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REVIEW

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Foundations and applications of artificial Intelligence for zero-day and multi-step attack detection

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Abstract

Behind firewalls, more and more cybersecurity attacks are specifically targeted to the very network where they are taking place. This review proposes a comprehensive framework for addressing the challenge of characterising novel complex threats and relevant counter-measures. Two kinds of attacks are particularly representative of this issue: zero-day attacks that are not publicly disclosed and multi-step attacks that are built of several individual steps, some malicious and some benign. Two main approaches are developed in the artificial intelligence field to track these attacks: statistics and machine learning. Statistical approaches include rule-based and outlier-detection-based solutions. Machine learning includes the detection of behavioural anomalies and event sequence tracking. Applications of artificial intelligence cover the field of intrusion detection, which is typically performed online, and security investigation, performed offline.

Keywords: Zero-day attack, Multi-step attack, Anomaly detection, Intrusion detection, Security investigation

1 Introduction

An ever growing percentage of cyberattacks is explicitly targeted at a specific organisation in order to steal data, to perform industrial espionage or to execute sabotage or denial of service [1]. The most dangerous cyberattacks include zero-day attacks and complex attacks [2]. Although they are beginning to be better understood by the community, they remain difficult to track and to identify in the massive haystack of system logs and alerts. Artificial intelligence tools are thus required to find both unknown and complex attacks. Unknown attacks are known as *zero-day attacks*. They exploit previously unknown system flows. Around 4000 of them were exploited in 2015 and 2016, 160 of which concerned industrial control [1]. Complex attacks are known as *multi-step attacks*. The danger they pose often emerges from the consecutive execution of steps which taken individually are either innocuous or insufficient to be characterised as an aggression.

This paper provides a review of the two main approaches for tracking hard-to-find cyberattacks: statistical analysis and machine learning [3], which are the two domains of data analysis. Statistical analysis covers the extraction of statistical rules and outlier detection. Outlier detection in particular necessitates the availability of suitable distance metrics, which can be computed either between individual points or between full distributions as for Kullback-Leibler Divergence. Machine learning supports the extraction of behaviour anomalies and abnormal event sequences. Statistical analysis and machine learning are applied in two complementary steps of the security analysis process: intrusion detection for the online supervision of computer systems and infrastructures, and post event investigation for the characterization of a given event of interest. We identify four consecutive generations of Intrusion Detection System (IDS) solutions, which are now often integrated in commercial products: expert systems, alert correlation, data mining, and behavioural IDS.

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Post event investigation involves providing experts with suitable security information to guide the search for significant malicious events and when relevant to characterise the actual properties of the cyberattack that these events are an indication of.

In this work, we therefore propose a comprehensive framework for the study of complex attacks and related analysis strategies through statistical tools, on the one side, and machine learning tools, on the other side. It puts these complex attacks in perspective with their core applications in the security domain: detection and investigation. Although numerous works and review papers deal with individual issues of this framework [4–6], no comprehensive survey, which is a strong requirement for characterising novel threats and matching countermeasures, exist so far.

We first define the core security concepts used in this work and describe the hard-to-track anomalies and attacks we focus on, such as zero-day attacks and multi-step attacks in Section 2. Section 3 presents the statistical foundations of anomaly detection relevant to cybersecurity. Section 4 describes specific cybersecurity solutions that are based on these foundations and take advantage of machine learning techniques and Bayesian statistics to highlight one-off security issues and to model event sequences in order to identify multi-step intrusions. Section 5 introduces the architectures and processes of security detection and investigation that rely on these models.

2 Definitions

The terms used in this paper are defined in this section.

2.1 The vocabulary around attacks

We use here the definition of the IETF RFC 4949 on Internet Security Glossary [7].

Anomaly: an activity that is different from the normal behaviour of system entities and system resources.

Attack: can be

1. An intentional act by which an entity attempts to evade security services and violate the security policy of a system. That is, an actual assault on system security that derives from an intelligent threat.
2. A method or technique used in an assault (e.g., masquerade).

Intrusion: can be

1. A security event, or a combination of multiple security events, which constitutes a security incident in which an intruder gains, or attempts to gain, access to a system or system resource without having authorization to do so.
2. A type of threat action whereby an unauthorised entity gains access to sensitive data by circumventing a system's security protections.

Threat: can be

1. A potential for violation of security, which exists when there is an entity, circumstance, capability, action, or event that could cause harm.
2. Any circumstance or event with the potential to adversely affect a system through unauthorised access, destruction, disclosure, or modification of data, or denial of service.

Traces: A mark, object, or other indication of the existence or passing of something[1], in the IT context an indicator of the occurrence of an action in the network (event in the form of log, alert or network packet).

Vulnerability: A flaw or weakness in a system's design, implementation, or operation and management that could be exploited to violate the system's security policy.

2.2 The scope of security issues

The field of cybersecurity covers all activities which tend to weaken [8]:

Confidentiality: the ability of a system to keep its data and operations unknown to unauthorised entities,

Integrity: the ability of a system to avoid alteration of its data or operations by unauthorised entities,

Availability: the ability of a system to continuously provide access to its data and operations to authorised users.

These are known as the *CIA* principles. These definitions emphasise the fact that the users of a system need to be authorised and therefore, as a prerequisite, identified. Thus, to allow a user or an entity to access some data or operation typically means that this access is forbidden to somebody else. Of course, some resources can be freely accessible, such as a web site, but this is a specific case only.

Confidentiality and integrity rely on mechanisms which enable authorised users to gain access to data and operations while protecting these resources against unauthorised ones [9]. They are based on cryptographic or system engineering tools used to identify the users and perform proper authorization and at the same time to restrict access to the data or operation without these controls. The definition of availability, on the other hand, poses a major challenge. For instance, any unauthorised user can challenge the system's ability to withstand numerous requests. However, technical contingencies can drastically reduce system access, with or without human intervention, and with or without malevolent intention.

2.3 Security analysis

We use this generic term to describe the processing of traces in order to find abnormal and potentially malicious events. Analysis covers detection and investigation:

Detection: the process of identifying events suspected to be of malicious origin, as the related traces arrive through the system probes. It occurs at runtime.

Investigation: the process of exploiting post-incident traces to reconstitute the actual course of an event which is suspected to be of malicious origin. Investigation is usually performed using technical forensics tools, after the incident.

Signature detection: uses a set of known malicious data patterns (signatures) or attack rules (heuristics) that are compared with current behaviour to decide if it is that of an intruder. It is also known as misuse detection [10].

Anomaly detection: enables to determine with a high level of confidence whether this behaviour is that of a legitimate user or that of an intruder based on the collection of data relating to the behaviour of legitimate users over a period of time [10].

2.4 Zero-day attacks

Since the 1980s, most security solutions have been based on the detection of malevolent communications or code through a signature-based approach [11]. However, the exploitation of unknown attacks, known as zero-day attacks, is a key success factor for highly focused as well as large-scale intrusions [12]. Attacks are considered zero-day when they occur before the exploit they rely on is disclosed publicly, as shown in Fig. 1.

Such a public disclosure typically concludes a process of introduction and discovery of the vulnerability. The vulnerability is first introduced in a new product or in a new feature of an existing product as a software or hardware flaw. Often, hacker groups discover the vulnerability and release exploit code in the wild, *i.e.* in more or less ethical-minded communities. At some point, the vulnerability becomes known by the vendor, for instance through access to the exploit code, through a warning of so-called *white-hat* hackers or even through an attack specifically targeted at their system. At this point, the vulnerability is still unknown to the user base of the product, including the system administrators of the editor's clients. No protection therefore exists and the exposure is maximal, but only a very restricted community is aware of the exploit and thus able to take advantage of it. When the vulnerability is disclosed publicly, a series of actions can be undertaken: disabling the weak system, updating anti-virus software signatures and publishing patches to close the vulnerability. Up to the moment when the patch is deployed on the complete software base using the vulnerable product, follow-up attacks can be performed. Usually, in this phase, scripts are released to ease the action of wannabe hackers, which make unprotected systems more vulnerable than in the pre-disclosure phase. The system update and security maintenance are therefore crucial in this regard.

In any case, zero-day attacks can only be identified by the deviation they imply in the existing behaviour of the system. Their discovery is a significant use case for anomaly detection.

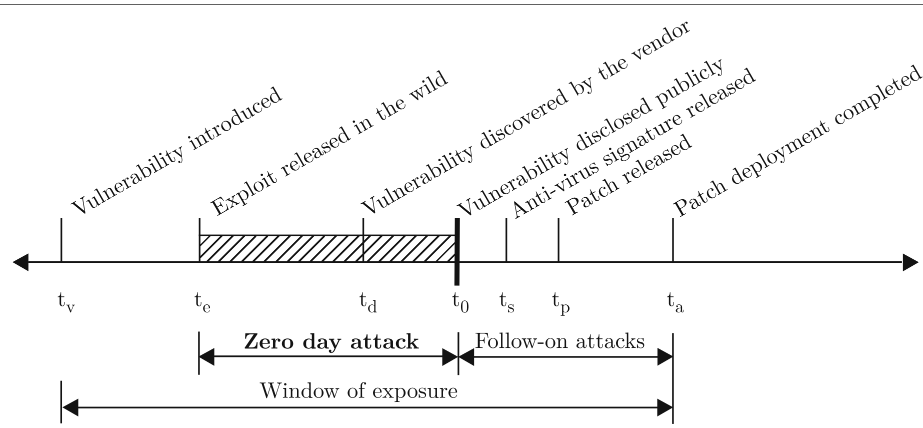

Fig. 1 The attack timeline for zero-day attacks [12]

2.5 Multi-step attacks

Since the exploitation of zero-day attacks requires a high skill level and significant time, they are usually used for high-end, high value-added attacks. Usually, the objectives are very specific, such as stealing valuable data in espionage efforts or disabling specific systems like the Stuxnet worm that hit the Iranian nuclear plants in 2010. Therefore, they are not exploited on their own, but in a sequence of operations that are specific to the system to be abused. These are known as multi-step attacks, or Advanced Persistent Threats (APTs). Their most relevant characteristics are [13, 14]:

1. They attack specific targets;
2. They use sophisticated tactics, techniques and procedures;
3. They constantly evolve their attack steps;
4. They largely infiltrate a network;
5. They perform repeated attack attempts;
6. They maintain long-term access to the target environment.

Their detection is all the more difficult since certain steps in the attack are performed manually to remain stealthy and to bypass detection approaches [15]. The detection of such attacks therefore requires a deep understanding of their construction and progress.

The main attack stages of multi-step attacks are:

- Pre-infection: reconnaissance, exploitation, re-direction.
- Infection: payload delivery.
- Post-infection: command and control, update, dropping, staging, exfiltration of stolen data.

A more detailed life-cycle, or 'kill-chain', can be identified [13, 16], as shown in Fig. 2 and including the following steps : (1) perform initial reconnaissance, (2) perform initial compromise, (3) establish foothold, (4) escalate privileges, (5) perform internal reconnaissance, (6) move laterally, (7) maintain presence and (8) complete mission. The phases 4 to 7 are repeated by the attackers to gain and maintain long-term access to the target environment.

The diverse technologies that are abused through multi-step attacks is a complementary factor which makes their identification difficult. Table 1 [15] shows the techniques and methods used in the operational phases of the main APT campaigns as of 2016, in the phases of initial compromise, lateral movement inside the system and command and control (C2). Exploitation of spear phishing is a common vector for initial compromise. Lateral movement, which involves taking control of focused resources inside the systems to support the final phase of the attack, is based on Operating System tools, password abuse and vulnerability exploitation. The final phase of the attacks, which gives the attackers access to their target resource, largely uses the HTTP and HTTPS protocols for communication and data exfiltration.

Their variety, as well as the generally semi-manual execution, make multi-step attacks very difficult to identify. When considering zero-day, multi-step or more common attacks, the threats are identified through symptoms, called *Indicators of Compromise* [17–19] (IoC). IoC are 'artifacts observed on a network or in an operating system that with high confidence indicates a computer intrusion'. They are best identified as anomalies with regard to the normal behaviour of a system.

3 Statistical foundations of anomaly detection

Since AI technologies are now used by malevolent agents to perform cyberattacks [20], it is of crucial importance for the protection of IT infrastructures that defensive solutions support suitable protections. Numerous

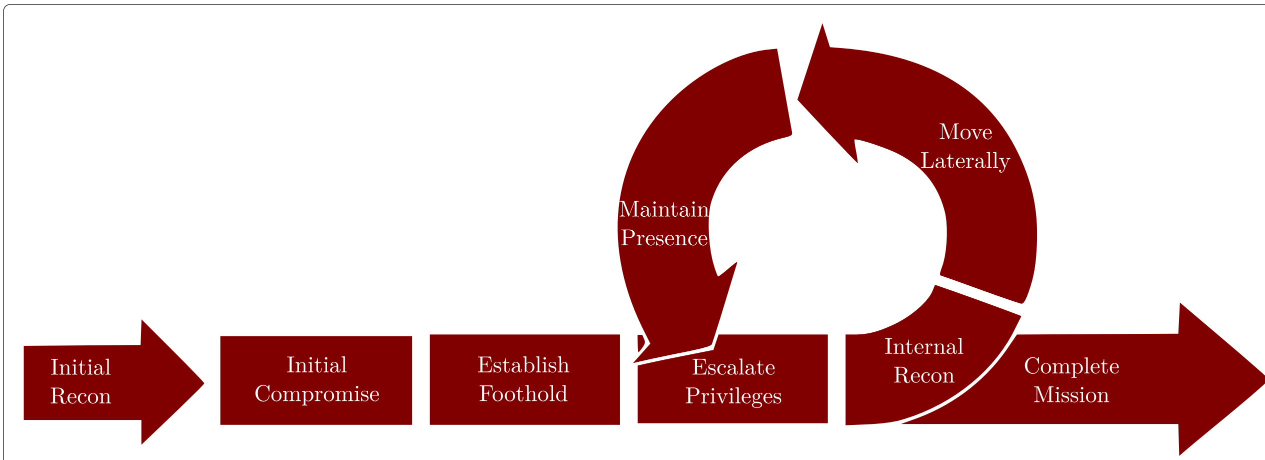

Fig. 2 The APT life-cycle by Mandiant [16]

Table 1 Techniques and methods used in the operational phases of main APT campaigns [15]

APT campaign/group	Initial compromise				Lateral movement			C2			Report
	Spear-phishing	Watering-hole attacks	Server attacks	Storage media	Standard OS tools	Hash and password dumping	Exploit vul-nerabilities	HTTP/HTTPS	Others	Custom proto-cols	
HeartBeat	✓									✓	[93]
Icefog	✓					✓		✓		✓	[94]
Darkhotel	✓	✓						✓			[95]
Operation Cleaver	✓				✓	✓	✓	✓	✓		[96]
Shell Crew			✓		✓	✓				✓	[97]
Regin								✓	✓		[98]
APT28	✓							✓	✓		[99]
Anunak	✓				✓	✓	✓	✓	✓	✓	[100]
Deep Panda	✓				✓	✓			✓		[101]
Cozy Duke	✓							✓			[102]
Hellsing	✓										[103]
MsnMM (Naikon Group)	✓				✓			✓			[104]
Carbanak	✓	✓			✓	✓		✓	✓		[105]
Duqu 2.0	✓				✓	✓	✓	✓	✓	✓	[106]
Thamar Reservoir	✓										[107]
Naikon APT	✓				✓			✓			[108]
APT30	✓							✓	✓		[109]
Woolen-Goldfish	✓							✓	✓		[110]
EquationDrug (Equation Group)	✓			✓			✓				[111]
Animal Farm		✓									[112]
Waterbug Group	✓	✓		✓				✓			[113]
Desert Falcons	✓							✓			[114]

research studies present overviews of the domain, for example, from the point of view of anomaly detection [21] or data mining and machine learning [22].

A classification of the problems of anomaly detection is now presented, as well as the two main detection strategies: rule-based and outlier-detection-based anomaly detection.

3.1 The problems of anomaly detection

The problems of statistical anomaly detection are described for discrete sequences by Chandola et al. [23, 24]. They define three classes of problems, which match three usage scenarios.

Scenario 1: The operator of a Security Operating Centre (SOC) performs an investigation to detect illegitimate user sessions on an enterprise information system in the current week. He or she will typically exploit the data of user sessions in previous weeks, such as sequences of system calls and commands, as training data. Using the first formulation, the suspicious traces are tested against this training data.

Scenario 2: The operator of a Security Operating Centre (SOC) performs an investigation to detect whether the account of a user was abused in the past few weeks. To achieve this, the operator can use the second formulation: the activity of the user is treated as a long sequence and is tested for anomalous subsequences.

Scenario 3: The operator of a Security Operating Centre (SOC) performs an investigation to determine whether the frequency of a given command is higher or lower than usual. A query pattern is defined as a sequence of commands. He or she can use the third formulation to compare the frequency of this query pattern in the activity of the user in a given time period with the frequency of past sequences to detect malicious behaviours.

For the specific case of semi-supervised learning, the three scenarios can be formulated as follows [24]:

Formulation 1: Given a set of n sequences, $\mathbb{S} = S_1, S_2, ..., S_n$, and a sequence S_q belonging to a test data set S, compute an anomaly score for S_q with respect to the training data set $\mathbb{S}$. The length of sequences in $\mathbb{S}$ and the length of S_q are not necessarily equal. After evaluating the anomaly score of the test sequence S_q, a complementary test is required to check whether it significantly deviates from the score of other sequences to characterise an actual anomaly. The problem itself can be defined as follows: Given a training set of n sequences $\mathbb{S} = S_1, S_2, ..., S_n$ and a test set S, find all sequences in S that are anomalous *wrt.* $\mathbb{S}$.

Formulation 2: Detect short sub-sequences s in a long sequence $\mathbb{S}$, which are anomalous with respect to the rest of $\mathbb{S}$.

Formulation 3: Given a short query pattern s, a long test sequence S and a training set of long sequences $\mathbb{S}$, determine whether the frequency of occurrence of s in S is anomalous with respect to the frequency of occurrence of s in $\mathbb{S}$.

The three main approaches for addressing these problems are kernel-based techniques, window-based techniques and Markovian techniques. Kernel-based techniques consist in building a global model of the system behaviour and looking for anomalies *wrt.* this model. Window-based techniques consist in tracking local behaviours and comparing each trace to be analyzed with each of the local behaviours. Markovian techniques predict the probability of the occurrence of each behaviour (each symbol), given n previous values. For each of these approaches, rule-based or outlier-detection-based strategies can be applied.

3.2 Rule-based anomaly detection

A representative example of how rules for anomaly detection are defined and applied is given by the LEarning Rules for Anomaly Detection (LERAD) model [25, 26]. LERAD defines a solution S as the representation of the normal behaviour of system calls. It triggers alarms when these rules are broken. LERAD is a supervised approach that requires a training set free of anomalies.

A solution S is a set of rules which expresses the values of system call attributes observed in the training set. S is defined as a 5-tuple, as given in Eq. 1. A is the set of N attributes, Φ is the set of all possible values for the attributes in A and I is the set of input tuples, which is a subset of the N-ary Cartesian product over A. The rule set itself is noted $\Re$, and ς is the maximum number of conditions in a rule. LERAD rules are defined in Eq. 2. Each rule is defined by an antecedent, the left term of the rule and, a consequent, the right term of the rule. The antecedent expresses for each attribute $\alpha_{i,j,...}$ the observed values $\phi_{p,q,...}$ for a given system call, with the maximum number of attributes less than or equal to ς. The consequent gives the set of values observed in the training set for the attribute α_k (α_k not in the antecedent) as a set $\{\phi_a, \phi_b, \ldots\}$.

$$S : (A, \Phi, I, \Re, \varsigma) \tag{1}$$

$$R: (\alpha_i = \phi_p) \wedge (\alpha_j = \phi_q) \ldots \varsigma \ terms \Rightarrow \alpha_k \in \{\phi_a, \phi_b, \ldots\} \tag{2}$$

For each rule R, a probability p of interpreting a call as an anomaly is defined according to n, the number of identical antecedent tuples (on the left term of the rule) that satisfy the rule during training, and r, the cardinality of the set of observed values for the consequent (right term of the rule). It is given in Eq. 3. r is necessarily smaller than or equal to n. $r = n$, and thus $p = 1$ if each occurrence of the antecedent matches a different value ϕ_a of α_k. $r << n$, and thus $p << 1$, if the same value ϕ_a of α_k occurs frequently for a given antecedent. The anomaly score of a novel event with regard to a given rule is defined as AS, as given in Eq. 4. AS is the inverse of p. $AS = 1$ if each occurrence of the antecedent matches a different value ϕ_a of α_k; in this case, a new value for α_k will not be a significant anomaly. $AS >> 1$ means that the antecedent usually matches a limited set of α_k, that new observations of the antecedent are likely to match a known value of α_k, and therefore that a call breaking the rule is likely to be a significant anomaly. The total anomaly score TAS is computed by considering all broken rules as well as the delay since last anomaly for a given rule. It is given in Eq. 5. i is the index of a rule which the tuple has violated. t is the time since the rule was last broken, which is an indicator of the rule stability and thus of its quality. Since anomalies often occur in bursts during an attack, the TAS will be high at the beginning of the attack, clearly labelling the moment when the potential aggression starts.

$$p = \frac{r}{n} \tag{3}$$

$$AS = \frac{1}{p} = \frac{n}{r} \tag{4}$$

$$TAS = \sum_i \left(\frac{t_i}{p_i}\right) = \sum_i \left(\frac{t_i n_i}{r_i}\right) \tag{5}$$

LERAD is designed to minimise the total number of rules and to avoid an excessive analysis overhead. One criteria for selecting rules is to favour the ones that describe the behaviour of the system well and that exhibit a stable behaviour over time, as shown in Fig. 3. The AS value quickly reaches its nominal value during the training phase, is not significantly modified during the validation phase and is stable during the test phase. This behaviour increases the probability that rule breaking indicates actual anomalies.

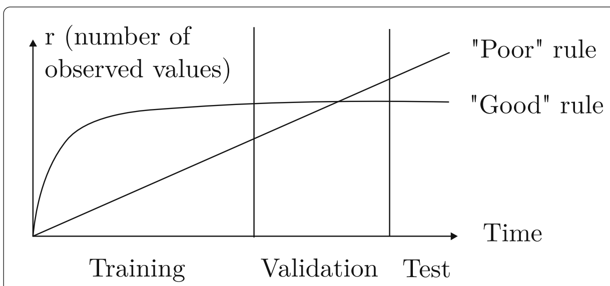

Fig. 3 Evaluating the quality of anomaly detection rules [25]

3.3 Measurement of distance between observations

Anomaly detection implies that 'normal' behaviours can be discriminated from 'abnormal' ones. A strong prerequisite is therefore that the degree of 'normality' can be quantified, i.e. that a distance measure between observed system traces and a reference trace set can be computed. According to the type of information available, such as single points, series or distributions of observations, various approaches should be used.

3.3.1 Euclidian distance

A simple metric for distance measurement between two points is the Euclidian distance, recalled in Eq. 6 for two dimensions. When more parameters are considered, the equation is extended accordingly. This is of course the most widely used measure of distance between two observations.

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{6}$$

3.3.2 Manhattan distance

In case of compact distributions, the Manhattan distance or city-block distance, defined in Eq. 7 for two dimensions, can be used to discriminate dense observations. When more parameters are considered, the equation is extended accordingly.

$$d = |x_2 - x_1| + |y_2 - y_1| \tag{7}$$

3.3.3 Reachability distance

When the objective is to extract observations that are further away from the others, it is often convenient to smooth the distance for densely located observations, where discrimination would be computationally costly but would contribute little additional information. This smoothing is supported by the reachability distance $reach\_dist$ [27]. The reachability distance is computed according to $d(p, o)$, the Euclidian distance between the objects p and o, and the k-distance of object p *wrt.* object o, denoted as $k - distance(p)$. Its definition is given in Eq. 8.

$$reach\_dist_k(p, o) = max(d(p, o), k - distance(o)) \tag{8}$$

For any positive integer k, the $k - distance$ of object p is defined as the distance $d(p, o)$ between p and an object $o \in D$ such that:

1. For at least k objects $o' \in D \setminus p$, $d(p, o') \leq d(p, o)$ holds, and
2. For at most k-1 objects $o' \in D \setminus p$, $d(p, o') < d(p, o)$ holds.

Figure 4 shows an example of the reachability distance $reach\_dist$ for four points. When an observation p is far

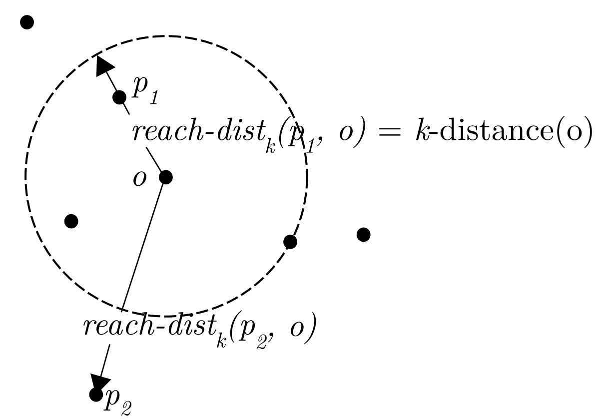

Fig. 4 Example of *reach_dist* for several points [27]

away from o, $reach\_dist_k(p, o) = d(p, o)$. When an observation p is close to o, the distance considered in the $k-distance$ of o.

3.3.4 Distance between sets of observations

It is often useful to reduce the dimension of sets of observations, for instance, as input to algorithm processing or to facilitate visualisation. Tandon et al. [26] proposes to use a distance metric between two sets of scalar observations inspired by the symmetric Mahalanobis distance [28, 29], as shown in Eq. 9. As output, observation sets are represented as points in a two-dimensional space. s_1 is an arbitrary reference observation set, and s_2 is the observation set whose distance *wrt.* s_1 is to be computed. x_{1_i} is the value of the i^{th} observation in s_1; x_{2_i} is the value of the i^{th} observation in $s2$. s_1 includes n_1 observations; s_2 includes n_2 observations. $(\bar{x}, \bar{y})$ are the means along the x and y axes, and (σ_x, σ_y) the standard deviations along these axes.

$$d_x = \frac{\frac{\sum_{i=1}^{n_1}\left(x_{1_i}-\bar{x}_2\right)}{\sigma_{x_2}} + \frac{\sum_{j=1}^{n_2}\left(x_{2_j}-\bar{x}_1\right)}{\sigma_{x_1}}}{n_1+n_2}, d_y = \frac{\frac{\sum_{i=1}^{n_1}\left(y_{1_i}-\bar{y}_2\right)}{\sigma_{y_2}} + \frac{\sum_{j=1}^{n_2}\left(y_{2_j}-\bar{y}_1\right)}{\sigma_{y_1}}}{n_1+n_2} \tag{9}$$

This approach can be used to reduce the dimensions of complex observations in order to plot the sequence space of call sequences, as shown in Fig. 5.

3.3.5 Distance between distributions: the Kullback-Leibler divergence

When the distribution of the observations is known, rather than the observations themselves, computing the distance between real sets is not relevant. Instead, the distance between the distribution of observations is computed. This approach allows in particular the evaluation of the quality of data models *wrt.* the original datasets. The Kullback-Leibler divergence [30, 31] is a tool which supports the computation of such a distance, as shown in Eq. 10. The Kullback-Leibler divergence between distributions P and Q is denoted $D_{KL}(P\|Q)$. It is based on the probabilities $P(i)$ and $Q(i)$ of distributions P and Q for each possible value i.

$$D_{KL}(P\|Q) = \sum_i P(i) log \frac{P(i)}{Q(i)} \tag{10}$$

The Kullback-Leibler divergence is linked to the notion of observed information, also known as the Fisher information metric, which is its infinitesimal form. Fisher Information and Kullback-Leiber divergence are significant concepts from the emerging mathematical field of Geometric Science of Information[2].

3.4 Outlier detection

The identification of novel and hard-to-track attacks such as zero-day attacks or multi-step attacks requires to bypass classical signature-based, ruled-based approaches for cyber-security such as defined in Section 3.2. Moreover, the rapid pace of evolution of IT ecosystems and the increasing variety of interconnections strongly limit the perspectives for the construction of a satisfactory explicit model for these attacks. Hence, the field of outlier detection, which is used to identify abnormal data based on previous observations, is currently experiencing a rapid growth, in particular in the domain of cybersecurity [32]. Outlier detection can be both univariate or multivariate [33]. According to the context and available data, it is based on unsupervised, supervised or semi-supervised algorithms [34].

Outliers can be either global, i.e. they deviate from a comprehensive model or kernel of the data space, or local, i.e. they exhibit properties deviating from neighbour observations. Figure 6 illustrates a global outlier, for one outlying observation in a two dimensional space.

3.4.1 Hawkins outlier

A generic definition of the concept of outlier is proposed by Hawkins, as 'an observation that deviates so much from other observations as to arouse suspicion that it was generated by a different mechanism' [35]. Although useful, this definition lacks the necessary formalism for further implementation. A more specific definition for a global outlier is thus needed.

3.4.2 $DB(pct, d_{min})$ outlier

An object p in a dataset D is a (global) $DB(pct, d_{min})$ outlier if at least a percentage pct of the objects in D lies at a distance greater than distance d_{min} from p, i.e. the cardinality of the set $q \in D | d(p, q) \leq d_{min}$ is less than or equal to $(100 - pct\%)$ of the size of D [36].

Since the $DB(pct, dmin)$ outlier is a global outlier, only certain types of outliers, which are radically different than the rest of the objects, can be captured.

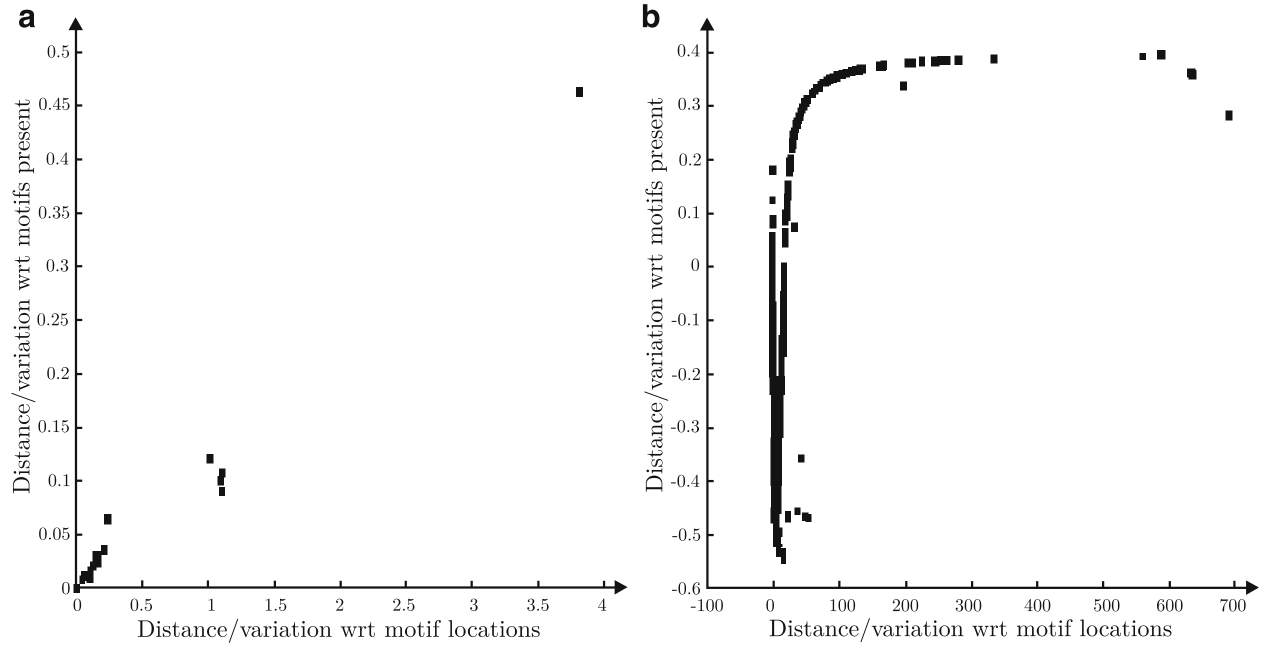

Fig. 5 Sequence space for two applications **a** ftpd (File Transfer Protocol Daemon) and **b** lpr (Line PRinter) [26]

3.4.3 Local outlier factor

In several scenarios, anomalies are indeed characterised as being abnormal *wrt.* similar elements, without necessarily being significantly different from normal observations. It is therefore necessary to consider local outliers, where abnormality is considered *wrt.* k-nearest neighbour elements [37]. The Local Outlier Factor (LOF) provides an example of local outlier detection.

The LOF is based on the reachability distance *reach_dist* metric, introduced in Section 3.3. A local reachability density is calculated for each object, which is the inverse of the average reachability distance of the object from its nearest neighbours [27]. $lrd_{MinPts}(p)$ is the local reachability density of object p. It is defined in Eq. 11. The LOF is defined for each object by comparing its reachability density with each of its neighbours. The local outlier factor $LOF_{MinPts}(p)$ for object p is computed based on the reachability distance as defined in Eq. 12. *MinPts* is the number of neighbours which are considered to belong to the local neighbourhood of the object, $N_{MinPts}(p)$ is the set of these neigbours.

$$lrd_{MinPts}(p) = 1 / \frac{\sum_{o \in N_{MinPts(p)}} reach\_dist_{MinPts}(p,o)}{|N_{MinPts}(p)|} \quad (11)$$

$$LOF_{MinPts}(p) = \frac{\sum_{o \in N_{MinPts(p)}} \frac{lrd_{MinPts}(o)}{lrd_{MinPts}(p)}}{|MinPts(p)|} \quad (12)$$

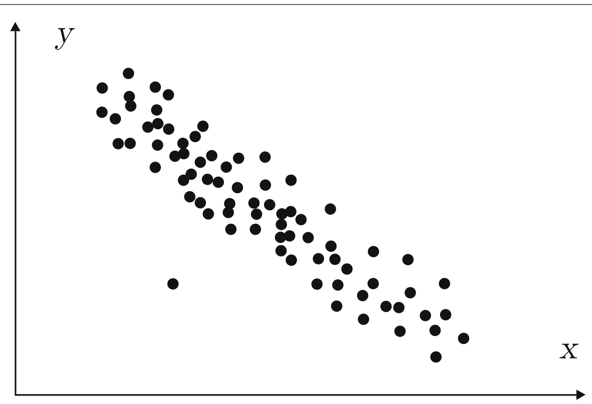

Fig. 6 Example of a two dimensional space with one outlying observation [33]

It is noteworthy that the proposed solution is inappropriate for online detection, since the approach requires knowledge of all process sequences. The Local Outlier Factor (LOF) [27] is an unsupervised approach, which is used in the LEarning Rules for Anomaly Detection (LERAD) model [25]. When applied to sequences of system calls, it defines the supervised Sequence-LERAD (S-LERAD) model [26]. The LOF is an example of distance-based outlier detection. When the number of observations is excessive, such approaches are highly resource consuming. Other approaches, such as density-based outlier detection, are needed.

3.4.4 Importance $w(x)$

This density-based outlier detection metric is defined in Eq. 13. To calculate the density at each potential location

x, the distribution of the training data $p_{tr}(x)$ and the distribution of the test data $p_{te}(x)$ is taken into account.

$$w(x) = \frac{p_{tr}(x)}{p_{te}(x)} \tag{13}$$

If the training and test data densities are equivalent, the value of $w(x)$ is 1. The importance value tends to be small in the regions where the training data density is low and the test data density is high. Thus, samples with small importance values are plausible outliers. This implies that the importance $w(x)$ needs to be computed region-wise, rather than on the whole distribution space [38].

3.4.5 Kullback-Leibler importance estimation procedure

Based on the definition of the importance metric, outlier detection can be performed through the estimation of distribution similarities by using the Kullback-Leibler Importance Estimation Procedure (KLIEP) as defined in Eq. 15 [38]. The importance can be modelled with a linear estimation of the importance distribution $\hat{w}$ as given in Eq. 14. To obtain $\hat{w}$, Kullback-Leibler divergence $KL[p_{tr}(x)\|\hat{p}_{tr}(x)]$ is minimised.

$$\hat{w} = \sum_{l=1}^{b} \alpha_l \phi_l(x) \tag{14}$$

$$KL[p_{tr}(x)\|\hat{p}_{tr}(x)] = \int p_{tr}(x) log \frac{p_{tr}(x)}{\hat{w}(x)p_{te}(x)} dx \tag{15}$$

Other outlier strategies include the kernel density estimator (KDE) and density ratio estimations [39] such as one-class support vector machine (OSVM) [40], Least Square Importance Setting (LSIF) and unconstrained LSIF [26]. The efficiency challenge is another key property of outlier detection algorithms, especially for high-dimensional datasets [41].

4 Machine learning

The identification of unknown attacks faces two major challenges: first, the ability to detect behaviour anomalies, especially for identifying zero-day attacks and, secondly, the ability to track abnormal event sequences, so as to address APTs. Machine learning, as well as advanced statistics, represents methods of critical importance for the online detection of intrusions, on the one hand, and the offline, 'post-mortem' investigation of security issues, on the other.

4.1 Detection of behaviour anomalies

The detection of behaviour anomalies is a rich field of investigation for machine learning approaches. More specifically, recursive Bayesian estimation, which is used to model the behaviour of individual entities of IT systems, provides an alternative method for quickly identifying deviations of this model.

4.1.1 Benchmark of machine learning techniques

The systematic presentation of machine learning techniques is beyond the scope of this work. Several significant publications will help the reader find his/her way in this vast domain [42, 43], although none of them provides a comprehensive view of the subject.

For the evaluation of machine learning techniques, the KDD99 dataset [44], as well as its improved version NSL-KDD [45], are still widely used today, in spite of their age. Some recent surveys using them give a good overview of the methods and the results obtained [4–6]. Table 2 summarizes the performance of the algorithms contained in the Weka workbench on the KDD99 dataset, according to the evaluation made by Modi and Jain [4]. The authors calculated the Percentage of Successful Predictions (PSP) and the Training Time (TT) for each studied algorithm. The best results in terms of successful predictions are achieved by MARS (Multivariate Adaptive Regression Splines). Of course, the results are fully contextual for this specific benchmark, but nonetheless provide an estimation of the relative performance of the considered algorithms.

Since machine learning algorithms are typically difficult to parameterise, as well as very dependent on the quantity of the training data, it is likely that solutions

Table 2 Performance comparison of algorithms in Weka workbench on the KDD99 dataset [4]

Algorithm	Percentage of successful prediction (%)	Training time (seconds)
K-Means	78.7	70.7
NEA	92.22	10.63
FCC	89.2	56.2
ID3	72.22	120
J48	92.06	15.85
PART	45.67	169
NBTree	92.28	25.88
SVM	81.38	222.28
Fuzzy logic	91.8	873.9
Naive Bayes	78.32	5.57
BayesNet	90.62	6.28
Decision Table	91.66	66.24
Random Forest Classifier	92.81	491
Jrip	92.30	207.47
OneR	89.31	3.75
MLP	92.03	350.15
SOM	91.65	192.16
GAU	69.9	177.4
MARS	96.5	67.9
Apriori	87.5	18

focusing on a single technology will achieve better results. This may be the case for instance for neural networks, which have been the subject of significant progress in the last few years.

4.1.2 Recursive Bayesian networks

Bayesian classification models have proved to be efficient tools for intrusion detection [46, 47]. Figure 7 shows an example of an anomaly detection approach based on Bayesian alert correlation [48] for IDS alerts. The process of alert correlation begins by the extraction of recent intrusion alerts. The comparison with historical intrusion alerts allows to extract the pseudo-Bayesian probabilities between a given event and its precursors. Based on these probabilities, the likelihood of alert correlation is computed for all relevant events. A threshold is applied to extract alert correlation graphs, which highlight alerts that are worth investigating.

The application of this process for systems with evolving states is called recursive estimation [49]. When performing such a recursive estimation at the level of each network device, machine and system user, efficient solutions for the identification of access rights abuses or of intrusions can be devised.

4.2 Tracking abnormal event sequences

Machine learning is typically able to identify anomalous behaviours and it is therefore a serious candidate to improve the tracking of zero-day attacks. Multi-step attacks, however, are only visible through traces that are scattered in vast amounts of data over large time periods and on heterogeneous devices. Their identification therefore requires the ability to track abnormal event sequences and first of all to reconstruct these sequences. To achieve this, two significant contributions have been proposed by the community: Galois lattice to rank actions and taint

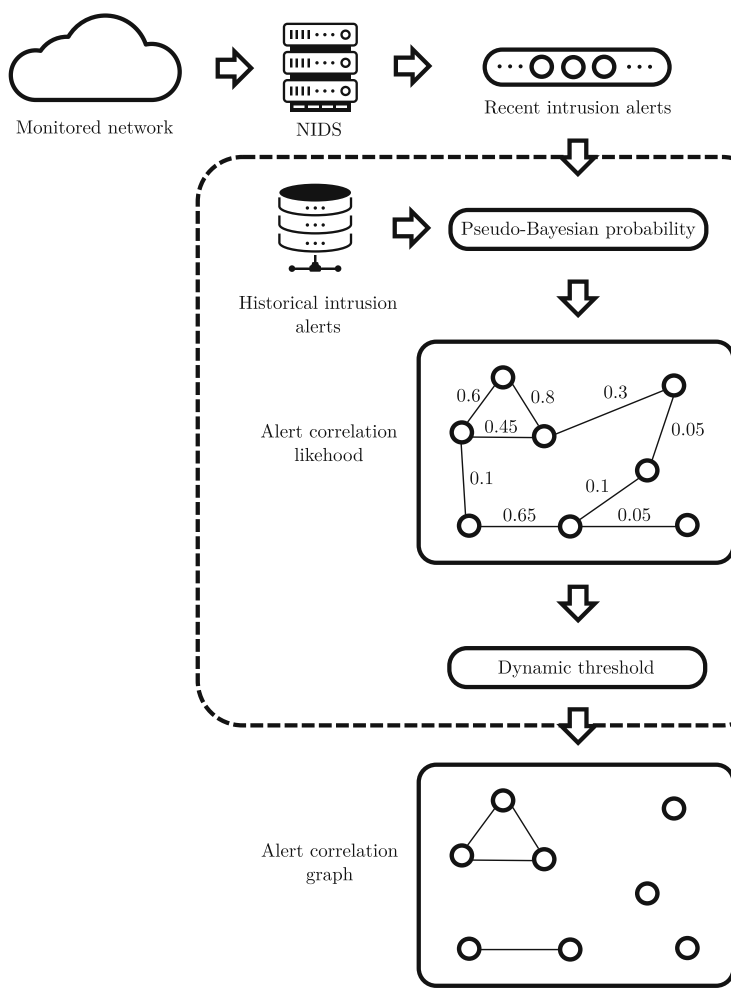

Fig. 7 High -level architecture for pseudo-Bayesian alert correlation [48]

analysis to trace the correlation between events. Both are based on oriented-graph models.

4.2.1 Galois lattice

A lattice is a mathematical object consisting of partially ordered sets, where each pair of elements has a unique least upper bound or supremum [50]. An example of a lattice is the set of natural numbers, which are partially ordered according to the divisibility operation: the least upper bound of an element pair is their least common multiple and their unique infimum is the greatest common divisor. A category theoretic approach to lattice leads to the use of Galois connections to build the lattice: in this case, the lattice is named a Galois lattice [51] and supports ordered relationships between compound elements from two different sets, provided these sets are monotonous. When the information is semantic rather than algebraic, the lattice becomes a concept lattice, according to Wille's theory of concepts [52]. It then supports formal concept analysis [53]. A comprehensive definition of concepts and Galois lattices can be found in [54].

Figure 8 shows an example of a Galois lattice for the reconstruction of a malicious event escalation [55]. The Galois lattice is built interactively: an event is codified through a Galois connection in the context of a pre-existing lattice. The event then inherits the properties of the matching lattice node, including meta-data such as the class of the performed action or the dangerousness level. To support the evolution of the reference Galois lattice *wrt*. the evolution of the system, this classification is validated by an expert. If modifications are required, the reference lattice is updated to integrate this new knowledge. In any case, either the incident is confirmed and suitable action is undertaken by the security operators or the risk level evaluation for the infrastructure being monitored is updated.

The classification of malicious actions can be used to rank the suspicious actions that take place inside an IT infrastructure, thereby announcing the escalation of dangerous actions and thus potentially an actual intrusion. Galois lattices support such ranking while taking into account multiple orthogonal security-related attributes.

4.2.2 Taint analysis

Taint analysis has the objective of systematically labelling paths available for data propagation. It originally comes from the world of static analysis and is increasingly used in the security domain both for the generation of virus signatures and for security investigation [56, 57].

The first application of taint analysis to security was designed for the automated detection and analysis of malicious exploits [58]. Beyond security-specific issues, a framework for the application of taint analysis to safety issues was proposed by [59].

An original application of taint analysis has recently been proposed for investigation by attack tracing and event correlation [60]. Figure 9 shows the signature derivation steps for tainted analysis of multi-step attacks [61]. The events, which are represented by the system logs, are first parsed, normalised and made available in a dedicated database. Then, the tainting operation itself is performed on this data according to taint policies and meta information, in order to generate the taint graphs of significant event sequences for the considered time period. Taint policies define the event attributes to be added to the set of taint sources or nodes, such as the IP address of the source or the communication protocol. Meta-information includes complementary data that

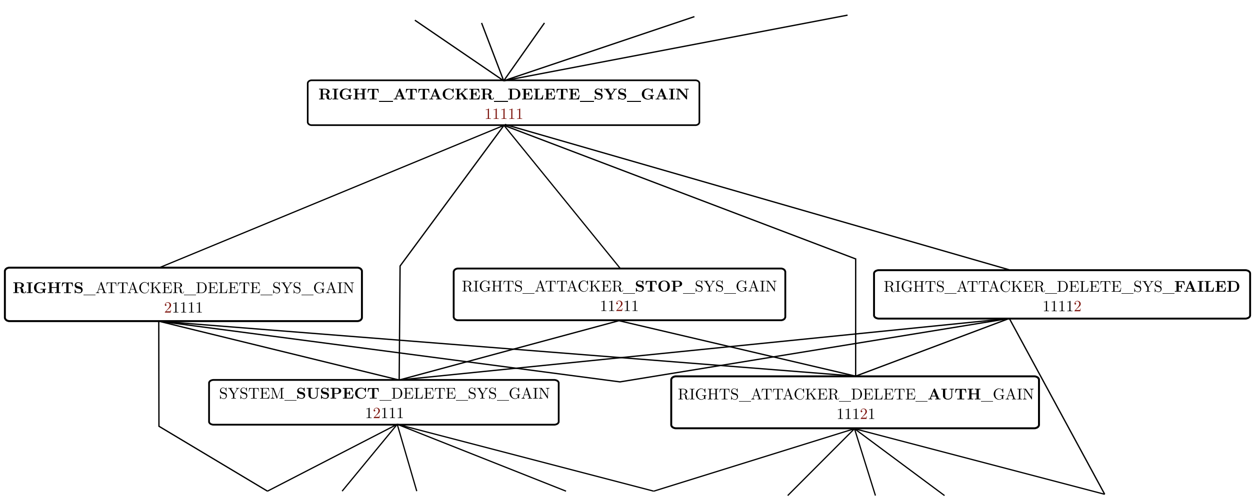

Fig. 8 Example of a Galois lattice for the reconstruction of a malicious event sequence [55]

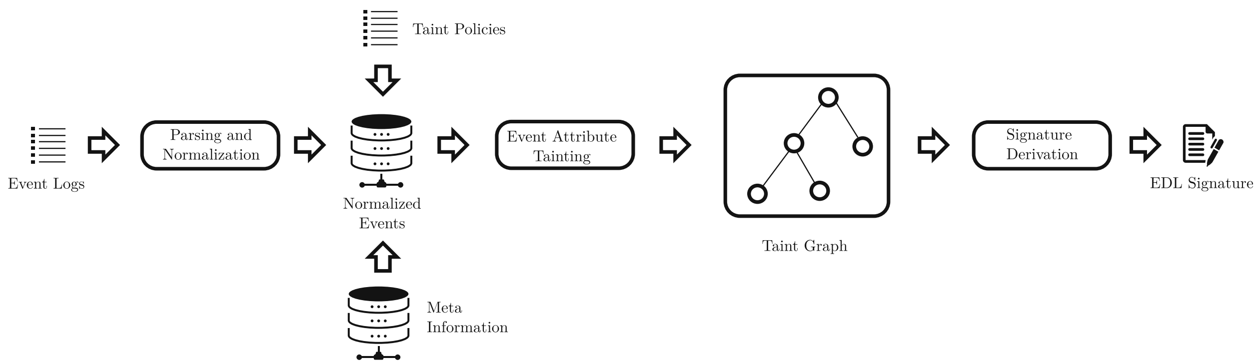

Fig. 9 Signature derivation steps for tainted analysis of multi-step attacks [61]

enable the identification of indirect relations between attributes. Finally, signatures are derived from the taint graphs and stored for further analysis or exploitation in later investigations.

The signature format used by the authors is the *Event Description Language* (EDL) language. Figure 10 shows an example of a graph signature in the EDL language [61]. It is worth noting that attack signatures can entail several paths for a single attack or even several different attacks that can occur in a given context.

5 Applications

The applications of anomaly detection and event sequence tracking to security analysis, i.e. detection and investigation, are now presented.

5.1 Intrusion detection

The first and probably most popular facet of security analysis is intrusion detection. It is defined as "the process of monitoring for and identifying specific malicious traffic" [62]. The devices that can monitor host processes or network packets in the search of malicious actions are called Intrusion Detection Systems (IDS). They are classified into two types, according to the method used for detection: anomaly detection or signature-based detection [63]. There are also alternatives that combine the two approaches [64]. Many surveys of work in Intrusion Detection Systems exist, each focusing on a certain aspect of the problem [6, 11, 63, 65]. Based on this literature survey, we identify four consecutive generations of IDSs: expert systems, alert correlation-based systems, data mining approaches, and behavioural IDSs.

5.1.1 First IDS generation: expert systems

The historical reference for IDS is the seminal work of Dorothy Denning in 1985 [66] concerning the requirements and the reference model from 1987 [67]. This model is still applicable regarding the overall requirements:

Detected intrusions should cover:

- **Attempted break-in** by outsiders;
- **Masquerading,** i.e. seemingly legitimate access following credential theft;
- **Penetration,** in particular resulting in confidentiality or integrity loss;
- **Second-order access violation,** i.e. gaining access to unauthorised information through the aggregation of individual information pieces to which access is piecewise allowed;
- **Information leak through covert channels;**
- **Denial of services;**
- **Side-effects** such as the disruption of services or damages to data and software following malware attacks.

Applicability to different hardware, operating systems and application environments;
Discriminating power ensuring a high detection rate as well as a low rate of false alarms;
Ease of use
Modifiability to adapt to evolving threats;
Self-learning of the normal behaviour of the system;
Real-time detection as well as after-the-fact sleuthing (or investigation);
Security of IDS and its database against confidentiality, integrity and availability threats.

Denning's work was focused on explicit expert rules, which were pervasive throughout the first generation of IDSs. Since then, richer solutions have been developed, including machine learning, which provide implicit but powerful models.

5.1.2 Second IDS generation: alert correlation

The second generation of IDSs was built around a model for alert correlation, which is considered as a prerequisite to efficient detection of security anomalies. They were typically built on three steps: normalisation, aggregation,

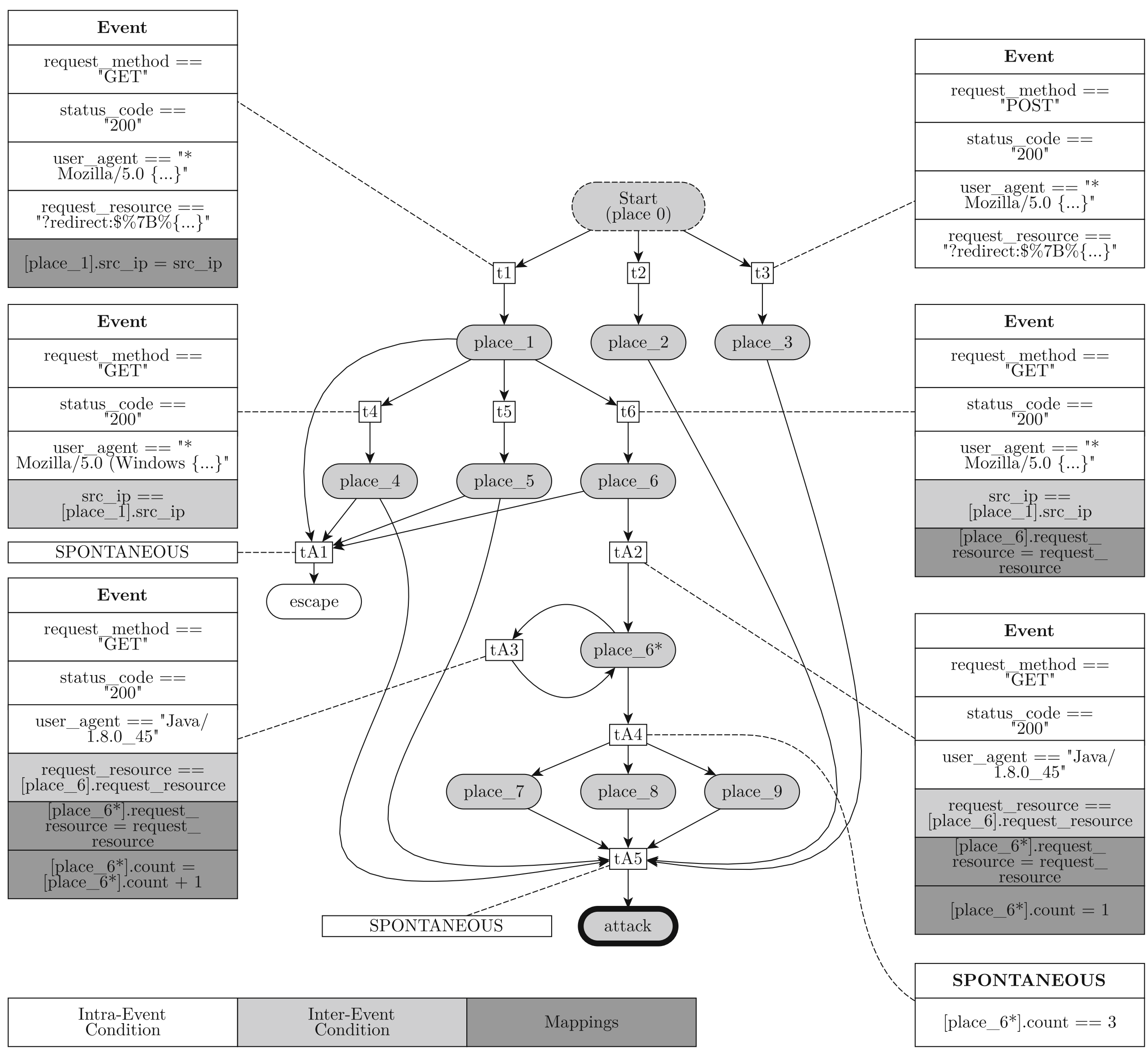

Fig. 10 Example of graph signature in the EDL language [61]

and correlation, known as the NAC process [68]. This process may be complemented by a clustering step [69, 70] to enrich detection capacity.

The requirements for alert correlation are [68]:

The semantic of the information to be correlated, which needs to be explicitly defined

The scalability of the analysis process for important data volumes and for the Intrusion Detection System itself

The reactivity, i.e. the automation of either collection of more information, modification of IDS probes, escalation to human experts or application of suitable countermeasures

The proactivity to anticipate expected alerts according to the data-flow type or time of day.

The CRIM model [71, 72] represents a potential architecture to support the NAC process as shown in Fig. 11. The alerts are first collected and then clustered to identify the main alert classes. Within these clusters, similar alerts are merged, which provides a reduced set of global alerts. Next, the correlation step itself is performed in order to infer candidate attack plans and possibly attack objectives, the 'intentions'. Ideally, a suitable reaction is then triggered [73].

The classic NAC model has been reviewed by Salah et al. [74]. They propose a new model taking into consideration the most relevant published alert correlation proposals. Their model is composed of four modules: preprocessing (equivalent to 'normalisation'), reduction (corresponding to 'aggregation'), correlation and prioritisation.

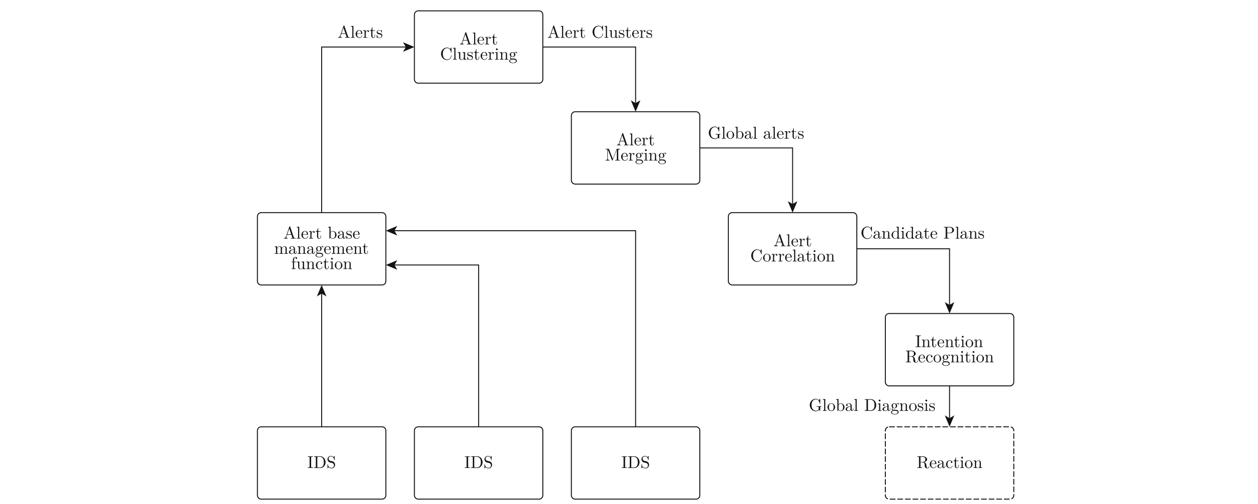

Fig. 11 The CRIM architecture for alert clustering, merging and correlation [71]

5.1.3 Third IDS generation: data mining

The third generation of Intrusion Detection Systems relied heavily on data mining approaches. It introduced a three-level architecture corresponding to the levels of data, information and knowledge, which are clearly different from one another. The data level collects the raw data, possibly enforcing normalisation to prepare for later analysis. The information level processes this data through transformation and selection. It is also known as the data fusion or data mining layer. The knowledge level

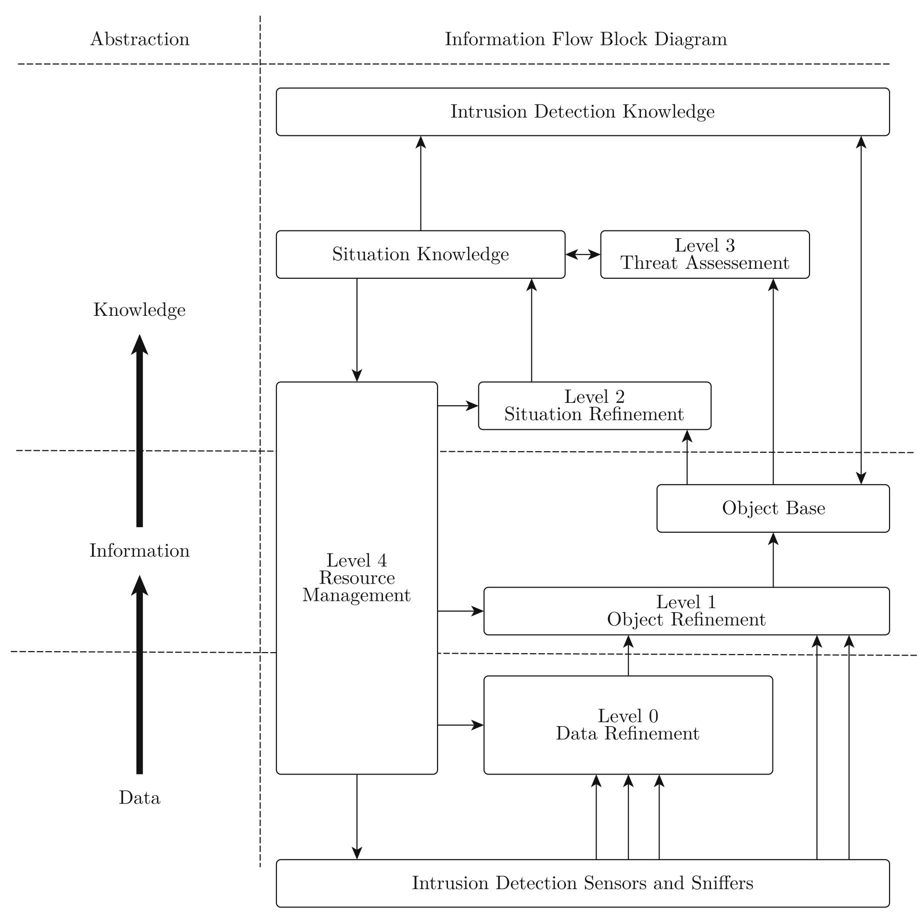

Fig. 12 Information flow for intrusion detection data fusion [75]

is responsible for discovering new behaviours and for the interaction with human operators through visualisation and external verification.

Figure 12 shows a representative model of the information flow for intrusion detection using multi-sensor data fusion [75]. Figure 13 shows a representative model of the information flow for intrusion detection data mining [75].

Among the classes of data mining techniques, anomaly-based intrusion detection plays a central role in the discovery of new attacks such as zero-day attacks and multi-step attacks: it encompasses both information and knowledge layers. Figure 14 shows a classification of anomaly-based detection techniques [76] used in IDSs, which cover statistical, knowledge-based and machine-learning-based techniques. Statistical approaches include univariate, multivariate and time-series models [77]. Knowledge-based approaches include Frequent Subgraph Mining (FSM), description languages and expert systems. Machine-learning-based approaches in this classification include Bayesian networks and outlier detection, which are advanced statistical techniques, as well as Markov models [78], neural networks [79], fuzzy logic, genetic algorithms [80], ant-colony-based solutions [81] and clustering [69].

Much work has been done to improve intrusion detection based on data mining. This approach is especially relevant when dealing with data from a set of heterogeneous sources. The high volume of data generated by the devices connected to a network poses big data challenges when trying to detect intrusions. The reader can find more information in [82] about the intrusion detection techniques developed in this context.

5.1.4 Fourth IDS generation: behavioural IDS

Advanced machine learning techniques can generate models that are fine-grained enough to be able to track the behaviour of individual entities of the IT infrastructure, including network devices, systems and individual users [4–6]. Any deviation of the usual behaviour of one of these entities is therefore perceived, which greatly improves the performance of the Intrusion Detection System, in particular using deep learning [83, 84] and distance-based [85, 86] approaches. These approaches have already been presented in Section 4.1.

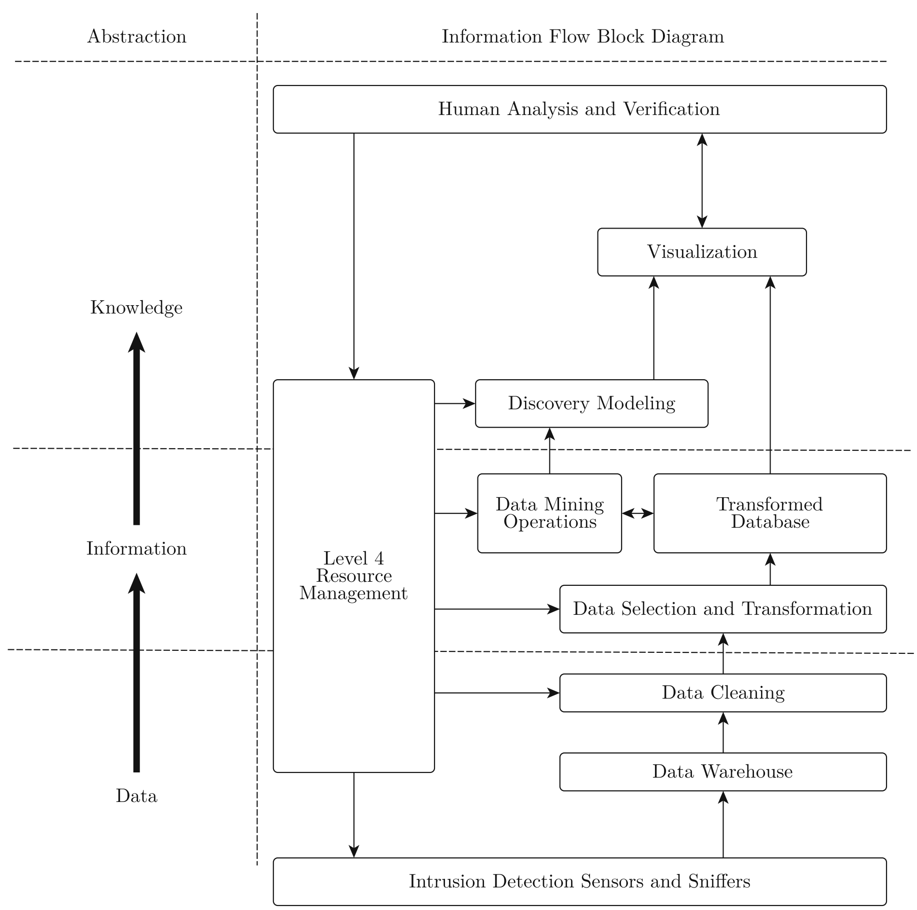

Fig. 13 Information flow for intrusion detection data mining [75]

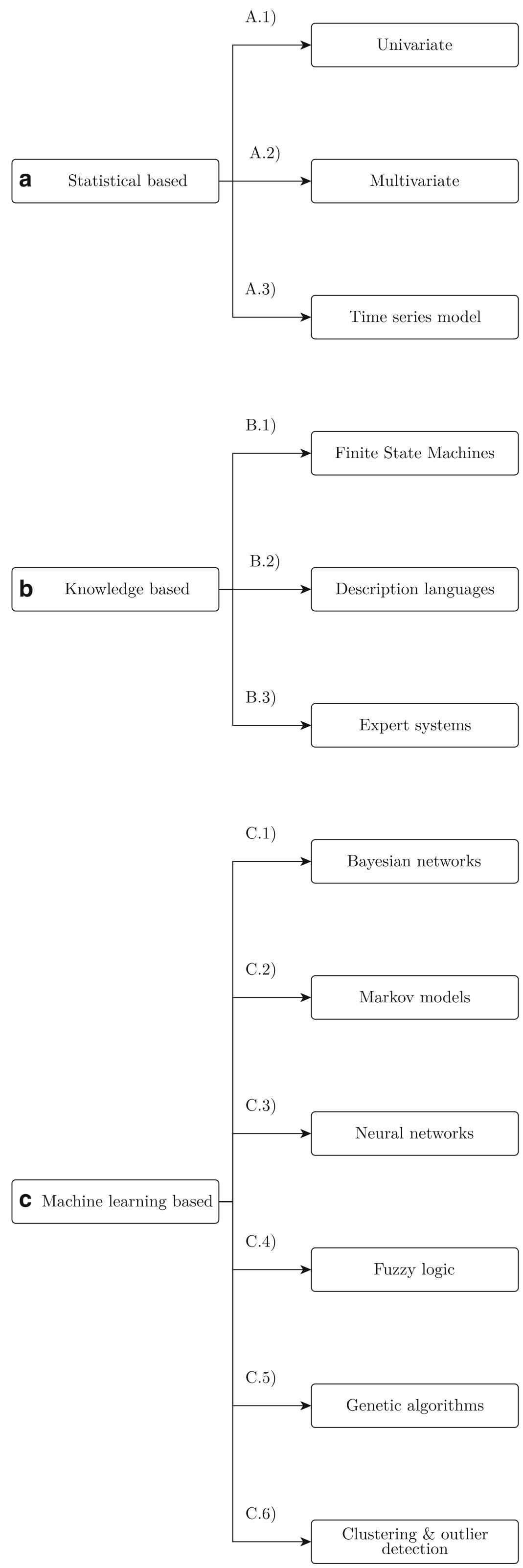

Fig. 14 Classification of anomaly-based detection techniques [76]

5.2 Security investigation

The second facet of security analysis is the so-called sleuthing or investigation. In case of ascertained network or system abuse, the reconstruction of the full-attack process and a detailed understanding of individual steps is necessary to be able to contain the attack, to patch damaged services and systems and to avoid repetition of similar attacks. Data mining is again a useful solution.

The process of security investigation relies more on the actions of the human user than intrusion detection. However, the amount of log data is steadily increasing, so that an automated support of the investigation process is of vital importance for its success. Figure 15 illustrates the process of data mining to support security investigation [87]. As in intrusion detection, the process starts with IDS alerts, which are stored in the IDS data-warehouse. Through data mining, activity patterns are extracted. The human investigators, for instance people from a Security Operating Center (SOC), start their work here. Through the interpretation of the activity patterns, insights are gained and highly focused manual verifications can be performed. When the root causes leading to the attack are determined, they can be fixed. Moreover, suitable filtering and correlation rules can be setup in the IDS to integrate the new aggressions as part as the IDS's knowledge. Clearly, systematic investigation is mandatory for the maintenance of operational and efficient IDSs. Figure 16 provides an example for a simple login to a Windows system using the anomaly signature language EDL [88], which is an attempt to provide a candidate language for solving this issue.

Security investigation is emerging as a research domain per se and poses several core challenges:

1. Cyber-threat intelligence [89] is becoming ever more powerful, which poses two complementary challenges to organisations: how to organise this intelligence internally and how to face attackers having access to a similarly growing amount of information.
2. No standardized language exists so far to support the description of abnormal behaviours, which dramatically reduces the perspectives for information exchange between various actors.
3. The analysis of encrypted traffic is of course greatly hindered [90], whereas clear text transmission is clearly not an option and rather part of the security problem. For instance, over 95% of the traffic on Remote Desktop Protocol can be read by an external malicious user. This is likely to strongly decline with the growing security awareness in organisations. Efficient tools for investigation of highly encrypted traffic thus need to be devised to avoid an important loss of security-critical information.

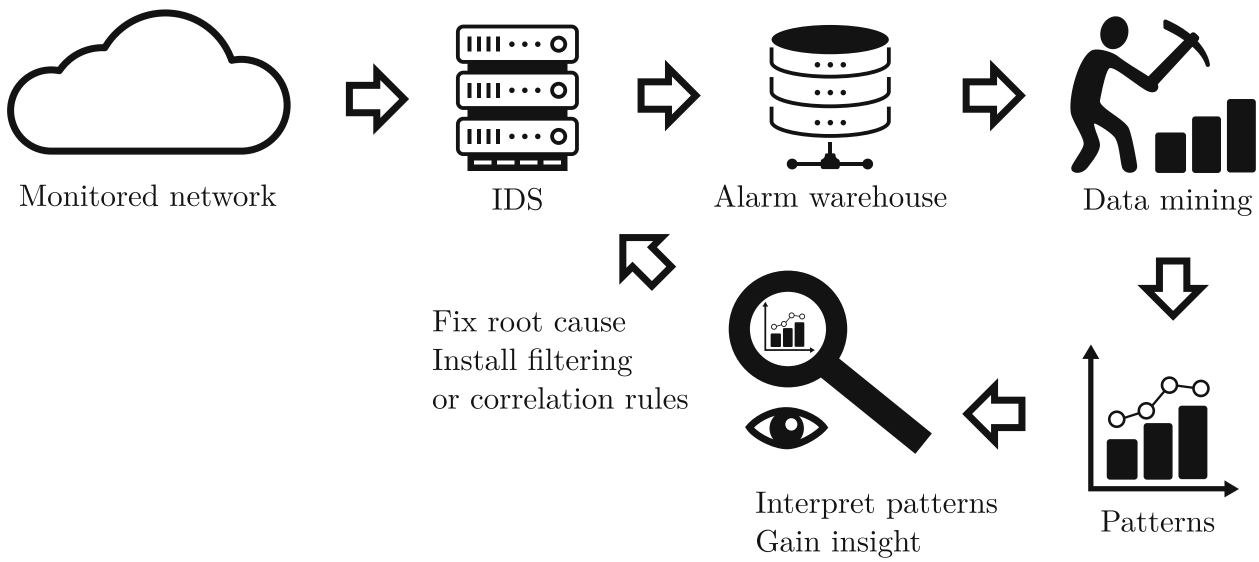

Fig. 15 A process for data-mining-supported security investigation [87]

6 Conclusions

In this work, we therefore propose a comprehensive framework for the study of complex attacks and related analysis strategies through statistical tools, on the one side, and machine learning tools, on the other side. It puts these complex attacks in perspective with their core applications in the security domain: detection and investigation. Although numerous works and review papers deal with individual issues of this framework [4–6], no comprehensive survey, which is a strong requirement for characterising novel threats and matching counter-measures, exist so far.

In this paper, we define a comprehensive framework for the study of complex attacks, related analysis strategies, and their core applications in the security domain: detection and investigation. This framework eases in particular the characterisation of novel complex threats and matching Artificial Intelligence-based counter-measures. We first define the core terms necessary to understand the domain: *anomaly*, *intrusion*, *attack*, *traces*, *threats*, and *vulnerabilities* and the security properties *confidentiality*, *integrity*, and *availability*, as well as the phases of the security analysis process: *detection* and *investigation*. *Zero-day attacks* and *multi-step attacks* are introduced and defined. The two main approaches of artificial intelligence for security analysis are reviewed: statistical analysis and machine learning techniques. Their applications in intrusion detection and security investigation are presented.

The advent of artificial intelligence (AI) thus opens up a promising field of investigation for cybersecurity [91], which already includes significant operational breakthroughs like the Darktrace behaviour analysis system[3] or COSE cognitive security solution[4]. Darktrace is a commercial solution based on recursive Bayesian networks to model the actual behaviours of systems, users and devices and to track abnormal deviations. COSE, now part of CISCO, exploits machine learning and game theory [92] with the objective of tracking advanced persistence threats and polymorphic malwares. Both provide

```
EVENT UserLogin
{
PLACES
Init {
TYPE INITIAL
}

LoggedIn {
TYPE EXIT
FEATURES
STRING username
}

TRANSITIONS
Init(+) LoggedIn {
TYPE NT_AUDIT_EVENT_4624
CONDITIONS
(True)
MAPPINGS
[LoggedIn].username=AccountName
ACTIONS
warnln("User "+AccountName+" successfully logged in")
}
}
```

Fig. 16 Example of an EDL signature called *UserLogin* for a simple login to a Windows system [88] significant examples of technology transfer from universities, in Cambridge (UK) and in Prague (Czech Republic), respectively, to successful industrial applications.

The diverse technologies contributing to the artificial intelligence field provide numerous approaches to support both online detection and offline investigation of security anomalies. Their rapid development is providing suitable solutions for tracking targeted zero-day and multi-step intrusions in an ever growing amount of traces generated by network devices, servers and application services.

Endnotes

[1] https://en.oxforddictionaries.com/definition/trace

[2] http://www.gsi2017.org/

[3] https://www.darktrace.com/

[4] https://www.cisco.com/c/dam/global/cs_cz/assets/ciscoconnect/2013/pdf/7_keynote_cose_michal_pechoucek.pdf

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Authors' contributions
PP coordinated the writing of the paper, wrote the major parts (Introduction, parts 2 and 5, Conclusions), and provided significant modifications to parts 3 and 4. JN is working on his Ph.D. in artificial intelligence for cybersecurity and contributed to part 4 and the bibliography. He contributed significant improvements to every other section. FG is working on his Ph.D. in statistical anomaly detection and contributed to part 3. He contributed significant improvements to every other section. AD is the Ph.D. director of Julio Navarro. She proof-read and added significant improvements to the paper. PC is the Ph.D. director of Fabio Guigou. He proof-read and added significant improvements to the paper. All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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