Committed by Accident:  
Studying Prevention and Remediation Strategies Against  
Secret Leakage in Source Code Repositories  

Alexander Krause\textsuperscript{c} Jan H. Klemmer* Nicolas Huaman\textsuperscript{c} Dominik Wermke\textsuperscript{c} Yasemin Acar† Sascha Fahl\textsuperscript{c}‡

\textsuperscript{c}CISPA Helmholtz Center for Information Security, Germany  
\{alexander.krause, nicolas.huaman, dominik.wermke, sascha.fahl\}@cispa.de  
*Leibniz University Hannover, Germany  
klemmer@sec.uni-hannover.de  
†George Washington University, USA  
acar@gwu.edu

Abstract—Version control systems for source code, such as Git, are key tools in modern software development environments. Many developers use online services, such as GitHub or GitLab, for collaborative software development. While software projects often require code secrets to work, such as API keys or passwords, they need to be handled securely within the project. Previous research and news articles have illustrated that developers are blameworthy of committing code secrets, such as private encryption keys, passwords, or API keys, accidentally to public source code repositories. However, making secrets publicly available might have disastrous consequences, such as leaving systems vulnerable to attacks. In a mixed-methods study, we surveyed 109 developers and conducted 14 in-depth semi-structured interviews with developers which experienced secret leakage in the past. We find that 30.3\% of our participants have encountered secret leakage in the past, and that developers are facing several challenges with secret leakage prevention and remediation. Based on our findings, we discuss challenges, e.g., estimating risks of leaked secrets, and needs of developers in remediating and preventing code secret leaks, e.g., low adoption requirements. We also give recommendations for developers and source code platform providers to reduce the risk of secret leakage.

1. Introduction

Version control systems (VCSs) are an essential technology for collaborative software development. Git [1], a fundamental tool to orchestrate collaborative development, has been voted as the most common tool in the recent Stack Overflow Developer Survey [2] with 93.4\% of participants specifying to use this tool in their development workflow. Git-based code repository platforms (e.g., GitHub [3] and GitLab [4]) aim to ease sharing, reviewing, and contributing to software projects. In modern development pipelines, software is commonly directly built, tested, and deployed within and from these code repositories. To deploy software on server infrastructure, automate interactions with third-party services, or handle authentication, developers need to provide secrets, e.g., credentials, authentication tokens, or secret encryption keys. However, these secrets must be protected from being leaked accidentally into the public codebase. This is no straightforward task, as recent work by Meli et al. [5] has shown that on GitHub, the most popular code sharing platform,\textsuperscript{1} thousands of automatically detectable secrets are leaked every day. GitLab also acknowledges this problem: “A recurring problem when developing applications is that people may accidentally commit secrets to their remote Git repositories.” (Gitlab [7]).

The actual impact of a leaked secret depends on the type of secret. In some cases, a leak can be highly critical, as in the case of SolarWinds: a password for their update servers was publicly pushed to GitHub in 2017. It allowed attackers to modify production code on SolarWinds’ build server and distribute vulnerable patches to up to 18,000 customers [8]. The ongoing attack was only discovered two years later [9].

Our research approach investigates code secret leakage and surrounding experiences utilizing a mixed-method approach including an online survey and semi-structured interviews to address the following research questions:

\textbf{RQ1. How prevalent is code secret leakage for developers?} The leakage of secrets and access tokens in code presents a potentially serious security threat. We survey developers about the prevalence of past secret leaks in their projects.

\textbf{RQ2. What are developers experiences with code secret leakage incidents?} Little is known about developers’ experiences when remediating code secret leaks. We interview developers on their latest and most impactful secret leaks to learn from their experiences, how they recognized a leak, and on their consequences.

\textbf{RQ3. What are developers’ experiences with code secret remediation techniques and tools?} Remediating code se-
secret leakage can be challenging. We examine deployed remediation approaches, developers’ experiences with these approaches, and developers’ requirements for approaches.

**RQ4. How are developers planning on preventing code secret leakage, and what are their experiences with prevention approaches?** Depending on the use case, prevention approaches can widely differ. We surveyed and interviewed developers to reveal prevention approaches and the experiences, challenges, and needs developers have when using them.

Overall, we conducted a survey with 50 freelancers from Upwork and 59 developers from GitHub. Additionally, for in-depth insights on developers’ experiences with code secret leakage incidents and the approaches they use to prevent and remediate those leaks, we interviewed 14 developers who had experienced code secret leakage in the past. We make the following key contributions:

**Identifying 18 Secret Leakage Prevention and Remediation Approaches.** We present results of a survey with both freelancers and GitHub developers, investigating their approaches and experiences with code secret prevention and remediation (Section 4.1). We discovered 18 approaches to prevent and remediate code secret leakage (Table 3). 30.3% of our participants reported first-hand experience with secret leakage in their projects.

**Identifying Challenges Developers face with Secret Leakage Prevention and Remediation Approaches.** In addition to the survey, we conducted in-depth interviews with GitHub developers which experienced code secret leakage in the past to gather more qualitative insights (Section 4.2). We report on how they detected the leaks, their experiences with code secret leak incidents, the approaches they use to prevent leaks, and their techniques and tools for secret leakage remediation. We identified several challenges with common remediation and prevention approaches, as well as usage reasons and needs for prevention approaches.

**Providing Recommendations to Reduce the Risk of Secret Leakage.** Based on our findings, we provide recommendations for future research, software developers, and collaborative source code platforms on how to prevent and remediate code secret leakage in Section 6.

**Providing a Full Replication Package.** To support future research, a full replication package is available in line with the effort to support replication of our work, containing all study materials in Appendix A.

## 2. Secrets in Source Code Repositories

This section introduces the mechanisms used to orchestrate software development, how they work, and how they shape security requirements for secrets. We further introduce the types of secrets relevant for our analysis.

**Version Control.** The most common approach to orchestrating software development for multiple developers is version control. Version control tracks each change or version as defined by developers as part of a list or tree. This list can be used to merge conflicting changes between multiple developers and to provide accountability for each change. Any secrets provided as part of the source code to a VCS get tracked in the list. Hence, removing secrets by providing a new version is insufficient because the old version will likely still contain these secrets. In modern VCSs (e.g., Git [1], Apache Subversion (SVN) [10]) this gets further amplified by multiple copies of changes shared across multiple systems.

**Source Code Platforms.** One common approach to software development is a central repository used as “ground truth” by all developers in their VCSs. This repository contains all developers’ software versions and often provides direct support for deploying or releasing software versions. Common examples for central repositories are open source code sharing platforms like GitHub [3] or GitLab [4], as well as closed source deployment platforms on Amazon Web Services (AWS) [11] or Google Cloud (GC) [12] offerings. Open source platforms provide source code and interaction possibilities to third parties, allowing for secret leakage to be easily spotted by external reviewers. Previous work by Meli et al. [5] used this to detect and analyze the pervasiveness of secret leakage in open source repositories. On cloud platforms like the ones provided by Amazon and Google, secret leakage mainly concerns software shared with or served to untrusted third parties and misconfiguration of deployments that leaks the secrets alongside servers. While secret leakage might be potentially less severe on these platforms, leaked secrets are also more challenging to detect, as analysis must be conducted manually. Nonetheless, secret leakage can still have severe consequences for public services since it might lead to further user data leakage or potential Denial of Service (DoS) attacks.

In this work, we investigate both freelancers working on cloud deployment platforms like AWS and GC, as well as developers active on GitHub. This allows obtaining a complete picture of code secret leakage in software development and version management.

**Secret Information.** For our analysis, we define secrets as secret information required by software to ensure security guarantees. A leak of these secrets might allow gaining unintended access to parts of the software or its dependencies. Therefore, leaks can result in vectors for privilege escalation, data leakage, or DoS attacks, depending on the kind of privilege gained. These secrets typically encompass credentials for access control within the software, certificates used for encryption, and application programming interface (API) keys used to authorize requests against this software or third-party APIs. The software needs access to these secrets to check credentials, authorize against third parties or other software components, and encrypt or decrypt information used within the software.

While practices exist to securely share secrets, like providing protected configuration files or external databases, these usually require additional setup. A developer might consider simply including the secrets as part of the source code for debugging purposes. These secrets can leak with
the source or as part of logs or other application output. Therefore, software developers require prevention and remediation techniques to deal with secrets and secret leakage during development.

3. Related Work

We discuss related work in two key areas: previous research on secret leakage in source code repositories and security information sources for developers.

3.1. Secret Leakage in Code Repositories

Some efforts have been made to quantify secret leakage in the wild in recent years. Besides those measurement studies, we shed light on the general process of secret detection and methods to improve its accuracy.

**Measurement Studies.** In 2015, Sinha et al. discussed different approaches on how to detect, prevent, and fix leaks of API keys in source code repositories [13]. In 2019, Meli et al. presented a large-scale measurement study on secret leakage in public GitHub repositories, finding more than 100,000 repositories with leaked secrets. They demonstrated and evaluated approaches to detect secrets on GitHub. In addition, potential root causes were examined, including the developer experience and practice of storing secret information in repositories [5].

**Secret Leakage Detection.** Secret scanners produce a high rate of false-positive results, as Sinha et al. demonstrated to be a significant problem in an evaluation of different detection methods. This is a major problem because developers have to review them manually – several papers utilized different approaches to improve this situation [13]. Meli et al. used past secret detection strategies; while they avoided high false-positive results using a multiphase process that combines multiple methods to detect potential secrets and secret evaluation [5]. However, automatic detection of secret leaks can be challenging. In 2020, Saha et al. applied machine learning to reduce the false-positive rate of secret scanners [14]. Furthermore, in this direction, Louinci et al. developed and evaluated machine learning classifiers to reduce false-positives [15]. Recently, Kall and Trabelsi proposed and evaluated an approach to improve the detection of leaked credentials in source code repositories [16].

3.2. Developers’ Security Information Sources

The idea to support developers with security information sources to strengthen software security has gained traction in recent years. As a result, researchers have started investigating and openly demonstrating the importance of resources that aid developers who work on security-critical software.

Acar et al. investigated the quality of Stack Overflow regarding security advice for developers in 2016. They surveyed 129 threads accessed during a study with 295 participants, finding that only 17% of them contained secure advice and code snippets [17].

Fischer et al. further investigated the impact of Stack Overflow code snippets on software development in 2017. They analyzed 1.3 million Android applications on Google Play, finding that 15.4% of them contained security-related code snippets from Stack Overflow, with 97.9% containing at least one insecure snippet [18]. In follow-up work, Fischer et al. proposed security nudging based on deep learning and demonstrated that significantly improves the situation for cryptography in Android [19]. Naikshina et al. qualitatively analyzed security problems when implementing secure password storage. The authors found conflicting advice to be an obstacle that developers struggle with [20]. Lopez et al. analyzed security-related conversations on Stack Overflow and found that developers use those to assist each other and exchange information and knowledge actively [21].

However, as found in another Stack Overflow study by Mengsu et al. that analyzed 953 groups of security-related code examples, the security implementation knowledge is unreliable as insecure solutions had more views than secure ones. Moreover, highly reputable users authored posts that were insecure in 34% of all cases [22].

Gorski et al. investigated the importance of security advice in the form of helpful warnings on the use of cryptographic APIs. They conducted a study with 53 participants, finding that 73% of participants receiving such advice fixed insecure coding in their development process [23]. To improve upon the advice for cryptographic APIs, Gorski et al. published a participatory design study with 25 developers in 2020. They propose warnings for different developer environments depending on the context, e.g., working environment and developer experience [24]. Recently, Fischer et al. conducted a study analyzing the effect of Google Search on security in software development. They conducted two studies with 410 software developers on the quality of Google search results and the effect of search result ranking on their security. Only 46.1% of participants did not encounter insecure Stack Overflow results in their Google search terms, and ranking and reordering search terms by their security significantly improved the security of the resulting code [25].

We investigate developers’ experiences with code secret leakage and management in our work. Therefore, we will take a similar approach of surveying developers and analyzing available resources. Using this approach, we identify gaps in the information available regarding code secret management for software developers and provide initial recommendations on how to improve this situation.

4. Methodology

In this section, we explain the methodology of our studies. A rough overview is depicted in Figure 1. After a detailed description of the online survey we conducted with Upwork and GitHub developers, we describe our interview study with developers from GitHub to gain further
insights into code secret incidents and their remediation and prevention approaches.

4.1. Online Survey with Developers

In this section, we provide details on the approach and structure of the survey which we conducted with 109 developers. We detail the analysis of qualitative questions as well as the quantitative questions.

4.1.1. Survey Procedure. Between September 6th and October 26th, 2022, we conducted an online survey with 50 freelancers from Upwork and 59 developers from GitHub. We used Qualtrics [26] to provide the survey and collect the respondent’s data.

Questionnaire. First, we conducted an exploratory analysis of online guides, reviewing 100 web pages for an impression of what kind of information for code secret leakage prevention and remediation is provided online. We developed our questionnaire based on the outcome of this exploratory analysis, previous research (cf. Section 3), and the research questions. In addition, we established additional areas of interest for our survey based on participants’ input during pre-testing. In both our survey and interview studies, we provided explanations for the terms code secret, code secret leakage, and code secret handling approaches for a shared understanding of the terms with participants (cf. Appendix B).

Pre-Testing. Before conducting the survey, we pre-tested our questionnaire with 11 participants. First, we conducted cognitive walkthroughs [27] with four usable security researchers. Subsequently, we had seven participants complete the survey unsupervised, with an additional feedback text box on each page of the questionnaire. Based on these pre-tests, we identified and improved unclear phrased questions and verified the survey flow, especially for the questions we had implemented with display logic.

4.1.2. Recruitment and Inclusion Criteria. We used two different recruitment strategies to obtain a diverse sample of developers: we posted job offers on Upwork and later cold emailed GitHub users who had provided a contact email address in their public profiles.²

Upwork. Upwork [29] is an online platform to hire freelancers from all over the world, including many freelancers in the broader area of IT and software development. On this platform, we published several identical postings from September 8 through October 23, 2021. Freelancers applied for our posting by writing a short proposal. This included answering our screening questions, which we used to accept only participants that met our inclusion criteria. Our criteria were that they were using VCS and platforms to ensure they potentially have to handle secrets on source code platforms. To recruit developers who worked with secret information in a source code repository in the past, we used the job category “Cloud Engineers”; we believe a cloud engineer meets our inclusion criteria. Nevertheless, all freelancers could see the post and send an application. We accepted applications when freelancers had worked with VCSs and platforms to manage their source code. They also were required to have collaborated with other people in the past. Freelancers were compensated for their time and effort with $25 to offer a competitive amount ($1/minute) so that professionals would also have an incentive to participate. We include the recruitment material, containing the Upwork posting and screening questions, in our replication package (Appendix A).

GitHub. GitHub is the most popular git-based source code platform for software development [2]. From October 18 to October 20, 2021, we cold-emailed 5,310 GitHubers (excluding those that did not exist or bounced), which had an activity on the 1st of September, 2021. We queried 103,646 contact email addresses available in the GitHubers public profiles. Three batches of 2000 randomly chosen mails were

² We refrained from extracting email addresses from commit messages (like prior research did [28]) to avoid ethical and data protection issues.
4.1.3. Survey Structure. This section outlines the topics and questions covered in the questionnaire (cf. Figure 1). The full survey can be found in Appendix B and in the replication package (Appendix A). We omitted the consent form (part of the replication package) here, which participants had to fill out before taking the actual questionnaire. They had to give their consent for participation and our data handling.

Both the participants from Upwork and GitHub received an almost identical survey: the consent form was adjusted to match the requirements of an unpaid study, we added a field where participants could optionally submit their GitHub username for possible further contact, and we changed the survey’s leave message. We used it to instruct the Upworkers to notify us via Upwork after finishing the study because they were not allowed to contact us outside of Upwork. Participants from GitHub did not have such restrictions.

Source Code Management. This initial block of questions aimed to gather a general understanding of source code management. Therefore, we asked questions regarding what types of source code repositories participants used (e.g., local only, remote platform, self- or third-party-hosted) as well as usage of different VCSs and platforms.

Experience with Secret Information. This block of questions aims to understand what type of different secrets participants encountered. We asked these questions for all past projects and the most recent project.

Threat Model for Secret Information. We consider it essential to understand how code secrets are handled in projects and to get an overall picture of the threat model. Therefore, we asked participants to answer in a matrix which other stakeholders had access to which secret information and who made this decision in the participants’ most recent project. This was followed by a brief introduction on what is considered a code secret and a code secret leakage for the remainder of the survey. We ensured that all participants clearly understood what they were asked in the following questions by providing these definitions. This question block concludes with two Likert scale questions regarding the perceived prevalence of code secret leakage and potential consequences.

Secret Leakage Remediation. One crucial aspect of a secret leak is resolving it with appropriate remediation measures. Therefore, we asked questions regarding whether the participants experienced code secret leakage themselves or knew someone who did. To get insights into current secret leakage remediation practices, participants were prompted to describe (based on the previous question’s answer) how they remediated code secret leakage themselves, how others did, or how they hypothetically would.

Code Secret Handling Approaches. The other important aspect, covered in this question block, are approaches to prevent code secret leakage in general. We again defined first what we consider a code secret handling approach and outlined that those are all approaches to avoid code secret leakage. To get an overview on prevalent practices, we asked participants in free text questions which approaches they have heard of, which ones they used, and why. Additionally, we are interested in potential problems with those approaches and therefore asked whether they had any issues using those, with which approaches, why the participant failed with that approach, and what they wanted to use the approach for. Lastly, we asked whether and how the participants helped co-workers handle secrets.

Demographics. The last block of the survey was generally about demographics. This included standard questions (e.g., age, gender, country, education, employment status), but also specialized questions to investigate the development (e.g., years in development, number of projects) as well as security experience. We also included the proposed screening questions by Danilova et al. [30] to assess whether the survey participants are actual developers, and ideally exclude those who are not. As 8 of 109 final participants (7.3%) failed those screening questions, we further investigated these cases. For example, a GitHub participant answered “Which of these websites do you most frequently use as aid when programming?” with Wikipedia and not Stack Overflow – the latter considered correct in the original paper. We hypothesize that, despite the high prevalence of Stack Overflow, Wikipedia might also be a valid answer because developers might search for background information and pseudocode on algorithms and data structures. Furthermore, the participant also provided his GitHub username, and we could verify that the participant is indeed a developer, as he regularly contributes to multiple open source projects. This was similar for some other cases. We also checked the free-text answers for the cases in doubt and found no indicators for a lack of programming experience. For these reasons, we decided against excluding participants based on failed screening questions.

4.1.4. Analysis. Our analysis is a mix of quantitative and qualitative evaluation. We report various counts and percentages of single and multiple-choice questions in text and figures in the results section of our survey (cf. Section 5). As we asked many free-text questions, two researchers used “iterative categorization” [31] to extract the used approaches on code secret prevention and remediation (Q11–15). To prevent mislabeling, the researchers first coded ten answers together and discussed problematic codes for each question. Subsequently, two researchers coded the answers independently, followed by a third researcher’s independent review of the coding. Finally, they resolved emerging coding conflicts in a consensus discussion or introduced new codes
if necessary. All previous answers were revisited and re-coded if new codes were introduced.

4.2. Interviews with Developers

To enrich and deepen the survey insights, we decided to complement those with qualitative insights from semi-structured interviews (n = 14). The interview results cover the reasons, experiences, and processes for the prevention and remediation approaches we collected in our survey. We reached saturation within the generic codes of our codebook. The average interview duration was 32 minutes (median: 32.5 minutes).

4.2.1. Interview Procedure. The 14 interviews were all conducted in June and July 2022. We utilized a setup with two interviewers. A main interviewer held the conversation with the interviewee and asked the questions according to the interview guide. A so-called shadow interviewer was present to listen and note what questions were asked and to make sure none were forgotten. At the end of the interview, the shadow interviewer also had the chance to ask questions to follow up on interesting aspects that emerged (and were not covered by questions from the interview guide). All interviews were conducted in English and remotely via a GDPR-compliant conference tool. We recorded each interview to create a transcript later on, after which we destroyed the recordings.

Pre-Questionnaire. Before the actual interview, each participant had to fill a short pre-questionnaire. This had multiple purposes. (1) We screened participants by only accepting those who experienced secret leakage. (2) We explained the purpose of the study and obtained consent for participation, our data handling, and recording. (3) Finally, we asked several demographics and background questions, which also helped the interviewer to prepare for the interview.

Piloting. We iteratively tested and improved the initial version of the interview guide after creating it. This mainly included three cognitive walkthroughs with usable security researchers. Those were basically simulations of the interviews to obtain feedback on question clarity, completeness, and to generally improve the interview guide with the interviewed researchers experience. After each interview, we tweaked question clarity to ensure a good interview flow. This was followed by two pilot interviews with developers from Upwork. As only minimal wording changes were necessary after the pilot interviews, we decided to include those together with all subsequent interviews.

4.2.2. Recruitment and Inclusion Criteria. As the goal of this study is to investigate secret leakage prevention as well as remediation, we decided to only interview developers who experienced secret leakage and therefore can report on remediation and past incidents. This was the only eligibility criteria to participate in an interview. Two developers from Upwork which also participated in our survey and stated that they experienced code secret leakage were invited and compensated with $60. Apart from the two piloting interviewees from Upwork, we recruited the remaining twelve participants via emails to GitHub users – analogous to the GitHub recruitment for the online survey. Due to legal restrictions of our institution, we offered these participants to sponsor a GitHub project with $60 instead of compensating them directly.

4.2.3. Interview Structure and Interview Guide. In the following, we describe the structure of the interview and the content of the questions. Therefore, we outline the sections containing some top-level questions and follow-up questions. The interview guide can be found in the Appendix C, as well as in the replication package (Appendix A).

Introduction. The interview sessions each started with an introduction part. This included greeting the participant, explaining the interview’s purpose and procedure, and obtaining consent from the participants. We especially underlined that we are only interested in personal opinions and experiences and not judging their case of secret leakage. Of course, the participants were free to decide which information they want to share and could skip questions anytime.

Code Secrets. In the first section, we talked about code secrets and made sure that the participants and we have the same understanding of what a code secret is. Moreover, we asked participants about their broader experiences with code secrets. This included where they came into touch with code secrets and their experiences regarding sensitivity, and code secret access.

Secret Leakage and Remediation Approaches. As we invited only participants who experienced code secret leakage, we continued with that in this section. Again, we established a uniform understanding of what a secret leak is. Then, we queried participants about their most impactful or latest (depending on what they remember in more detail) secret leak they experienced. To get detailed insights, we asked questions on reasons why the leak occurred, consequences, and changes to secret handling that were triggered by the incident. Related to the leak, we asked questions regarding the remediation of the secret leak, including experiences, challenges, involved individuals/teams, and consulted resources.

Secret Leakage Prevention Approaches. The third section is about preventive measures against secret leakage. We asked questions on approaches they have used, including related experiences, their understanding of the approach, and potential challenges. We also asked for approaches they tried to use but failed with and the reason for this, as well as approaches they know but do not use. If a participant had not taken any prevention approach, we followed up with questions to look for the reasons why. The section concludes with an open question on what they wish or want to improve for future prevention approaches.

Outro & Debriefing. After we asked all the questions, we held a debriefing with the participants to clarify any remaining questions, to give participants an opportunity to add something we might not have specifically asked for, and to gather feedback for the interview.
4.3.1. Limitations. Our work includes some limitations compensation, and we were able to at least sponsor a GitHub conducting the interviews, we could solve the issue of when offering different compensation incentives [33]. While might increase sample diversity, like prior research observed compensation for participants recruited via GitHub due to median hourly pay for software developers varies between results in an hourly wage of $60, respectively, Upwork’s to send before we could hire them for the survey. That time of 20 minutes and additional 5 minutes to answer our ve with $25. This was calibrated on an average piloting question or select “Prefer not to answer”. Therefore, both studies always offer the option to skip a question or select “Prefer not to answer”.

We compensated all Upworkers who completed the survey with $25. This was calibrated on an average piloting time of 20 minutes and additional 5 minutes to answer our screening questions within the proposal, the freelancers had to send before we could hire them for the survey. That results in an hourly wage of $60, respectively, Upwork’s median hourly pay for software developers varies between $30–$120+ [32]. Unfortunately, we could not offer any compensation for participants recruited via GitHub due to our institution’s administrative and legal restrictions. This might increase sample diversity, like prior research observed when offering different compensation incentives [33]. While conducting the interviews, we could solve the issue of compensation, and we were able to at least sponsor a GitHub project of the participant’s choice with $60.

4.3.1. Limitations. Our work includes some limitations typical for these types of survey and interview studies and should be interpreted in context. In general, self-report studies may suffer from several biases, including over- and under-reporting, sample bias, self-selection bias, and social desirability bias [28], [34]–[37]. Contributors who might have agreed to speak with us are more (or less) security-conscious than those who declined.

Furthermore, our recruitment methods focusing on Upwork and GitHub participants might introduce a sampling bias by excluding developers active on other platforms. We chose GitHub due to its popularity3 compared to other platforms like GitLab. Kaur et al. [38] compared different freelancer recruitment channels for studies with developers, and Upwork seems to be the best choice for our study. It offers recruitment for freelancers worldwide, allowing us to gather a more complete picture compared to country specific platforms. We provide details on the diversity of our sample in Section 5.1.

3. According to the Tranco list [6] generated on January 5, 2022, available at https://tranco-list.eu/list/Q674.

5. Results

In the following section, we report combined results for all 109 valid survey responses (153 respondents started, one respondent was excluded due to fake responses), as well as for all 14 interview participants. We report survey results mainly for prevalence, followed by in-depth qualitative interview results. If only a few insights were available from the survey on a specific topic, or we asked interview questions that only came up after running the survey, we only report interview results.

We report survey respondents’ and interview participants’ quotes as transcribed, with minor grammatical corrections and omissions marked by brackets (“[…]”). Survey respondents are numbered with a leading S (e.g., S56), while interview participants are numbered with a leading I (e.g., I4). Due to space constraints, we reported on relevant and interesting responses during our survey and interviews below. A full list of counts and codes for all questions is provided as part of our replication package (cf. Appendix A).

5.1. Demographics

We hired 109 respondents for the survey, and recruited 14 participants for the interviews. Overall, our survey respondents and interview participants were predominantly male, with roughly 10% female, and were about 30 years old on average. Country-wise, we have a highly diverse sample of survey respondents from more than 33 distinct countries including the U.S., India, and Germany as the top three, as well as Canada, the UK, Russia, Pakistan, Portugal, the Netherlands, Mexico, Australia, Egypt, Brazil, and Indonesia. Interview participants were from nine distinct countries, including the U.S., India, and Pakistan as the top three, as well as Canada, Belarus, Italy, Kenya, and Brazil. While most survey respondents were full-time (71, 65.1%) or part-time employees (11, 10.1%), some participants reported to be self-employed/freelancers (33, 30.3%) or students (12, 11.0%). Overall, the respondents and participants were highly experienced, with the majority of survey respondents (59, 54.1%) having developed software for more than five years. About 85% of the survey respondents and 95% of the interview participants said they taught themselves how to program. Other ways of learning were at college or university, on the job, or in online classes. Table 1 provides the detailed overview of survey respondents’ and interview participants’ demographics. Overall, the demographics in terms of gender, age, top three countries, and education are comparable to those of the last Stack Overflow developer survey [2].

5.2. Version Control Systems and Platforms

In the survey, we asked respondents for the different VCSs and corresponding platforms they used within the last 12 months. All 109 respondents reported using Git, which was by far the most popular VCS. In addition to Git, 12 respondents (11.0%) used Subversion as their next
Table 1: Selected participant demographics from both the survey and interviews. We omit “Other” and “Prefer not to disclose” answers for space reasons.

|                  | Survey | GitHub | Combined |
|------------------|--------|--------|----------|
| Started          | 52     | 101    | 153      |
| Finished         | 51     | 59     | 110      |
| Gender           |        |        |          |
| Male             | 86.0%  | 88.1%  | 87.2%    |
| Female           | 10.0%  | 1.7%   | 5.5%     |
| Non-Binary       | 0.0%   | 6.8%   | 3.7%     |
| Age [years]:     |        |        |          |
| Median           | 29.0   | 33.0   | 30.0     |
| Mean             | 31.3   | 34.9   | 33.2     |
| Country of Residence: |      |        |          |
| U.S.             | 2.0%   | 32.2%  | 18.3%    |
| India            | 20.0%  | 3.4%   | 11.0%    |
| Germany          | 0.0%   | 18.6%  | 10.1%    |
| Pakistan         | 14.0%  | 3.4%   | 8.3%     |
| Other            | 60.0%  | 40.7%  | 49.5%    |
| Development/Programming Education: |      |        |          |
| Self-taught      | 92.0%  | 94.9%  | 93.6%    |
| College/University| 54.0% | 62.7%  | 58.7%    |
| On-the-job training | 72.0% | 42.4%  | 56.0%    |
| Online class     | 60.0%  | 28.8%  | 43.1%    |
| Coding camp      | 18.0%  | 8.5%   | 12.8%    |

1 Multiple answers allowed; may not sum to 100%.

Figure 2: Platform usage reported by the survey respondents. We allowed multiple answers.

most popular VCS. Other mentioned VCSs have been Concurrent Versions System (CVS) (5, 4.6%), Microsoft Team Foundation Version Control (TFVC) (4, 3.7%), Perforce (2, 1.8%), and Mercurial (2, 1.8%).

Closely related to the high prevalence of Git, both GitHub and GitLab were the platforms most often reported by 99 survey respondents (90.8%) and 48 respondents (44.0%), respectively. Besides these public services mainly known for open source software development, respondents reported services targeted at companies which offer commercial features for private source code repositories. This included cloud solutions like Microsoft’s Azure DevOps Server (18, 16.5%), AWS CodeCommit (12, 11.0%), and GC Source Repositories (2, 1.8%), but also self-hosted solutions like Gitea (3, 2.8%). One respondent reported to use general file synchronization solutions instead of specialized services or hosting platforms. Figure 2 depicts system and service usage in detail.

Figure 3: Secret usage reported by the survey respondents. We allowed multiple answers.

Table 2: Summary of which groups of persons had access to secrets (besides the participants themselves).

|                  | Other team members | Management | Members of other teams | Public |
|------------------|--------------------|------------|------------------------|--------|
| Had access       | 171                | 90         | 42                     | 8      |
| Had no access    | 62                 | 129        | 191                    | 231    |
| I don’t know      | 2                  | 13         | 4                      | 3      |
| Prefer not to disclose | 15                 | 18         | 13                     | 8      |

Overall, hosting source code repositories using a third-party service or provider are the most prevalent for both public (95, 87.2%) or private (77, 70.6%) repositories. Contrary, self-hosting repositories were reported less than half as often and are more prevalent for private repositories (39, 35.8%) than for public ones (26, 23.9%).

5.3. Secrets, Access, and Threat Model

Regarding the types of secret information, the survey respondents reported that they predominantly handled login credentials (81, 74.3%), API keys (79, 72.5%), and authentication and access tokens (78, 71.6%) within their past projects. This is similar for their most recent projects, as shown in Figure 3. Respondents also said that they encountered cryptographic keys and certificates, either for personal or server use, as well as special service passwords or keys used in CI/CD pipelines. The same applies for the interview participants.

Which other stakeholders have access to the secrets is a relevant consideration. In general, the respondents reported 171 times that other members within the same team had access. Most commonly, these were managements (90) and members of other teams (42). Only in eight cases the general public had access. Conversely, the public had no access in the majority of cases, which can be inferred from Table 2 among other details.

Most respondents shared secrets with their team members, some with their management, only a few with other
teams, or with the public (cf. Figure 4). Developers shared passwords for services, API keys, and authentication/access tokens more often than personal keys or certificates.

Most of our interview participants could describe or construct a basic threat model for their use cases, and included sharing secrets as a risk. Six of them used a model of full confidentiality, and one participant said that code secrets are not critical to them at all.

Access control for secrets was most often configured by the respondents themselves, as 44 respondents (40.4%) reported. Sporadically, these decisions were jointly made (15, 13.8%) or at least with some involvement of the respondent (18, 16.5%). In those cases, respondents reported that decisions were made with architects, team leaders, management, the whole development team, or a security team. In 15 cases (13.8%), these parties made the decision without direct involvement of the respondents. The interviews revealed that it is also common to grant access to a secret on request. Nevertheless, there were also companies or teams where everyone was considered as trusted and got full access to all secrets, e.g., “Really just any time you ask, you’ll just get access to whatever you want.” (I16).

To summarize, developers have to deal with a diverse set of different secrets. In addition, other stakeholders like team members, management, and sometimes other teams need access to particular secrets. Sharing with the public is usually not desired.

5.4. Code Secret Leakage Incidents

Our survey respondents reported a high prevalence of code secret leakage; 51 respondents agreed or strongly agreed that it is prevalent, and acknowledged the harmful impact of code secret leakage. Most (87.0%) agreed or strongly agreed that data protection, information security, or software security issues can arise due to leaked code secrets.

This is reflected in the reports of whether survey respondents experienced secrets leakage themselves, or knew someone who did. While the majority of respondents reported not to have experienced secret leakage (57, 52.3%), 33 reported having experienced this in their projects. Notably, 42 respondents stated to know others who experienced secret leakage.

Based on insights from our interviews, we know that code secret leakage can happen multiple times. Five of our participants reported that they experienced code secret leakage more than once, and we had two additional participants stating that it happens repeatedly. “[Code secret leakage] happens four or five times a year, I would say.” (P15). Our interview participants tend to have code secret leakage on collaborative code platforms, such as GitHub. It happened in both public and restricted repositories, e.g., a GitLab self-hosted by a company. The most commonly leaked secret types were access keys, API tokens, and configuration files. Reasons for leakage included that secrets were either hardcoded as a string within a file or were leaked because of several other reasons, e.g., “[forgot] to actually add the secrets file to the gitignore, so I pushed it to GitHub.” (P16), or “If there is a new developer [...] He will just hardcode the secret key in the repo, or the code repository itself” (P11).

Recognition and Consequences. Our interview participants reported that if the leak was in a repository on GitHub, the majority of the leaks were detected by the built-in GitHub secret scanner that at least notified the affected developers by email, or triggered a revocation of the leaked secret. Many leaks were also detected randomly. In a few cases, the leak was identified because of suspicious behavior of underlying infrastructure, e.g., “somebody just looked into the console and they were surprised to see [crypto mining AWS] instances” (I1). Only a few survey respondents reported on the consequences of code secret leakage. Two mentioned that there were no consequences resulting from their leak. Others mentioned data breaches due to credential loss or service unavailability, e.g., due to DoS. Most of our interview participants suffered no consequences from their leaks, but those who did observe different immediate consequences for their company, project team, or external stakeholders. On the one hand, companies’ reputation got damaged by leaks that affected their customers, e.g., “[invalidating] a bunch of users passwords” (S4), or because they had to do a transparent disclosure. On the other hand, code secret leaks caused additional workload for the developers, e.g., for the remediation itself and for required changes to prevent the same leak in the future again, or delays, e.g., “[code secret leakage] put the brakes on the project because the customer [...] was unhappy with the event.” (I11)

Most participants reported on newly introduced prevention measures as a result of the code secret leak (cf. Section 5.6). Only two participants said that there were no
new measures introduced, e. g., due to time constraints: “No. Right now, I don’t have the time to do that.” (I8) 

5.5. Code Secret Remediation Approaches

We summarize all remediation approaches from the survey in Table 3. The interviews did not reveal any new approaches compared to the survey. Most of the interview participants have performed safe remediation measures, but three had misconceptions on how VCSs work, e. g., “We did not revoke all secrets and then regraded them. We just cleaned our Git history.” (I12). However, a cleaned Git history does not protect the secret owner from external copies of the repository made in the meantime.

Experiences. Overall, our interview participants had a positive experience with remediation approaches, but four participants mentioned problems applying the remediation.

“If you have a backward process, and you’ve never tried, would your backup process work? [...] We never really had to rotate secrets on this level. We had to make changes to the underlying application to allow this rotation to happen.” — I4

One complained that “That was painful and suspicious for everybody.” (I7).

Challenges. Our interview participants reported several challenges when applying remediation: three participants mentioned problems estimating the consequences of the leaked secrets and felt uncomfortable, e. g.,

“It was a challenge not being able to say with 100% certainty that these secrets had never been misused because of the nature of how it works. There are scenarios where somebody could’ve had that and used it in such a way that it would be very difficult to detect, and we would have missed it. I didn’t like that feeling that I couldn’t say with certainty there was no impact.” — I4

Another three participants reported problems related to the leak when applying new approaches to the project, e. g., “What doesn’t work [was] introducing tooling to actually handle secret management and just watching them for leaks.” (I6).

Lessons Learned. Those participants who were notified by the built-in GitHub secret scanner were grateful for the message. In consequence, they were able to instantly remediate the leak which reduced the risk of secret abuse, e. g.,

“[I committed] to the repo, and then just had a notification from GitHub saying, Oh, your OAuth token has been compromised. So I was like okay, I committed such a large file like five seconds ago so it is probably there and indeed it was. [...] the notification was really helpful.” — I3 or “I think that if I had not received a warning via mail, probably some days would have passed before I noticed the issue.” (I8). Notably, one participant wanted to have an enhanced process for transparent disclosures to the users, e. g., “I would like to have improved how [the remedy] was done, so it would be transparent to the user.” (I4). While four participants would like to apply the same remediation process for future incidents, they requested remediation tools to be easier to use and more effective, e. g.,

“The time it takes for you to implement and set up [...] is a huge time ticking process [...] I would really look forward to something like more advanced tools, GUI type of tool that automatically [remediates leaked secrets].” — I12.

5.6. Code Secret Prevention Approaches

We summarize all prevention approaches from the survey in Table 3. This section includes details on specific approaches, experiences, and challenges developers had with them. We used the responses on prevention approach experiences and challenges of our interview participants to identify the reasons and needs for prevention approaches, as well as problems with them.

5.6.1. Reasons and Needs for Prevention Approaches. Based on our interviews, we identified the reasons and requirements developers had for using prevention approaches.

Human Error. One of the most commonly encountered challenges in our interviews was human error. This led to participants often introducing educational and awareness measures for developers, or “[looking] for ways to automate that.” (I10).

Low Costs. The low cost of a particular solution often allowed for effortless adoption. These included approaches such as open source secret scanners, the use of environment variables, encryption, or the use of .gitignore files. Developers hesitated to automate more because of potential high costs: “Everything automated incurs a lot of costs that are hard to predict.” (I7).

Easy Adoption. Ease of use or low adoption requirements were also an important factor for our interview participants. Participants reported that security was not always in the first place, e. g., “[Our prevention approach is] not the most secure. I consider it to be okay with our way of working.” Participants appreciated a good documentation and when the approach worked with little effort, e. g., “My experience was pretty good, when working with AWS. The documentation, the community, it was very helpful [...] it is easy to do.” (I2).

5.6.2. Problems with Prevention Measures. While a third of all survey respondents (33, 30.3%) reported to have had code secret leakage in the past, only a few respondents (7, 6.4%) reported that they had failed to apply a code secret handling approach when using environment variables, git filter-branch command, or external tools. We could identify further problems with prevention measures from the participants we interviewed.
Cost and Time Constraints. Almost all interview participants complained about time and cost requirements of adopting a code secret management tool. This included the time it took to set up a method or educate all involved developers about the method. It also involved adopting the method into existing projects, often requiring refactoring work.

Documentation. Finally, documentation was one of the more commonly cited challenges, especially “the lack of actual documentation available [for] open source software or open source approaches.” (I14). This required special care and more time from developers during the setup of an approach, while securely deploying an approach in their infrastructure, and while using it.

Awareness and Education. Our interview participants also indicated that getting developers to work carefully and use a secret management approach was a challenge: if a tool required too many workflow changes, it would slow down development, so developers try to bypass prevention approaches, e.g.,

“Oh, someone was doing something off the books, by off the books I mean: Oh, they were just creating another repository that might just be not within the organisation, but maybe just under a personal account or something. Those you can’t really fix with tooling, at the end of the day those are just people problems, and ultimately that’s what it is. We have these tools, then what’s left are the people problems, and we can fix that through training, or fix that through policy.” — I6.

Maintenance. Maintaining an approach can be challenging, for example, having to update secret definitions in secret scanners. About half of our interview participants reported that maintenance proved to be challenging when adopting prevention approaches. The biggest complaint was that maintenance was so time-consuming and not user-friendly.

6. Discussion

This section discusses our findings, makes recommendations for service providers and developers, and ideas for future research.

Prevalence of Code Secret Leakage. Our first point of discussion returns to the 30.3% of participants that experienced code secret leakage in our survey, which turns out to be highly prevalent (cf. Section 5.4). One reason for this is that
previous work focused on detectable secrets, for example API keys which were included in our survey, but additionally asked for credentials that need to be shared and encryption keys a program needs to access. Our participants reported relying on the externalization, blocking, and encryption of secrets. Monitoring secrets through code scanners was less commonly reported, which we relate to the high false positive rate and additional manual review work required by developers, e.g., “Most of the time, it just raises warnings about some secrets that are really supposed to be in the code and you have to manually exclude it from being scanned.” (113), and also as established in related work [5], [13].

Usability and Adoption Aspects. While only a smaller number of participants reported having had problems with secret handling approaches, many participants stated adopting approaches because of their ease of use. At the same time, using approaches that participants used before or already knew about was a major theme. This might indicate an adoption burden that developers could not be willing to overcome, since light-weight approaches like blocking secrets via VCS (e.g., .gitignore) were adopted often while others were not. For example, using short-living secrets that are rotated regularly, is a good fit to reduce temporal attack surface and therefore potential secret leakage’s impact – but was reported rarely. However, this would require more automation. While Secret-as-a-Service (SaaS) solutions and secret management tools like HashiCorp Vault can provide this out-of-the-box, developers especially in small development teams tend to might not use them because they require additional setup and learning (cf. Section 5.6.1).

Overall, we believe that approaches need to be light-weight to be adopted, or ideally needing no developer effort at all. An excellent example for the latter is GitHub’s secret scanning program, which is enabled by default for all public repositories [39] – therefore driving adoption at scale.

Secret Leakage Reporting. An interesting mismatch we found is the low number of reports of problems using a code secret handling approach (7, 6.4%) in relation to the number of people that experienced leakage (33, 30.3%). Developers could experience leaks in their teams, for example, through a team member accidentally leaking hard-coded data not sufficiently secured through secret management approaches. Possible explanations are that developers do not relate the experienced code secret leakage with failed secret handling approaches. They may also have not used any approach, so they could not fail, e.g., “We were a startup, [we didn’t had any prevention approaches in place], we took all the measures after the secret leakage.” (12). Moreover, as a final factor, developers may have used an insufficient approach, so they have not failed this approach directly but leaked a code secret nevertheless.

Stop Privilege Creep. As mentioned before, developers may not feel responsible for secret leakage. However, our participants frequently reported other team members, other teams, management, clients, and even the public in some cases having access to secrets. This is likely caused by secrets being shared as part of the trust chain to supervisors, or as a way to hand over the product to clients or users (cf. Section 4), for example. We argue that this is unnecessary, as these secrets, especially credentials, keys, and tokens, are usually deployed in replaceable and revokable ways. Therefore, supervisors, especially clients or users, should not require access to secrets but rather the authority to revoke and replace secrets. This way, fewer stakeholders would need to manage these secrets, which leads to a reduced risk of leakage. To support developers with this, the research could put increased focus on secure key-sharing and management platforms for supervisors, or SaaS providing secret transfer and revocation between clients and contractors. In general, guidelines should not assume that supervisors have access to secrets if they lack the required experience and tools to manage them.

Lack of Helpful Resources. In both the survey and the interviews, we found a lack of comprehensive resources that guide developers in the case of secret incidents. This, however, is a burden for developers when observing secret leakage. Although secret leakage is prevalent, it is not common in a developer’s daily life, so no one expects them to instantly know what measures to take. Nonetheless, an incident idealy requires instant action. Therefore, we argue that easily accessible online resources are needed that contain actionable steps for easy, fast, and secure remediation. Even though the documentation of code hosting platforms has room for improvement in this direction, we think they are still an important place to provide such information. The problem continues when it comes to prevention approaches, developers complain about insufficient or missing documentation for deployment or usage (cf. Section 5.6.2).

Constructive Incident Handling. One interesting consequence of secret leakage was the firing of a full team or the complete termination of client contracts as a reaction to a secret leakage, potentially caused by a single person. Considering our findings on the resources for secret leakage in general, we assume that this is more of an education and awareness issue, so systemic consequences like these are unlikely to prevent further leakage, especially considering that these members/clients are usually replaced with new, potentially less experienced stakeholders. Furthermore, it is problematical when developers not report secret leakage to team members or leaders, e.g., “I didn’t ask anyone, I knew what to do, I just responded directly.” (15). This participant applied insufficient remediation approaches and others could still misuse the leaked secrets. We propose to instead use intelligent access management, support through security teams, and education of team members and clients to prevent issues like these in the future.

Developer Awareness. Developers must be more aware of the risk and consequences of code secret leakage. After studying the experiences, challenges, and needs that developers had with prevention approaches, the human factor seems to be the most relevant regarding code secret leakage prevention, e.g., “Even with all the technology that we can employ to prevent secret codes leakage, the biggest contributor to secret code leakage is the human factor, or
negligence.” (I2). Companies have to onboard new developers when entering the team to reduce the risk of secret leakage by training them or by policies (cf. Section 5.6.2). They also need to be trained and should be supported in developing and understanding threat models [40].

6.1. Recommendations for Developers

Prevention. We suggest using a combination of different approaches to decrease the likelihood of code secret leakage. First, developers should externalize secrets and block secrets to prevent a commit or push of a code secret to publicly available source code repositories. These approaches can be strengthened by also applying monitoring, especially as a pre-commit approach, so that potential code secrets can be detected before pushing a commit to the server. Sometimes, developers need to share code secrets through the repository with others. In that particular case, developers should use encrypted secrets, so unauthorized third parties cannot access them. This approach is also helpful because even secrets not aimed to be pushed to a repository are secured by accidental publishing. This prevents misuse of the code secret if leaked.

Remediation. Typical steps that should always be taken to effectively remediate code secret leakage are renew or revoke secrets that leaked, analyze leaks and using those results revising access management. We also consider it essential to notify the concerned roles for legal and ethical reasons, if not to get the appropriate help from security and privacy experts. While we consider other steps necessary, these steps will handle all consequences of a secret leak. Removal from source code and cleanup VCS history are important steps. However, they cannot save a leaked secret on GitHub or similar platforms, since those services are frequently crawled for archival purposes [5]. This and the risk of archival of public websites empathize the need to renew or revoke secrets that have leaked in public spaces. Server Operations and Systemic consequences depend heavily on company policies, the type of leak and how well leakage damage can be prevented when stakeholders can just renew or revoke secrets that have leaked. We also suggest developers to verify their approaches will work in case of a leak. Occasionally, it can be very hard, when no supporting approach is in place, e.g., rotating leaked secrets in a large collaborative project without a secret management tool.

6.2. Recommendations for Service Providers

Improving Online Guides. We found that there is a lack of actual documentation available for secret leakage countermeasures. As platforms are the central instance, those can potentially reach many developers and should therefore provide easy-to-understand, accessible, and actionable guidance on secret leakage prevention and (especially) remediation. The approaches identified in this paper might serve as a good starting point for providing comprehensive guidance.

Provide and Extend Secret Scanning. We highly appreciate the platforms’ effort in deploying large-scale secret monitoring, e.g., GitHub [39] and GitLab [7], that automatically scan public repositories for secrets and notify developers in case of a leak. In the example of GitHub, secrets with a known format are scanned using regular expressions. Those formats are supplied by several partnering service providers and limited to their API keys and access tokens. Additionally, the tokens are checked by the partner services for validity and automatically revoked if valid [41]. We believe this to be a good approach as it allows fully automated and, therefore, instant remediation. However, this is currently limited to the predefined set of secrets and would benefit from including more secret types, like SSH keys. Although those cannot be revoked automatically (there is no central service provider), at least notifying the developers would be possible.

6.3. Future Work

Based on our findings we provide and discuss ideas for future work.

Usability of Prevention and Remediation Approaches. To investigate usability aspects of prevention and remediation approaches in detail, we propose conducting a controlled experiment with developers. Those would have to solve a programming task applying different code secret leakage prevention approaches to measure and compare their usability, or they have to remediate a given secret leak.

Improving Secret Detection and Leakage Prevention. As outlined by several studies [13]–[16] discussed in related work (Section 3), general secret detection has high false-positive rates. Future work should aim to improve detection accuracy so that platforms and developers can get useful secret scanners at hand. The other aspect that needs to be researched is secret leakage prevention. One approach is to develop and evaluate API designs that aim to prevent secret leakage by forcing a strict separation of code and data, e.g., the secrets. This may ensure security by default. Related to both secret scanning and prevention, the appropriate moment for this is unclear. It could be investigated in a study, e.g., constantly scanning secrets in code through an IDE plugin and proposing fixes, when code gets committed locally, when attempting to push to a remote platform, or sometime later by a platform secret scanner.

7. Conclusion

In our online survey with 109 experienced software developers, we learn about developers experiences with code secret leakage. We identified nine approaches developers use to prevent themselves from code secret leakage and nine approaches for code secret leakage remediation. We found that 30.3% of the survey participants had code secret leakage in the past. In 14 in-depth, semi-structured interviews with developers which experienced code secret leakage in the
past, we identified several problems and challenges developers have to face when preventing and remediating code secret leakage. We make recommendations for both developers and service providers and outline ideas for future research based on our analysis. Overall, we strongly recommend that developers take preventative measures and be aware of the risks associated with leaking secret information.

References

[1] Git Project, Git, https://git-scm.com/ (visited on 01/10/2022).
[2] Stack Overflow, Stack Overflow Developer Survey 2022, https://survey.stackoverflow.co/2022/ (visited on 08/08/2022), 2022.
[3] GitHub Inc., GitHub, https://github.com/.
[4] GitLab Inc., GitLab, https://gitlab.com/.
[5] M. Meli, M. R. McNiece, and B. Reaves, “How bad can it git? characterizing secret leakage in public github repositories,” in NDSS, 2019.
[6] V. Le Pochat, T. Van Goethem, S. Tajali zadeh khooob, M. Korczyński, and W. Joo sen, “Tranco: A research-oriented top sites ranking hardened against manipulation,” in Proc. 26th Network and Distributed System Security Symposium (NDSS’19), 2019.
[7] GitLab Inc., Secret Detection, https://docs.gitlab.com/ee/user/application_secret/secret_detection/ (visited on 02/01/2022).
[8] I. Jibilian and K. Canales, The US is readying sanctions against Russia over the SolarWinds cyber attack, https://www.businessinsider.com/solarwinds-hack-explained-government-agencies-cyber-security-2020-12 (visited on 02/01/2022).
[9] L. Williams, “The people who live in glass houses are happy the stones weren’t thrown at them [from the editors],” IEEE Security & Privacy, vol. 19, no. 3, pp. 4–7, 2021.
[10] The Apache Software Foundation, Apache Subversion, https://subversion.apache.org/ (visited on 01/10/2022).
[11] Amazon Web Services, AWS CodeCommit, https://aws.amazon.com/codecommit/ (visited on 01/10/2022).
[12] Google, Cloud Source Repositories, https://cloud.google.com/source-repositories/ (visited on 01/10/2022).
[13] V. S. Sinha, D. Saha, P. Dhollia, R. Padhye, and S. Mani, “Detecting and mitigating secret-key leaks in source code repositories,” in 2015 IEEE/ACM 12th Working Conference on Mining Software Repositories, 2015, pp. 396–400.
[14] A. Saha, T. Denning, V. Srikumar, and S. K. Kasera, “Secrets in source code: Reducing false positives using machine learning,” in 2020 International Conference on Communication Systems Networks (COMSNETS), 2020, pp. 168–175.
[15] S. Lounici, M. Rosa, C. Negri, S. Trabelsi, and M. Önen, “Optimizing leak detection in open-source platforms with machine learning techniques,” in Proc. 7th International Conference on Information Systems Security and Privacy (ICISSP), SciTePress, 2021.
[16] S. Kall and S. Trabelsi, “An asynchronous federated learning approach for a security source code scanner,” in Proc. 7th International Conference on Information Systems Security and Privacy (ICISSP), SciTePress, 2021.
[17] Y. Acar, M. Backes, S. Fahl, D. Kim, M. L. Mazurek, and C. Stransky, “You Get Where You’re Looking For: The Impact of Information Sources on Code Security,” in Proc. 37th IEEE Symposium on Security and Privacy (SP ’16), IEEE, 2016.
[18] F. Fischer, K. Böttinger, H. Xiao, C. Stransky, Y. Acar, M. Backes, and S. Fahl, “Stack Overflow Considered Harmful? The Impact of Copy&Paste on Android Application Security,” in Proc. 38th IEEE Symposium on Security and Privacy (SP ’17), IEEE, 2017.
[19] F. Fischer, H. Xiao, C.-Y. Kao, Y. Stachel scheid, B. Johnson, D. Razav, P. Fawkesley, N. Buckley, K. Böttinger, P. Muntean, et al., “Stack overflow considered helpful? deep learning security nudges towards stronger cryptography,” in 28th USENIX Security Symposium (USENIX Security 19), 2019, pp. 339–356.
[20] A. Naikashina, A. Danilova, C. Tiefenau, M. Herzog, S. Decchand, and M. Smith, “Why Do Developers Get Password Storage Wrong?: A Qualitative Usability Study,” in Proc. 24th ACM Conference on Computer and Communication Security (CCS’17), ACM, 2017.
[21] T. Lopez, T. Tun, A. Bandara, L. Mark, B. Nuseibeh, and H. Sharp, “An anatomy of security conversations in stack overflow,” in 2019 IEEE/ACM 41st International Conference on Software Engineering: Software Engineering in Society (ICSE-SEIS), 2019.
[22] M. Chen, F. Fischer, N. Meng, X. Wang, and J. Grossklags, “How reliable is the crowdsourced knowledge of security implementation?” In 2019 IEEE/ACM 41st International Conference on Software Engineering (ICSE), 2019, pp. 536–547.
[23] P. L. Gorski, L. L. Iacono, D. Wermke, C. Stransky, S. Möller, Y. Acar, and S. Fahl, “Developers deserve security warnings, too: On the effect of integrated security advice on cryptographic API misuse,” in Fourteenth Symposium on Usable Privacy and Security (SOUPS 2018), 2018, pp. 265–281.
[24] P. L. Gorski, Y. Acar, L. Lo Iacono, and S. Fahl, “Listen to Developers! A Participatory Design Study on Security Warnings for Cryptographic APIs,” in Proc. CHI Conference on Human Factors in Computing Systems (CHI’20), ACM, 2020.
[25] F. Fischer, Y. Stachel scheid, and J. Grossklags, “The effect of google search on software security: Unobtrusive security interventions via content re-ranking,” in Proceedings of the 2021 ACM SIGSAC Conference on Computer and Communications Security, ser. CCS ’21, Virtual Event, Republic of Korea: ACM, 2021.
[26] Qualtrics LLC, Qualtrics, https://www.qualtrics.com/.
[27] S. Presser, M. P. Couper, J. T. Lessler, E. Martin, J. Martin, J. M. Rothgeb, and E. Singer, “Methods for testing and evaluating survey questions,” Public opinion quarterly, vol. 68, no. 1, pp. 109–130, 2004.
[28] Y. Acar, M. Backes, S. Fahl, S. Garfinkel, D. Kim, M. L. Mazurek, and C. Stransky, “Comparing the Usability of Cryptographic APIs,” in Proc. 38th IEEE Symposium on Security and Privacy (SP’17), IEEE, 2017.
[29] Upwork Global Inc., Upwork, https://www.upwork.com/ (visited on 02/01/2022).
[30] A. Danilova, A. Naikashina, S. Horstmann, and M. Smith, “Do you really code? designing and evaluating screening questions for online surveys with programmers,” in Proc. 43rd International Conference on Software Engineering, IEEE, 2021.
[31] J. Neale, “Iterative categorization (ic): A systematic technique for analysing qualitative data,” Addiction, vol. 111, no. 6, pp. 1096–1106, 2016.
[32] Upwork Global Inc., Software Developer Hourly Rates, https://www.upwork.com/hire/software-developers/cost/ (visited on 02/01/2022).
[33] G. Hsieh and R. Kocielnik, “You Get Who You Pay for: The Impact of Incentives on Participation Bias,” in Proc. 19th ACM Conference on Computer-Supported Cooperative Work & Social Computing, ser. CSCW ’16, ACM, 2016.
[34] E. M. Redmiles, Z. Zhu, S. Kross, D. Kuchhal, T. Dumitras, and E. Rothgeb, and E. Singer, “Methods for testing and evaluating survey questions,” in Proceedings of the 2018 ACM SIGSAC Conference on Computer and Communications Security, ser. CCS ’18, ACM, 2018.
[35] M. Peixoto, D. Ferreira, M. Cavalcanti, C. Silva, J. Vilela, J. Araújo, and T. Gorschek, “On understanding how developers perceive and interpret privacy requirements research preview,” in International Working Conference on Requirements Engineering: Foundation for Software Quality, ser. REFSEQ 2020, Springer, 2020.
[36] A. Senarath and N. A. G. Arachchilage, “Why developers cannot embed privacy into software systems? an empirical investigation,” in Proceedings of the 22nd International Conference on Evaluation and Assessment in Software Engineering 2018, ser. EASE’18, ACM, 2018.
[37] A. H. Mhaidli, Y. Zou, and F. Schaub, “‘We Can’t Live Without You!’ App Developers’ Adoption of Ad Networks and Their Considerations of Consumer Risks,” in Proc. 15th Symposium on Usable Privacy and Security (SOPUS’19), USENIX, 2019.
[38] H. Kaur, S. Amft, D. Votipka, Y. Acar, and S. Fahl, “Where to recruit for security development studies from: Comparing six software developer samples,” in In 31st USENIX Security Sympo-
sium, USENIX Security ’22, Boston MA, USA, August 10-12, 2022, USENIX Association, Aug. 2022.

[39] GitHub Inc., Secret Scanning, https://docs.github.com/en/code-security/secret-scanning/about-secret-scanning (visited on 02/01/2022).

[40] A. Shostack, “Elevation of privilege: Drawing developers into threat modeling,” in 2014 USENIX Summit on Gaming, Games, and Gamification in Security Education (3GSE 14), San Diego, CA: USENIX Association, Aug. 2014.

[41] GitHub Inc., Secret scanning partner program, https://docs.github.com/en/developers/overview/secret-scanning-partner-program (visited on 02/01/2022).

Appendix A.
Replication Package

To allow full replication of our research as well as meta-research, we provide a replication package (anonymized and anonymous hosting for reviewing) at https://prismatic-meerkat-6f3f86.netlify.app.

The replication package includes 1) survey and interview recruitment materials (including Upwork post and invitation as well as GitHub invite emails), 2) the survey and interview pre-survey questionnaire, 3) the survey and interview consent form, and 4) survey and interview codebooks.

Appendix B.
Survey

The following questionnaire (excluding the initial consent form which can be found in the replication package, cf. Appendix A) was used in Qualtrics to conduct the study with cloud engineers from both Upwork and GitHub:

B.1. Source Code Management

Q1. What types of source code repositories have you actively used to manage your source code within the last 12 months? Please check all that apply.

☐ Public repository (third party provider)
☐ Private repository (third party provider)
☐ Public repository (self-hosted, own server)
☐ Private repository (self-hosted, own server)
☐ Private repository (on local device)
☐ Work on local project (without a repository)
☐ Other, please specify [Free text]

Q2. What types of version control system technologies have you actively used to manage your source code within the last 12 months? Please check all that apply.

☐ Git
☐ Mercurial
☐ Subversion
☐ CVS
☐ Other, please specify [Free text]

Q3. [Displayed only if Q2 was answered with “Public repository (third party provider)” or “Private repository (third party provider)”]
Which platforms have you actively used to manage your source code within the last 12 months? Please check all that apply.

☐ GitHub
☐ GitLab
☐ Other, please specify [Free text]

Q4. What types of secret information have you personally dealt with in your projects and source code in the past? Please check all that apply.

☐ Service Passwords
☐ Personal Certificates (e.g., S/MIME certificates)
☐ Server Certificates
☐ API-Keys
☐ CI/CD-Keys
☐ Personal Cryptographic Keys (e.g., private RSA keys)
☐ Login-Credentials
☐ Auth-Token / Access-Token
☐ Other, please specify [Free text]

Q5. [Displayed only options that were also chosen in Q4.]
What types of secret information have you personally dealt with in your projects and source code in your most current project? Please check all that apply.

☐ None
☐ Service Passwords
☐ Personal Certificates (e.g., S/MIME certificates)
☐ Server Certificates
☐ API-Keys
☐ CI/CD-Keys
☐ Personal Cryptographic Keys (e.g., private RSA keys)
☐ Login-Credentials
☐ Auth-Token / Access-Token
☐ Other, please specify [Free text]

B.2. Experience with Secret Information

Q6. Who had access to which secret information in your most current project? [Select options that apply in a matrix (Table 4).]

Q7. [Displayed only if Q5 was answered.]
Who decided who had access to which secret information?

☐ I made this decision.
☐ I was involved, but the decision was made by someone else. Please specify who made the decision. [Free text]
☐ I was not involved and the decision was made by someone else. Please specify the person who made the decision. [Free text]
☐ It was a joint decision. Please specify who else was involved. [Free text]

Information. Code secrets: In the rest of this questionnaire, we will refer to so-called code secrets. All of the aforementioned response options are examples for code secrets that you might use in source code. These are for example: Service Passwords, Personal Certificates, Server Certificates, API-Keys, CI/CD-Keys, Personal Cryptographic Keys, Login-Credentials, and Auth/Access-Tokens. In general, a code secret is any secret information that your program needs to access without user-input.

Code secret leakage: This term refers to leaking code secrets, for example through source code repositories, build scripts or CI and similar approaches to source code sharing.
Table 4: Matrix the participants had to fill. Only displayed lines which were previously selected in Q5. Every cell in the matrix had a dropdown field with the options: “Had access”, “Had no access”, “I don’t know”, and “Prefer not to answer”.

| Other team members | Members of other teams | Management | Public |
|--------------------|------------------------|------------|--------|
| Service Passwords  |                        |            |        |
| Personal Certificates | (e.g., S/MIME certificates) |            |        |
| Server Certificates |                        |            |        |
| API-Keys           |                        |            |        |
| CI/CD-Keys         |                        |            |        |
| Personal Cryptographic Keys | (e.g., private RSA keys) |            |        |
| Login-Credentials  |                        |            |        |
| Auth-Token / Access-Token |                    |            |        |
| Other              |                        |            |        |

Q8. For the following questions, we are interested in your professional opinion. Please rate your agreement to the following statements.

[5-point Likert-scale from “Strongly disagree” to “Strongly agree”, and “I don’t know” option.]

- Code secret leakage is prevalent.

Q9. Code secret leakage can contribute to …

[5-point Likert-scale from “Strongly disagree” to “Strongly agree”, and “I don’t know” option.]

- intellectual property issues.
- software security issues.
- information security issues.
- data protection issues.
- Other, please specify [Free text]

B.4. Secret Leakage Remediation

Q10. Based on your experiences, please check all that apply.

☐ I experienced code secret leakage in one of the projects I have worked on.
☐ I know people that have experienced code secret leakage.
☐ I have not experienced code secret leakage.

Q11. [Displayed only if Q10 was answered with “I experienced code secret leakage in one of the projects I have worked on.”] Please tell us briefly how you remediated code secret leakage. Please also include your experiences, obstacles you went through, and consequences the secret leakage had. [Free text]

Q12. [Displayed only if Q10 was answered with “I know people that have experienced code secret leakage.”] Please tell us briefly how the people you know remediated code secret leakage. [Free text]

Q13. [Displayed only if Q10 was answered with “I have not experienced code secret leakage.”] Please tell us briefly how you would remediate code secret leakage. [Free text]

B.5. Secret Handling Approaches

Information. Code secret handling approaches include everything you do to avoid leaking secret information.

Q14. What code secret handling approaches have you heard of?

☐ Please specify: [Free text]
☐ None

Q15. What code secret handling approaches have you used in the past?

☐ Please specify: [Free text]
☐ None

Q16. [Displayed only if Q15 was not answered with “None”.] Why did you use these specific approach(es)? [Free text]

Q17. Have you tried to use code secret handling approaches but failed to use them?

☐ Yes
☐ No
☐ Prefer not to disclose

Q18. [Displayed only if Q17 was not answered with “Yes”.] What code secret handling approaches have you tried to use but failed with? [Free text]

Q19. [Displayed only if Q18 was answered.] Please explain why you failed to use the code secret handling approaches you mentioned above. [Free text]

Q20. [Displayed only if Q17 was not answered with “Yes”.] Please describe the purpose you would have used the approach(es) for. [Free text]

Q21. Have you ever helped a co-worker with handling code secrets?

☐ Yes
☐ No
☐ Prefer not to disclose

Q22. Please tell us how you helped your co-worker with handling code secrets. [Free text]

B.6. Programming Knowledge Assessment

Q23. Which of these websites do you most frequently use as aid when programming?

☐ Wikipedia
☐ LinkedIn
☐ StackOverflow
☐ MemoryAlpha
☐ I have not used any of the websites above for programming
☐ I don’t program

Q24. Choose the answer that best fits the description of a compiler’s function?

☐ Refactoring code
☐ Connecting to the network
☐ Aggregating user data
☐ I don’t know
☐ Translating code into executable instructions
☐ Collecting user data

Q25. Choose the answer that best fits the definition of a recursive function?

☐ I don’t know
☐ A function that runs for an infinite time
☐ A function that does not have a return value
☐ A function that can be called from other functions
☐ A function that calls itself
☐ A function that does not require any inputs
Q26. Which of these values would be the most fitting for a Boolean?
- Small
- I don’t know
- Solid
- Quadratic
- Red
- True

B.7. Development Experience

Q27. How long have you been developing software in general?
- Less than 1 year
- 1–2 years
- 2–5 years
- more than five years

Q28. How long have you been a cloud engineer?
- Less than 1 year
- 1–2 years
- 2–5 years
- more than five years
- not applicable

Q29. How many software projects have you worked on in the past?
- 0 projects
- 1–5 projects
- 5–10 projects
- 10–25 projects
- 25 or more projects

Q30. How did you learn to develop software? Please check all that apply.
- Self-taught
- Online class
- College/University
- On-the-job training
- Coding camp
- Other, please specify [Free text]

B.8. Security Experience

Q31. Please rate your agreement to the following statements. [5-point Likert-scale from “Strongly disagree” to “Strongly agree”].
- I am responsible for information security.
- I take care of the security in the source code I write.
- I feel confident about implementing security measurements myself.

Q32. Where did you receive training in information security? Please check all that apply.
- Self-taught
- Online class
- College/University
- On-the-job training
- Coding camp
- I didn’t receive any kind of information security training
- Other, please specify [Free text]

B.9. Demographics

Q33. What is your age? [Number field]

Q34. What is your gender?
- Woman
- Man
- Non-binary
- Prefer not to disclose
- Prefer to self-describe [Free text]

Q35. In which country do you currently reside? [Dropdown with countries]

Q36. What is the highest level of school you have completed or the highest degree you have received?
- Less than high school
- High school or equivalent
- Some college, currently enrolled in college, or two-year associate’s degree
- Bachelor’s degree
- Some graduate school, or currently enrolled in graduate school
- Master’s or professional degree
- Doctorate degree

Q37. What is your current employment status? Please check all that apply.
- Employed full-time
- Employed part-time
- Self-employed/Freelancer
- Out of work and looking for work
- Out of work but not currently looking for work
- Stay-at-home-parent
- Student
- Military
- Retired
- Unable to work
- Prefer not to disclose
- Prefer to self-describe [Free text]

Q38. How have you worked in the past? Please check all that apply.
- Solo
- As part of a software development team in a company
- As a contributor to an open source project
- Prefer to self-describe [Free text]

Q39. [Only displayed for participants from GitHub.] Please tell us your GitHub profile name. (Optional) [Free text]

Appendix C.
Interview Questions

In the following, we present the interview questions used to conduct the semi-structured interviews. The initial demographic and screening pre-survey including the consent form, and the complete interview guide can be found in the replication package (cf. Appendix A). We used a numbering format where S stands for section and Q for question.
S1 Code Secrets

S1Q1. Secret Types: Please tell us about the kind of secret information you come into contact with when writing and maintaining your source code.

Definition Code Secret: A code secret is any secret information that your program needs to access without user-input. For example, this could be an API key or a private key.

☐ S1Q1.1 Use Cases: Please provide some typical examples of where you used code secrets before?

☐ S1Q1.2 Sensibility: What do you think about the “sensibility” of these secrets? How confidential/critical are these secrets?

☐ S1Q1.3 Access: How do you decide on components or users that can access these code secrets?

☐ S1Q1.4 Participants: Who (components and people) typically had access to these secrets?

S2 Code Secret Leakage & Recommendation

You are here because you experienced code secret leakage in the past.

Definition: Code Secret Leakage refers to leaking code secrets, for example through source code repositories, build scripts or CI and similar approaches to source code sharing.

Examples: Also, a push of an API-Key to a publicly available source code platform without consequences is considered as a code secret leak. Or if the leak is inside a company platform – for example through source code repositories, build scripts or CI and similar approaches to source code sharing.

To better understand the prevalence of code secret leakage, we would like to know how often you have experienced it.

S2Q1. Prevalence: How often did you experience secret leakage?

Please elaborate on your most impactful or latest code secret leakage and the experiences you had with it.

S2Q2. Becoming aware: How did you recognize that a secret leakage happened?

S2Q3. Experience

☐ S2Q3.1 Reason: How did the code secret leak happen?

☐ S2Q3.2 Consequences: Can you describe the immediate consequences?

– S2Q3.2.1 For the Company: What consequences were there for the company? Cyberattacks? Monetary damage?

– S2Q3.2.2 Authorities (If they got attacked): Did you attempt to contact authorities/prosecute the attackers?

– S2Q3.2.3 For external Stakeholders: Data Leakage/Monetary Damage/ Other inconvenience for the client or other parties?

☐ S2Q3.3 Changes: Were there any new measures/approaches introduced to prevent secret leakage in the future?

S2Q4. Remediation: How did you react to the incident? How did you remediate the code secret leak?

☐ S2Q4.1 Experiences: What were your experiences when applying the approach(es)? What went well?

☐ S2Q4.2 Involved Roles: Who was actually involved in remediating the code secret leak?

☐ S2Q4.3 Challenges: Did you encounter any challenges? Why?

☐ S2Q4.4 Resources: Please tell us about the information sources you used to remediate the code secret leak. In example, online blogs, official documentation, other developers, or the it-security team / incident response team.

☐ S2Q4.5 Satisfaction: If a code secret leak happen again, would you like to apply the same process for future code secret leakage remediation, or is there something you would like to change or improve?

S3 Prevention Approaches

Let’s talk about your experiences regarding code secret leakage prevention approaches.

S3Q1. Used approaches: If you used prevention approaches before, please provide an example of approaches or tools you used to prevent code secret leakage. (If missing, provide examples: Externalize Secrets, Block Secrets, Monitoring, Restrict Access)

☐ S3Q1.1 Understanding: Please describe how you used the approach/tool in your project and why?

☐ S3Q1.2 Reason: What was the rationale, or reason, why this approach was introduced in your processes?

☐ S3Q1.3 Experiences: Please tell us about the experiences with these approaches and tools. Would you consider it easy to use, effective, or secure?

☐ S3Q1.4 Challenges: Please tell us about any challenges or problems you faced.

☐ S3Q1.5 Satisfaction: Does the approach fulfill your needs, or do you desire changes to improve the approach?

S3Q2. Used approach and failed with: Have you had problems trying to apply an approach or failed with an approach? Please tell us about them.

☐ S3Q2.1 Reason: What was the reason you decided for the approach you failed with?

☐ S3Q2.2 Causes of Failure: What caused the approach to fail (in your specific accident)?

☐ S3Q2.3 Improvements: What changes do you suggest could improve the concept?

S3Q3. Known, but unused approaches: Can you name any further approaches that you did not use so far and why?

☐ S3Q3.1 Reason: Why did you decide not to use those?

– S3Q3.1.1 Future Use: Do you want to try them for future projects?

– S3Q3.1.2 Experiences: Do you think the approach would be easy-to-use?

– S3Q3.1.3 Challenges: Do you think you might encounter any challenges or problems along the way? What are these challenges?

☐ S3Q3.2 Satisfaction: Do you think the approach would fulfill your needs, or are you requesting changes to improve the approach?

S3Q3 [If in S3Q1 stated]. Secret Scanner: A popular approach to detect secret leaks, are so-called secret scanners, that scan code, repositories, or commits for any contained secrets. What are your experiences if you have any?

☐ S3Q3.1 Utilization: When is this scanner executed in your project? (CI/CD, pre-commit, regular, etc.)?

☐ S3Q3.2 False Positives: Do you think the scan results are reliable? Why?

☐ S3Q3.3 Challenges: Did you encounter any challenges or problems along the way? What are these challenges? Have you solved them?

S3Q4. Not used: [If not used any approaches/tools]: Have you ever considered using an approach to prevent code secret leakage? Can you elaborate on your decision?
S3Q5. Needs: Looking back at all your experiences with code secret leakage and its prevention, what do you currently miss or think might be helpful to successfully prevent code secret leakage? (Then if nothing comes to their mind, we could specifically ask for resources, tools, approaches.)