

# Analyzing and Defending Against Web-Based Malware

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Web-based malware is a growing threat to today's Internet security. Attacks of this type are prevalent and lead to serious security consequences. Millions of malicious URLs are used as distribution channels to propagate malware all over the Web. After being infected, victim systems fall in the control of attackers, who can utilize them for various cyber crimes such as stealing credentials, spamming, and distributed denial-of-service attacks. Moreover, it has been observed that traditional security technologies such as firewalls and intrusion detection systems have only limited capability to mitigate this new problem.

In this article, we survey the state-of-the-art research regarding the analysis of—and defense against—Web-based malware attacks. First, we study the attack model, the root cause, and the vulnerabilities that enable these attacks. Second, we analyze the status quo of the Web-based malware problem. Third, three categories of defense mechanisms are discussed in detail: (1) building honeypots with virtual machines or signature-based detection system to discover existing threats; (2) using code analysis and testing techniques to identify the vulnerabilities of Web applications; and (3) constructing reputation-based blacklists or smart sandbox systems to protect end-users from attacks. We show that these three categories of approaches form an extensive solution space to the Web-based malware problem. Finally, we compare the surveyed approaches and discuss possible future research directions.

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## 1. INTRODUCTION

The Web has become the core of our daily computing experience. Web applications and services have been developed and deployed with unprecedented speed, providing various important functionalities to the end-user such as office applications, social networking, content sharing, education, and entertainment. From 2005 to 2008, the number of indexable Web pages has grown from a few billion to a trillion [Gulli and Signorini 2005; Google Web Index 2008]. In 2010, the population of Internet users was about two billion [Internet Stats 2010]. Moreover, these numbers are rapidly increasing.

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Given its popularity and ubiquity, the Web also attracts the attention of malicious entities. Indeed, the Web and its global user community have observed various forms of attack in the past [Rubin and Geer 1998; Garfinkel and Spafford 2001]. Among these attacks, using the Web as a channel to distribute malware (i.e., malicious software) has become a prominent issue. This issue has generated a great deal of attention from both the security research community and the general public. Web-based malware is disseminated when victim users visit malicious Web sites. This malware is designed to conduct various cyber crimes, such as gaining control of the victim system, stealing private information, launching denial-of-service attacks and spamming. According to the latest report from Dasient, a Web security solutions vendor, the number of Web sites that deliver malware has doubled in one year, between 2009 and 2010 [Dasient Report 2010].

The arms race between attackers and defenders has led to the adoption of increasingly sophisticated malware distribution tactics. The traditional malware distribution model is *push based*—attackers actively search for and infect the victim systems. However, security technologies such as firewalls have been widely deployed in enterprise networks, which provide good defense against techniques that were commonly used for push-based propagation. As a result, the malware distribution has evolved to a *pull-based* model, where victims unknowingly visit malicious Web sites. Under the pull-based model (i.e., Web-based malware distribution), the channel for attack is initiated and established by potential victims, which significantly lowers the defense barrier for attackers to cross.

Defending against Web-based malware is a difficult task. First of all, as the Web browser becomes the battlefield, the defense boundary is very long—not only billions of active personal computers, but also portable devices with Web browsing functionality can become the target of the attack [Schmidt et al. 2009; Fleizach et al. 2007]. Second, typical Web users may not have enough knowledge and expertise to protect themselves, making them potentially the weakest link in the entire defense chain. Third, since the Web is a huge distributed system, there is no single trust authority, making the defense strategy inherently collaborative. A global defense is infeasible in practice given that certain parts of the Web have been known to be miscreant friendly [RBN Study 2007]. Finally, the bar for conducting effective Web attacks is rather low; key techniques and vulnerabilities of victim devices are well-documented [Daniel et al. 2008]. Automatic tools for facilitating the attacks are also easily obtainable [Binsalleeh et al. 2010; Ormerod et al. 2010].

Recent trends in Web application development further complicate the problem. The current generation of Web applications (i.e., Web 2.0) concentrates on presenting user-generated content. Although the openness of these applications provides useful functionalities to the end-user, at the same time, it opens holes for attacks [Lawton 2007]. Moreover, a popular Web programming paradigm known as the *mashup* has been adopted to quickly develop new applications by reusing existing content [Sabbouh et al. 2007]. However, this trust of external data and code is blind and creates new vulnerabilities [Tipton 2009; Magazinius et al. 2010]. For instance, a huge number of existing Web sites depend on the income from advertisements, which are provided by third-party ad syndications. It has been observed that many legitimate Web sites are involved in delivering malware due to unsafe advertisements [Provos et al. 2008].

### 1.1. Outline

Considering all of the challenges discussed before, it is clear that understanding the Web-based malware problem and developing effective solutions are urgent tasks for the security of the Internet. Indeed, great effort has been made by security researchers, who are attempting to shed light on this issue. This work analyzes many different aspects

<b>2. Background</b>	<b>5. Identification of Application Vulnerability</b>
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of the problem and provides insights for designing systematic defense strategies. In this article, we present a survey of the literature, which is organized into four main topics.

- (1) *The Status Quo of Web-Based Malware.* Section 3 presents an analysis of the current status of Web-based malware problems that are measured by Internet-scale monitoring; this analysis illustrates the scope of this issue.
- (2) *Attack Detection.* Section 4 surveys the approaches that detect existing Web-based malware attacks. These approaches help researchers have a better understanding of the problem in order to design effective countermeasures.
- (3) *Vulnerability Identification.* Section 5 surveys code analysis techniques that are designed to minimize the number of vulnerabilities that exist in Web applications. These vulnerabilities are often used by attackers to turn legitimate Web sites into a part of the malware distribution infrastructure.
- (4) *Attack Protection.* Section 6 surveys the defense techniques that protect victim systems from being infected. These approaches are effective for mitigating the impact of existing attacks.

Representative approaches surveyed in this article are shown in Table II. Section 7 presents a detailed discussion of the surveyed work regarding its ideal deployment scale, comparative effectiveness, degree of autonomy, adaptiveness, and gamesmanship. In Section 8, we conclude the article with possible future research directions. Before delving into the technical details, the background and the attack model of Web-based malware are presented and analyzed in Section 2. A table of contents of the article is shown in Figure 1.

## 2. BACKGROUND

In this section, we first formulate the attack model of Web-based malware. Then, we discuss the root causes and vulnerabilities that enable Web-based malware attacks. Approaches proposed in the literature to address the problem from various aspects are highlighted. Finally, related survey studies are presented and briefly discussed.

### 2.1. Terminology

To understand Web-based malware, it is important to carefully define the terms that we use throughout this article. *Malware*, which is short for “malicious software”, is

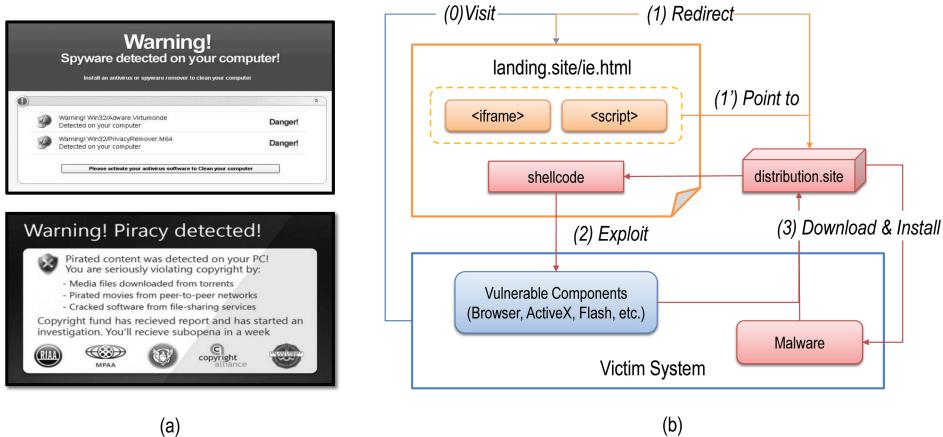


Fig. 2. (a) Screenshots of social engineering tactics; (b) drive-by download attack scenario.

software designed to access the resources of a computer system without the owner's informed consent [Christodorescu et al. 2007]. Malware includes computer viruses, worms, spyware, and other malicious and unwanted software. A *Web-based malware attack* is defined as the process of malware downloading and installing on a victim computer system through visiting infected landing Web sites. In this article, we use the terms “Web-based malware attack”, “Web-based malware”, and “attack” interchangeably. Similar to the definition in Provos et al. [2008], the term *landing Web site* or *landing site* is defined as the Web site that initiates Web-based malware attacks, when victim users visit it. On the other hand, Web sites that host malicious shellcode or malware used in the attack are termed *malware distribution sites* or *distribution sites*. Detailed discussion on the relationship between landing sites and distribution sites is presented in Section 3.2.

According to IETF RFC 2828, a *vulnerability* of a computer system is defined as 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 [RFC-2828 2000]. A *zero-day vulnerability* is defined as a vulnerability without an effective patch. *Shellcode* (also known as an *exploit*) is a small piece of computer software that takes advantage of a vulnerability to cause unintended behavior of a computer system, which is commonly used to distribute malware.

## 2.2. Attack Model

There are two types of techniques used by attackers to perform Web-based malware attacks, namely: (1) *social engineering*, that is, using psychological manipulations and decoys to trick the victims into authorizing the downloading and installation of malware; and (2) *drive-by download*, that is, designing a Web page that contains malicious code to trigger the downloading and installation of malware automatically.

The social engineering technique often involves using alluring descriptions and enticing a victim to make decisions that compromise his computer security. Screenshots of real social engineering attacks are illustrated in Figure 2(a). Social engineering tricks are designed to exploit the cognitive biases of the human decision-making process rather than exploiting the vulnerabilities of the victim computer systems. For example, the malicious Web page can alert the victims with fake virus detection messages and ask them to download rogue antivirus software [Cova et al. 2010b], or display fake

award notifications for victims to collect by clicking URLs linked to malware [Sidiropoulos et al. 2005].

On the other hand, the drive-by download attack may form a larger threat to victims given its automated nature. Therefore, it also requires more careful study to understand the attack mechanism. In general, the drive-by download malware attack involves three major steps as shown in Figure 2(b).

- (1) *Fetch and Prepare Malicious Shellcode.* In this step, shellcode used for exploiting a victim system is fetched from the distribution site through a visit to the landing site. This is usually achieved in two ways: (1) by placing script or iframe tags on the landing site with src attributes pointing to the distribution site or (2) by redirecting the browser window through various mechanisms (e.g., HTTP 302 temporary redirect or JavaScript APIs). The malicious code being fetched is often highly obfuscated to complicate investigation and to escape signature-based security scanners [Feinstein and Peck 2007]. In order to increase the probability of a successful attack, the malicious code often checks the environment of the victim system, such as the browser type, available plugins, or version information. This enables the attacker to find all available vulnerabilities to exploit. As observed in Wang et al. [2006], attackers often target multiple vulnerabilities during one attack in order to increase their chance of success.
- (2) *Exploit Vulnerability.* The shellcode that attackers want to execute is injected by exploiting browser vulnerabilities. Various techniques (e.g., heap overflow [Daniel et al. 2008; Ratanaworabhan et al. 2009]) can be used to hijack the execution flow of the browser or its components (e.g., ActiveX control, Flash player, PDF helper object). Most of the techniques are based on the idea of conducting clever memory allocations through the manipulation of a number of JavaScript strings [Sotirov 2007; Sotirov and Dowd 2008]. Regardless of the technique used by the attackers, the shellcode is designed to initiate the download and installation of binaries on the victim system to achieve a larger attack goal.
- (3) *Download and Install Malware.* The last step of the attack is to download malicious binaries from a remote malware distribution site and install them on the victim system. A plethora of malware types have been observed in past attack instances, including viruses, backdoors, Trojan downloaders, and spyware [Wang et al. 2006]. Typically, victim machines will become parts of a botnet and used as resources to perform other types of cyber crime, such as Distributed Denial-of-Service attacks (DDoS), or spamming [Polychronakis et al. 2008].

### 2.3. Root Causes and Vulnerabilities

As we discussed before, there are three necessary conditions for a successful Web-based malware attack, as illustrated in Figure 3: (1) the presence of vulnerable Web browsers or end-users who are gullible to social engineering tricks, (2) effective exploits or URLs pointing to malware present on landing sites, and (3) the access of landing Web sites. The first condition regarding software vulnerability and human decision-making weakness has been studied extensively in computer security research. The third condition is the *pull-based* malware propagation model, which is straightforward. In this section, we primarily focus on studying the second necessary condition. The following question can be reasonably raised: How are exploits or malware URLs placed on a landing site?

One possible answer is that all the landing sites are operated by the attackers themselves. Then it would be trivial for attackers to place the necessary exploits or URLs. However, a recent study has shown that it is not the case for most of the real-world attacks, since a large portion of the landing sites are in fact legitimate sites being

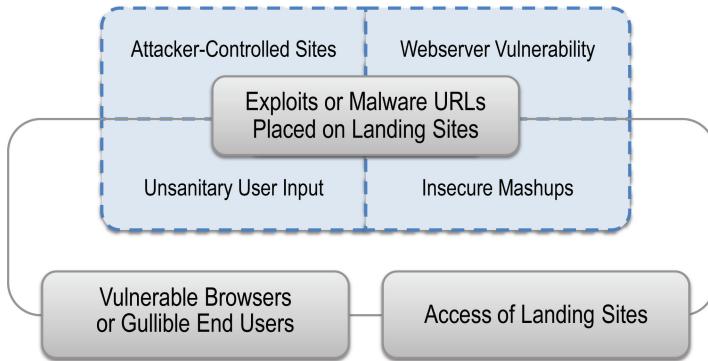


Fig. 3. Necessary conditions of Web-based malware attack.

infected [Provost et al. 2008]. Here, we identify and discuss three main causes that lead to infections.

- (1) *Web Server Vulnerability*. If an attacker is able to gain control of a Web server, he can modify the Web content hosted on the server for his own benefit. A sophisticated Web server usually has a large set of software installed, and the Web server is only as secure as its weakest component. Operating systems and application software used by Web servers are often found to contain vulnerabilities. This makes attacks on Web servers feasible and dangerous. For example, BIND vulnerabilities [1998] would allow attackers to gain root privileges on a Web server system. This type of attack is particularly damaging to large virtual hosting farms. As observed in Provost et al. [2007], it can turn the whole Web hosting infrastructure into a large malware distribution center.
- (2) *Unsanitary User Input*. Many Web applications allow users to contribute content [Lin 2007]. Apart from being an important functionality to normal users, it may also open doors for attackers to place malicious content. Without a careful sanity check, content provided by attackers might be presented directly to other users of the same Web application (e.g., cross-site scripting attacks), or be used by the Web application itself in security-critical operations (e.g., SQL injection attacks). Such security vulnerabilities lie in the code of Web applications. A typical Web application often has code executing at either the server side (e.g., ASP.NET, JSP, PHP) or the client side (e.g., JavaScript, Flash). Efforts have been made to check vulnerabilities of the server-side code, and thousands of such vulnerabilities are reported every year [Bau et al. 2010]. However, as demonstrated in a recent study, insecure client-side coding practices are also prevalent [Yue and Wang 2009]; these practices favor the attackers.
- (3) *Insecure Mashup*. In Web development, a mashup is a hybrid Web application that combines content from two or more sources to create new services [Crites et al. 2008]. Concrete examples of mashup often include using advertisements from third-party ad syndication, widgets, and code libraries. As a popular Web development paradigm, mashup implies trust on external code or data. However, as the external content is usually delivered to a user's browser directly from the external source, mashup builders have very limited control over it. Indeed, the current practice of Web mashup has been problematic, and it has become a major channel to infect legitimate sites for conducting Web-based malware attacks [Provost et al. 2008; Cova et al. 2010a].

Table I. Strengths and Weaknesses of General Defense Approaches

Approach	Strength	Weakness
Updated Browser	High availability; built-in upgrade support; effective for known vulnerabilities.	Ineffective for zero-day vulnerabilities; significant lag and risk.
Anti-Virus Software	Well maintained malware definition databases are available; low false positives for known binaries.	High false negatives for newly observed binaries; system performance may be slower due to scanning overhead.
Sandbox	Adaptive to different attacks by setting proper security policies.	Learning curve to properly configure the corresponding policies is considerable.

## 2.4. Existing Defense Approaches

With the root causes of the Web-based malware problem in mind, in this section, an overview of existing defense approaches is presented with brief discussions on how these approaches operate by addressing one or more of the root causes.

**2.4.1. General Defense Approaches.** A Web-based malware attack is not greatly different from a traditional push-based malware attack, except for its distribution channel and propagation model. Therefore, general defense mechanisms (see Table I) against traditional malware can be adopted to mitigate the problem.

- (1) *Using the Most Updated Browser and Plugins.* This approach attempts to eliminate the first necessary condition (see Section 2.3) by minimizing the number of vulnerabilities that can be exploited by an attacker. Specifically, this approach works by shortening the lag between the time of patch release and the time of patch installation by the end-user. Most popular Web browsers and their plugin components have built-in upgrade mechanisms to facilitate this process. However, as demonstrated in Wang et al. [2006], many landing sites actively use zero-day exploits to attack victim systems, and sophisticated attackers keep discovering new exploits to improve their probability of success. It sometimes takes a significant amount of time for the software vendors to release patches for newly discovered vulnerabilities. Therefore, using the most updated software is not enough to defend against Web-based malware attack.
- (2) *Using Antivirus Software.* Since the main objective of the attack is to download and install malware on the victim machine, antivirus tools can be used to detect and remove the binaries that are covertly fetched. If the antivirus engine can correctly identify all types of malware, this approach can form a powerful defense. Unfortunately, the state-of-the-art antivirus techniques still depend on certain forms of signature matching and need to update the malware definition continuously to be effective. Arguably, the malware definitions can never be complete, as malware keeps evolving over time. Indeed, Provos et al. [2008] have shown that even the best antivirus engine on the market (armed with the latest definitions) can only achieve an average detection rate of 70%. Therefore, this approach alone is not sufficient either.
- (3) *Using Sandbox for Untrusted Software.* A *sandbox* is a well-studied security mechanism for running untrusted programs. Typically, the sandbox provides an environment with limited resources for untrusted programs to run in. Well-known examples of sandboxing include virtual machines, capability systems, and the rule-based

Table II. Taxonomy of Surveyed Work

Approach		Other Work
Detect Attack Vector Presence on the Web (DA) (See Section 4)	VM-based	Wang et al. 2006; Moshchuk et al. 2006; Provos et al. 2007; Provos et al. 2008; Polychronakis et al. 2008;
	Signature-based	Roesch 1999; Toth and Kruegel 2002; Akritidis et al. 2005; Polychronakis et al. 2007; Nazario 2009; Ratanaworabhan et al. 2009; Curtsinger et al. 2010; Song et al. 2010; Cova et al. 2010a
Identify the Vulnerabilities of Web Applications (IV) (See Section 5)	Server-side	Huang et al. 2004; Jovanovic et al. 2006a; Xie and Aiken 2006; Wassermann and Su 2007; Lam et al. 2008; Balzarotti et al. 2008; Bau et al. 2010; Baldazzi et al. 2011
	Client-side	Chugh et al. 2009; Guarnieri and Livshits 2009; Saxena et al. 2010a (FLAX); Saxena et al. 2010b (Kudzu); Chang et al. 2011
Protect Victims from Attacks (PA) (See Section 6)	Blacklist	Ma et al. 2009; Antonakakis et al. 2010
	Sandbox	Cox et al. 2006; Jain et al. 2008; Grier et al. 2008; Reis and Gribble 2009; Lu et al. 2010; Li et al. 2011

execution framework. The main drawback of the sandbox mechanism is the difficulty of its policy configurations, that is, which programs should be executed inside the sandbox, and what privileges should be given to the untrusted software. However, common computer users often lack the expertise to set such security policies properly. For instance, malware delivered by social engineering tricks may entice a user to make incorrect decisions that compromise his own computer security.

**2.4.2. Specific Defense Approaches.** Realizing the insufficiency of the general defense mechanisms, many approaches have been proposed that focus on addressing the special characteristics of the Web-based malware problem. Such approaches can be classified into three categories, and we survey representative approaches for each category as shown in Table II. Table III describes the necessary conditions (see Section 2.3) that these approaches attempt to break, and the corresponding deployment location.

- (1) *Detect Attack Vector Presence on the Web (DA).* Approaches in this category attempt to detect existing attacks to facilitate further study of the problem. By detecting existing attack vector presence, researchers can discover new exploitation techniques and zero-day vulnerabilities used by attackers. Two types of approaches are surveyed in this regard: (1) building a high interaction honeypot using a Virtual Machine (VM), and (2) building signature-based attack detection systems.
- (2) *Identify the Vulnerabilities of Web Applications (IV).* Approaches in this category address the second necessary condition by conducting effective code analyses to discover Web application vulnerabilities. As a result, the chance of legitimate Web sites becoming malicious landing sites decreases significantly. Two types of approaches are surveyed in this article: (1) using code analysis or testing to identify server-side component vulnerabilities, and (2) using static analysis or hybrid techniques to discover client-side code vulnerabilities.

Table III. Comprehensiveness of Surveyed Work

Approach		Target Necessary Condition	Deployment
DA	VM-based	Condition 3: victim visiting the landing sites to be infected.	Third party
	Signature-based		
IV	Server-side	Condition 2: effective exploits or URLs linked to malware being placed on the landing sites.	Web Server
	Client-side		
PA	Blacklist	Condition 3: victim visiting the landing sites to be infected.	Client System
	Sandbox	Condition 1: vulnerable web browsers or components being used by the victim.	

- (3) *Protect Victims from Attacks (PA)*. Approaches in this category attempt to mitigate the impact of existing attacks. This is achieved by countering the third necessary condition. Two approaches<sup>1</sup> are surveyed in this article: (1) designing smart sandbox mechanisms that nullify the functionality of the malware downloaded; and (2) calculating the reputation of malware landing sites to construct dynamic blacklists, which can then be used by end-users to avoid visiting dangerous sites.

These three categories cover the cutting-edge research regarding the Web-based malware problem. Together, these approaches form an extensive solution space by addressing all the necessary conditions of Web-based malware attacks. Before delving into the details of these approaches, we present the status quo of Web-based malware based on Internet-scale monitoring, which illustrates the severity of the issue and provides useful insight into the problem.

## 2.5. Related Work

To our best knowledge, this article is the first comprehensive survey focusing on Web-based malware analysis and defense. A summary comparison of this article and related work is illustrated in Figure 4. Christodorescu et al. [2007], Vinod et al. [2009], and Idika and Mathur [2010] focus on understanding the state-of-the-art of malware detection techniques in general. These studies compare three major classes of malware detection (i.e., behavior based, signature based, and specification based) and malware code obfuscation techniques. Further, Jacob et al. [2008] and You and Yim [2010] present a more detailed survey on behavior-based malware detection and malware code obfuscation techniques, respectively. Siddiqui et al. [2008] and Shabtai et al. [2009] survey the adoption of machine-learning approaches to detect malware using file features. All these studies advance the understanding of building accurate and robust malware detection tools, which are considered general defense mechanisms against Web-based malware as discussed in Section 2.4.1. Qing and Wen [2005] and Li et al. [2008] studied the traditional push-based malware propagation model used by Internet worms and the research efforts on the detection and containment of such cyber attacks. Combining our work and the useful insights provided by these studies, one can form a better view of how the malware propagation model evolved over time.

Considering the Web-based malware attack as a generic threat to system security, studies such as Lunt [1993], Mukherjee et al. [1994], Bai and Kobayashi [2003],

<sup>1</sup>The attack detection techniques can also be extended to act as protection mechanisms by dissuading the end-users from visiting the sites with known malware presence. Discussion is presented in Section 6.

		Related Work	
This Paper		Jacob et al. 2008; Christodorescu et al. 2007; P. et al. 2009; Ilika and Mathur 2010	Qing and Siddiqui et al. 2008; Shabtai et al. 2009; You and Yim 2010
Scope	Web-based Malware	✓	Lunt 1993; Mukherjee et al. 1994; Bai and Kobayashi 2003; Murali and Rao 2005; Sadeghi and Ghorbani 2006; Martinis et al. 2008; Sabahi and Movaghar 2008; Hosseinpour et al. 2010
	General Malware	✓	Peng et al. 2007; Zhu et al. 2008; Li et al. 2009; Bailey et al. 2009; Feily et al. 2009; Zeidanloo et al. 2010
	Internet Worm	✓	
	System Intrusion	✓	
	Botnet	✓	
	Push-based	✓	
Propagation Model	Pull-based	✓	
	Attack Detection	✓	✓
	Vulnerability Identification	✓	✓
	Attack Protection	✓	✓
	Post-Attack Recovery		✓

Fig. 4. Summary comparison of related work.

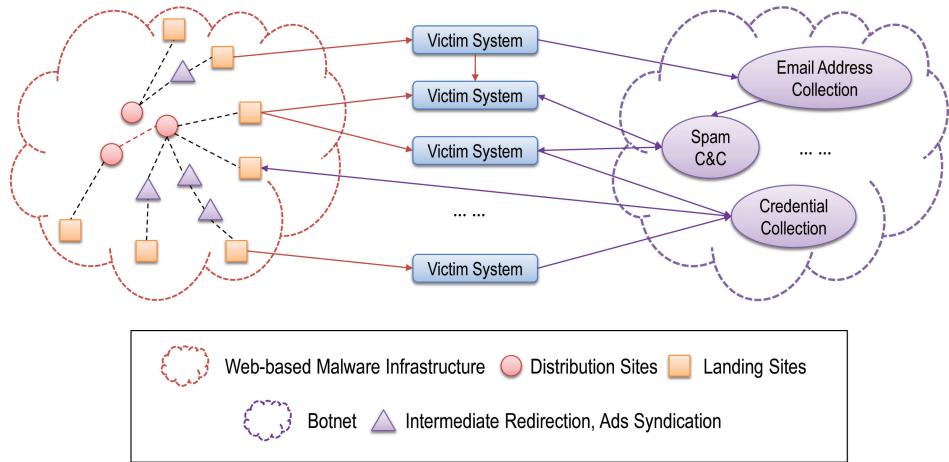


Fig. 5. Example of Web-based malware infrastructure.

Murali and Rao [2005], Sadoddin and Ghorbani [2006], Marhusin et al. [2008], Sabahi and Movaghar [2008], and Hosseinpour et al. [2010] shed light on the understanding of generic system intrusion issues and the countermeasures. Focusing on the botnet threats and detection techniques, studies Peng et al. [2007], Zhu et al. [2008], Li et al. [2009], Bailey et al. [2009], Feily et al. [2009], and Zeidanloo et al. [2010] extend our discussion on the postmalware infection consequences in Section 3.3. These two categories of studies complement our work and offer different viewpoints for cogitating the entire network security ecosystem.

### 3. THE STATUS QUO OF WEB-BASED MALWARE

From Jan. 2007 to Oct. 2007, 66 million URLs were examined in depth to discover existing Web-based malware attacks [Provos et al. 2007, 2008; Polychronakis et al. 2008]. This Internet-scale measurement built a representative corpus to study the current status of the Web-based malware problem. An illustration of the studied Web-based malware infrastructure is shown in Figure 5. Techniques adopted by this study to detect Web-based malware are very similar to the approach proposed in Wang et al. [2006] (see Section 4.1). Here, we first present the observations made in this study.

#### 3.1. Attack Prevalence

*—Drive-by download attacks are prevalent, and are becoming increasingly common.* During the study phase, over 3 million URLs were found pointing to Web pages that conducted effective drive-by download attacks. These malicious URLs correspond to 180,000 landing sites, and 9,000 malware distribution sites.

*—The risk of users being exposed to an attack is significant.* The malicious URLs are uniformly distributed over different Web site functional categories (e.g., news, sports, arts). Moreover, 1.3% of search queries to Google returned at least one malicious URL, and this number increased linearly by 0.1% every month. Further, 0.6% of the top million URLs that appear most frequently as Google's search results were malicious.

#### 3.2. Distribution Infrastructure Analysis

*—Weak security practices are prevalent on landing site Web servers.* A large fraction of the landing site servers were running outdated software with documented vulnerabilities. For example, 38.1% of Apache Web servers and 39.9% of servers with

PHP scripting support reported using an old version of software with known security vulnerabilities.

- Web advertisements are a significant channel to deliver attacks.* On average, 2% of the landing sites and 12% of landing pages were malicious due to unsafe advertisements. Ad-delivered attacks have three special characteristics: (1) malware delivered via ads have longer chains between landing sites and distribution sites due to multiple levels of ad syndication; (2) certain ad syndications have been observed to deliver malware directly (instead of being intermediate nodes); and (3) attacks appear in short-lived spikes—many landing sites are affected simultaneously by the same infected ad syndication. But once detected by the ad provider, the malicious content is removed very quickly.
- Strong locality has been observed.* In terms of geography, a handful of countries were hosting around 85% of all the landing and distribution sites. Moreover, the landing sites and the corresponding distribution sites are highly localized within the same geographic boundaries. In terms of network, a small IP range was found to host up to 210 distribution sites. Moreover, 70% of all the malicious sites have IP addresses belonging to 58.\* - 61.\* and 209.\* - 221.\* network ranges. Further, 98% of these sites were hosted by only 210 Autonomous Systems (out of 40,000 active ASes).
- The topology of the malware distribution infrastructure has interesting properties.* The distribution-versus-landing site ratio is a long-tail distribution: a large percentage (around 45%) of the distribution sites had only one landing site; on the other end of the curve, some distribution sites had more than 21,000 associated landing sites. This distribution pattern can be explained by attackers making a trade-off between the ease of management and detection avoidance. Interestingly, 80% of the distribution sites share at least one landing site with each other.

### 3.3. Malware and Post Infection Analysis

- Web-based malware has great diversity and keeps evolving.* 3% of the distribution sites hosted more than 100 different binaries. Adware, Trojans, and computer worms are the top three malware types on the Web. Moreover, these malware binaries keep changing with a frequency ranging from once every few hours to once every several days. Some malicious URLs have been observed changing the corresponding binaries almost every hour. This dynamism could explain the insufficiency of the signature-based antivirus technique for detecting Web-based malware.
- Web-based malware seriously threatens a victim's system security.* A successful attack leads to on average 8 different malware binaries downloaded into the victim system. In 7% of the cases, victim machines had the new Browser Helper Object (BHO)<sup>2</sup> installed, 23.5% had the browser home page or the name server changed, 36.2% had the firewall and other security settings changed, and 51.3% had the system startup setting modified in order to have malware persist across reboots.
- Web-based malware provides a cornerstone for large-scale electronic crime.* After installation on the victim system, malware notifies attackers about the compromised system and the sensitive exfiltrated information. Many common Windows protocols (e.g., NETBIOS, SMB, DCOM, MSSQL) are also probed by malware to scan for the vulnerabilities of neighboring computers to propagate further. Moreover, various communication protocols (e.g., HTTP, IRC) are used by malware to join botnets for conducting other cyber crimes (e.g., denial-of-service, spamming).

---

<sup>2</sup>BHO is a type of plugin for Internet Explorer browser to provide extra functionality.

Table IV. Summary Comparison of Measurement Studies

Paper				
	Provost et al. 2008;	Wang et al. 2006	Moshchuk et al. 2006	Bailey et al. 2007
Study Scope	Web-based Malware	Web-based Malware	Web-based Spyware	Malware
Study Scale	Billions of URLs	17,000 URLs	18 million URLs	3698 pieces of binaries
Approach	VM-based Detection	VM-based Detection	VM-based Detection	Anti-virus Software

### 3.4. Related Measurement Studies

Prior to this Internet-scale measurement study, several relatively small-scale studies were conducted. A summary comparison of such studies is shown in Table IV. Wang et al. [2006] examined 17,000 URLs and found about two hundred of them to be malicious in nature. In this study, multiple zero-day vulnerabilities were also discovered and studied. In May 2005, 18 million URLs were crawled to study a specific type of malware—spyware—on the Web [Moshchuk et al. 2006]. Using a security scanner, 45,000 URLs were found to be linked to spyware. Further, the authors observed that different exploit mechanisms were used to target different browser platforms. It is important to note that the detection techniques used by these papers can suffer false negatives, which make their measurement result a conservative estimate of the real situation. Therefore, all these works emphasize the trend of Web-based malware attacks as a rising threat for the Internet.

Bailey et al. [2007] focus on achieving better understanding on the nature of malware spreading over the Internet, which is orthogonal to the studies discussed earlier. Motivated by the observations that host-based antivirus software provides inconsistent information about the underlying threats, the authors design a behavior-based classification technique to automatically categorize malware. By evaluating the proposed scheme over 3698 pieces of malware collected over 6 months, this behavior-based classification technique demonstrates better completeness and accuracy than existing approaches. This work can benefit the postinfection analysis of Web-based malware attacks.

## 4. WEB-BASED MALWARE DETECTION

As we saw in Section 3, to gain a better understanding of the Web-based malware problem, it is necessary to detect the instances of existing attacks. Given the huge number of Web pages on the Internet and their rapidly evolving nature, manual inspections are clearly insufficient. Therefore, techniques have been proposed in the literature to automate this process. Such approaches can be categorized into two types—virtual machine based and signature based—which are effective for detecting Web-based malware delivered through drive-by download attacks. A brief summary of surveyed work in this section is shown in Table V.

### 4.1. Virtual Machine-Based Detection

In Wang et al. [2006], the authors proposed an automatic detection system named HoneyMonkey, which follows a black-box approach and detects drive-by download

Table V. Summary of Web-Based Malware Detection Techniques

Category	Paper	Contribution Summary
VM-Based	Wang et al. 2006	Using VM to effectively detect web-based malware attacks and zero-day vulnerabilities.
	Moshchuk et al. 2006; Provos et al. 2008	Enabling efficient VM-based detection of web-based malware attacks over large-scale dataset.
Signature-Based	Cova et al. 2010a	Using an instrumented web browser to extract effective signatures to detect drive-by download attacks.
	Song et al. 2010	Extracting signature of browser communication behavior to detect drive-by download attacks.
	Curtsinger et al. 2010	Extracting syntax signature of malicious JavaScript to detect drive-by download attacks.
	Roesch 1999; Nazario 2009	Matching data-flow signature at network or application level to detect potential system intrusions.
	Toth and Kruegel 2002; Akritidis et al. 2005; Polychronakis et al. 2007; Ratanaworabhan et al. 2009	Using memory overflow signatures to detect buffer overflow attacks.

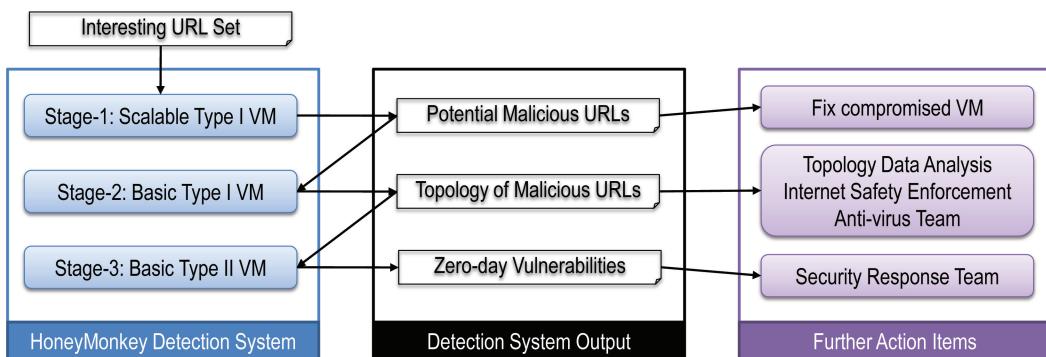


Fig. 6. HoneyMonkey system design.

attacks using Virtual Machines (VMs). The system is given the name HoneyMonkey for two reasons: (1) the system is a “honeypot”, which attracts attacks, and (2) a computer program (monkey) is designed to simulate the Web browsing activities of a human and to detect attacks.

The system design of HoneyMonkey is shown in Figure 6. Two types of VM are used in the HoneyMonkey system: Type I, namely unpatched virtual machines with known vulnerabilities; and Type II, that is, fully patched virtual machines that are only vulnerable to zero-day exploits. Both types are designed to run the Microsoft Windows

operating system. Before running HoneyMonkey for detection, a set of candidate URLs needs to be collected; these URLs are then used as the input of the HoneyMonkey system. HoneyMonkey works in three stages.

- (1) Stage-1 HoneyMonkey visits  $N$  number of URLs simultaneously by the monkey program in a Type-I VM instance. A timeout is set to properly load all the URLs in the VM. By closely monitoring a group of persistent-state changes in the VM (e.g., executable file creation, Windows registry modification, etc.), the program decides on whether further investigations are needed. That is, if no persistent-state change is found (i.e., the VM state is *clean*), then the system fetches the next  $N$  URLs from the candidate URL pool and restarts Stage 1. Otherwise, the HoneyMonkey system will switch to Stage 2.
- (2) Stage-2 HoneyMonkey pinpoints a subset of the  $N$  URLs that trigger the persistent-state changes. To achieve this, only one URL is loaded in a Type-I VM every time. By combining Stage 1 and 2, the system can reuse a clean VM instance for a rather large number of URLs without sacrificing accuracy. When a malicious URL that triggers persistent-state changes is discovered in Stage 2, it is further examined in Stage 3.
- (3) Stage-3 HoneyMonkey reloads the malicious URL in a Type-II VM to discover zero-day exploits.

Five pieces of information are recorded during the detection using various techniques [Wang et al. 2003; Beck et al. 2005; Joshi et al. 2005]: (1) file operations, (2) the process creation log, (3) the Windows registry modification log, (4) exploited vulnerabilities, and (5) browser redirection activities. Careful analyses of the recorded information are used to understand the attack techniques and the malware distribution infrastructure. Within the first month of system deployment, 752 malicious URLs and 1 zero-day exploit were discovered by HoneyMonkey, proving its effectiveness.

Moshchuk et al. [2006] and Provos et al. [2008] improved the basic VM-based detection system by adding a preprocessing phase. During the preprocessing, Web pages are checked using static code analysis techniques or various heuristics (e.g., whether the Web pages contain URLs linked to known attacking sites or heavily obfuscated JavaScript code) to filter out a large portion of benign Web pages and reduce the cost of launching VM instances. This improvement enables the efficient examination of candidate Web pages at large scale (i.e., from millions to billions), using VM-based detection systems.

## 4.2. Signature-Based Detection

Using VMs as high interaction honeypots has its own challenges. In particular, an attack can be detected only if the vulnerabilities that are being exploited by the attackers are present in the honeypot system. However, since there are so many different versions of Web browsers and hundreds of components (e.g., PDF plugins, Flash, and ActiveX controls) have been targeted to launch Web-based malware attacks, it would be very difficult to configure any one system as being the most “vulnerable” to detect all possible attacks. Otherwise, the false negative rate would be rather high, as observed in Seifert et al. [2009].

In Cova et al. [2010a], the authors proposed an alternative approach to build high interaction honeypots. Their approach is named JSAND, which combines the usage of an instrumented browser, a set of effective signature features, and machine-learning techniques to detect drive-by download attacks. The instrumented browser is designed to facilitate three tasks: (1) to simulate the personality of various browsers (e.g., Internet Explorer, Firefox, Chrome) to expand the available attack surface; (2) to simulate arbitrary system environments and configurations (for example, requests for loading

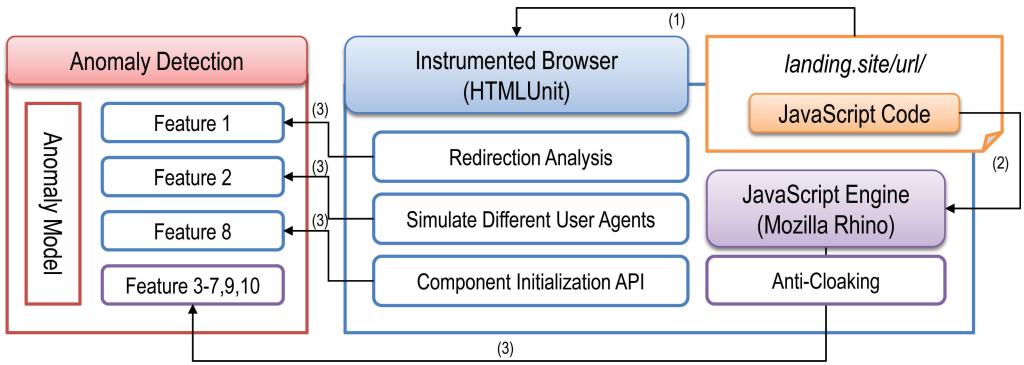


Fig. 7. JSAND system design.

ActiveX controls or plugins can be fully customized); and (3) to track all JavaScript function definitions and invocations for implementing anticloaking mechanisms [Moser et al. 2007; Wilhelm and Chiueh 2007]. The overall design of the JSAND system is illustrated in Figure 7. Ten signature features are identified and used in training the anomaly model of drive-by download attacks. The authors argue that these ten signature features are effective to distinguish between benign Web pages and malicious ones.

- Feature 1: the length and target of the redirection chain.* It has been observed that malicious landing sites often have unusually long redirection chains toward malware distribution sites.
- Feature 2: the browser personality and history-based differences.* As many attacks only target a specific platform (e.g., Internet Explorer 6 running on Windows XP), the landing Web sites might return different content accordingly.
- Features 3 to 5: the ratio of string definitions and string uses, the number of dynamic code executions, and the length of dynamically evaluated code.* These features are included to capture the characteristics of code obfuscation techniques, which are often used by malicious sites to avoid signature-based detection.
- Features 6 and 7: the number of bytes allocated through string operations, and the number of likely shellcode strings.* These features are included to capture the characteristics of common attack techniques, such as heap overflow.
- Feature 8: the number of instantiated components.* As we discussed in Section 2.2, attackers often attempt to exploit a number of vulnerabilities to maximize their success rate.
- Features 9 and 10: the values of attributes and parameters in method calls, and the sequence of method calls.* These features are included to encode the unique behavior of the vulnerability exploit phase.

All the signature features are fed into a machine-learning algorithm proposed in Kruegel and Vigna [2003] to train an anomaly model. Then, the model is used to detect attacks by assigning a score to the Web page of interest. The higher the score, the higher the probability of its being anomalous (i.e., triggering drive-by download attacks). Specifically, 150,000 URLs were examined by JSAND. It has been shown that by selecting a proper training set, JSAND can achieve both lower false positives and lower false negatives than other signature-based [Nazario 2009] and VM-based [Provos et al. 2008] approaches.

Complementing the 10 signature features proposed in JSAND, Song et al. [2010] identify anomaly communication signatures between different Web browser

## (1) Vulnerable PHP Code and XSS Attack Example

```
echo "Here is what you wrote: $_GET['input']"
http://example.com/?input=<script>alert();</script>
```

## (2) Vulnerable PHP Code and SQLI Attack Example

```
$sql = "SELECT * FROM product WHERE pid = '". $_GET['pid']."'"
http://example.com/?id=1';DROP TABLE product;#
```

Fig. 8. Simple vulnerable PHP script and attack examples.

components under drive-by download attack scenarios by modeling the common attack workflow (as discussed in Section 2.2). The authors demonstrated that such communication behavior could offer accurate and robust signatures for identifying real-world drive-by download attacks. Alternatively, Zozzle [Curtsinger et al. 2010] explores the possibility of using JavaScript code signatures to detect Web-based malware attacks. Zozzle uses a semiautomated machine-learning approach to extract a large set of code signatures from previously detected malicious JavaScript code. It then uses this signature database to do fast string matching with any new code observed. Zozzle can be implemented as a JavaScript engine extension, which detects malicious JavaScript code and the potential Web-based malware attacks on-the-fly. Other early signature-based work includes Snort IDS [Roesch 1999], which performs dataflow signature matching of attack patterns at network level, and PhoneyC [Nazario 2009], which performs similar techniques at application level.

It is worthwhile to note that Toth and Kruegel [2002], Akritidis et al. [2005], Polychronakis et al. [2007], and Ratanaworabhan et al. [2009] investigate signature-based approaches for detecting the stack or heap overflow techniques. Such memory overflow techniques are widely used by attackers to inject malicious shellcode for conducting drive-by download attacks. These studies use emulation approaches at either the network or application level to detect memory overflow signatures. Various heuristics are proposed in these studies to improve the detection accuracy and performance overhead.

## 5. IDENTIFICATION OF APPLICATION VULNERABILITY

As we discussed in Section 2.3, unvalidated user input is one of the principle causes that allows attackers to use legitimate Web sites used by the attackers to propagate malware. Indeed, the Top Ten Project [2011] of the Open Web Application Security Project (OWASP) has listed injection attacks as the number one threat to Web application security. One example of this injection attack is commonly known as the cross-site scripting (XSS) attack [Kirda et al. 2006; Jim et al. 2007; Wassermann and Su 2008]. In the case of XSS, the attackers leverage vulnerable functions of a Web application to send malicious JavaScript code as the output of the Web application to other users' browsers for execution. Another well-known problem is the SQL Injection (SQLI) attack [Halfond et al. 2006; Geneiatakis et al. 2006]. In the case of SQLI, the attackers supply carefully crafted input into vulnerable Web applications, which leads to modifications or leakage of important information (e.g., administrator credential) stored in the back-end database system. Figure 8 shows examples of vulnerable scripts and possible attacks.

The main functionalities of a Web application have long been implemented by its server-side components. Therefore, many of the previous research efforts have been devoted to finding server-side code vulnerabilities. We survey this research branch in Section 5.1. As the complexity of the client-side components keeps increasing, more

Table VI. Summary of Vulnerability Identification Techniques

Category	Paper	Contribution Summary
Vulnerability Identification of Server-side Code	Jovanovic et al. 2006a	Using static analysis of PHP code to identify XSS vulnerabilities.
	Huang et al. 2004; Xie and Aiken 2006; Wassermann and Su 2007; Lam et al. 2008	Improving existing static analysis techniques of the server-side code component by enhancing the analysis precision, scalability, or the policy specification process.
	Balzarotti et al. 2008	Combining the use of static and dynamic code analysis to improve the vulnerability identification capability.
	Bau et al. 2010; Balduzzi et al. 2011	Using black-box code testing techniques to identify server-side code vulnerabilities.
Vulnerability Identification of Client-side Code	Saxena et al. 2010b (FLAX); Saxena et al. 2010a (Kudzu)	Combining the use of tainting analysis and black-box fuzzing tests to identify client-side validation vulnerabilities.
	Chugh et al. 2009; Guarnieri and Livshits 2009; Chang et al. 2011	Using various static code analysis techniques to identify potential client-side code vulnerabilities.

recent attention has been given to study the potential flaws. This research branch is discussed in detail in Section 5.2. A brief summary of the surveyed work in this section is shown in Table VI.

### 5.1. Server-Side Code Vulnerability

A well-studied approach to discovering code vulnerabilities is tracking the information flow within Web applications [Sabelfeld and Myers 2003]. Three important terms are defined within this context: (1) *source*: untrusted data or operations; (2) *sink*: critical data or operations that are vulnerable and need to be protected; and (3) *policy*: the specification of security requirements, for example, the confidentiality or the integrity of data. Using data tainting and flow analysis techniques, the Web application code is analyzed to identify the information flow from sources to sinks, or vice versa. Depending on the policy, a flow from sources to sinks may violate the integrity requirement (e.g., XSS attacks). At the same time, a flow from sinks to sources may violate the confidentiality requirement (e.g., Web site cookies that are leaked to the attackers). Such violations are then caught and reported as vulnerabilities.

5.1.1. *Static Code Analysis*. In Jovanovic et al. [2006a], Pixy, the first open-source tool for statically detecting XSS vulnerabilities in PHP code, was developed.<sup>3</sup> An example of Pixy usage is illustrated in Figure 9. In Pixy, the sources include several types

<sup>3</sup>In this article, we choose PHP as the representative server-side scripting language due to its popularity in practice. However, the techniques being surveyed in this article can have much broader applicability.

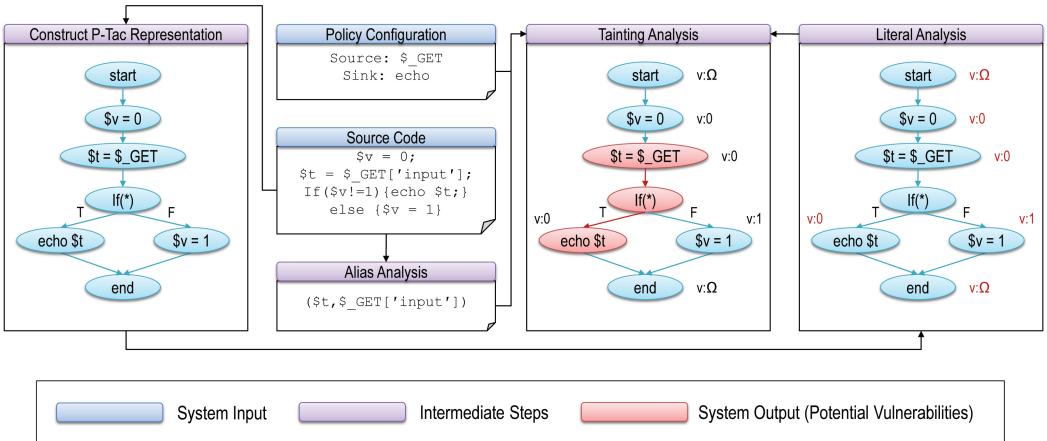


Fig. 9. Example of Pixy system usage.

of program entry points, such as GET, POST, and COOKIE arrays. All the routines that return data to the browser, such as echo, print, and printf are considered to be the sensitive sinks. The notion of a *sanitation routine* is defined as the functions that can destroy potentially malicious characters contained in the sources. Several built-in PHP functions, such as htmlentities and htmlspecialchars, are considered proper sanitation functions. The goal of Pixy is to identify the integrity vulnerabilities: any information flow from sources to sinks without sanitation is considered problematic.

Static dataflow analysis is used in Pixy to achieve the design goal. The Pixy system takes PHP source-code files as its input. First, parse trees are constructed by parsing the PHP input files. These parse trees are then transformed into an intermediate representation that is called *P-Tac*. The P-Tac representation is a form of the three-address code [Aho et al. 1986] enhanced with the control-flow graph for every invoked function. The last and the most important step is to conduct a flow analysis over the intermediate P-Tac representation. This analysis identifies all of the sensitive sinks that can be reached by source dataflows as potential vulnerabilities.

Several important features are implemented in Pixy to achieve better analysis accuracy. First, it performs an alias analysis to correctly propagate the taint value to both the variables and all of their aliases. This alias analysis technique is proposed in Jovanovic et al. [2006b] for reference-based scripting language. Second, a literal analysis is used to collect information about the literal values that variables or constants may hold at every program point. The literal information is then used by the flow analysis to evaluate branch conditions and to ignore program paths that cannot be executed at runtime. Third, all the built-in PHP functions except for the sanitation routines are thought to preserve dataflow by default. The same is true for user-defined functions, unless a specification of the true behavior is provided. This design choice is made to minimize the false negatives. False positives can often be solved by manual inspections; however, there is no effective way to handle false negatives. The authors used Pixy to scan six real-world PHP Web applications and reported about 50 vulnerabilities. The authors also found that Pixy suffered both false positives and false negatives that were caused by certain dynamic properties of the PHP language, which the static analysis is incapable of handling.

Similar to Pixy, Huang et al. [2004], Xie and Aiken [2006], Wassermann and Su [2007], and Lam et al. [2008] focus on the static information-flow analysis to detect the vulnerabilities of Web applications. The differences among these studies varies,

depending upon the analysis capabilities or target language. Besides identifying the vulnerabilities, Huang et al. [2004] also insert runtime guard code to ease the vulnerability patching process. In Xie and Aiken [2006], the authors improve the capabilities of static code analysis to handle many dynamic features of the PHP language. Meanwhile, Wassermann and Su [2007] propose a technique to automate the policy specification process and the scalability of existing code analysis systems. A declarative policy specification language is proposed in Lam et al. [2008], and the authors demonstrate several examples to show that the proposed policy language is expressive enough for encoding succinct descriptions of many real-world vulnerabilities.

**5.1.2. Combining Static and Dynamic Analysis.** False negatives could occur due to the assumption that if a sanitation function was applied on the information-flow path from source to sink, then this path is safe. However, this assumption does not always hold. For example, Su and Wassermann [2006] discussed the possibility of subtle SQL injection vulnerabilities that can be exploited even when the input is processed by a built-in PHP sanitation routine. This issue is more problematic when custom checking routines are used. The correctness of these custom checking cannot be guaranteed due to the lack of systematic testing.

To address this problem, Balzarotti et al. [2008] extended Pixy with dynamic code analysis capabilities to design a new tool called Saner. The capabilities of Pixy are preserved to identify all the information flow from source to sink. By overapproximation of the values that each string variable can hold for every point in the program, Saner then checks whether these values contain any element that may pose a security risk. A dynamic analysis is then performed by executing the code with a large set of different inputs that includes many ways of encoding and hiding malicious characters. By doing this testing, Saner attempts to confirm the existence of vulnerabilities by finding program input that can bypass the sanitation routines and reach the sinks.

The dynamic testing phase of Saner is conducted in two steps. First, Saner constructs a sanitization graph for each source and sink pair provided by the static analysis. In the second step, a number of attack strings are used to confirm the potential vulnerabilities. If the testing process confirms that there is no effective sanitation between a source and a sink, it triggers an alert and provides the problematic program path along with sample attack strings. This information can then be leveraged by the developers to fix the vulnerability. The authors showed that Saner can identify many previously unknown vulnerabilities in real-world Web applications.

**5.1.3. Black-Box Code Testing.** Another type of approach, black-box code testing, is also widely used in practice to find software bugs. Instead of analyzing the program source code, black-box testing feeds known malicious input into Web applications as test cases to identify potential vulnerabilities. In Bau et al. [2010], eight automated black-box testing tools from leading vendors are compared. The comparison shows that these tools are effective in identifying well-studied vulnerabilities, but they are insufficient for discovering more complex and subtle flaws.

Focusing on the URL parameter as the sensitive source, Baldazzi et al. [2011] propose PAPAS—the first system that automatically discovers URL parameter pollution vulnerabilities of Web applications. The PAPAS system adopts a black-box testing approach to inject URL parameter test cases into target Web applications and uses a set of heuristics to determine potential vulnerabilities. By using the proposed technique to analyze about 5,000 popular Web sites, the authors observed that about 30% of these sites contain vulnerabilities that can be exploited to conduct various SQLI or XSS attacks.

## 5.2. Client-Side Code Vulnerability

Similar to the server-side code, client-side components of Web applications can also be vulnerable. Such client-side components are usually written in interpreted script language (e.g., JavaScript) to enhance interactivity and to provide functionalities. Client-side script has the power to interact with Web pages and the browser; however, it also opens doors for many browser-based attacks. Several studies have been conducted to enhance the current browser implementation of the same-origin policy [Jackson and Wang 2007; Crites et al. 2008]. Such work focuses on designing a secure interface for untrusted principals (e.g., Web pages from different domains) to communicate with each other, but the secure interfaces are not the solutions for addressing the emerging security challenges and vulnerabilities (e.g., unsanitary user input, and insecure mashup paradigm) related to the Web-based malware problem, as we discussed in Section 2.3.

*5.2.1. The Status Quo of Insecure JavaScript Practices.* A large-scale measurement study on insecure JavaScript practices is presented in Yue and Wang [2009]. In this study, two types of insecure practices were considered: (1) *JavaScript inclusion*: including JavaScript files from external domains into the top-level document of a Web page; and (2) *dynamic JavaScript generation*: using reflective functions, such as `eval` to generate new scripts at runtime. Both types of insecure practices can lead to vulnerabilities and allow for the injection of malicious scripts from the attackers.

As a part of Yue and Wang's study, the home pages of 6,805 popular Web sites in 15 different genres were visited. It has been observed that 66.4% of the measured Web sites have the insecure JavaScript inclusion problem. More than 74.9% of the measured Web sites use dynamic script generation techniques. In other words, insecure JavaScript practices are prevalent on the Web. These results warn both Web site developers and administrators to pay serious attention to these issues and to use safe alternatives to avoid them.

*5.2.2. Discovering Client-Side Code Vulnerability.* In Saxena et al. [2010b], a class of validation vulnerabilities is formally analyzed for client-side code. This Client-Side Validation (CSV) vulnerability is defined as a programming flaw that results from using untrusted source data in a critical sink without sufficient validation. Data from the external Web principal or end-users are defined as untrusted sources. In fact, the sources could be messages from remote servers, cross-window communications (e.g., HTML-5 `postMessage`) or user input (e.g., form fields on a Web page). The sinks are defined to include various critical data structures (e.g., `document.cookie` and `document.forms[*].action`), functions (e.g., `eval` and `document.write`), which might be vulnerable to attacks (e.g., code injection, parameter injection). Similar to Saner, the authors propose a code analysis technique named FLAX, which employs taint-enhanced black-box testing.

FLAX is inspired by Ganesh et al. [2009], and it uses a two-step process to identify CSV vulnerabilities. This two-step process is designed to reduce program size and the corresponding search space for the black-box test. In the first step, the Web application is executed with the initial input  $I$  to conduct a dynamic taint analysis at character level. The taint analysis identifies all the potential uses of untrusted source data in critical sinks. It then extracts an input set  $I_S$ , on which the arguments of a sink operation  $S$  depend. All the program statements that are directly dependent on  $I_S$  are then extracted into an executable stand-alone subprogram, termed an *acceptor slice*. In the second step, each extracted acceptor slice is fed with test cases to find vulnerabilities. This process is sink aware as the test input is specifically designed for

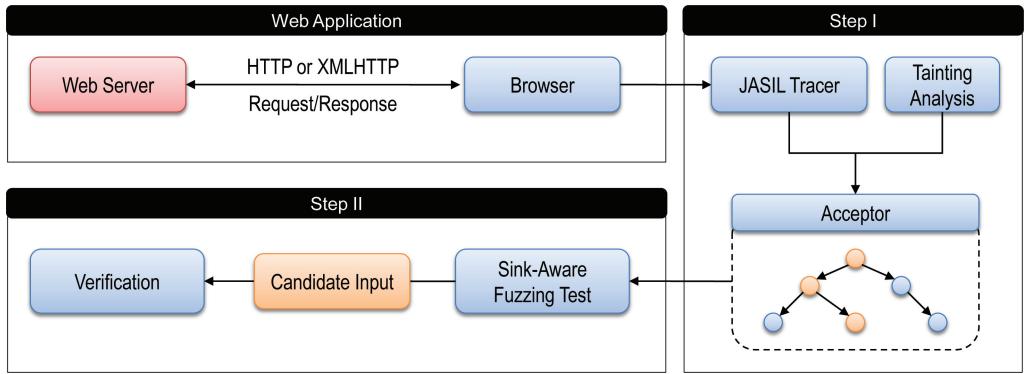


Fig. 10. FLAX system design.

different types of sinks. For example, a large corpus of XSS attack vectors is used to test the sinks that are vulnerable to code injection attacks. The system design of FLAX is illustrated in Figure 10.

Important design choices were made to handle various technical challenges of implementing FLAX. First, a simplified version of JavaScript named JASIL has been designed to facilitate the analysis process. Second, when tainted data is sent to external servers, FLAX performs the longest common substring matching over the returned data. Finally, implicit sinks are also considered to reduce false negatives. By running FLAX over 40 Web applications, 11 previously unknown vulnerabilities were discovered. After manual verification of the application code, the authors argue that FLAX has a low false positive and a low false negative rate. Using these identified vulnerabilities, four proof-of-concept attack scenarios were illustrated, including origin misattribution, code injection, application command injection, and cookie corruption.

In Saxena et al. [2010b], the authors enhance the design of FLAX and propose a new system called Kudzu for identifying CSV vulnerabilities. Test cases are supplied as input to the FLAX system for conducting black-box fuzzing test. Unlike FLAX, Kudzu generates high-quality test cases automatically. Further, Kudzu uses a new language to express string constraints and adopts a novel constraint solver to explore the symbolic execution space of JavaScript code. By identifying code injection vulnerabilities in real-world applications, Kudzu demonstrates its effectiveness without suffering false positives.

Unlike FLAX, Chugh et al. [2009], Guarneri and Livshits [2009], and Chang et al. [2011] adopt different static code analysis techniques to identify insecure JavaScript program behavior that leads to potential client-side code vulnerabilities. GateKeeper [Guarnieri and Livshits 2009] is a code validation tool that is useful for Web widget portals (e.g., iGoogle) to enforce customized security policies before allowing new widgets to be published. By disallowing dynamic code generation features of the JavaScript language, GateKeeper uses mostly static code analysis (e.g., pointer analysis, static call graph) to enforce security policies. The satisfaction of the corresponding policies by a widget is considered as a certification process of the widget portal. Chugh et al. [2009] is a staged information-flow approach to enforce dataflow policies for JavaScript code. The proposed scheme identifies syntactically enforceable rules during an offline analysis stage and enforces them during the execution of JavaScript code to achieve minimal performance overhead. ToMaTo [Chang et al. 2011] is a development tool that combines a novel trust policy language and a static code analysis engine to examine vulnerabilities introduced due to the usage of external JavaScript libraries in mashup Web



Fig. 11. Screenshot of Google safe browsing.

applications. ToMaTo enables the mashup developers with three essential capabilities for identifying potential vulnerabilities to build trustworthy JavaScript code mashups: trust policy specification, policy adherence evaluation, and vulnerability (i.e., policy violation) handling. Overall, these static analysis approaches are sound but suffer false positives due to the nature of the techniques.

## 6. PROTECTION AGAINST WEB-BASED MALWARE

The last line of defense against Web-based malware is to protect the end-users from being infected. As we saw in Section 2.4.1, instead of focusing specifically on Web-based malware, traditional protection mechanisms, such as antivirus software, sandbox techniques, and security patches are generally effective against a larger range of threats. Notably, alternative patching schemes have been explored in Wang et al. [2004] and Reis et al. [2006]. Their studies provide techniques for patching known vulnerabilities of client machines at network level to ease the patch application process. Despite the usability advantage, accurate specification of network-level patches for the corresponding host vulnerabilities is still a challenging task.

The detection techniques discussed in Section 4 can often be extended to act as protection mechanisms as well. The idea is that if malice can be effectively detected and the end-users are notified about the risk, then they can avoid visiting those Web sites that expose them to danger. For instance, the VM-based detection technique adopted in Provos et al. [2008] has been used in the Google Safe Browsing Project [2011], which constructs a blacklist of detected landing sites. Browsers, such as Firefox and Chrome, which incorporate the blacklist, can dissuade end-users from visiting high-risk Web sites (see Figure 11). Moreover, the detection mechanisms can also be encapsulated as proxy services, which perform online detection of attacks before sending unsafe content to end-users [Moshchuk et al. 2007; Rieck et al. 2010].

In this section, we discuss two categories of approaches: (1) sandbox systems, which are specially designed to prevent Web-based malware infection; and (2) URL reputation schemes, which improve the dynamics and the predictability of static malware blacklists. A brief summary of surveyed work in this section is shown in Table VII.

### 6.1. Building Attack-Agnostic Sandbox

Sandboxing is a well-studied and widely used security mechanism to execute untrusted code by restricting its privileges in a trusted system. In Lu et al. [2010], the authors propose a smart sandbox mechanism, called BLADE, to protect end-users from all

Table VII. Summary of Web-Based Malware Protection Techniques

Category	Paper	Contribution Summary
Attack-Agnostic Sandbox	Lu et al. 2010	Using sandbox mechanism to isolate untrustworthy downloads created by web-browsers.
	Cox et al. 2006; Li et al. 2011	Providing strong isolations between the execution of untrustworthy web applications and the host operating system.
	Jain et al. 2008	Providing a sandbox system that both limits the effects of attacks and simplifies the post-intrusion recovery process.
	Grier et al. 2008; Reis and Gribble 2009;	Using sandbox mechanism for secure web browser designs.
URL Reputation	Ma et al. 2009	Building a dynamic and predictive blacklist using URL reputation.
	Antonakakis et al. 2010	Building a dynamic reputation system for domain names.

forms of drive-by download malware attacks. In BLADE, the end-user is the root of trust. All downloaded content with explicit user consent is considered trustworthy. It is important to note that BLADE will not work for Web-based malware delivered through social engineering tricks. The goal of BLADE is to put content downloaded without a user's consent into an isolated sandbox environment to prevent any damages it might cause. The authors argue that BLADE is attack agnostic, as it does not require any understanding of the exploit techniques or vulnerabilities. In contrast, it needs to correctly capture user's consent.

The system design of BLADE is shown in Figure 12. By default, BLADE puts all files downloaded from the browser process into a nonexecutable secure zone. Once BLADE can correlate a downloaded file with a user's permission, the file will be moved out of the sandbox. Therefore, the key challenge of BLADE is to build a robust, user-transparent, and browser-independent correlation mechanism between the user authorization and the downloaded content. BLADE achieves this goal in four steps: (1) BLADE monitors kernel window events to look for the appearance of a download consent dialog triggered by the browser. A handful of User Interface (UI) signatures are used to identify these consent dialog windows and to extract (URL, file path) information from them. (2) Once such a dialog is discovered, BLADE begins to sense user-invoked hardware signals (e.g., mouse clicks or keystrokes), which may indicate the user's consent. Once such a signal has been observed, the correlation process starts. (3) The correlation process establishes proper mappings between user download authorizations and downloaded files. The (URL, file path) pair extracted in step 1 is used to provide information for the correlation process. File path information is used as the ID to find the candidate file from the sandbox zone. Meanwhile, the URL is used to double check against a log of TCP sessions to increase the robustness of the correlation result. (4) Once a correlation is established, the downloaded content with a user's permission will be

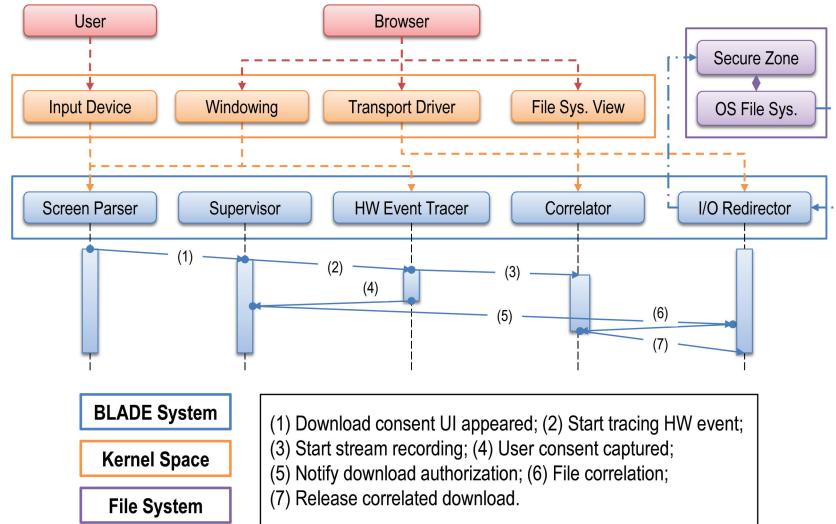


Fig. 12. BLADE system design.

redirected from the sandbox to the OS file system. Security policies are enforced by BLADE to enable a complete containment of disk footprints affected by the downloaded content. The authors evaluate BLADE against 4,000 malicious Web pages that contain drive-by download exploits. The experiment showed that BLADE is effective against all these attacks and only introduces a time delay of 4% compared with benign content downloading.

Cox et al. [2006] and Li et al. [2011] propose alternative sandbox schemes for isolating the execution of untrustworthy Web applications. Cox et al. [2006] propose a new trusted software layer, the Tahoma Web browsing system, to provide strong isolations between different Web applications and the host operating system. Having the same security management capabilities of native applications on current operating systems, Web applications are explicitly controlled and managed by the Tahoma system. By utilizing a carefully designed virtual machine system, the Tahoma system achieves strong isolation and safety without compromising the application performance. WebShield [Li et al. 2011] is a sandbox system that implements the principle of program isolation at network level. The WebShield system treats all the JavaScript code of Web applications as untrustworthy and executes it inside a sandbox. Serving as a proxy server, WebShield only forwards the consequences of JavaScript code execution (e.g., DOM modifications) to the client-side browsers for rendering. The interactivity of Web applications is also preserved by implementing special event handlers and communication protocol between the client-side browser and the sandbox proxy. The authors argue that WebShield has more general capabilities than existing network-level isolation schemes such as Reis et al. [2006] and Moshchuk et al. [2007]. Solitude is a sandbox system that is designed to both limit the effects of attacks and simplify the postintrusion recovery process [Jain et al. 2008]. Instead of focusing on any specific type of attack, Solitude provides a transparent and isolated environment for running all types of untrusted applications. Moreover, Solitude supports a more fine-grain privilege model than BLADE.

The Chromium Web browser also provides a sandbox mechanism to isolate different Web programs by taking advantage of existing OS-level isolation between different processes [Reis and Gribble 2009]. However, it is designed to enhance the current

same-origin-policy implementation to defend against XSS attacks. Indeed, malware delivered through client-side exploits against Chrome has already been observed [Chrome Malware 2010]. Similarly, in Grier et al. [2008] the authors also address the principle of secure Web browser design. Grier et al. [2008] advocates a scheme that uses formal methods to drive the application of the security design principles of modern operating systems. The overall idea is to design a Web browser that consists of function modules and a small browser kernel, where the browser kernel controls and interposes communications between all the subsystems and components. The authors argue that the proposed scheme will be less error prone and ease the task of pinpointing attack scenarios and potential vulnerabilities.

## 6.2. Calculating URL Reputation

Current ways to build a URL blacklist depend on explicit feedback; malice is observed by either manual inspections or automatic detections. Inevitably, these blacklists are not complete—many malicious URLs are not blacklisted. There are two main reasons for this defect: (1) the URL is “new”, meaning that it has not yet been evaluated; or (2) the evaluation result is incorrect due to the false negative exhibited by the detection approach.

Motivated by the insufficiency of a static blacklist, Ma et al. [2009] proposed an approach to build a dynamic and predictive blacklist using URL reputation. Note that this technique is not limited to detecting Web-based malware problems. It is also effective for other Web threats, such as phishing and spamming, as demonstrated by Ma et al. [2009]. The proposed reputation scheme assigns a binary reputation value to the URL, indicating whether it is malicious or not. In Ma et al. [2009], various features and classification models were studied to gain a better understanding of the problem.

Instead of analyzing the content pointed at by the URL, two sets of lightweight features are considered when building the URL reputation. The first is a lexical feature set, which is the textual properties of the URL itself. Lexical features include the length of the hostname, the length of the entire URL, the number of dots in the URL and a “bag-of-words” representation of tokens (a string delimited by “.”, “?”, “/”, “=”, “\_”, etc.) in the URL. The second feature set, the host-based feature set, contains information about the host of a Web site. IP address properties (e.g., AS and prefix information, whether the IP address appears in any other blacklists), WHOIS properties (e.g., domain registration data, registrar information), DNS properties (e.g., time-to-live value), and geographic properties (e.g., the country to which the host IP belongs, the speed of the uplink connection) are included as the host-based features. A feature comparison study showed that the following four features are the most relevant for correct classifications: the number of dots in a URL, whether the hostname contains an IP address, the WHOIS registration date, and the membership in six static blacklists.

Three basic machine learning models were studied by the authors: the Naive Bayes (NB), the Support Vector Machine (SVM), and the Logistic Regression (LR). A comparative study between the three models shows that SVM and LR produce similar results, and both out-perform the NB model. Moreover, SVM has smaller training and testing overhead, making it more desirable when the performance is a concern. In contrast, LR often needs more computation power to train, but the resulting model is easier to interpret in terms of relevant and irrelevant features. In all, 30,000 benign URLs and 10,000 malicious URLs were collected as the dataset to validate the reputation scheme. The dataset is grouped into four subsets, and 95% predication accuracy was observed for the training and testing the reputation model within each subset. However, the accuracy decreases significantly when the training data and testing data are from different subsets. The authors argue that a comprehensive and representative training

Table VIII. Approach Comparison Summary (IV: identification of Web application vulnerability; DA: detection of Web-based malware attacks; PA: protection against Web-based malware attacks)

Comparator	IV	DA	PA
Deployment	Global web application deployment	Partial, third-party deployment	Global user system deployment
Effectiveness	Both false positives and false negatives	Both false positives and false negatives	Mainly false negatives
Autonomy	High human involvement	Limited human involvement	Almost no human involvement
Adaptiveness & Gamesmanship	Attack-dependent	Attack-dependent	Attack-independent

dataset is critical to make the proposed reputation scheme effective in the real world. How to obtain such a training dataset is still an open challenge.

There is little related work in the literature focusing on building dynamic reputations for Web-based malware distribution sites. Instead of focusing on the URL, Notos [Antonakakis et al. 2010] is a dynamic reputation system for domain names. Notos uses reputation to quantify the probabilities of domain names being used to participate in botnet or spamming activities by adopting a hierarchical machine-learning model. Notos does not use any lexical features to calculate reputation, but focuses only network features. With the same design goal as Notos, EXPOSURE [Bilge et al. 2011] is another system for identifying malicious domains used in cyber attacks. Adopting a different feature set and learning algorithm than Notos, the authors argue that the EXPOSURE system achieves better accuracy and requires less training data for building an accurate classifier. However, it is still unclear how to apply the schemes proposed by Notos and EXPOSURE for the effective classification of domain names used by malware landing or distribution sites.

## 7. DISCUSSION

In the previous sections, we introduced different techniques for defending against Web-based malware. Now, we examine these methods comparatively. Our dimensions for comparison are not intended to be exhaustive. Instead, we choose attributes which highlight the strengths and weaknesses of each approach and help to design a comprehensive defense strategy. Table VIII summarizes the comparison of the surveyed approaches.

### 7.1. Deployment Scale

To defend against a rising security threat is a complicated issue in the real world. Even if one makes the assumption that the proposed approaches can work perfectly, there are still many other factors that can reduce the desired impact in practice. One aspect is the deployment scale: how widely one approach needs to be deployed in order to achieve the global defense goal.

Ideally, every Web application on the Internet should be properly checked for potential vulnerabilities, in order to minimize the risk of becoming a landing Web site. However, there are two important factors that can be taken into consideration to relax this requirement. First, a small percentage of top Web sites attract a large percentage of the global Web traffic. These popular Web sites should be given the highest priority to check for vulnerabilities. If these top sites could always keep themselves safe, their users would also be safe. Second, many Web applications are built upon popular Web application platforms. For example, many online forums are powered by open-source

Web applications, such as Phorum and phpBB. These platforms serve as the “template” with customization capabilities to produce new applications. Since the code of these platforms is highly reused, it is important to make sure that they contain as few vulnerabilities as possible. The same is true for client-side code, as many Web applications are dependent on a handful of popular JavaScript code libraries, such as jQuery and YUI. Moreover, it is reasonable to assume that both top Web site administrators and popular Web platform developers have more resources and better expertise for this task. As a result, it is also their responsibility to contribute more towards building a safe Web ecosystem.

Attack detection mechanisms can be deployed on a much smaller scale and remain effective. Indeed, Google checks a large portion of existing Web pages continuously in its Safe Browsing project, with only local deployments [Provost et al. 2008]. If we can reduce the performance cost of detection techniques and add more computing resources, it is still possible to expect real-time and rather complete detection of attacks in the wild. Further, detection systems can also focus more on the top popular Web sites to be more cost effective. However, the impact of a successful detection mechanism would be limited without reaching out to the end-users.

On the other hand, the protection mechanisms surveyed in this article require a complete coverage of all end-hosts to achieve the best results. From the attacker’s perspective, there is almost no difference between different victim machines, that is, “every machine counts”. However, looking at the history of defending against other computer security threats, it is reasonable to argue that achieving a full deployment is not likely to happen in reality. Therefore, designing better techniques to ease the deployment process and to achieve a better coverage percentage might be a very desirable next step.

## 7.2. Comparative Effectiveness

Another comparison can be made by assuming a full deployment of all proposed approaches and focusing on their comparative effectiveness. Given the different nature of proposed approaches, we want to understand their mitigation limitations.

Vulnerability identification mechanisms cannot identify all potential vulnerabilities. The code analysis techniques often try to identify the necessary conditions of successful exploits to minimize false negatives by increasing false positives. However, without the formal specifications of correct program behavior, many alerts triggered by the vulnerability scanners might simply be ignored by developers to preserve functionality. On the other hand, black-box testing only uses known attacks as test cases. Presumably, this testing process will suffer both false positives and false negatives. Further, the code of Web applications is often quickly evolving to meet new user requirements. The vulnerability checking process needs to be performed every time the code changes. Otherwise, new vulnerabilities introduced by the code modification cannot be detected. In other words, none of the existing vulnerability identification mechanisms can remove all the bugs and flaws from Web applications. The risk of buggy software will always be present.

As discussed in Section 4.2, VM-based detection mechanisms suffer false negatives given the complexity of configuring the most vulnerable honeypot to detect all attacks. Meanwhile, signature-based detection mechanisms use either pattern-matching or machine-learning techniques for detection. Both methods depend on detected attacks to build a signature database or an anomaly model. However, there are still no known ways to build a complete or at least a representative attack vector set. Moreover, both the attack signature and the anomaly model often capture the necessary conditions of successful attacks. Therefore, signature-based detection mechanisms will have both

false positives and false negatives. It is highly possible that new attack types cannot be detected by these approaches until a large-scale outbreak is observed.

A URL reputation mechanism has the same types of problems as signature-based detection. In contrast, the sandbox technique seems very promising, if it can be fully deployed. The only drawback is that it assumes that end-users are the root of trust. However, end-users may often make incorrect security decisions due to their lack of necessary knowledge or their victimization by social engineering tricks. Regardless, for attacks that are fully automated (e.g., drive-by download), the smart sandbox system forms very effective protection.

### 7.3. Degree of Autonomy

We next examine the degree of autonomy from which each of the proposed approaches operates. That is, what role do humans play in the operation of these approaches? This is an important issue to understand since humans can sometimes be the most unreliable link of the entire defense chain.

Vulnerability identification mechanisms need a great deal of human participation. The alerts triggered by the scanning tools need to be examined by the developers one by one to decide whether true vulnerabilities are present. Sometimes, using the scanning tools requires deep knowledge of potential attacks. Further, developers are required to develop correct patches for the identified vulnerabilities without introducing new flaws.

Signature-based detection mechanisms also require humans to determine the correctness of detected attacks with further investigations. VM-based detection requires less human input. However, when it is used for detecting zero-day vulnerabilities, it still needs researchers to study the details in order to have a good understanding of the problem.

Two protection mechanisms surveyed in this article are almost fully automated and require almost no human participation. A static or dynamic URL blacklist can be embedded in the browser itself and be shipped to end-users. For instance, the Firefox browser implements the Google Safe Browsing API and blocks any visits to the malicious sites automatically. The BLADE sandbox systems are also designed to be transparent to end-users once installed on the system. It extracts information from normal browsing behavior and uses it to reason about user authorizations without the need for extra input.

### 7.4. Adaptiveness and Gamesmanship

Finally, we discuss how proposed approaches need to be modified to adapt to new attacks, and how existing attacks might change themselves to evade these approaches.

To detect new types of vulnerability, the vulnerability identification mechanisms based on code analysis need to take new sources or sinks into consideration, or change the checking policies to include new security violations. However, some vulnerabilities will require significant improvement of the code analysis capability, for example, to support more dynamic language features. Black-box testing requires adding new attacks into their test cases to be adaptive. To evade these mechanisms, the attackers need to use more advanced and subtle techniques as demonstrated in Bau et al. [2010].

If new attacks are designed to target new vulnerabilities, the VM-based detection mechanism needs to include these vulnerabilities into the VM image to still be effective. Otherwise, no modifications are needed. For the signature-based detection mechanism, it requires including new attacks in the training dataset to learn special characteristics from these attack instances. To evade both of the detection mechanisms, malicious landing sites can perform a reverse Turing test (e.g., CAPTCHA) to judge whether the end-user is a human or a machine. Then they can deliver only benign content, if no

human user is involved. Moreover, if the attackers have knowledge of the detection infrastructure, for example, IP addresses, then the landing sites can simply block detections by using an IP blacklist.

The URL reputation calculation also needs to include new malicious links to be adaptive, similar to the signature-based detection mechanism. In contrast, the sandbox approach is attack agnostic, and it requires almost no changes for new attacks. Also, it is difficult to game the sandbox system under reasonable trust assumptions [Lu et al. 2010].

## 8. CONCLUSION

In this article, we survey three categories of approaches to analyze, identify, and defend against the Web-based malware problem. Each category of approach has its relative advantages and disadvantages, and each has been demonstrated effective via empirical evaluations. Further, we discuss how these approaches complement each other and how they can work together to form a comprehensive solution space. In order to advance the state-of-the-art, we have identified five promising directions for future research.

- (1) *Building Benchmark Platforms.* Almost all the approaches suffer either false positives or false negatives; however, there is no commonly accepted dataset or testing framework to comparatively evaluate their effectiveness. Therefore, a well-designed benchmark framework is clearly needed to scientifically study and compare different proposed approaches.
- (2) *Securing Code Mashup.* The client-side code of Web applications can be reused and dynamically loaded from external sources. This code mashup requires a different security model than any traditional programming paradigms. Given the prevalence of client-side code mashups, it is imperative to design a sound approach to enhance the flexibility of the current mashup programming practice with guaranteed security.
- (3) *Studying Social Engineering Tricks.* Current detection approaches mainly focus on the Web-based malware delivered through drive-by download attacks. The studies on malware delivered through social engineering tricks is very limited. However, as the technologies for mitigating drive-by download attacks become more mature and more broadly deployed, it is reasonable to assume that the attackers will focus more on using social engineering tricks to improve their chance of success.
- (4) *Studying the Economy.* Understanding the incentives and the economic chains of Web-based malware is still an open area. Similar studies have been done for other network security problems such as email spam [Kanich et al. 2008; Motoyama et al. 2010]. This type of study is critically important for security researchers to understand the landscape better and to design more effective defense strategies.
- (5) *Studying the Epidemiology.* Existing detection mechanisms can be used to build the topology of the malware distribution infrastructure. However, there is no study on the liveness property of this topology: understanding how the connections between landing sites and distribution sites evolve over time. Similar studies have been done for traditional push-based malware propagation in Garetto et al. [2003]. An accurate epidemic model is therefore useful to evaluate how fast and prevalent a defense mechanism needs to be deployed to effectively fight against a Web-based malware outbreak.

Given the scale and complexity of the Web-based malware problem space, building a safe Web browsing environment is the responsibility of every Web participant. On the whole, for a healthy and secure Internet ecosystem, a challenging road is still ahead for everyone in the foreseeable future.

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