Is the future Web more insecure? Distractions and solutions of new-old security issues and measures

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ABSTRACT
The world of information and communication technology is experiencing changes that, regardless of some skepticism, are bringing to life the concept of "utility computing". The nostalgics observed a parallel between the emerging paradigm of cloud computing and the traditional time-sharing era, depicting clouds as the modern reincarnation of mainframes available on a pay-per-use basis, and equipped with virtual, elastic, disks-as-a-service that replace the old physical disks with quotas. This comparison is fascinating, but more importantly, in our opinion, it prepares the ground for constructive critiques regarding the security of such a computing paradigm and, especially, one of its key components: web services. In this paper we discuss our position about the current countermeasures (e.g., intrusion detection systems, anti-malware), developed to mitigate well-known web security threats. By reasoning on said affinities, we focus on the simple case study of anomaly-based approaches, which are employed in many modern protection tools, not just in intrusion detectors. We illustrate our position by the means of a simple running example and show that attacks against injection vulnerabilities, a widespread menace that is easily recognizable with ordinary anomaly-based checks, can be difficult to detect if web services are protected as they were regular web applications. Along this line, we concentrate on a few, critical hypotheses that demand particular attention. Although in this emerging landscape only a minority of threats qualify as *novel*, they could be difficult to recognize with the current countermeasures and thus can expose web services to new attacks. We conclude by proposing simple modifications to the current countermeasures to cope with the aforesaid security issues.

Categories and Subject Descriptors
C.2 [**Computer-Communication Networks**]: Distributed Systems—*Client/server, Distributed applications, Network operating systems*; C.2 [**Computer-Communication Networks**]: General—*Security and protection*

General Terms
Security. Web Services. Cloud Computing.

1. INTRODUCTION
The emerging concept of cloud computing is both widespread and puzzling [44]. Indeed, it has been talked, blogged, written and discussed about as an unprecedented paradigmatic change in the information and communication technology world. As it often happens, this also brought forth confusion in new terms and buzzwords such as *"public cloud"*, *"private cloud"*, *"*-as-a-service"*, etc. As noted in [8], the lack of a widely-accepted definition may indeed distract users and experts. In [1], the authors have begun to shed some light on this new concept. According to their definitions, cloud computing enables organizations to run web applications (often referred to as services) on a pay-as-you-go basis on top of reliable, highly-available, scalable software and hardware infrastructures referred to as *clouds*. This is also, in general, the widespread perception shared by users and developers. In some sense, clouds can be seen as modern, large mainframes [30] with virtually infinite resources, and the term cloud *computing* refers to the use of such resources to deliver web services.

Cloud security and web service security are also, unsurprisingly, ill-defined and vague fields. Community-driven initiatives [3] and organizations such as the Cloud Security Alliance [32] are pursuing the common objective of gathering knowledge and joining efforts to devise security measures appropriate for cloud computing. The rapid growth of Cloud Security Alliance [19] is, somehow, signaling that the community is concerned about cloud security. The current Web certainly poses new security challenges, although it may be very difficult to distinguish between issues *specifically* caused by emerging computing paradigms, and issues that, by coincidence, occur on a system deployed on a cloud or that leverages cutting-edge web services and hosted stacks [8]. On one hand, the community of users is worried about the fragility of the future Web [6, 31, 5, 22, 39, 12, 38, 23] and concerns have arisen recently regarding the significant outages of the major cloud and web service providers. On the other hand, it is quite easy to observe that such security issues and outages are mainly caused, as usual, by programming errors. In other words, while clouds and services unquestionably offer sophisticated and flexible deployment platforms, they still run pieces of software, which can be just as insecure as any piece of software running on traditional environments. For instance, in 2008 Amazon's S3 experienced two outages due to an overload of the authentication service [40] and an error in a single bit [41]. Also, Google AppEngine suffered a "blackout" because of a programming error [47]. Clearly, such vulnerabilities have nothing to do with cloud computing itself.

In environments characterized by distraction and lack of solid understanding, it is clearly very difficult to reason about security threats[1]. In our opinion, it is however important to recall that the Web is not a safe place, with more than 97,500 *known* web application vulnerabilities disclosed in 2009 [20], and more than 350 million sensitive records involved in security breaches in the United States since 2005 [9]. Moreover, less than one year ago, the number of entries in the Google Safe Browsing Malware List has doubled between June 2008 and August 2009. The black hats are somehow "weaponizing" malware [7] and, in addition [42], provide full-fledged attacking infrastructures (e.g., botnets) available (to inexperienced users) on a pay-per-use basis. One may argue that such threats are, unavoidably, part of the Internet and, in some way, they have contributed to the natural evolution of the Internet itself and therefore, they are also unavoidably part of the cloud computing realm.

Nevertheless, as discussed in Section 2, we deem it important to critically re-examine the known security issues in the light of the changes induced by the adoption of large-scale, highly-distributed, web-service-based applications. Motivated by this need for rethinking some aspects of security, in this paper we analyze the aforesaid changes by leveraging the parallel between the new and the old computing approaches. The consequences of such changes are the key point of our position, and are illustrated by means of a running example that considers automatic protection techniques for web applications. We chose this case primarily because web applications are widespread and their defense is a major concern. In addition, this example is simple to analyze, it explains the essence of several modern detection approaches and, as summarized in Section 3, it is the core of many security tools other than web application protection tools. We remark, however, that anomaly detection is just a case study chosen to merely illustrate our point and does not, in any way, represent a complete solution to security issues that appear in modern applications deeply based on web and in-the-cloud services.

Although throughout our discussion we borrow examples and concepts from real-world applications that revolve around cloud computing (e.g., Amazon EC2), our position focuses on cloud computing and service orientation as a paradigmatic shift (discussed in Section 4), and the extent to which it affects known security issues and countermeasures. Other aspects related web services and cloud computing, such as new business models, economics, or mobility, are far from the scope of this paper and thus are not considered, as they do not impact directly the security concerns (while they are, of course, the fundamental reason for the adoption of cloud computing).

2. SECURITY CHALLENGES

In this section we briefly review the major challenges brought forth by cloud computing and service orientation. In particular, we focus on security-related challenges, referring the interested reader to [1] for a more comprehensive vision of the new obstacles induced by cloud computing. We divide security-related challenges into two groups. On one hand, there are challenges that are already evident to web users (e.g., web service providers, developers), hence need practical solutions (Section 2.1). On the other hand, there are challenges that will significantly influence the security of the Web in the long run. As motivated in Section 2.2, this second group of challenges is relevant, yet less obvious.

2.1 Challenges with immediate impact

The challenges described in this section are already visibly impacting users and providers. In particular, given the amount of data shared across these infrastructures, data confidentiality, trust relationships and shared reputation are concerning issues.

2.1.1 Data confidentiality

The obvious and, in general, effective measure to protect data confidentiality is encryption. However, encryption is not always a feasible solution, especially for data-intensive applications that require high I/O throughput (note that, in [1], the relatively low speed of the Internet has been already identified as a concerning obstacle). Although homomorphic encryption [18] can be exploited for limiting decryptions and re-encryptions when data needs to be transformed, in its current stage this solution requires significant efforts to be adopted in high-speed, real-world deployments. In addition, encryption is not straightforward when data is distributed. Also, this solution may have a low acceptance rate and, more importantly, raises the issue of data property. As most of the users refrain from encrypting their laptop hard-drive because of the technical and computational overhead, in a similar vein, would users bother encrypting their virtual, remote storage? Moreover, if a remote storage is transparently encrypted (i.e., by the provider), whom the data belongs to? The user, the provider? And, is this fact provable? How?

2.1.2 Sharing shared resources

The security issues typical of shared hosting environments are magnified in the case of highly distributed, in-the-cloud systems that host modern web services. The additional, *unperceived*, complexity due to dynamic resource slicing, allocation, replication and optimization, gives indeed each user the illusion of being unique. In reality, each user (e.g., an actual system user or an application) operates in a *shared* environment with "porous" boundaries. Therefore, users may behave maliciously, or compromise virtualization software, affecting other users and their reputation. A recent incident [24] that affected the reputation of a whole, shared Amazon EC2 cloud is discussed in [8] as a noteworthy example of this specific issue.

Observation 1 To what extent users sharing the same cloud or the same service are isolated? Is it feasible to employ simple fail-over mechanisms to transparently "move" a misbehaving user or process onto another cloud or service instance; and would this offer an adequate degree of protection?

In reality, a cloud instance is nothing more than an advanced and very well managed virtual machine hypervisor (and a

[1]We refer to the most general definition of *security threat* as any opportunity (for a malicious entity) to compromise confidentiality, integrity or availability of a system. In this context, the term *system* may refer to different objects, such as a bare-metal computer, a virtual or physical network, an application, a service, a file-system, or a database.

web service is basically a sophisticated and well managed web application instance). Thus, the feasibility of compromising other slices of a cloud or other accounts of a service depends a good deal on the security of the service management platforms. As a representative example, vulnerabilities in VMware have grown 35 times between 1999 and 2007 [27]. This, unfortunately, is not comforting. In our opinion, the efforts to secure cloud instances should focus on two complementary directions. On one hand, hypervisor-based detection mechanisms such as the one proposed in [16] could be effectively adapted to cloud systems to recognize misbehaving slices. On the other hand, once identified, malicious slices could be dynamically re-allocated in a honeypot-like environments, not only to contain their activity but also to collect data and analyze their actions in order to design specific countermeasures.

2.2 Challenges with delayed impact

Debugging and auditing in large-scale, distributed systems unavoidably affect the foundations of secure software development. Although their impact may be delayed, and no incidents can be attributed directly to them as of now, we believe that these obstacles will influence significantly the security of the software developed for, or deployed onto, modern computing infrastructures.

2.2.1 Debugging in large distributed systems

Programmers know how to pinpoint and solve software flaws using debuggers, which allow to precisely track the execution of even complex, multi-threaded processes and inspect the memory content. This routine task turns out to be a challenging research problem in the case of distributed applications [11, 17, 37]. Besides the intrinsic difficulties that programmers have to face, i.e., understanding what is "the memory", or the "process state", debugging tools devised for large-scale distributed systems are quite obtrusive (e.g., they require code annotation). In general, the existing tools are designed for critical systems and suitable for C-like languages, rather than web-oriented frameworks. In addition, bugs are difficult to reproduce in local, smaller configurations because testing and development environments might differ significantly from deployment conditions.

A less obvious complication that affects debugging is the "invasion" of web development frameworks. Rapid development frameworks are indeed very popular[2] and can speed up significantly the work of a programmer, because they hide many low-level details, exposing powerful abstract primitives. In some notable cases, such frameworks *are* the hosted service, thus are tightly coupled with the (cloud) service provider, e.g., Google AppEngine. Because debugging modern applications is an inherently difficult task, software flaws may become more prevalent. And, since such flaws are the main cause of security vulnerabilities, these aspects are likely to result in new venues for intrusions, and thus need to be considered thoroughly.

Observation 2 A natural question regarding debugging may arise. What is the actual "programming language" moderns web application are written in? Is it the high-level, abstract (cloud) framework or the language the framework is built upon?

A flaw may hide deep down in this programming stack and, thus, affect *more* than one deployment (just like bugs in shared libraries in older systems were an enormous security issues in the mid-nineties). Cases like Google AppEngine are particularly interesting as the programming stack is actually the service. Thus, on one hand, such centralized infrastructure is, in principle, easier to secure or fix. On the other hand, however, the share of affected users may be large if the provider becomes popular. In our opinion, the debugging obstacles are those that require most efforts as they are inherently very difficult to solve. Instead, designing the current and future programming stacks with security in mind would require less efforts yet offering delayed benefits.

2.2.2 Auditability

When disasters occur, reconstructing a "picture" of the system's status is vital. From a purely forensic point of view, monitoring and keeping track of a system's activity is as important as debugging. Unfortunately, this might in turn be very difficult in large-scale, service-based systems, since data and processes are distributed rather than contained within well-defined boundaries. Even simple tasks such as collecting logs are naturally more challenging when applications are distributed and provided by different sources (e.g., mash-ups). In case of successful exploitation, a likely event in immature systems, the risk is that the compromised applications might leave insufficient or unreachable tamper evidence. For instance, is it always feasible to access the logs of all those hosted web services leveraged by an application that *we* developed? Despite the level of abstraction and the transparency offered by modern services, developers should be aware that software is *not* running on bare-metal hardware under their full control.

3. AVAILABLE COUNTERMEASURES

Given the threat scenario briefly summarized in Section 1 and the obstacles mentioned in Section 2 (in particular, those described in Section 2.2), it is useful to discuss the potential consequences of combining a growing underground economy, armed with fast-spreading automated attacks, with the inherent fragility of a new, sophisticated and somehow exciting infrastructure. To do so, we need to look at current security countermeasures: but of course, this is by no means a complete or exhaustive survey; it is limited to those concepts that are needed to explain our position.

Until now, research on security of web services and service oriented architectures (which are one of the key components of cloud computing) has focused on designing secure protocols for exchanging messages that meet the confidentiality, integrity and availability requirements [2, 14, 4, 34]. Other approaches concentrated on secure patterns for modeling and developing services, mostly from a software engineering perspective [35, 21]. The goals of such measures are, basically, to prevent programmers — who are not necessarily security experts — from writing vulnerable code, rather than protecting services directly.

[2]According to the most comprehensive ranking we were able to find, there are 98 web application development frameworks (as of April 2010) `http://hotframeworks.com/rankings`

Protection for existing systems often revolves around the use of detection and prevention mechanisms, which nowadays are quite sophisticated. In general, they are rooted onto two complementary approaches that have been part of intrusion detection from its first inception [15]: recognizing known patterns of malicious signs (misuse detection), *versus* recognizing deviations from known normal activity (anomaly detection). For instance, the *Intrusion Detection System* (IDS) described in [25] models the normal characteristics of benign interactions between clients and the server-side applications at the HTTP layer. This system can effectively detect, for instance, code-injection attacks, which are visible into HTTP parameters. A similar system, described in [10], further develops client-side protection measures and, in addition, can detect attacks against the database tier by profiling benign queries to recognize suspicious ones. These systems are said to be application-aware, because the knowledge they leverage is specific to the application layer protocol (e.g., HTTP).

To explain our position, we make use of the following example. We remark that this example is used throughout the paper merely as a simple case study and do not necessarily contain solutions to the modern and future security issues.

Running Example Let us assume that an HTTP-aware, anomaly-based IDS employs two simple models that capture, respectively, the length and the alphabet of the string parameters submitted through HTTP requests, which have the following structure:

```
POST /authenticate HTTP/1.1
Host: www.example.com
Content-Type: text/xml
Content-Length: ...

&name=administrator
```

In this case, the /authenticate handler accepts the name parameter via POST. If we exclude the data encoded in the header, the payload of the HTTP request is &name=administrator.

Let us suppose that the protected web application is designed to accept a limited set of values for the name parameter, i.e., administrator (length 13, alphabet [a-z]), logs (length 4, alphabet [a-z]), or activities (length 10, alphabet [a-z]). After having examined a sufficient amount of benign requests, the IDS learns that the normal length is, for example, 9, the variance is 21, and the alphabet is [a-z] (i.e., lowercase letters).

Let us now assume that the procedure invoked by the /authenticate handler is vulnerable to code injections, because the name parameter is not sanitized. Thus, an attacker may attempt to deploy a malware kit by submitting name=<script src=//j.mp/xss> (length 23, alphabet [.<>/=a-z]). The simple models used in this example (yet employed in advanced prototypes such as [25, 10]) are able to recognize the injection because [.<>/=a-z] $\not\subseteq$ [a-z]. Note that, in the case of particularly short injection vectors, the length model cannot recognize the attack. To alleviate this type of problems, modern systems actually adopt multiple models as well as probabilistic approaches, to assess the degree of anomaly in a more sound manner. However, the goal of this example is to show the essential concepts of anomaly detection to recognize evidence of malicious activity. In the following, the same example will be used to discuss the reliability of current, state-of-the art protection tools in the upcoming Web.

The aforesaid techniques have inspired many other protection tools other than network-based or protocol-based IDSs. For instance, they are suitable to protect operating systems. Notably, a very effective technique to detect misbehaving processes consists in modeling the data passed to system calls and extracting some representative characteristics of the *Control Flow Graph* (CFG). The tools described in [33, 28] adopt this approach to detect, for example, whenever a program is forced to invoke an out-of-sequence system call, or a system call with unexpected, i.e., too long, string parameters likely to be evidence of attacks. In simple words, these techniques encode a process' behavior in terms of some features, which are then leveraged to assess the goodness of the system call sequences observed at runtime.

4. SIGNS OF A PARADIGMATIC SHIFT

Even if cloud computing and the massive service orientation appear as exhilarating revolutions in the information technology world, they are ongoing changes, and thus it is crucial to precisely evaluate their impact on security. Indeed, as noticed in Section 1, and thoroughly detailed in [8], the majority of current threats actually exploit vulnerabilities of the software, rather than of the cloud computing paradigm itself. Thus, at a first glance, one may think of protecting applications using traditional countermeasures (e.g., IDSs, anti-malware). On the other hand, applying available countermeasures as they are, under the assumption that applications running in cloud computing environments are *just* regular applications, reveals pitfalls in some cases.

To stimulate constructive reasoning about security in the new scenario, we recall some analogies between the centralized approach of mainframes and the apparently centralized (but actually distributed) approach of cloud computing. There is an obvious difference in *scale* between the two eras: what was a single, powerful mainframe connected to dumb clients through a local, high-speed, switched network, has become a cluster of consolidated, managed machines (either virtual or physical) connected to clients through public, broadband, best-effort routed networks. Despite these differences, applications taking advantage of the cloud computing paradigm have striking similarities with the old-fashioned centralized software.

The case of web services is a particularly expressive example, as they are, to some extent, the unit of execution in software delivered as a service, much in the same way as the primitive functions of traditional operating systems. In fact, functions take arguments (e.g., numeric values, file descriptors, strings) and, when invoked by a process, perform a certain operation then, optionally, return a result. Similarly, services are invoked by clients in an RPC fashion and react according to the input given (e.g., SOAP or JSON data). A careful examination reveals that a web service is just *incidentally* a web application (i.e., merely from a technical point of view), since it relies on web-oriented technologies, but on a global scale it actually reminisces more of a procedure call.

If one ignores this observation, protection mechanisms like HTTP-aware IDSs would appear a natural solution to protect web services. Unfortunately, these IDSs are aimed at blocking attacks directed toward classic web applications. But as we noticed, it is common practice to compose services together to provide richer functionalities. From a global viewpoint, these mash-ups of different services are likely to offer subtler exploitation opportunities. For instance, single services may be invoked in a benign manner, such that an IDS deployed to protect the underlying web application (which supports the service) would not recognize any anomalous activity. However, said services could be invoked in such a way to create a malicious action that is visible only globally. In some sense, this is the dual of mimicry attacks [45], a stealthy evasion technique in which a process is violated by scrupulously altering the data passed to one or more single system calls, while the characteristics of the CFG are preserved, in order to bypass CFG-based checks. In the type of attacks that we envision against web services, the idea of mimicry attacks is reversed, that is, the "global CFG" (where functions nodes are replaced by services) is altered, while each elementary service receives benign data (e.g., regular HTTP requests with no injections). This observation is further discussed in Section 4.2. In addition, in Section 4.1 we show a case where current approaches exhibit shortcomings in detecting code injections even against a single web services.

In the remainder of this section, we detail the aforesaid cases by means of examples, to stimulate other questions and critiques.

4.1 The HTTP is the TCP

The practice of using application protocols, mainly HTTP, to encapsulate a wide spectrum of data types (e.g., binary files, streams of videos, chunks of data with well-defined semantics such as RDF) is becoming very popular. In some sense, HTTP is playing the role of a transport layer, that is, encapsulating a payload and sending it. Complex (even proprietary) protocols offer transparent communication layers between services over HTTP. A simple example is the WebDAV protocol (adopted, for instance, by the popular Google Calendar web service), which relies on HTTP to interface calendar clients and servers (actually, services). As we all know, HTTP sits on top of a real transport layer; but since TCP is so transparent, reliable and highly-available, to some extent it can be considered as a network (or even physical) layer. In our opinion, the spreading of web services and cloud computing modifies the way the Internet networking stack is used by software, as shown in Figure 1.

4.1.1 *What's new about security?*

From a security perspective, with this observation we suggest that, in the need of designing a network monitoring system, a further layer of inspection is desirable to effectively detect those threats that leverage the actual communication protocol employed by a service. In fact, since the networking stack is evolving, the protection mechanisms (especially those that inspect the application layer) should step up as well, as exemplified in the following.

Running Example In Section 3, we described how a protocol-aware IDS analyzes HTTP messages and checks for their validity with respect to normal usage of the protected web application. Let us assume that a SOAP-based authentication system (also vulnerable to injections) is employed instead of the old-fashioned, pure-HTTP web application. The requests have the following template:

```
POST /authenticate HTTP/1.1
Host: www.example.com
Content-Type: text/xml
Content-Length: ...

<SOAP-ENV:Envelope
  xmlns:SOAP-ENV="http://schemas.xmlsoap.org/soap/envelope/"
  xmlns:SOAP-ENC="http://schemas.xmlsoap.org/soap/encoding/"
  xmlns:xsd="http://www.w3.org/2001/XMLSchema"
  xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" ... >

  <SOAP-ENV:Header>
    <h:BasicAuth xmlns:h="http://soap-authentication.org/basic
          /2001/10/"
       SOAP-ENV:mustUnderstand="1">
      <Name>administrator</Name>
      <Password>broccoli</Password>
    </h:BasicAuth>
  </SOAP-ENV:Header>
  ...
</SOAP-ENV:Envelope>
```

In this example, the payload of the HTTP request is the whole SOAP envelope, which is just a sequence of characters. Suppose, however, that the IDS has a fallback procedure that, in absence of GET or POST parameters, extracts the alphabet (`[.:="/<>a-zA-Z0-9]`) and the length's mean and variance[3] of the request body.

Let us complicate this example a little bit and assume that the IDS also employs a more sophisticated technique to extract the *syntax* of the body and encode it as a probabilistic grammar or a Markov model (a technique commonly used to detect attack vectors that alter the syntax of a string [33]). After training on some samples, such models can calculate the likelihood of a string with respect to the grammar learned. So, for example, given the sequence of symbols into an HTTP request body, it could tell XML, JSON or plain text apart, because they contain different symbols and also their syntax is dissimilar. Note that, however, this is far from having a syntax-agnostic parser capable of extracting the real parameters (i.e., `name`, `password`) that influence the behavior of the service. Thus, analyzing the entire SOAP block with the aforesaid approach is insufficient to distinguish between messages that contain "`administrator`" *vs.* "<script src=//j.mp/xss>", because, intuitively, these values are well "buried" by the extra content. Also, the vector's alphabet, `[.<>/=a-z]`, is perfectly compatible with `[.:="/<>a-zA-Z0-9]` as it contain no extra characters. For similar reasons, the length model is of little help, since injection vectors can be notably (almost arbitrarily) short.

Obviously, more accurate models may be devised to deal specifically with the simple case illustrated in this example; however, it is just as obvious that such an approach would be difficult to generalize. In fact, such models would require a language-specific parser to extract relevant content from the messages processed by the (custom) application. In addition, the structure of these messages must be known in advance, case by case, because it is impossible to automatically derive the actual variables (while this is doable for HTTP parameters).

As observed in this example, the ongoing change in the networking stack suggests that protocol-aware protection system should account for the actual protocol used by the services *on top* of HTTP. Otherwise, new threats that exploit the upper-layer protocols (e.g., legitimate SOAP content that hides malicious parameters) are difficult, or completely impossible, to detect. To make once again a comparison, anomaly detectors that inspect the payload of IP packets to recognize attacks [26, 29, 46, 48] are inaccurate at detecting most of those vectors that are malicious only by means of the application layer's semantic (e.g., a POST parameter with anomalous content). From the viewpoint of a lower-layer protocol, code injection can be "confused" with payload that encodes regular strings.

Observation 3 To what extent the attacks against the future application (i.e., service) layer are recognizable at the future transport layer (e.g., HTTP)? Is it just a matter to perfecting existing tools to allow deeper examination, or the technical obstacles hide more issues?

4.1.2 Viable mitigation strategies

The obvious workaround to this issue is to opt for a host-based solution, by moving the inspection into the web application that supports the web service. In this way, the extraction of the real input parameters is demanded to the (custom) protocol parser, thus bringing us back to the key-value semantic of HTTP. However, all of the advantages of network-based solutions, which, in some cases, are the only viable deployment, would be lost. Indeed, a host-based protection tool would be simply too obtrusive and require a significant amount of deployment efforts, not to mention the need of modifying the application to be protected.

In our opinion, a first step toward better application-layer packet analyzers is to modify the parameter extraction phase to make it somehow independent from the encapsulated protocol (e.g., JSON into HTTP). To this end, text processing

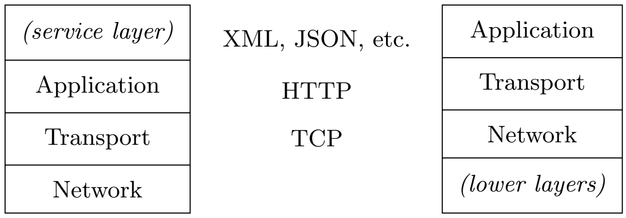


Figure 1: As described in Section 4.1, the change in the networking stack is noticeable from the traditional application layer (left) that, in the case of HTTP, is playing the role of a transport protocol (right) to encapsulate upper layer protocols (e.g., SOAP, JSON, XML), typical of modern web services.

algorithms [13] capable of inferring the syntax by observing a few samples could be leveraged to remove the recurring elements in lower-layer messages (e.g., key-value semantic of HTTP), so to obtain the varying, interesting data on which learning and detection can be performed. Along this line, a custom template-extraction mechanism [36] has been recently proposed to automatically construct spam e-mail templates by observing messages collected by a spamming botnet. These approaches could potentially extract relevant data from HTTP messages, regardless of the syntax of the data they encapsulate.

4.2 The services are the functions

In the previous section we discussed the changes in the networking aspect of computing caused by service orientation and cloud computing. Similarly, in this section we discuss how the cloud computing paradigm is impacting the way applications are constructed and executed.

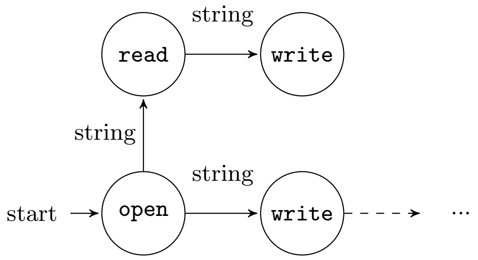
In a local system, processes originate whenever a certain program (e.g., a calendar application, an e-mail client) is executed. Basically, these programs are built upon a set of primitive functions, exposed by a certain programming language[4]. Cloud computing extends that model to a larger scale. Indeed, the development of applications is increasingly drifting toward the reuse of services (which have well-defined APIs, as classic functions do!), as opposed to the simple reuse of code.

In a traditional operating system, processes can be modeled by means of their CFG. A simple example is shown, using a simplified graphical notation, in Figure 2: (a) the `read` system call receives a string value, `open` is invoked to open a file which content is passed to `read`, and finally wrote to the standard output. Assuming that the process has a race condition vulnerability, for instance, an attacker may leverage such flaw to cause an unexpected transition in the CFG (b). In a similar vein, "distributed processes" of modern, distributed operating systems[5] rely on several

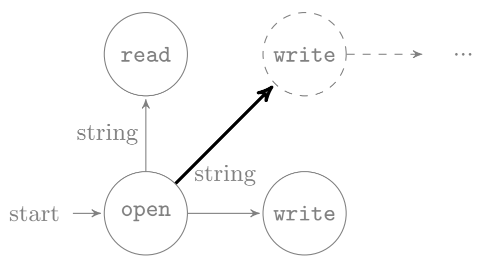
[3]Mean and variance could be calculated assuming that valid values for the `name` are exactly the same as in the previous run of the example, and assuming that the SOAP messages have a recurring structure, which is perfectly realistic. The variance is indeed identical.

[4]Note that, although higher level functions and concepts such as libraries, objects, or classes are available to the programmer, from the operating system's perspective, running programs is all about invoking function in a certain sequence and passing data across functions.

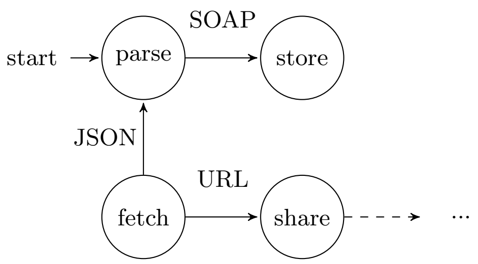
[5]Note that operating systems delivered as mash-ups of web services actually exist in the real world. Notable exam-



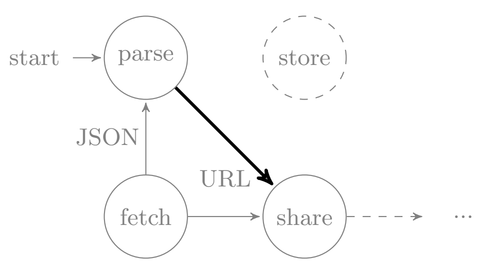
(a) A local process.



(b) An altered local process.



(c) A "distributed process".



(d) An altered "distributed process".

Figure 2: Example of snippets of processes in a traditional operating system (a), modeled by means of the system calls they invoke. Data is passed across functions via parameters. In a similar vein, "distributed processes" (c) of modern applications rely on several services (e.g., parse, build, share) to perform certain tasks and to achieve a global goal. In this example, we imagine an application that parses data submitted by a user through a form, serializes it onto a remote storage and shares a link to it on a social network. In both the cases, malicious behaviors can be exemplified as deviations from the expected work-flow. On local processes, violations (b) of the CFG can be detected with simple checks. As discussed in Section 4.2, it is however more difficult to think of a similar approach to recognize (d) when a "global CFG" is altered.

services (e.g., parse, build, share) to perform certain tasks and to achieve a global goal. In the example drawn in Figure 2 (c), a service parses data submitted by a user through a form (e.g., `http://www.formspring.com/`, `http://www.formsite.com/`), serializes it onto a remote storage (e.g., `http://aws.amazon.com/s3/`, `http://drop.io`) and shares (e.g., `http://www.wuala.com/`) a link to it on a social network. Similarly to the case of local process exploitation, an attacker may leverage logic vulnerabilities to cause, for instance, a malicious redirection in such "distributed process" (d).

4.2.1 *What's new about security?*

From a security perspective, in both cases, malicious behaviors can be exemplified as deviations from the expected sequence. On local processes, violations of the CFG can be detected with simple checks. It is, however, more difficult to envision a similar approach to recognize violations of a "global CFG". Since services are logically very similar to functions, we believe that the same techniques used to recognize bad-behaving processes may inspire new approaches to mitigate stealthy attacks against service mash-ups.

Observation 4 In the light of the aforesaid points, would we need to revamp our knowledge on protecting local operating systems and scale it for the next generation, global operating systems?

ples are `http://www.silveos.com/`, `http://cloudo.com/`, `http://eyeos.org/`, `http://ghost.cc/`

4.2.2 *Viable mitigation strategies*

Besides the inherent difficulty of dealing with complex, distributed processes, an aspect that deserve attention is the existence of languages (and also standards) used by designers and developers to strictly specify the inputs, the outputs, the semantic and even the composition of web services and mash-ups. Notable examples are WS-BPEL and RESTful. To the best of our knowledge, nothing similar exists for formally specifying the control-flow or the data-flow of a local operating system processes. In our opinion, detection approaches rooted on such languages could benefit from an accurate description of the services and thus can be very effective at detecting deviations from the expected "orchestration". One major disadvantage of this direction is that, at the time of writing, many services and mash-ups do not fully leverage such languages to expose their architecture or semantic.

To some extent, the task of detecting distributed attacks to the service layer has some similarities with event correlation mechanisms [43] originated from the need of detecting related alerts across several IDSs. However, these tools have provided no ultimate solutions to detect large-scale, slow attacks, which is indeed a very difficult problem. Interestingly, this type of attacks resemble the aforesaid global mis-behaving processes. One may ask whether correlation techniques may attract research efforts than in the past to finally mitigate a longstanding issue.

5. CONCLUSIONS

In this paper, we have discussed some key points that, in our opinion, motivate a constructive reconsideration of the current security measures.

The simple observation that paradigmatic changes (e.g., from thin client connected to a mainframe, to powerful workstations, to, once again, thin clients connected to a cloud) induce parallel changes in the security world, suggests a broad approach to the "novel" security issues. In the approach that we envision, the stack offered by the cloud computing paradigm needs to be mapped to the well-known hardware and software stack. In principle, this would help at mapping also the patterns of the traditional security issues onto the new stack. Examples of the insights that we believe this will make possible are outlined in Sections 4.1 and 4.2. Obviously, this mapping will not, by itself, lead to a complete description of the new threats. Rather, it will point out key areas to develop and refine, in a much similar way to what the periodic table did for the discovery of unknown chemical elements. Similarly, for some areas, this approach will indicate that many issues can be solved through an appropriate "porting" of the traditional security countermeasures to the cloud computing paradigm.

Even if exploring new business models opened up by cloud computing falls entirely outside of the scope of this paper, it is undeniable that the fast-growing underground economy has already embraced the cloud model (in fact, botnets are an embryonic distributed malicious infrastructure [7]). The fact that business-to-business interactions will also embrace this paradigm makes the problem even more evident and alarming, leading to a number of potential frauds on pay-per-use services.

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