on a USB pen that is mounted by a computer user
   a. The credential of the user were stolen
4. A malware is installed from a blacklisted URL

In the first hypothesis we speculate that the document is sent as an email attachment to an internal employee. Since Outlook is the only email client in the list of the installed programs (133), we analysed available Outlook data files (administrator.pst and outlook.pst) containing Jean inbox (222 received emails) and outbox (23 sent emails), and the administrator inbox (1 received emails) and outbox (0 sent emails). We noticed that the confidential document was sent as an email attachment by Jean as a response to another email that she received from an external address (tuckgorge@gmail.com). From this evidence we speculate that Jean was the victim of a phishing attack and hypothesis 1 is not viable.

Hence, the second hypothesis we formulated is that the document is sent by Jean as an email attachment to an ex-
The third hypothesis we formulated is that the confidential document was copied by a user on a storage device. To demonstrate this hypothesis we inspected the system Windows registry hive and we noticed that among the removable media (3 results) a USB pen (S/N: 7&162a431980) was mounted on E: on 2008-07-20T01:26:18. Although the confidential document was last accessed near after this USB storage was mounted, we cannot prove that the confidential document was copied onto a USB storage.

The fourth hypothesis we formulated is that a malware was downloaded form a blacklisted URL. However, only one of the installed programs (QQBubbleArena) can be malicious, since its signature does not belong to the NIST National Software Reference Library (NSRL) \cite{29}, which contains the files that are known to be good. From the web history (~1470 results) we did not identify any blacklisted URLs. Indeed, we can only conclude that hypotheses 2 and 3 are likely.

8.2 Reactive Digital Investigation

As a first step we modeled the crime scene associated with the digital forensic scenario. This is very similar to the one proposed for our previous case study. The general model also includes additional entities to represent urls, programs, more specific programs such as email clients (eClient) and browsers, email accounts and files hashes. Programs can also have a state as they can be installed. We also included in the general model a function that identifies the signature of a file (MD5) and two unfimed predicates that indicate if a program is not a malware (InNSRL) and if a url is blacklisted (IsBlack). The concrete model includes additional monitored events to represent sent emails (Sent_Email), sent emails with attachments (Sent_Attach), file searches (File_Search) and web requests (Web_Request) for urls. As an investigation starting point we considered the time instant in which the confidential file was created. All programs that were installed before that time were initially considered as installed. At that point in time all the users were considered not logged and all devices not mounted.

The hypotheses of a crime were modelled as shown in Figure 12. Each hypothesis was customised depending on the elements represented in bold. For example, hypotheses 1 and 2 are customised depending on the users (Jean, Devon, and Administrator), on the email accounts found in the disk image (e.g., jean@m57.biz, alison@m57.biz) (6 accounts) and on the email clients (Outlook), for a total of 18 options. Hypothesis 3 is customised depending on the users (3 options), while hypothesis 4 is customised depending on the installed programs (134) and the browsers (Mozilla and IE), for a total of 266 options.

All the evidence that is possible to gather from the disk image was converted into an ordered sequence of events. Sub-hypotheses were only evaluated for the concrete values on which their parent hypotheses are satisfied. For example, since hypothesis 2 is completely satisfied for user Jane, email jean@m57.biz.com, and email tuckgorge@gmail.com, hypotheses 2.a and 2.b were only evaluated for these values. However, hypotheses 2.a and 2.b are not satisfied. Hypothesis 3 is 75% likely since only one of the monitored events is abduced (event Sys_Copy). Indeed the results we obtained are consistent with those obtained in a traditional digital investigation and are slightly more accurate.

Forensic requirements make it possible to reduce the amount of evidence used to evaluate each hypothesis, since only the
Jean was pretending to be the victim of a phishing attack. The evidence collected from the disk image shows that the attacker was proactively. We envisioned two possible situations. In the reactive case, the attacker was much smaller than the attacker that had been collected in the reactive case compared to the traditional one.

### 8.3 Proactive & Reactive Digital Investigation

To evaluate proactive activities, we simulated a sequence of possible monitored events that could have been collected proactively. We envisioned two possible situations. In the first case, we crafted an event snapshot that complies with the evidence collected from the disk image and shows that Jean was pretending to be the victim of a phishing attack (i.e., she was sending emails from her laptop as the victim). We assumed that this evidence was not available in the disk image because it was concealed. The evaluation of the crafted event snapshot shows that hypothesis 2.a is completely satisfied. In the second case, we crafted an event snapshot demonstrating that Jean copied the confidential document onto a USB pen. In this case, hypothesis 3 is completely satisfied, since event Sys_Copy is considered in the evaluation of the hypothesis and does not have to be abducted. The aforementioned cases demonstrate the usefulness of proactive investigations when some evidence is concealed by an attacker (case 1) or is ephemeral and cannot be retrieved from a disk image (case 2).

We estimated the effectiveness of proactive activities by focusing on case 1. Together with the crafted event snapshot for hypothesis 2.a, we also included 3 event snapshots that did not cause the satisfaction of any hypothesis. In addition, we also assumed a new monitored event is triggered hourly, with a uniform distribution. Note that we considered that hypothesis 2.a is associated with a suspicious event condition that a user is logged on the computer. Indeed events Sys_Login and Sys_Logout will be collected to check the start and stop condition and, additionally, events Sent_Email and Sent_Attach will be gathered during the full evidence collection. For this set of monitored events the Proactive Collection only preserves the snapshots related to the satisfaction of a suspicious event and avoids gathering all the events necessary to satisfy a hypothesis. The overhead of the Proactive Collection is only given by the events necessary to evaluate the start and stop conditions. Proactive activities provide non-negligible savings in the amount of evidence analysed, as shown in Figure 14.

The storage space required to preserve evidence collected proactively for this case can be inferred by examining the workloads of local systems within an organization. We expect that ~10 GB per desktop system per year would be a reasonable internal size.

### 8.4 Discussion

This section discusses the limitations of our approach and proposes possible mitigation actions. Our approach makes the assumption that the possible crimes that can be committed can be defined in advance. For this reason, it is not viable to investigate those crimes that exploit undiscovered vulnerabilities, or that can be performed by unforeseen offenders, or that simply do not follow a predefined scheme (e.g., intrusions, DDoS). However, in the future we are planning to investigate how learning techniques can be employed to integrate the results of completed investigations or new discovered vulnerabilities and attacks in the model of forensic requirements. Furthermore, our approach does not aim to completely replace traditional digital investigations, since we recognise that in some cases the random guess by an experienced investigator can be very close to the reality. Instead, we aim to speedup repetitive analysis and collection activities that are more suitable to be automated.

Modelling the hypotheses can be cumbersome and error-prone and requires some automation. Our work is amenable to leveraging existing model-based diagnosis approaches (e.g., [11, 24, 23]) that generate speculative hypotheses of a crime by using, for example, planning techniques. In particular, in the future we might encode the hypotheses generation as a planning problem that starts from the initial state of the crime scene and terminates when the crime condition is achieved.

The Event Calculus-based analysis has an exponential complexity. For this reason, the Event Calculus representing the potential hypotheses must be built in a way that the problem dimension does not exceed ~10000 variables, which is the saturation point of SAT based problems. To achieve this objective we employed some heuristics. A heuristic tries to decompose a hypothesis into sub-hypotheses whose predicates to be evaluated are disjoint and temporally independent. A similar strategy was employed for hypotheses 2 and 2.a. Another heuristic reduces the length of the temporal window by splitting a hypothesis into 2 or more hypotheses evaluated over shorter and adjacent temporal windows. This strategy can be suitable for situations in which a sequence of monitored events leads the crime scene again to
the condition in which a hypothesis was initially evaluated.

9. RELATED WORK

We now review related work on automating evidence collection, analysis, and presentation.

9.1 Evidence Collection

Existing tools that perform evidence collection are aimed to support computer forensics [20, 4, 38, 6], data recovery [1] and live data collection [23, 40]. However, these approaches do not apply proactive evidence collection and analysis during the normal functioning of a system. Live acquisition of digital evidence is only performed after an incident happened and, therefore, some evidence or the traces concealed by an offender can be missed. Shield et al. [37] have recently proposed the idea to perform continuous proactive evidence collection. However, they do not suggest any possible way to select the evidence to be collected depending on the crimes that can take place in a certain environment. Compared to previous work, our approach does not only preserve important evidence that could be lost, but it also allows using collected evidence to trigger and guide an investigation, by indicating hypotheses to examine and additional evidence to collect.

9.2 Evidence Analysis

Formal techniques have been mainly used to analyse digital evidence. Petri Nets were used to model occurred events and identify the root causes that allowed an incident to occur [40]. Gladyshev and Patel [18] formalise evidence as a series of witness stories that restrict the possible computation of a finite state machine that describes the behaviour of the system. All possible scenarios of incident are obtained by backtracking transitions from the initial state of the system. Other work is specialised on identifying attackers’ traces (e.g., evidence and timestamps improperly manipulated by an attacker), from violations of invariant relationships between digital objects [39] or by applying model checking techniques on a set of events expressed in a multi-sorted algebra [3].

Model-based reasoning techniques [11, 24, 23, 35] have been used extensively to deduce investigative hypotheses. Plan recognition techniques have been applied to generate possible attacks sequences, simulate them on the victim model, and perform pattern matching recognition between their side-effects and log files entries. Abductive reasoning [24] was used to explain a crime scenario from a set of events and domain assumptions and to suggest additional evidence to be collected. Experts’ assessments of the probability of the hypotheses was also used to rank the evidence collection strategies to be performed during an investigation [23]. However, the aforementioned approaches are reactive and available evidence might not always be enough to reconstruct a crime. For this reason, Rekhis et al. [35] propose a language to create hypothetical attacks scenarios in case no attack can be explained. Similarly to model-based approaches, our work allows reasoning on speculative hypotheses that are implicitly inferred from collected evidence [11, 24, 23] or explicitly modeled [35]. However, our approach is not focused on proposing a new technique for evidence analysis. Our objective, instead, is to use forensic requirements to engineer systems able to preserve important evidence that can be fundamental to solve a case. When an investigation starts the amount of evidence analysed is highly reduced compared to the case when all the evidence is collected. Despite the idea of integrating proactive collection and analysis within a digital investigation has been already proposed, existing work [19, 2] do not offer a pathway to implementation and do not specify how proactive and reactive activities can be coordinated.

9.3 Presentation

Our work uses structured arguments to demonstrate how collected evidence can demonstrate a set of hypotheses to be defended in court. Another work [12] proposes to achieve the same objective by testing and replaying an attack in an isolated environment that is similar to the real one. When the test is finished, the analyst can relate the effects of the attack in the virtual environment to the digital evidence in the digital crime scene. If the identified effects do not support the hypotheses, the hypotheses should be reformulated, and the necessary test events should be replayed. The main drawback of this approach is that it requires reproducing an attack in a realistic environment to understand how it took place. Instead, we explicitly model the crime scene and the hypotheses of a crime to build structured arguments that formally demonstrate a hypothesis and explain how a crime took place.

10. CONCLUSIONS AND FUTURE WORK

This paper has proposed an approach to engineer forensic-ready software systems. We proposed an adaptive process to systematically perform the activities to be conducted before and during a digital forensic investigation. The process performs proactive activities to preserve important evidence and suggests immediate investigative directions. Second, we introduced the notion of forensic requirements to systematically configure the activities of the proposed digital forensics process depending on a specific crime scene and on the speculative hypotheses of a crime. Finally, we explained how structured arguments can be used to present the findings of an investigation. Our results suggest that our approach reduces significantly the evidence that needs to be collected and the hypotheses that need to be analysed during an investigation. In the future we are planning to apply our approach in pervasive and distributed environments, such as cloud platforms, where a large amount of evidence is ephemeral. We are also investigating new techniques to elicit forensics requirements from existing regulations.

11. REFERENCES


