Revisiting Email Spoofing Attacks

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Abstract—The email system is the central battleground against phishing and social engineering attacks, and yet email providers still face key challenges to authenticate incoming emails. As a result, attackers can apply spoofing techniques to impersonate a trusted entity to conduct highly deceptive phishing attacks. In this paper, we describe our efforts and experience in evaluating the effectiveness of user-level protections against email spoofing. We answer the above questions in two key steps. First, we examine how popular email providers detect and handle forged emails using end-to-end measurements. Particularly, we examine under what conditions can forged/phishing emails reach the user inbox and what security cues (if any) are used to warn users. Second, we measure the impact of the security cues on users through a series of user studies (N = 913). To obtain reliable experiment results, we conduct both simulated and real-world phishing experiments.

Measurements. By scanning Alexa top 1 million hosts in January and October 2017, we confirm that the adoption rate of SMTP security extensions is still low (SPF 45.0%, DMARC 4.6%). This motivates us to examine how email providers handle incoming emails that failed the authentication. We conduct end-to-end spoofing experiments on 35 popular public email providers used by billions of users. We treat each email provider as a blackbox and vary the input (forged emails) to monitor the output (the receiver’s inbox).

We find that forged emails can penetrate the majority of email providers (33/35) including Gmail, Yahoo Mail and Apple iCloud under proper conditions. Even if the receiver performs all the authentication checks (SPF, DKIM, DMARC), spoofing an unprotected domain or a domain with “weak” DMARC policies can help the forged email to reach the inbox. In addition, spoofing an “existing contact” of the victim also helps the attacker to penetrate email providers (e.g., Hotmail). Overall, the result indicates that providers tend to prioritize email delivery when the email cannot be reliably authenticated.

More surprisingly, while most providers allow forged emails to get in, rarely do they warn users of the unverified sender. Only 9 of 35 providers have implemented some security cues: 8 providers have security cues on their web interface (e.g., Gmail) and only 4 providers (e.g., Naver) have the security cues consistently for the mobile apps. Even worse, certain email providers have misleading UI elements which help the attacker to make forged emails look authentic. For example, when attackers spoof an existing contact (or a user from the

1Our study has been reviewed and approved by our local IRB (IRB-17-397).
same provider), 25 out of 35 providers will automatically load either the sender’s profile photo, name card or email history from their internal database for this forged email. These designs are supposed to improve email usability by providing the context on “who sent this email”. However, when the sender address is actually spoofed, these designs, in turn, help the attacker with the deception.

**User Studies.** While a handful of email providers have implemented security cues, the real question is how effective they are. We answer this question using a series of user studies ($N = 913$) where participants examine spoofed phishing emails with or without security cues on the interface. Our methodology follows a hybrid approach. First, we conducted a “role-playing” where users examine phishing and benign emails in a controlled hypothetical scenario. While the role-playing method is widely used for usability studies [52], [59], [63], [65], [67], our concern is that certain artificial conditions may affect the user behavior. To this end, we also run a real-world phishing test to validate our results.

Our result shows that security cues have a positive impact on reducing risky user actions consistently across the role-playing experiment and the real-world phishing test. The impact is also consistently positive for users of different demographics (age, gender, education-level). In addition, comparing with the role-playing setting, we find that the impact of security cues in the real-world setting is not as significant when users are caught off guard. The result indicates that the security cue is useful but cannot eliminate the phishing risk. The design of security cue also should be further improved to maximize its impact.

**Contributions.** Our work has three key contributions:

- **First**, our end-to-end measurement sheds light on how email providers handle forged emails. We reveal the trade-offs made by different email providers between email availability and security.
- **Second**, we are the first to empirically analyze the usage of security cues on spoofed emails. We show that most email providers not only lack the necessary security cues (particularly on mobile apps), but introduce misleading UIs that in turn help the attackers.
- **Third**, we conduct extensive user studies to evaluate the effectiveness of the security cue. We demonstrate its positive impact (and potential problems) using both role-playing experiments and real-world phishing tests.

II. BACKGROUND AND METHODOLOGY

Today’s email system is built upon the SMTP protocol, which was initially designed without security in mind. Security extensions were introduced later to provide confidentiality, integrity, and authenticity. In this paper, we primarily focus on email authenticity, a property that is often abused by phishing attacks. Below, we briefly introduce SMTP and related security extensions. Then we discuss the key challenges to defend against email spoofing and introduce our research questions and methodology.

A. SMTP and Email Spoofing

Simple Mail Transfer Protocol (SMTP) is an Internet standard for electronic mail transmission [54]. Figure 1 shows the three main steps to deliver an email message. (1) Starting from the sender’s Mail User Agent (MUA), the message is first transmitted to the Mail Submission Agent (MSA) of the sender’s service provider via STMP or even HTTP/HTTPS. (2) Then the sender’s Mail Transfer Agent (MTA) sends the message to the receiver’s email provider using SMTP. (3) After processing, the message is delivered to the receiving user by the Mail Delivery Agent (MDA) via Internet Message Access Protocol (IMAP), Post Office Protocol (POP) or even HTTP/HTTPS.

When initially designed, SMTP did not have any security mechanisms to authenticate the sender identity. As a result, attackers can easily craft a forged email to impersonate/spoof an arbitrary sender address by modifying the “MAIL FROM” field in SMTP. Email spoofing is a critical step in a phishing attack — by impersonating a trusted entity as the email sender, the attacker has a higher chance to gain the victim’s trust. In practice, attackers usually exploit SMTP in step (2) by setting up their own MTA server.

B. Email Authentication

To provide security for the email system, various security extensions have been proposed and standardized. Here, we briefly describe the extensions that are designed to support email authenticity and prevent spoofing (e.g., SPF, DKIM and DMARC). There are other security extensions that provide confidentiality and integrity (e.g., STARTTLS), which are beyond the scope of this paper.

**SPF.** Sender Policy Framework (SPF) allows an email service (or an organization) to publish a list of IPs that are authorized to send emails for its domain (RFC7208 [38]). For example, if a domain “a.com” published its SPF record in the DNS, then other email services can check this record when receiving an email that claims to be from “{someone}@a.com”. In this way, only authorized IPs can send emails as “a.com”. SPF makes it convenient for an organization to use third-party/cloud-based email providers by simply adding the provider’s IP range to the SPF record. In addition, SPF allows the organization to specify a policy regarding how the receiver should handle the email that failed the authentication.

**DKIM.** DomainKeys Identified Mail (DKIM) uses the public-key based approach to authenticate the email sender (RFC6376 [18]). The sender’s email service will place a digital signature in the email header signed by the private key associated to the sender’s domain. The receiving service
can retrieve the sender’s public key from DNS to verify the signature. In order to query a DKIM public key from DNS, one not only needs the domain name but also a selector (an attribute in the DKIM signature). Selectors are used to permit multiple keys under the same domain for more a fine-grained signatory control. DKIM does not specify what actions that the receiver should take if the authentication fails.

**DMARC.** Domain-based Message Authentication, Reporting and Conformance (DMARC) is built on top of SPF and DKIM (RFC7489 [49]). DMARC is not a standalone protocol. It allows the domain administrative owner to publish a policy to specify what actions the receiver should take when the incoming email fails the SPF and DKIM check. A domain’s DMARC record is available under _dmarc.domain.com in DNS. Another protocol called ADSP (Author Domain Signing Practices) also allows domain owners to publish DKIM signing policies, but ADSP was declared “historic” in 2013 [46].

**C. Practical Challenges to Prevent Spoofing**

In theory, we already have the tools to secure the email system against spoofing. However, significant challenges remain when these tools are not properly deployed in practice. Recent measurements conducted in 2015 show that the adoption rates of SMTP security extensions are far from satisfying [22], [26]. Among Alexa top 1 million domains, only 40% have published an SPF record, and an extremely low percentage of domains (1%) have a DMARC policy. In addition, the majority of policies are not strictly reject (“reject” policy means the receiver should reject the email if it failed the authentication [26]).

These results indicate a real challenge to protect users against email spoofing. First, with a large number of domains not publishing an SPF/DKIM record, email providers cannot reliably detect incoming emails that spoof unprotected domains. Second, even a domain is SPF/DKIM-protected, the lack of (strict) DMARC policies puts the receiving server in a difficult position. Without a clear instruction to reject these emails, what would the receiving email providers do? Existing works mainly examined the authentication protocols on the server-side. However, there is still a big gap between the server-side spoofing detection and the actual impact to users.

**D. Research Questions and Method**

Our study seeks to understand email spoofing and related protections from the user perspectives. We have three key questions. (1) When email providers face uncertainty in authenticating incoming emails, how would they handle the situation? Under what conditions would forged emails be delivered to the inbox? (2) Once forged emails get in, what types of warning mechanisms (if any) are used to notify users of the unverified sender address? (3) How effective are existing warning mechanisms to protect users? Answering these questions is critical to understanding the actual risks that are exposed to users by email spoofing.

**Methods.** We answer question (1)–(2) through end-to-end spoofing experiments (§III, §IV and §V). For a given email provider, we treat it as a “blackbox”. By controlling the input (e.g., forged emails) and monitoring the output (receiver’s inbox), we infer the decision-making process inside the blackbox. In addition, we empirically examine the usage of visual security cues to warn users of forged emails.

We answer question (3) by conducting a large user study (§VI and §VII). The idea is to let users read spoofing/phishing emails with and without security cues on the interface. Instead of simply applying traditional user study methods (which has limitations to capture realistic user behavior [58]), our approach combines controlled “role-playing” experiments with “deceptive” real-world phishing tests in order to produce reliable results.

**Ethics.** We have taken active steps to ensure research ethics. Our measurement study only uses dedicated email accounts owned by the authors and there is no real user getting involved. In addition, to minimize the impact on the target email services, we have carefully controlled the message sending rate (one message every 10 minutes), which is no different than a regular email user. For the user studies, all the experiments have obtained user consent either before or after the study. Email samples used in the user study are completely benign (screenshots or emails with benign links). For the user study that involves “deception”, we worked closely with IRB to review and revise the experiment design. More detailed ethical discussions will be presented in later sections.

**III. ADOPTION OF SMTP EXTENSIONS**

The high-level goal of our measurement is to provide an end-to-end view of email spoofing attacks against popular email providers. Before doing so, we first examine the recent adoption rate of email security extensions among Internet domains compared with that from two years ago [22], [26]. This helps to provide the context for the challenges that email providers face to authenticate incoming emails.

**Scanning Alexa Top 1 Million Domains.** Email authentication requires the sender domains to publish their SPF/DKIM/DMARC records to DNS. To examine the recent adoption rate of SPF and DMARC among potential sender domains, in January and October 2017, we crawled two snapshots of the DNS record for Alexa top 1 million hosts [1]. Similar to existing work [22], [26], this measurement cannot apply to DKIM, because querying the DKIM record requires knowing the selector information for every each domain. The selector information is only available in the DKIM signature in the email header, which is not a public information. We will measure the DKIM usage later in the end-to-end experiment.

**Results.** Table [1] shows the statistics for the October 2017 snapshot. The results from the January snapshot are very similar and we refer interested readers to Appendix A. As shown in Table [1] SPF and DMARC both have some increase in the adoption rate compared to two years ago, but the increases are not very significant. About 45.0% of the domains have published a valid SPF record in October 2017 (40% in 2015 [26]), and 4.6% have a valid DMARC record in 2017.
TABLE I

| Status          | All Domains # (%) | MX Domains # (%) |
|-----------------|-------------------|------------------|
| Total domains   | 1,000,000 (100%)  | 803,720 (100%)   |
| w/ SPF          | 493,367 (49.3%)   | 475,506 (59.2%)  |
| w/ valid SPF    | 449,848 (45.0%)   | 432,669 (53.8%)  |
| Policy: soft fail| 275,244 (27.5%)  | 270,994 (33.7%)  |
| Policy: hard fail| 123,084 (12.3%)  | 111,231 (13.8%)  |
| Policy: neutral | 50,437 5.0%      | 49,381 (6.1%)    |
| Policy: pass    | 1083(0.1%)       | 1,063 (0.1%)     |
| Policy: quarantine| 4,603 (0.5%)     | 4,509 (0.6%)     |

(1.1% in 2015 [26]). The invalid records are often caused by the domain administrators using the wrong format for the SPF/DMARC record. Another common error is to have multiple records for SPF (or DMARC), which is equivalent to “no record” according to RFC7489 [49].

Among the Alexa top 1 million domains, 803,720 domains are MX domains (i.e., mail exchanger domains that host email services). The adoption rates among MX domains are slightly higher (SPF 53.8%, DMARC 5.4%). For non-MX domains, we argue that it is also important to adopt the anti-spoofing protocols. For example, office.com is not a MX domain but it hosts the product web page for the Microsoft Office software. A potential attacker can spoof office.com to phish Microsoft Office users (or even Microsoft employees).

SPF and DMARC both specify a policy regarding what actions the receiver should take after the authentication fails. Table I shows that only a small portion of the domains specify a strict “reject” policy: 12.3% of the domains set “hard fail” for SPF, and 0.6% set “reject” for DMARC. The rest of the domains simply leave the decision to the email receiver.

“Soft fail”/“quarantine” means that the email receiver should process the email with caution. “Neutral”?“none” means that no policy is specified. SPF’s “pass” means that the receiver should let the email go through regardless. If a domain has both SPF and DMARC policies, DMARC overwrites SPF as long as the DMARC policy is “none”.

Domains that use DKIM also need to publish their policies through DMARC. The fact that only 4.6% of the domains have a valid DMARC record and 0.6% have a “reject” policy indicates that most DKIM adopters also did not specify a strict reject policy.

IV. END-TO-END SPOOFING EXPERIMENTS

Given the low adoption rate of SPF and DMARC among Internet domains, it is still challenging for email providers to reliably authenticate all incoming emails. When encountering questionable emails, we are curious about how email providers make the trade-off between email delivery and security. In the following, we describe our experiment methodology to answer two key questions: First, under what conditions will email providers let forged emails get into the user inbox? Second, when it happens, would users receive any warnings?

A. Experiment Setup

We conduct end-to-end spoofing experiments on popular email providers that are used by billions of users. The high-level idea is illustrated in Figure 2. For a given email provider (B.com), we put it to the receiving end. We set up a user account under B.com as the email receiver (test@B.com). Then we set up an experimental server (E.com) to send forged emails to the receiver account. Our server runs a Postfix mail service [2] to directly interact with the target mail server using SMTP. By controlling the input (the forged email) and observing the output (the receiver account), we infer the decision-making process inside of the target email service.

Selecting Target Email Providers. This study focuses on popular and public email services with two considerations. First, popular email services such as Yahoo Mail and Gmail are used by more than one billion users [44], [30]. Their security policies and design choices are likely to impact more people. Second, to perform end-to-end experiments, we need to collect data from the receiver end. Public email services allow us to create an account as the receiver. Our experiment methodology is applicable to private email services but requires collaborations from the internal users.

To obtain a list of popular public email services, we refer to Adobe’s leaked user database (152 million email addresses, 9.3 million unique email domains) [39]. We ranked the email domains based on popularity, and manually examined the top 200 domains (counting for 77.7% of all email addresses). After merging domains from the same service (e.g., hotmail.com and outlook.com) and excluding services that don’t allow us to create an account, we obtained a short list of 28 email domains. To include the more recent public email services, we searched in Google and added 6 more to the list (34 in total). We notice that Google’s Gmail and Inbox have very different email interfaces and we treat them as two different services.

In total, we have 35 popular email services which cover 99.8 million email addresses (65.7%) in the Adobe database. As an additional reference, we also analyze the Myspace database (131.4 million email addresses) [53]. We find that 101.8 million email addresses (77.5%) are from the 35 email services, confirming their popularity.

B. Controlled Parameters

To examine how different factors affect the outcome of email spoofing, we apply different configurations to the experiment. We primarily focus on parameters of three aspects: the spoofed sender address, email content, and the receiver’s email client (user interface).
Spoofed Sender Address. The spoofed sender address is likely to affect the spoofing result. For example, if the spoofed domain (A.com) has a valid SPF/DKIM record, then the receiver (in theory) is able to detect spoofing. In addition, A.com’s SPF/DMARC policy may also affect the decision of the receiving email service. We configure three profiles for the spoofed sender domain: (1) no SPF/DKIM/DMARC record; (2) SPF/DKIM with a “None” policy; and (3) SPF/DKIM with a “reject” policy. For each profile, we pick a qualified domain for the primary experiment (easychair.org, xxx.edu, and facebook.com). We use three addresses to intuitively illustrate the problem. Then to validate the results, we perform a shadow experiment by randomly selecting 20 domains for each category (60 in total) from the Alexa top 2000 domains. The shadow domains are listed in Appendix B.

Email Content. Email content can affect how spam filters handle the email [10]. Different keywords may have different weights for the spam filter, leading to almost an infinite testing space. Our experiment, however, focuses on spoofing (sender address is forged) instead of spam, and we want to minimize the impact of spam filters. To this end, we configure 3 emails with blank content to measure the decision made on forgery alone. The email content is configured as (1) a blank email, (2) a blank email with a benign URL (http://google.com), and (3) a blank email with a benign attachment (empty text file). The reason for using “benign” content is to test how much the “spoofing” factor alone contributes to the email providers’ decisions. In addition, to test whether a phishing email can penetrate the target service, we also include (4) an email with phishing content. This phishing email is a real-world sample from a phishing attack targeting our institution in 2017. The email impersonates the technical support to notify the victim that her internal account has been suspended and ask her to reactivate the account using a URL (to an Amazon EC2 server).

Email Client. We examine how different email clients warn users of forged emails. We consider 3 common email clients: (1) a web client, (2) a mobile app, and (3) a third-party email client. All the 35 selected services have a web interface, and 28 have a dedicated mobile app. Third-party clients refer to the email applications (e.g., Microsoft Outlook and Apple’s Mail) that allow users to check emails from any email providers.

V. SPOOFING EXPERIMENT RESULTS

In this section, we describe our findings from the end-to-end spoofing experiments. First, to provide the context, we measure the authentication mechanisms (SPF/DKIM/DMARC) that the email providers use to detect forged emails. Then, we examine how email providers handle forged emails and identify key factors that help forged emails reach user inbox. For emails that successfully get in, we examine whether and how email providers warn users about their potential risks. Finally, we present case studies on email providers that have misleading UIs which help the attacker to make the forged email look more authentic.

A. Authentication Mechanisms

To better interpret the results, we first examine how the 35 email providers authenticate incoming emails. One way of knowing their authentication protocols is to analyze the email headers and look for authentication results of SPF/DKIM/DMARC. While this method works for some of the email providers, it will miss those (e.g., qq.com) that do not add the authentication results to the header. Instead, we follow a more reliable measurement method [26]. The high-level idea is to setup an authoritative DNS server for our own domain. Then we send a forged email to the target email service by spoofing our own domain. In the meantime, the authoritative DNS server will wait and see whether the target email service will query our SPF/DKIM/DMARC record. We set the TTL of the SPF, DKIM and DMARC records as 1 (second) to force the target email service always querying our authoritative DNS server for these records. The results (collected in August 2017) are shown in Table II (left 4 columns). 35 email providers can be grouped into 3 categories based on their protocols:

- **Full Authentication (16):** Email services that perform all three authentication checks (SPF, DKIM and DMARC). This category includes the most popular email services such as Gmail, Yahoo Mail, Hotmail and Apple’s iCloud.
- **SPF/DKIM but no DMARC (15):** Email services that check either SPF/DKIM to authenticate incoming emails, but do not check the sender’s DMARC policy. These email services are likely to make decisions on their own.
- **No Authentication (4):** Email services that do not perform any of the three authentication protocols.

During this experiment, we observe that gmx.com, mail.com and inbox.lv block all the emails from dynamic IPs. In our spoofing experiment, we use dynamic an IP as default to simulate a worse-case scenario for attackers, but we use a static IP for these three services.

B. Decisions on Forged Emails

Next, we examine the decision-making process on forged emails. As a primary experiment, we send 12 forged emails to each of the 35 email services (3 spoofed addresses × 4 types of email content). In August 2017, we shuffled all the emails and set a sending time interval of 10 minutes to minimize the impact to the target services. Note that we do not send a large volume of emails (only 12 emails per service). This traffic volume is extremely low compared to the hundreds of billions of emails sent over the Internet every day [41]. We intentionally limit our experiment scale so that the experiment emails would not impact the target services (and their email filters) in any significant ways. This is also to avoid emails sent earlier affecting the ones sent later in the experiments. To validate the results of the primary experiment, we will also conduct a shadow experiment by testing more spoofed domains.

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3For anonymous submission, we use “xxx.edu” to represent our institution’s email domain. “xxx” does not necessarily mean it contains three letters.
## TABLE II

RESULTS OF THE END-TO-END SPOOFING EXPERIMENT (PRIMARY). TO BETTER ILLUSTRATE THE RESULTS, (●) INDICATES THE EMAIL IS DELIVERED TO THE INBOX; (○) INDICATES THE EMAIL IS PLACED TO THE SPAM FOLDER; (●●) INDICATES THE EMAIL IS BLOCKED WITHOUT DELIVERY.

| Email Provider | Supported Protocols | Spool easychair.org (No SPF/DKIM/DMARC) | Spool xxx.edu (SPF/DKIM;DMARC=none) | Spool facebook.com (SPF/DKIM;DMARC=strict) | # to Inbox |
|----------------|---------------------|------------------------------------------|--------------------------------------|---------------------------------------------|-----------|
| hotmail.com    | ✓ ✓ ✓               | ●                                        | ●                                    | □                                            | 0/12      |
| aol.com        | ✓ ✓ ✓               | ● ●                          ●            | ●                                    | □                                            | 1/12      |
| seznam.cz      | ✓ ✓ ✓               | ● ●                          ●            | ●                                    | □                                            | 2/12      |
| 163.com        | ✓ ✓ ✓               | ○ ●                          ●            | ●                                    | □                                            | 2/12      |
| 126.com        | ✓ ✓ ✓               | ○ ○                          ○            | ○                                    | □                                            | 3/12      |
| yeah.net       | ✓ ✓ ✓               | ○ ○                          ○            | ○                                    | □                                            | 3/12      |
| yahoo.com      | ✓ ✓ ✓               | ● ●                          ●            | ○ ○                                  | □                                            | 4/12      |
| mail.ru        | ✓ ✓ ✓               | ● ●                          ●            | ○ ○                                  | □                                            | 5/12      |
| tutanota.com   | ✓ ✓ ✓               | ○ ○                          ○            | ○                                    | □                                            | 7/12      |
| gmail.com      | ✓ ✓ ✓               | ○ ○ ○                        ○          | ○ ○ ○                                | □                                            | 7/12      |
| gmai inbox     | ✓ ✓ ✓               | ○ ○ ○                        ○          | ○ ○ ○                                | □                                            | 7/12      |
| icloud.com     | ✓ ✓ ✓               | ● ○ ○                        ●          | ○ ○ ○                                | □                                            | 7/12      |
| protonmail.com | ✓ ✓ ✓               | ○ ○ ○                        ○          | ○ ○ ○                                | □                                            | 7/12      |
| fastmail.com   | ✓ ✓ ✓               | ○ ○ ○                        ○          | ○ ○ ○                                | □                                            | 7/12      |
| inbox.lv       | ✓ ✓ ✓               | ○ ○ ○                        ○          | ○ ○ ○                                | □                                            | 7/12      |
| runbox.com     | ✓ ✓ ✓               | ○ ○ ○                        ○          | ○ ○ ○                                | □                                            | 7/12      |
| o2.pl          | ✓ ✓ ✓               | ● ●                          ●            | ●                                    | □                                            | 1/12      |
| wp.pl          | ✓ ✓ ✓               | ● ●                          ●            | ●                                    | □                                            | 1/12      |
| interia.pl     | ✓ ✓ ✓               | ○ ○ ○                        ○          | ○                                    | □                                            | 5/12      |
| sapo.pl        | ✓ ✓ ✓               | ○ ○ ○                        ○          | ○                                    | □                                            | 5/12      |
| mynet.com      | ✓ ✓ ✓               | ○ ○ ○                        ○          | ○                                    | □                                            | 5/12      |
| op.pl          | ✓ ✓ ✓               | ○ ○ ○                        ○          | ○                                    | □                                            | 6/12      |
| gmx.com        | ✓ ✓ ✓               | ○ ○ ○                        ○          | ○                                    | □                                            | 8/12      |
| mail.com       | ✓ ✓ ✓               | ○ ○ ○                        ○          | ○                                    | □                                            | 8/12      |
| qq.com         | ✓ ✓ ✓               | ○ ○ ○                        ○          | ○                                    | □                                            | 8/12      |
| daum.net       | ✓ ✓ ✓               | ○ ○ ○                        ○          | ○                                    | □                                            | 10/12     |
| zoho.com       | ✓ ✓ ✓               | ○ ○ ○                        ○          | ○                                    | □                                            | 11/12     |
| sina.com       | ✓ ✓ ✓               | ○ ○ ○                        ○          | ○                                    | □                                            | 12/12     |
| juno.com       | ✓ ✓ ✓               | ○ ○ ○                        ○          | ○                                    | □                                            | 12/12     |
| sohu.com       | ✓ ✓ ✓               | ○ ○ ○                        ○          | ○                                    | □                                            | 12/12     |
| rediffmail.com | X X X               | ○ ○ ○                        ○          | ○                                    | □                                            | 7/12      |
| freemail.hu    | X X X               | ○ ○ ○                        ○          | ○                                    | □                                            | 8/12      |
| t-online.de    | X X X               | ○ ○ ○                        ○          | ○                                    | □                                            | 11/12     |
| excite.com     | X X X               | ○ ○ ○                        ○          | ○                                    | □                                            | 12/12     |

The experiment results are shown in Table II. We group email providers based on the supported authentication protocols. Then within each category, we rank email providers based on the number of forged emails that arrived the inbox.

**Observations.** First, we find that forged emails are able to penetrate most of the email services. 33 out of the 35 services allowed at least one forged email to arrive the inbox. 30 services allowed at least one phishing email to get into the inbox. Particularly, this phishing email has penetrated email providers that perform full authentications (e.g., Gmail, iCloud, Yahoo Mail) when spoofing easychair.org and xxx.edu. This suggests that even though the email providers detected the email forgery (based on SPF/DKIM), they still deliver the phishing message to the user inbox.

Second, comparing different email providers, we observe that those without authentication schemes are indeed more vulnerable. To better illustrate the trend, we plot Figure 3(a) and Figure 3(b) to show the penetration rate (the ratio of emails in the inbox over all the emails). Clearly, email providers with no authentications have the highest penetration rate ranging from 0.56–1.0 depending on the spoofed address. Since these services did not check the SPF/DKIM record, it is possible they rely on the domain reputation or sensitivity to take different actions (e.g., Facebook is more sensitive than Easychair). As a comparison, email providers that perform authentications have a lower penetration rate: 0.43–0.77 for those that only perform SPF/DKIM, and 0.03–0.61 for those that perform full authentications.

Third, from the sender domain’s perspective, setting a “reject” policy makes a big difference. For example, facebook.com has a “reject” DMARC policy. As long as the email providers check the DMARC record, almost 100% of them rejected the emails. The only exception is iCloud which allows two forged Facebook emails to pass. We suspect that iCloud treated the sender policy as a “feature” in their decision function instead of enforcing the policy.

**Shadow Experiment.** While the primary experiments help to illustrate the problem in an intuitive manner, the choice of the 3 spoofed domains may introduce biases. Here we run a shadow experiment to make sure our observations are not entirely dependent on the 3 selected sender addresses. As previously described, the shadow experiment spoofs 60 domains, 20 for each of the 3 sender profiles: (1) No SPF/DKIM/DMARC; (2) SPF/DKIM and “none” policy; (3) SPF/DKIM
and “reject” policy. The complete list of sender domains is shown in Appendix B. The emails are also shuffled and sent with a 10-minute interval. The result is shown in Figure 3. The penetration rates are not exactly the same with the primary experiment but the overall trends and conclusions remain consistent. For example, facebook.com has a lower penetration rate than the corresponding group in the shadow experiment. This is likely because facebook.com is a more “sensitive” domain. The consistent trends are: (1) domains that published SPF/DKIM/DMARC and/or strict policies are harder to spoof; (2) email providers that perform authentication are harder to penetrate.

**Impacting Factors in the Experiment.** To determine which factors contribute more to a successful penetration, we perform a “feature ranking” analysis. We divide all the emails in the primary and shadow experiments into two classes: positive (inbox) and negative (spam folder or blocked). For each email, we calculate three features: email content (F1), spoofed sender profile (F2) and receiver authentication group (F3), all of which are categorical variables. Then we rank features based on their distinguishing power to classify emails into the two classes. We use two widely used feature ranking metrics: Chi-Square Statistics [43] and Mutual Information [16]. As shown in Table III, consistently, “spoofed sender profile” is the most important factor, followed by the “receiver authentication method”. Note that this analysis only compares the relative importance of factors in our experiment. We are not trying to reverse-engineer the whole spoofing detection system, which will require analyzing more features.

**Discussion.** It takes both the sender and the receiver email services to make a reliable email authentication. When one of them fails to do their job, there is a higher chance for the forged email to get into the user inbox. In addition, we find that email providers have the tendency to prioritize email delivery over security. When an email fails the SPF/DKIM/DMARC check, most of the providers (including Gmail and iCloud) would still deliver the email as long as the policy of the spoofed domain is not “reject”. Based on the earlier measurement result (§III), only 12.3% of the top 1 million domains have set a “reject” or “hard fail” policy, which leaves plenty of room for attackers to perform spoofing attacks.

**C. Email Clients and Security Cues**

Our results show that most email services allow forged emails to reach the inbox. Next, we examine email interfaces to see what type of security cues are displayed to warn users.

**Web Client.** During our experiment, only 6 email services have displayed security cues on forged emails to alert users, including gmail and protonmail (US), naver (South Korea), mail.ru (Russia), and 2 services from the same company in China: 163.com and 126.com. All the other email services display forged emails without any visual alert (e.g., Yahoo Mail, iCloud). Note that Gmail and Google Inbox are developed by the same company, but the web version of Google Inbox has no security cue.

Figure 4 (a)–(e) show the screenshots of the security cues. Gmail’s cue is a “question mark” on the sender’s icon. Only when users move the mouse over the image, it will show the following message: “Gmail could not verify that <sender> actually sent this message (and not a spammer)”. The red lock icon is not related to spoofing, but to indicate the communication between MX servers is unencrypted. On the other hand, services like naver, 163.com and protonmail use explicit text messages to warn users.

**Mobile Client.** Compared to the web interface, mobile apps have even fewer security cues. Out of the 28 email services with a dedicated mobile app, only 4 services have mobile security cues including naver, protonmail, gmail, and google inbox. The other services removed the security cues for mobile users. Compared to the web interface, mobile apps have more limited screen size. Developers often remove or hide less important information and UI elements to keep a “clean” interface. Unfortunately, the security cues are among the removed elements.

**Third-party Client.** Finally, we check emails using third-party clients including Microsoft Outlook, Apple Mail, and Yahoo Web Mail. We test both desktop and mobile versions, and find that none of them provide security cues for forged emails.

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**Table III**

| Feature                          | Chi-square | Mutual Information |
|----------------------------------|------------|--------------------|
| Spoofed sender profile           | 202.30     | 0.063              |
| Receiver authentication method   | 152.59     | 0.058              |
| Email content                    | 0.62       | 0.00069            |

Fig 3. Penetration rate for different combinations of the sender and the receiver. The x-axis shows 3 spoofed sender profiles: Profile1: No SPF/DKIM/DMARC (easychair.org); Profile2: SPF/DKIM and none policy (xxx.edu); Profile 3: SPF/DKIM and reject policy (facebook.com). The legend displays the 3 authentication groups of the receivers. The primary experiment covers 3 sender addresses. The shadow experiment covers 60 sender addresses, 20 for each sender profile.
emails. This is not too surprising considering that the email client and the mail server are from different companies.

D. Misleading UI Elements

Under special conditions, attackers may trigger misleading elements on the user interface (UI) to make the forged email more realistic. In the following, we describe three special conditions that can trigger misleading UIs.

Spoofing an Existing Contact. We find that when an attacker spoofs an existing contact of the receiver, the forged email can trigger misleading UI elements. Certain email services will automatically load the contact’s photo, name card or previous email conversations alongside the forged email, which helps the attacker to make the forged email look authentic. To demonstrate this phenomenon, we perform a quick experiment as follows: First, we create an “existing contact” (contact@xxx.edu) for each receiver account in the 35 email services, and add a name, a profile photo and a phone number (if allowed). Then we spoof this contact’s address (contact@xxx.edu) to send 4 forged emails to each target service (4 types of content).

Table IV shows the 25 email providers that have misleading UIs: 6 services automatically load the contact’s profile photo, 17 services have a clickable name card, and 17 services display a link (or a widget) for historical emails with this contact (screenshots in Appendix C). We believe that these designs aim to improve the usability of the email service by providing the context information for the sender. However, when the sender address is actually spoofed, these UI elements would help attackers to make the forged email look more authentic.

In addition, spoofing an existing contact allows forged emails to penetrate new email providers. For example, Hotmail blocked all the forged emails in Table I. However, when we spoof an existing contact, Hotmail delivers the forged email to the inbox and adds a special warning sign as shown in Figure I(i).

Same-domain Spoofing. Another way to trigger the misleading UI element is to spoof an email address that belongs to the same email provider as the receiver (Table V). For example, when spoofing <forged@seznam.cz> to send an email to <test@seznam.cz>, the profile photo of the spoofed sender will be automatically loaded onto the interface. Because the spoofed sender is also from the same provider, the email provider can easily load the sender’s photo from its own database. This phenomenon applies to Google Inbox and Gmail (mobile) too.

Same-domain spoofing, however, is more difficult to deliver the forged email to the inbox. As a simple experiment, we send 4 emails each target email provider by spoofing their own domains. Only 14 email providers have allowed a forged email to reach the inbox (the corresponding number is 33 for Table I). Providers also alert users more with special security cues. As shown in Figure II-(f)-(h), related email providers include protonmail, gmail and daum.net. This suggests that email providers are doing a better job in detecting forged emails that claim to be from their own services. Together with previously observed security cues, there are in total 9 email services that provide at least one type of security cues.

False Security Cues. One email provider seznam.cz displays a false security cue to users. seznam.cz performs
full authentications but still delivers a phishing email to the inbox. Figure 5 shows that seznam.cz displays a green checkmark on the sender address even though the address is forged. When users click on the icon, it displays “trusted address”, which is likely to give users a false sense of security.

E. Other Vulnerabilities

We find that 2 email services “sapo.pt” and “runbox.com” are not carefully configured, allowing an attacker to piggyback on their mail servers to send forge emails. This threat model is very different from our experiments above, and we briefly describe it using Figure 4. Here, the attacker is the sender MUA, and the vulnerable server (e.g., runbox.com) is the sender service. Typically, Runbox should only allow its users to send an email with the sender address as “{someone}@runbox.com”. However, the Runbox’s server allows a user (the attacker) to set the “MAIL FROM” freely (without requiring a verification) in step 1 to send forged emails. This attack does not help the forged email to bypass the SPF/DKIM check. However, it gives the attacker a static and reputable IP address. If the attacker aggressively sends malicious emails through the vulnerable mail server, it can damage the reputation of the IP. We have reported the vulnerability to the service admins.

VI. Effectiveness of Security Cues

Thus far, our results show that email providers tend to prioritize email delivery over security when the sender address cannot be verified. As a result, forged emails have the chance to reach the user inbox. While most email services fail to warn users, a few did have implemented visual security cues on the user interface. In the following, we seek to understand how effective these security cues are to improve user efficacy in detecting phishing emails.

A. Challenges in Security Usability Study

To evaluate the effectiveness of security cues, we seek to design a user study where participants examine phishing emails (with forged sender addresses). By controlling the security cues on the interface, we assess how well security cues help users to handle phishing emails more securely.

Implementing this idea faces a key challenge in security usability study, which is to capture realistic user reactions to security attacks. Ideally, participants should examine phishing emails without knowing that they are in an experiment. This leads to key challenges to: (1) to set up the experiment and obtain user consent upfront; (2) to test a variety of experiment conditions since each participant can only be “deceived” once.

As a result, most security usability studies follow a “role-playing” approach, where participants are instructed to play a pre-defined role in a hypothetical scenario [52], [59], [63], [65], [67]. Researchers often hide the true purpose of the study and observe the user behavior. The “role-playing” method allows researchers to test a variety of controlled settings. The drawback, however, is that participants may behave differently from the real-world.

To this end, we explore a hybrid approach by combining role-playing experiments with real-world deceptive studies (Table VI). We leverage the controlled role-playing experiments to test a variety of conditions and then use a deceptive phishing experiment to perform a more focused study.

B. Study 1: Role-Playing Experiment

First, we conduct a “role-playing” experiment where participants play a pre-defined role to read a set of phishing and non-phishing emails.

Study Procedure. We conduct a user survey where the participant plays the role of an employee (named Pat Jones) in a company. The participant is expected to see emails from his colleagues, the company’s IT department, and various online services. Each email is presented as a screenshot of the full email interface. After the participant reads each email, we ask “how would you respond to this email” with 8 options including “Reply by email”, “Contact the sender by phone or in person”, “Delete the email”, “Do nothing”, “Click on the URL”, “Copy and paste the URL to the browser”, “Visit the website directly”, and “Others (please specify)”. The last option is to collect open answers. The participant can check multiple options that apply.

Like most role-playing studies, we avoid mentioning the keywords “security” or “phishing” in the instruction. Instead, we distract the participants using a non-security task, stating that the survey is to study email usage habit, email miscommunications and how people handle different types of emails. We also ask a few distraction questions regarding how long they have been using email services, and how often they check their personal emails.

TABLE VI

| Experiment | Conditions | Variables |
|------------|------------|-----------|
| Study 1 (N₁ = 425) | role-playing | content (4) × security cue (2) |
| Study 2 (N₂ = 488) | real-world | content (1) × security cue (2) |

TABLE VII

| Email ID | A Brief Description of the Email |
|----------|----------------------------------|
| P-Dired | Upgrading your Office 360 for free. |
| P-Curiosity | Your message delivery is delayed, check the reason here. |
| P-Urgency | You got 24 hours to verify your account. |
| P-Fear | Our evidence shows that you sent a terrorist threat. |
| Legit-1 | An updated meeting schedule sent from a colleague. |
| Legit-2 | A welcome message from Twitter. |
| Legit-3 | Try-one-month-for-free from Netflix. |
| Legit-4 | Email from Facebook to reset your password. |

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Email Samples. We select 4 phishing emails representing 4 types of human emotions that are commonly exploited in social engineering including greed, curiosity, urgency, and fear. Table VII shows a brief description of the email content. All 4 emails are real-world phishing emails that once targeted our institution. For comparison, we select another 4 real-world legitimate emails. All emails contain a URL link in the email body. To avoid overwhelming the participant, each participant will only read 5 emails including the 4 legitimate emails and 1 phishing email.

Security Cues. Based on our previous measurement, most email services adopted text-based cues (Figure 4(b)-(i)). Even Gmail’s special cue (Figure 4(a)) will display a text message when users move the mouse over. To this end, we use text-based cue and make two settings, namely with security cue and without security cue. We added the security cue to all the phishing emails’ interfaces to measure its impact. We present the screenshots of the full email interfaces as shown in Appendix D. We use Yahoo Mail interface to be consistent with the later study 2. We also add the cue to 1 of the 4 legitimate emails to measure the impact of the false alert.

Recruiting Participants. We recruited N = 425 participants in total from Amazon Mechanical Turk (MTurk). MTurk users usually come from diverse backgrounds, more diverse than typical college student samples. The participants are evenly divided into 8 groups (46-65 users per group). Each group works under one experiment setting (8 settings in total: 4 phishing emails × 2 security cues). To avoid non-serious users, we apply the screening criteria that are commonly used in MTurk. We recruit users from the U.S. who have a minimum Human Intelligence Task (HIT) approval rate of 90%, and more than 50 approved HITs. Each participant can only take the survey once to earn $0.5. To make each experiment independent, we strictly limit a user to only participating in one experiment setting (the uniqueness is guaranteed both within HITs and across HITs).

Demographic analysis shows that our participants come from relatively diverse backgrounds: 44.2% are male and 55.5% are female (0.2% chose not to disclose). Most participants are 30–39 years old (34.4%), followed by users within 19–29 (32.2%), above 50 (17.2%) and 40–49 (16.2%). Most of the participants have a bachelor degree (39.1%) or a college degree (29.2%). About 20.8% have a graduate degree and 11.1% are high-school graduates.

Study Procedure. This study contains two phases. Phase 1 is to set up the deception and phase 2 carries out the phishing experiment. Like study 1, we also frame the study with a non-security purpose.

Phase 1: The participant starts by entering her own email address. Then we immediately send the participant an email and instruct the participant to check this email from her email account. The email contains a tracking pixel (a 1×1 transparent image) to measure if the email has been opened. After that, we ask a few questions about the email (to make sure they actually opened the email), and other distractive questions such as their email usage habits. Phase 1 has three purposes: (1) to make sure the participants actually own the email address they entered; (2) to test if the tracking pixel works, considering that some users may configure their email service to block images or HTML; (3) to set up the deception: after phase 1, we give the participants the impression that the survey is completed (participants get paid after phase 1). In this way, participants would not expect a second phishing email.

Phase 2: We wait for 10 days and send the second phishing email. The second email contains a benign URL pointing to our own server to measure whether the URL is clicked. In addition, the email body contains a tracking pixel to measure if the email has been opened. The second email is only sent to users whose email service is not configured to block HTML or tracking pixels (based on phase 1). We wait for another 20 days to monitor user clicks. After the study, we send a debriefing email which explains the true purpose of the experiment and obtain the informed consent. Participants can withdraw their data anytime. By the time of our submission, none of the users have requested to withdraw their data.

Email Samples. For phase 2, we use P-Curiosity, since it is the most effective content in study 1. We impersonate Amazon Mechanical Turk (support@mturk.com) to send this email. For phase 1, we use a different content (P-Greedy) to reduce the probability that the participant realizes the second email is part of the study.

Security Visual Cues. To be consistent with study 1, we also have 2 settings for security cues. The key difference is that we no longer use screenshots, but display the security cues on the actual email interface. For the group without security cue, we recruit users from Yahoo Mail. We choose Yahoo Mail users because Yahoo Mail is the largest email service that has not implemented any security cues. For the comparison group with security cue, we still recruit Yahoo Mail users and add our own security cues to their interfaces. More specifically, when sending emails, we can embed a piece of HTML code in the email body mimicking a text-based cue (see Appendix D). Note that this is how most email providers insert their warning cues in the email body (except Gmail). To be consistent, study 1 was also using Yahoo Mail’s interface to take the screenshots.
Uncontrolled Parameters. Since we cannot give any instructions in phase 2, we cannot control if a user uses the mobile app or the website to read the email. This is not a big issue for Yahoo Mail users. Yahoo’s web and mobile clients both render HTML by default. The text-based cue is embedded in the email body by us, which will be displayed consistently for both web and mobile users.

Recruiting Participants. To collect enough data points from phase 2, we need to recruit a large number of users given that many users may not open our email. In total, we recruited \( N = 488 \) users from MTurk: 243 users for the “without security cue” setting and 245 users for the “with security cue” setting. Each user can only participate one setting for only once to receive $0.5. If a user already participated in study 1, this user will be no longer qualified for study 2. In the recruiting letter, we explicitly informed the users that we need to collect their email address. This may introduce self-selection bias: we are likely to recruit people who are willing to share their email address with our research team. Our result shows that the resulting user demographics are still very similar to those in study 1: 49% are male and 51% are female. Most participants are 30–39 years old (39.1%), followed by users under 29 (31.8%), above 50 (14.5%), and 40–49 (14.5%). Most of the participants have a bachelor degree (35.0%) or a college degree (33.8%), followed by those with a graduate degree (20.7%) and high-school graduates (10.5%).

D. Ethic Guidelines

Our study received IRB approval, and we have taken active steps to protect the participants. In study 1, phishing emails are presented as screenshots (not clickable) which incur no risks. For study 2, only benign URLs are placed in the emails which point to our own server. Clicking on the URL does not introduce practical risks to the participants or their computers. Although we can see the participant’s IP, we choose not to store the IP information in our dataset. In addition, we followed the recommended practice from IRB to conduct the deceptive experiment. In the experiment instruction, we omit information only if it is absolutely necessary (e.g., the purpose of the study and details about the second email). Revealing such information upfront will invalidate our results. After the experiment, we immediately contact the participants to explain our real purpose and the detailed procedure. We offer the opportunity for the participants to opt out. Users who opt-out still get the full payment.

VII. User Study Results

We now analyze the user study results to answer the following questions. First, how effective are security cues in protecting users? Second, how does the impact of security cues vary across different user demographics?

A. Results from Role-Playing Experiments

To establish a baseline, we first analyze user behavior under no security cues. Table VIII shows the top 3 user reactions to phishing and legitimate emails. We observe that user action is highly dependent on the email content. For example, P-Curiosity and P-Urgency are most effective in tricking users to click on the URL in the email (the riskiest action). For P-Greed and P-Fear, “clicking” is the second most common action. The result demonstrates the effectiveness of phishing emails.

Figure 6 shows the “click-through rate” of the URLs when security cues are presented. Note that for study 1, the “clicking” is simulated, which refers to users selecting the “click on the URL” option in the survey. We observe that the security cue has a clear impact on the user action. Comparing with the groups “without security cues”, the click-through rate of those “with security cue” drops by 12.3%–37.9%. The examine the statistical significance of the observed differences, we run the Fisher’s exact test for the two controlled groups (“with cue” and “without cue”) and the outcome (“clicked” and “not clicked”). Across all 4 email types, the differences are significant \( p < 0.05 \). The results suggest that security cues have a significant impact to reduce the user tendency of clicking on phishing URLs. In addition, Figure 6 shows that false alerts also reduce URL clicks — false alerts do not introduce direct harms to users. The negative impact might be in the long run: if users are constantly exposed to false alerts, users are more likely to ignore similar alerts.

B. Results from Real-world Phishing Tests

For study 2, the click-through rate should be computed based on users who opened the email instead of all the users. This is because some participants did not check their inbox during our monitoring period, and did not have the chance to see the security cue. To evaluate the impact of the security

3 We also run the Chi-Square test and the results are consistent. In the rest of the paper, if not otherwise stated, we omit the Chi-Square result for brevity.
Fig. 7. The joint impact of demographic factors and security cues on click rates. For age, we divide users into Young (age<40) and Old (age>=40); For education level, we divide users into High-Edu (bachelor degree or higher) and Low-Edu (no bachelor degree). The thresholds are chosen so that the two compared groups have relatively even sizes.

| Phase   | Users | Without Security Cue | With Security Cue |
|---------|-------|----------------------|-------------------|
| Phase1  | All Participants | 243                  | 245               |
|         | Not Blocking Pixel | 176              | 179               |
| Phase2  | Opened Email | 94                   | 86                |
|         | Clicked URL | 46                   | 32                |
|         | Click Rate | 37.2%                | 37.2%             |

Fig. 8. Click-through rate of P-Curiosity in study 1 (role-playing) and study 2 (real-phishing).

cue, we first identify users who opened the email based on the tracking pixel. As shown in Table IX, 176 and 179 users did not block tracking pixels in phase1. During phase2, 94 and 86 of them have opened the email.

The results indicate that security cues have a positive impact to reduce phishing risks. When the security cue is presented, the click rate is numerically lower (37.2%) compared to that without security cues (48.9%). This result is consistent with study 1. In addition, we observe that the difference between the two user groups in study 2 is not as big as that in study 1 as shown in Figure 8. Fisher’s exact test for phase 2 shows that \( p = 0.1329 \), indicating the difference is insignificant. Under realistic phishing experiments, the impact of the security cue is not as strong as that in the role-playing setting. This may attribute to the fact that users are caught off guard in phase 2.

C. Demographic Factors

Finally, we cross-examine the results with respect to the demographic factors in Figure 7. For the role-playing statistics, we aggregate the results for all 4 types of email content. To make sure each demographic group contains enough users, we create binary groups for each factor. For “education level”, we divide users into High-Edu (bachelor degree or higher) and Low-Edu (no bachelor degree). For “age”, we divide users into Young (age<40) and Old (age>=40). The thresholds are chosen so that the two groups are of relatively even sizes. As shown in Figure 7, the click rates are consistently lower when a security cue is presented for all the demographic groups. The differences are statistically significant for all the role-playing settings (\( p < 0.05 \) based on Fisher’s test). The differences for real-world phishing are insignificant (the smallest \( p = 0.06 \) which is produced by the low-edu group). The result confirms the positive impact of security cue across different user demographics. The statistically significant result from the role-playing experiment suggests that security cues have the potential to improve user efficacy in detecting phishing emails. The result from the real-world phishing tests indicates that the impact of security cues is not as strong when users are caught off-guard. Further research is needed to improve the design of security cues to maximize its positive impact.

VIII. DISCUSSION

Email Availability vs. Security. Our study shows many email providers choose to deliver an unverified email to the inbox even when the email fails the authentication. This is a difficult trade-off between security and email availability. If an email provider blocks all the unverified emails, users are likely to lose their emails (e.g., from domains that did not publish an SPF, DKIM or DMARC record). Losing legitimate emails is unacceptable for email services which will easily drive users away. The current challenge is the slow adoption rates of these anti-spoofing protocols among the Internet and MX domains.

Countermeasures. If the email providers decide to deliver an unverified email to the inbox, we believe it is necessary to place a security cue to warn users. Our user study shows a positive impact of security cues in reducing risky user actions. Another potential benefit of implementing security cue is that it can act as a forcing function for sender domains to configure their SPF/DKIM/DMARC correctly.

There are other fixes that email providers (and protocol designers) may consider. First, email providers should consider adopting SPF, DKIM and DMARC. Even though they cannot authenticate all the incoming emails, they allow the email providers to make more informed decisions. The current
Email Confidentiality, Integrity and Authenticity. Extensive work is needed to make them easier to deploy and configure, to avoid major disruptions to the existing email operation [14].

Second, email providers should make the security cues consistently for different interfaces. Currently, mobile users are exposed to a higher-level of risks due to the lack of security cues. Another example is that Google Inbox (web) users are less protected compared to Gmail users. Third, misleading UI elements such as “profile photo” and “email history” should be disabled for emails with unverified sender addresses.

Questions Moving Forward. Security cues help to reduce the phishing risk but cannot eliminate the risk completely. Further research is needed to understand how to design more effective cues to maximize its impact on users. Another related question is how to maintain the long-term effectiveness of security cues and overcome “warning fatigue” [7]. For security-critical users (e.g., journalists, military personnel), security cues can only be a complementary solution. A better alternative is to use end-to-end encryption schemes such as PGP [28]. Further efforts are still needed to make PGP widely accessible and usable for the broad population [29], [47].

Study Limitations. Our study has a few limitations. First, our measurement focuses on public email services. Future work will explore if the conclusion also applies to non-public email services. Second, while we have taken significant efforts to maintain the validity of the user study, there are still limits to what we can control. For example, in study 1, we use a non-security task to distract the participants. It is possible that some participants may still infer that security is the focus of the study. In study 2, we only perform the user study on Yahoo Mail users with a focus on a text-based cue. Our future work will look into expanding the experiments to cover other email services and explore different security cue designs (e.g., color, font, the wording of the message). Third, we use “clicking on the phishing URL” as a measure of risky actions, which is still not the final step of a phishing attack. However, tricking users to give away their actual passwords would have a major ethical implication, and we decided not to pursue this step.

IX. RELATED WORK

Email Confidentiality, Integrity and Authenticity. SMTP extensions such as SPF, DKIM, DMARC and STARTTLS are used to provide security properties for email transport. Recently, researchers conducted detailed measurements on the server-side usage of these protocols [22], [26], [34]. Unlike prior work, we focus on the user-end and demonstrate the gaps between server-side spoofing detection and the user-end notifications. Our study is complementary to existing work to depict a more complete picture.

Email Phishing. Prior works have developed phishing detection methods based on features extracted from email content and headers [19], [21], [25], [35], [50], [55]. Phishing detection is different from spam filtering [56] because phishing emails are not necessarily sent in bulks [64] but can be highly targeted [33]. Other than spoofing, attackers may also apply typosquating or unicode characters [5] to make the sender address appear similar (but not identical) to what they want to impersonate. Such sender address is a strong indicator of phishing which has been used to detect phishing emails [40], [42]. Another line of research focuses on the phishing website, which is usually the landing page of the URL in a phishing email [17], [32], [62], [64], [69], [70].

Human factors (demographics, personality, cognitive biases, fatigue) would affect users response to phishing [51], [31], [36], [52], [59], [63], [65], [67], [15], [45]. While most of these studies use the “role-playing” method, there are rare exceptions [56], [51] where the researchers conducted a real-world phishing experiment. Our work is the first to examine the impact of security cues on phishing emails, using both role-playing and realistic phishing experiments. Our results show the different behavior of users in the role-playing and real-world settings. An early work also demonstrates behavioral differences in the role-playing experiments in online authentication scenarios [58].

Visual Security Cues. Security cues are commonly used in web or mobile browsers to warn users of insecure web sessions [24], [37], [60], [48], phishing webpages [20], [23], [67], [68], and malware sites [6].Existing work shows that users often ignore the security cues due to the lack of understanding of the attack [67] or the frequent exposure to false alarms [41]. Researchers have explored various methods to make security UIs harder to ignore such as using attractors [11], [12], [13]. Our work is the first to measure the usage and effectiveness of security cues on forged emails. We find that although security cues cannot completely eliminate users’ risky actions, they help to reduce such risk.

X. CONCLUSION

Through extensive measurements, controlled user studies and real-world phishing tests, our work reveals a concerning gap between the server-side email spoofing detection and the actual protection on users. We demonstrate that most email providers allow forged emails to get to user inbox, while lacking the necessary warning mechanism to notify users (particularly on mobile apps). For the few email services that implemented security cues, we show that security cues have a positive impact on reducing risky user actions under phishing attacks but cannot eliminate the risk. Moving forward, we believe more effective protections are needed to defend users against spoofing and phishing attacks.

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APPENDIX A – SPF/DMARC ADOPTION

We examine the adoption rate of SPF and DMARC by crawling the DNS record for Alexa top 1 million hosts. Table [X] shows statistics for January 2017.

### TABLE X

| Status            | All Domains # (%) | MX Domains # (%) |
|-------------------|-------------------|-------------------|
| Total domains     | 1,000,000 (100%)  | 818,682 (100%)    |
| w/ SPF            | 477,484 (47.7%)   | 461,402 (56.4%)   |
| w/ valid SPF      | 433,640 (43.4%)   | 418,284 (51.1%)   |
| Policy: soft fail | 268,886 (26.9%)   | 264,185 (32.3%)   |
| Policy: hard fail | 110,225 (11.0%)   | 100,665 (12.3%)   |
| Policy: neutral   | 53,218 (5.3%)     | 52,150 (6.4%)     |
| Policy: pass      | 1,311 (0.1%)      | 1,284 (0.2%)      |
| w/ DMARC          | 30,594 (3.1%)     | 29,681 (3.6%)     |
| w/ valid DMARC    | 30,594 (3.1%)     | 29,310 (3.6%)     |
| Policy: none      | 23,336 (2.3%)     | 22,728 (2.8%)     |
| Policy: reject    | 4,199 (0.4%)      | 3,581 (0.4%)      |
| Policy: quarantine| 3,059 (0.3%)      | 3,001 (0.4%)      |

APPENDIX B – SHADOW EXPERIMENT

Table XI lists the 60 domains used by the end-to-end spoofing experiment (shadow experiment). The domains per category are selected from Alexa top 2000 domains.

APPENDIX C – MISLEADING USER INTERFACE

Figure 9 shows three examples of misleading UI elements. Figure [9(a)] and [9(b)] show that when an attacker spoofs a user from the same email provider as the receiver, the email provider will automatically load the profile photo of the spoofed sender from its internal database. In both Google Inbox and Seznam, the forged emails look like that they were sent by the user “Forged”, and the photo icon gives the forged email a more authentic look.

Figure [9(c)] demonstrates the misleading UIs when the attacker spoofs an existing contact of the receiver. Again, despite the sender address (contact@xxx.edu) is spoofed, Zoho still loads the contact’s photo from its internal database. In addition, users can check the recent email conversations with this contact by clicking on the highlighted link. These elements make the forged email look authentic. The profile photos used in the Figures 9(a) and 9(b) are stolen from the contact@xxx.edu and contact@xxx.edu contacts, respectively.
the examples are not from the authors, but we received the permission from the photo owner. Eyes are obscured for the paper submission.

**APPENDIX D – PHISHING EMAIL SCREENSHOTS**

Figure 10 shows the example phishing email used in our user studies (for both study 1 and study 2). The email content is P-Curiosity. These are screenshots taken from the inbox of Yahoo Mail, reflecting what the participants saw in the phishing experiments.

![Email Screenshot](image)

(a) Without Security Cue

![Email Screenshot](image)

(b) With Security Cue

Fig. 10. The phishing email screenshot.