EXPLORING SECURITY PRACTICES OF SMART CONTRACT DEVELOPERS

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ABSTRACT

Smart contracts are self-executing programs that run on blockchains (e.g., Ethereum). 680 million US dollars worth of digital assets controlled by smart contracts have been hacked or stolen due to various security vulnerabilities in 2021. Although security is a fundamental concern for smart contracts, it is unclear how smart contract developers approach security. To help fill this research gap, we conducted an exploratory qualitative study consisting of a semi-structured interview and a code review task with 29 smart contract developers with diverse backgrounds, including 10 early stage (less than one year of experience) and 19 experienced (2-5 years of experience) smart contract developers.

Our findings show a wide range of smart contract security perceptions and practices including various tools and resources they used. Our early stage developer participants had a much lower success rate (15%) of identifying security vulnerabilities in the code review task than their experienced counterparts (55%). Our hierarchical task analysis of their code reviews implies that just by accessing standard documentation, reference implementations and security tools is not sufficient. Many developers checked those materials or used a security tool but still failed to identify the security issues. In addition, several participants pointed out shortcomings of current smart contract security tooling such as its usability. We discuss how future education and tools could better support developers in ensuring smart contract security.

Keywords Smart contract, security, blockchain, developer

1 Introduction

Blockchains are cryptographic platforms that can securely host applications and enable the transfer of digital assets in a decentralized manner. Smart contract blockchains like Ethereum are increasingly capable of supporting sophisticated computations (a.k.a., decentralized apps or dApps) \[1\]. Smart contracts are program scripts that define customized functions and rules during transactions, and can run autonomously once deployed on a blockchain \[2\]. To support this unique form of computation, domain specific programming languages, such as Solidity and Vyper have been created to allow developers to write smart contracts.

A wide variety of industry applications in finance, healthcare, and energy have been rapidly exploring the use of blockchain technology and smart contracts to enable system transparency and traceability. Since deployed smart contracts can perform critical functions of holding a considerable amount of digital assets, tokens or currencies in circulation, they become a hotbed for attacks. According to DeFi Pulse\[3\] there is about $109B USD worth of total value locked (TVL) as of November 2021 controlled by deployed smart contracts in Decentralized Finance (DeFi) applications. While DeFi is a promising domain and has the potential to disrupt traditional financial systems, there has been several security incidents, in which digital tokens worth of millions of dollars have been stolen. In June 2016, vulnerabilities in the Maker DAO (decentralized autonomous organization) smart contract code were exploited to empty out more than two million Ether, which were worth 40 million USD \[3\]. This attack exploited the reentrancy vulnerability in the ‘splitDAO’ function of the code. Since the code was not designed carefully, a call to the function

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\[1\]https://defipulse.com/
that behaved as a regular call was modified into a recursive call and used to make multiple withdrawals, effectively depleting the account. Section 2 provides a technical overview of blockchains and smart contracts.

More recently, since DeFi started skyrocketing in 2020, there has been a new wave of smart contract attacks that led to the loss of hundreds of millions of dollars in value (e.g., [4]). Clearly, security is critical for smart contracts, and various smart contract security resources and tools have been created. However, it is not clear how people who write smart contracts (we denote as smart contract developers) think about and approach security in smart contract projects. To help bridge this gap, we conducted an exploratory qualitative study consisting of a semi-structured interview and a smart contract code review task with 29 smart contract developers with diverse backgrounds, including 10 early stage (less than one year of experience) smart contract developers and 19 experienced developers (2-5 years of experience).

Research questions. Specifically, our study aims to answer the following research questions:

- **RQ1:** How do smart contract developers approach or ensure security for smart contracts? Are there any differences between early stage and experienced developers?
- **RQ2:** How do smart contract developers conduct code reviews and whether they are able to identify common smart contract security vulnerabilities in the code?

Summary of findings. Our study findings show that our participants have a wide variety of smart contract security perceptions and practices, including various tools and resources they used. In general, the experienced developers tended to have more awareness of smart contract security (e.g., vulnerabilities, best practices, resources, tools) and perform better in the code review task than their early stage counterparts. Early stage developers tended to think security is not important for their projects because they do not think their projects have much impact in part because they are often not deployed in the mainnet and thus are not an interesting target for attackers. As a result, they often lack motivations and awareness of smart contract security issues as well as resources and tools about smart contract security. In the code review task, our early stage developer participants had a low success rate (15%) of identifying security vulnerabilities in the reviewed code. In comparison, 55% of the experienced developers were able to identify these common vulnerabilities and many used a combination of security tools such as static analysis, and interactive call graphs. Our hierarchical task analysis [5] of their code reviews implies that just by accessing standard documentation, reference implementations and security tools is not sufficient. Many developers especially those early staged did check those materials or use a security tool but still failed to identify the security issues. In addition, both experienced and early stage developers expressed their challenges with existing smart contract security tools. They pointed out lack of comprehensive tools to identify existing smart contract security vulnerabilities. They also found those tools hard to use (e.g., their user interfaces and the fact that these are separate tools that they have to use outside of the compiler).

Main contributions. Our work makes the following contributions: (1) our rich interview data offer novel results on the various security perceptions and practices of smart contract developers with diverse backgrounds; (2) results from our smart contract code review task sheds light on how smart contract developers actually examine smart contract code for security vulnerabilities; and (3) we discuss implications for security education and tools that could better support developers in ensuring smart contract security.

2 Blockchain and Smart Contract

The financial industry is seen as a primary user scenario of the blockchain concept. Blockchain is well known not only because of its popular application - cryptocurrency, but also for the characteristics of solving the process inefficiencies in financial services, by tracing ownership over a longer chain of changing buyers overtime. It is a sequence of blocks, which hold a complete list of tamper-resistant transaction records in a distributed fashion without any central authority [6,7]. Each block contains a timestamp, the hash value of the previous block, and a nonce, which is a random number for verifying the hash using cryptographic means. [6]. It guarantees reliability and consistency of data by adopting decentralized consensus mechanism [8,9]. Blockchain ecosystem contains multiple components- a core blockchain software that consists of client software such as Go Ethereum [10] in the case of Ethereum. People participating in a blockchain network run this client software, called node, which is often bundled with software/hardware wallets [11].

The most popular blockchain systems, Bitcoin and Ethereum, Ethereum is a decentralized, open-source blockchain with smart contract functionality. It enables developers to build decentralized applications with built-in economic functions in smart contracts [12]. While providing high transparency, and neutrality, it also reduces/eliminates censorship, and reduces certain counterparty risks. Ether is the native cryptocurrency of this platform and second-largest cryptocurrency by market capitalization2

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2https://coinmarketcap.com/
Smart contracts are essentially containers of code that encode real world contractual agreements in the digital realm [13]. It is a protocol that can automatically verify and process the content that represents a binding agreement between two or more parties, where every entity must fulfill their obligations of the contract. Once a smart contract is confirmed by the consensus protocol and submitted to the blockchain, it will be run in terms of the prior negotiation without the interference of any third party. The code execution of smart contract is distributed and verified by the network nodes in a decentralized blockchain network [12]. It can enable the encoding of complex logic including, payoff schedule, investment assumptions, interest policy, conditional trading directives, pricing dependent on geographic or other environmental input, etc [14]. Gaming, music distribution, remote purchases, and many other business interactions can utilize automatically-enforced smart contracts for secure and verified transactions, without a need for intermediaries or third-party trust [14].

There are many smart contract languages, such as Solidity, Serpent, and Vyper. On Ethereum, the most popular smart contract language is Solidity [3]. Solidity is a JavaScript-like scripting language with static types. Solidity is strongly-typed and has built-in constructs to interact with the Ethereum platform. Programs written in Solidity are compiled into low-level untyped bytecode to be executed on the Ethereum platform by the Ethereum Virtual Machine (EVM). The EVM is a low-level stack-machine with an instruction set for identifying contracts and calling out to different contracts based on signatures, exception-related instructions, and transaction cost computation. Data is stored either on the blockchain, in the form of persistent data structures, or in contract local memory. In Ethereum, solidity smart contracts are generally designed to manipulate and hold funds denominated in Ether.

3 Related Work

3.1 User Studies of Security Practices

The existing studies on end-users and their attitude towards security and privacy of emerging technologies discussed human factors of software security [15] and how developers were considered as the “weakest link.” Research highlighted the need for a deeper understanding of the evolving field of software development [16]. To this end, [17] outlined an agenda towards understanding developer’s attitude, available security development tools, and proposing design suggestions to support developers in building secure applications. There was frequently cited research on developer’s lack of security education [18] and security thinking during writing code [19], which was perceived as the reason for different software vulnerabilities. The assumption was that if developers have learned about security, they could better avoid vulnerabilities [20]. To advocate software security education, some presented that there was a lack of security guidelines mandated by the industries [21], [22] which lead to the lack of ability [18] or proper expertise [23] to identify vulnerabilities. In this work, we aim to uncover details about security practices in real-world development and deployment in the emerging landscape of smart contracts.

3.2 Smart Contract Vulnerabilities

Smart contracts are running on distributed and permission-less networks, which leads to vulnerabilities due to the malfunctioning of the smart contract execution. The financial aspect of smart contracts makes them very tempting attack targets, and a successful attack may allow the attacker to directly steal funds from the contracts. Recent literature introduces common vulnerabilities in EVM-based smart contracts, including re-entrancy [24, 25, 26], unhandled exception [27, 28], integer overflow [29, 24], and unrestricted action or access control [30, 24]. For re-entrancy to be exploited, there is a call to an external contract which invokes and re-entrant callback to the contract [26]. Some low-level operation such as “send,” “transfer,” and “call” are dangerous and can lead to vulnerabilities if they do not handle exceptions [27]. Severe consequences could happen by integer overflow where funds of a contract could become completely frozen [24]. Lack of critical authorization check can lead to execution of arbitrary code [30].

Blockchain technologies are evolving dramatically which are creating design flaws in smart contract languages. Developers of decentralized apps are often confronted with changing platform features [31]. Thus, common software weaknesses such as access control, incorrect calculation, race condition and many other security weaknesses may be amplified on blockchain platforms [4]. Also, smart contracts are utilized as an anonymous payment method, which is an attractive target for hackers. The infamous disasters involving the DAO [5] and the Parity Wallet [6] have highlighted such risks. Attackers exploited programming bugs to steal approximately $70M USD. Recently, a series of suspicious

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3https://docs.soliditylang.org/en/v0.8.13/
4https://swcregistry.io/
5https://hackingdistributed.com/2017/07/22/deep-dive-parity-bug/
6https://fortune.com/2016/06/18/blockchain-vc-fund-hacked/
transactions happened in yCREDIT smart contract where a number of minted tokens were inconsistent. xToken suffered attacks with a loss of $24M USD. One attack was due to a flash loans within the xSNXa contract. Recent work shows systemic consensus-layer vulnerabilities due to miner extractable value (MEV) where attackers can front run orders by observing and placing their own orders with higher gas fees.

Recent study identified 16 major vulnerabilities in smart contracts, and limitation of analysis tools to identify the vulnerabilities. Most of the known vulnerabilities in smart contracts are related to the fallback function where attackers could hijack the invoked contract and force it to execute. A study pointed out that there were 34,200 contracts marked as vulnerable in a million samples due to vulnerabilities related to contract programming languages’ design defects. Some research focused on demonstrating the difficulties of estimating vulnerabilities in practice. They surveyed six academic projects with 21,270 vulnerable contracts within datalog based queries level exploit discovery in EVM traces to contrast the reported and actual vulnerabilities in those smart contracts.

3.3 Smart Contract Security Methods/Tools

In order to ensure smart contract security, a wide variety of practices have been adopted to operate at different stages of smart contract development life cycle.

Testing tools. A large number of tools have been developed to analyze either contract source code or its compiled EVM bytecode, and look for known security issues, such as re-entrancy, overflow, etc. Some of the well-known tools are Oyente, ZEUS, Maian, SmartCheck, ContractFuzzer, Vandal, Ethainter, Security, and MadMax. ConsenSys Diligence - an enterprise for comprehensive code reviews of smart contracts developed Mythril which supports detecting security vulnerabilities in EVM-compatible blockchain and MythX to cover a wider range of security issues.

Development and testing frameworks. Truffle is the most common development framework for smart contracts. It allows developers to write both unit and integration tests. Another development environment is Hardhat which facilitates running tests, automatically checking code for mistakes, and interacting with a smart contract, runs on a development network. It provides plugins for code coverage, measuring gas usage per unit test, automatically verifying contracts on Etherscan, etc. As a local blockchain, Ganache is one of the most popular standalone implementation of the EVM built for development purposes. There is also a go-to suite of tools for developers called Remix. It is known for its convenient browser IDE which supports development, testing and deploying smart contract.

Code auditing. Code auditing is an integral part of the defensive programming paradigm, which attempts to reduce errors before the software is released. Audits should preferably be performed while contracts are still in the testing phase. However, given the relatively high cost of auditing (usually around 30,000 to 40,000 USD), some companies choose to perform audits later in their development cycle. Some of the tools used frequently in auditing are Surya, Mythril, and MythX. Third party companies who perform audits include Trail of Bits, OpenZeppelin, ConsenSys Diligence, etc. During audit, vulnerabilities are detected in three main ways: (1) extracting features of malicious code, and doing semantic matching on source code; (2) using mathematical approaches to prove a system’s completeness, where auditor specifies every possible input and lists every situation that might happen; (3) generating a control flow graph by contract’s logic units by which auditor can traverse all code paths to detect logical design flaws. Furthermore, code auditing depends on many factors such as time, budget, and resources availability in different organizations. Code auditing is an extra layer of security instead of a primary consideration. Recent research has been driving towards security from the beginning posture rather than depending solely on auditing.

Bug bounty programs. Another common practice for organizations is to run bounty programs. It remains ongoing throughout a contract’s lifetime and allows community members to be rewarded for reporting vulnerabilities. Com-

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7 https://blocksectream.medium.com/deposit-less-get-more-ycredit-attack-details-f589f71674c3
8 https://blocksectream.medium.com/deposit-less-get-more-ycredit-attack-details-f589f71674c3
9 https://github.com/enzymefinance/oyente
10 https://github.com/solidified.io/
panies or projects run bounty programs, e.g., the 0x project\textsuperscript{19} offers bounties as high as $100K USD for critical vulnerabilities.

3.4 User Studies of (Secure) Smart Contract Development

Recent work has focused on security assessment tools for smart contracts\textsuperscript{42} and comparing existing tools for their capabilities to identify vulnerabilities\textsuperscript{43,39}. The majority of the tools were still in progress, and several shortcomings were identified for improvement\textsuperscript{44}, such as the user interfaces for visualizing results. Also, the root causes for the occurrence of severe smart contract vulnerabilities were discussed\textsuperscript{45}, but notably only technical factors were covered. These approaches were helpful, however they did not address developers’ actual practices with the underlying programming languages which could facilitate writing buggy code in the first place. A closer look at the incidents revealed that eventually a large number of vulnerabilities in smart contracts occurred because of developers’ mistakes\textsuperscript{45}. Hence, avoidance of vulnerabilities in smart contracts meant secure development with users in mind during the development life cycle\textsuperscript{42}. This included a well thought-out design as well as adhering to best-practice patterns for ensuring security\textsuperscript{42}, and involving users/developers during the design process. Research proposed that developers’ needs should be considered as a primary requirement in new tool design for smart contracts\textsuperscript{46}.

There is a lack of empirical user studies that examine smart contract development, particularly security practices. One exception is a study by Parizi et. al\textsuperscript{47} where they compared the uses of smart contract languages: Solidity\textsuperscript{20}, Pact\textsuperscript{21} and Liquidity\textsuperscript{22}. This study is focused on the usability aspect of smart contract programming languages by measuring the amount of time for novice participants to complete programming tasks. To the best of our knowledge, our study is one of the first to empirically explore smart contract developers’ security perceptions and practices. Despite the wide range of vulnerabilities and exploitation reported in smart contracts\textsuperscript{35}, and existing research on assessing the effectiveness of security analysis tools\textsuperscript{48}, we still know little about whether, when and how smart contract developers deal with the security aspect of their contract code. We try to bridge these research gaps in this work.

4 Method

Our study was inspired by user studies of software developers’ security practices (e.g.,\textsuperscript{49,47,50}). We conducted a user study with smart contract developers. The study included a semi-structured interview to understand participants’ smart contract development experiences and practices particularly around the security aspect. The study also includes a smart contract code review task to understand how developers identify vulnerabilities in smart contracts. Since Solidity is the most popular language for smart contracts\textsuperscript{51}, and has a simple syntax\textsuperscript{47}, we decided to focus on Solidity developers in our study. The study was approved by the IRB and conducted online during the summer of 2021. Each study session took about one hour and each participant was compensated a gift card worth of $30 US dollars. The study data were collected upon participants’ permission. All quotes included in this paper have been anonymized to protect privacy of the participants. Below we describe the protocol of our study.

4.1 Participant Recruitment

To help reach a wide range of developers, we recruited through different methods: (1) snowball sampling from our contacts in the broader Ethereum community, (2) posting on our Twitter and Facebook as well as ethresear.ch and Discord channels, and (3) contacting Solidity developers of public smart contract projects on GitHub.

We selected participants based on the responses of our screening survey. Respondents were invited to our study if they met our selection criteria: a) is a solidity-based smart contract developer; b) has some smart contract development experience; c) should provide proper explanation of their developed smart contract(s). We did two waves of recruitment. In total, we received 67 responses from our screening survey. We reached out to 38 of them via email based on our selection criteria. In total, 29 people agreed to participate in our study. Eight participants were from word-of-mouth by our contacts in the Ethereum community. Two were from GitHub public projects. 19 were from our postings on Twitter, Facebook, Discord, and the ethresear.ch online forum. We decided not to recruit further because no new insights emerged from our four latest study sessions, indicating a sign of theoretical saturation\textsuperscript{52}.

The participation in our study was completely voluntary, and participants were allowed to quit at any time. Each participant received a $30 Amazon e-gift card upon completion of the study. The whole study lasted about one hour,

\textsuperscript{19}https://0x.org/docs/guides
\textsuperscript{20}https://solidity.readthedocs.io/en/develop/
\textsuperscript{21}https://pact.kadena.io
\textsuperscript{22}https://github.com/OCamlPro/liquidity
where the initial interview took about 25 minutes, the code review task 25 minutes, and the exit interview about 10 minutes.

4.2 Initial Interviews

Since we did not know much about the phenomenon under investigation (security practices of smart contract developers), we felt that an exploratory qualitative study would be appropriate since it will provide rich data about the phenomenon. Therefore, we started with a semi-structured interview. In the study, we first presented the study consent to our participants. Once they have agreed, we proceeded with a semi-structured interview. We designed the interview scripts based on our research questions outlined in the introduction section. The entire script can be found in our study GitHub. We started by asking about their general background including their usage of programming languages, their role and experiences in developing software, as well as their experience and motivation on how they started smart contract development. Sample questions are like “What role do you typically play in cryptocurrency projects?”, “What programming languages do you use regularly?”, “How did you learn smart contract development?.” Then we asked a series of questions to understand their knowledge and experiences of developing smart contracts and handling security issues thereof. Their experiences include tools for writing contracts, guidelines for smart contract development, factors considered and challenges encountered during development.

To understand how smart contract developers tackle potential security risks in the development process, we also asked about their current practices (e.g., use of coding standards, policies, and security analysis tools as well as any educational resources) related to smart contract security. To get rich anecdotal data, we also asked about their personal experiences and stories of how they handled specific smart contract security related issues in the past.

Thus, interview questions get at not only general practices but also specific cases (e.g., “What are the most frequent security issues you have encountered? Please tell us about any incident that you can remember when your developed smart contract was exposed to certain security vulnerabilities. What types of methods/tools are you/your organization currently using to ensure the security of smart contracts? Have you used any automated security analysis tools? Can you explain more about the tools? Is it easy or hard to use?”). Through qualitative analysis of interview data, we identified coding themes emerged from the data on development practices of smart contract developers. Example themes include “functionality correctness is a priority,” “security is not important when projects are deployed on testnets,” “Solidity language limitations make smart contract security hard.” The code review task was designed to show how “concretely” they go about reviewing the code and identifying potential vulnerabilities.

4.3 Smart Contract Code Review Task

The next study component was a smart contract code review task. Since code review is a common task in smart contract development, this task was designed to understand how smart contract developers conduct code review particularly for identifying security vulnerabilities. Each participant was asked to review one smart contract that we created. Specifically, they were instructed to do the following: (1) share their computer screen and allow us to record the screen with their permission to understand how they conduct the code review; (2) have at most 25 minutes for the code review; (3) search/use any resources/tools they need; (4) i. review the code; ii. identify security vulnerabilities and/or areas for improvement; iii. modify the code accordingly; (5) explain the modifications and rationale behind them.

4.3.1 Code Review Task Design

We designed this study component to model the real-world code review task that developers would be reasonably expected to encounter in their smart contract development. We chose to include two vulnerabilities in each smart contract where one vulnerability is more well-known and should be easier to identify than the other. We measured the difficulty level of these vulnerabilities based on our pilot participants’ feedback. We also included some minor code writing standard issues, such as indentation, space/tabs, and blank lines which should be easily detectable.

We chose four smart contract vulnerabilities based on the recent literature on smart contract exploitation ([24, 48]) and reports ([24] on most frequent exploitation. The four chosen vulnerabilities are: 1) re-entrancy, 2) unchecked low level calls, 3) integer overflow, and 4) improper access control. The first two vulnerabilities were included in one contract and the last two vulnerabilities in another contract. The contract code can be found in our study GitHub repo. Table 1 summarizes the four security vulnerabilities we included in the code review task and ways to avoid/address these vulnerabilities.

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23Our study repo includes study scripts, smart contracts for the code review task, analysis code book: https://github.com/AccountProject/SmartContract
24https://swcregistry.io/
Table 1: Vulnerabilities in code review task as well as effective strategies to address these vulnerabilities.

| Vulnerability               | Description                                                                 | Possible Prevention Technique                                           |
|----------------------------|----------------------------------------------------------------------------|------------------------------------------------------------------------|
| Reentrancy                 | Calling external contracts is that they can take over the control flow, and make changes to the data that the calling function is not expecting. | Make sure it does not call an external function or use the Checks-Effects-Interactions pattern. |
| Unchecked Low-Level Calls   | This can lead to unexpected behaviour and break the program logic. A failed call can even be caused by an attacker, who may be able to further exploit the application | Ensure to handle the possibility that the call will fail by checking the return value. |
| Integer Overflow           | An integer overflow occurs when an arithmetic operation attempts to create a numeric value that is outside of the range | Use of vetted safe math libraries for arithmetic operations consistently throughout the smart contract system. |
| Improper Access Control    | Exposing initialization functions by wrongly naming a function intended to be a constructor, the constructor code ends up in the runtime byte code and can be called by anyone to re-initialize the contract. | Implement controls so withdrawals can only be triggered by authorized parties or according to the specs of the smart contract system. |

We created our two smart contracts using a boilerplate contract of ERC-20 token which provides basic functionalities to transfer tokens and allow tokens to be approved so they can be spent by another account. The ERC20 token contract is commonly used as a basis for smart contract (DeFi) projects. Numerous DeFi projects and open source smart contracts adopt the ERC20 standard interface. The ERC20 standard interface can create tokens on Ethereum and can be re-used by applications such as wallets and decentralized exchanges. We believed that most smart contract developers would have some familiarity with this contract and our pilot study confirmed our assumption. Our contracts for code review have the same basic ERC-20 functionalities.

To select smart contracts vulnerabilities, we conducted an extensive review of exploited smart contracts from different security vulnerability reports, such as Smart Contract Weakness Classification and Test Cases (SWC)\(^{25}\), Consensys Known Attacks\(^{26}\), different GitHub repositories and etherscan source code of abandoned or previously exploited smart contracts\(^{27}\). To make our code review task realistic for participants to complete in 25 minutes, we trimmed down some auxiliary functions from the selected contract sample code. Both of the contracts for code review are ERC-20 based and there are no major differences in size. We then modified the contract by adding the vulnerabilities. We got feedback from solidity programmers and tested the contracts in our pilot. We included comments in the contract code for participants to understand the overall context of the contract functions. We also added explicit comments to those function that are not part of the ERC20 token standard (interface).

During the task, we provided the instructions verbally. After giving the instructions, we provided the GitHub link which contained the smart contract for review to the participants through Zoom chat. We provided some extra time for participants to set up their development environment before we started counting the 25-min task time. This set-up time which was not counted in the 25 minutes. Since the target participants are very busy, we limited our study to about one hour. Code review time (25 minutes) is based on the code length, which varies significantly in practice (10-1000 lines of code). It is a limitation but for practical reasons it was a trade-off between study time and participant’s availability.

4.4 Exit Interview

Once the task was completed or the time ran out, the participants were asked a few questions in the exit interview. We asked their opinions about the task they worked on and how they perceived the difficulty of the task. We also asked their overall experience with the code review task and if they would like to share any other experiences of security practices in smart contract development. We also asked if they had any feedback on this study and whether this study has changed their perspectives and/or attitudes towards smart contract security. Finally, we asked about their desired features of security tools to help them better ensure smart contract security. We received the modified code by each participant via email. This data allowed us to determine whether they correctly identified the vulnerabilities.

\(^{25}\)https://swcregistry.io/

\(^{26}\)https://consensys.github.io/smart-contract-best-practices/known-attacks/

\(^{27}\)https://etherscan.io/directory/Smart-contracts
4.5 Pilot study

We conducted two rounds of pilot study with a total of four smart contract developers to test our study design. We revised our interview questions and code review tasks based on their feedback. Details of the pilot study and the changes we made based on the pilot results are described in the Appendix 8.1.

4.6 Data Collection and Analysis

Study data were obtained primarily through Zoom audio/video/screen recording of the interviews and the code review task upon participants’ permission. We collected each participant’s interview responses, smart contract code from the code review task, think-aloud responses, and exit interview responses during the session. We transcribed the recordings and analyzed the transcripts using thematic analysis [53].

4.6.1 Qualitative Data analysis

Two researchers performed open coding independently on a sample of the data (20%). Then they met regularly to discuss the coding and reached a consensus on a shared code book before coding the remaining data. We calculated the inter-coder reliability in Cohen’s Kappa, which was 0.94 and considered very good [54].

Our open coding followed an inductive analysis method to explore practices and behaviours towards smart contract development. Our codebook includes 46 codes. Then data and concepts that belonged together were grouped into sub-categories. Further abstraction of the data was performed by grouping sub-categories into generic categories, and those into main categories. We then grouped related codes, organized them in high-level themes, and iterated this process to finally produce 18 themes to interpret the results of smart contract developers’ security practices, security concerns and individual experiences and challenges with tools and development methods. Some example themes are: perceived priorities in smart contract development, use of information resources, use of development tools, use of smart contract security tools, and limitations of smart contract security tools.

4.6.2 Assessing The Code Review Task Outcome

For the code review task, recorded videos of the participants performing the code review task were analyzed to measure the success rate, based on whether a participant correctly identified the security vulnerabilities in the smart contract. Prior to conducting the lab study, we created and verified the correct/secure solutions for each task. The general ideas for these solutions are described in Table 1. This ensured that we could verify whether participants successfully identify the vulnerabilities and provide a correct/secure answer or fix. We also paid attention to how they conducted the code review, e.g., whether and how they searched and used any resources/tools. Specifically, we conducted a hierarchical task analysis [5], a common Human-Computer Interaction (HCI) technique, to break down the process of how a participant performed the code review into detailed steps and to help identify how the processes of successful and failed code reviews differ. We also checked whether their suggestions or modified code could potentially fix the vulnerabilities.

5 Findings

In this section, we present our study results in diverse views and practices of smart contract security. We have found none of the early stage developers consider security as a main factor and lack awareness of relevant information resources and tools for smart contract security. We also discuss our lab study in terms of task success rate and time to identify security vulnerabilities, use of different code review approach. We found that experienced developers (3-5 years of experience) were able to identify these common vulnerabilities and many used a combination of security tools such as static analysis, and interactive call graphs.

5.1 Participants

We had a total of 29 participants. 24 of them are male and the rest are female. More than one third of our participants are from the US, and the rest are from many other countries, including India, China, Australia, Ghana, Egypt, Iran, UK, Canada, Germany, New Zealand, Greece. Our participants include fourteen smart contract practitioners who work full-time in the DeFi industry, three freelance smart contract developers, three software developers mainly worked in other domains, eight college/graduate students, and one professor. Table 2 summarizes our participant demographics. To explore the relationship between our participants’ different levels of Solidity development experiences and their security practices, we categorized our participants into two groups: early-stage (less than 1 year of experience) and
Table 2: Participant demographics and background. We consider those with less than one year of experience in Solidity as early-stage developers and those with longer experience as experienced developers.

| ID     | Gender | Country    | Occupation         | Year(s) Exp. | Focus                                      | Types of Projects Developed                                  |
|--------|--------|------------|--------------------|---------------|--------------------------------------------|-------------------------------------------------------------|
| P1     | Male   | USA        | Developer, DeFi Company | <1            | Backend                                   | Distributed systems, cryptography                             |
| P3     | Male   | USA        | Masters Student, CSE  | <1            | Backend                                   | Security applications in Software                            |
| P4     | Male   | Australia  | Researcher, DeFi Company | <1            | R&D                                       | Smart Contract                                               |
| P5     | Male   | India      | Bachelors student, CSE | <1            | Front-end                                 | React apps development                                        |
| P7     | Female | USA        | Masters Student, CSE  | <1            | Backend                                   | Security product on authorization                             |
| P9     | Male   | USA        | Professor, CSE       | <1            | Backend                                   | Security auditing of smart contracts                         |
| P16    | Male   | India      | Freelance Smart Contract Dev | <1          | Backend                                   | Blockchain based project                                    |
| P20    | Male   | USA        | Bachelor Student, CSE | <1            | Backend                                   | Class project on Blockchain                                 |
| P24    | Female | Canada     | PhD Student, CSE     | <1            | Full-Stack                                | Research on blockchain                                       |
| P28    | Male   | USA        | Developer, De-Fi Industry | <1         | Backend                                   | Distributed Ledger Technology                                |

| Experienced |
|-------------|
| P2         | Female  | USA        | Developer, DeFi Company | 2-3          | Front end                                 | Software for Retail                                          |
| P6         | Male    | USA        | PhD Student, CSE       | 3-5          | Backend                                   | Formal framework in cryptography                             |
| P8         | Male    | Ghana      | Freelance Smart Contract Dev | 3-5        | Full-stack                                | Blockchain software from scratch                             |
| P10        | Male    | USA        | Developer, DeFi Company | 3-5          | Full-stack                                | Software for privacy, blockchain                             |
| P11        | Female  | China      | Dev, DeFi Company      | 2-3          | Full-stack                                | Application for finance, game, NFT                          |
| P12        | Female  | Egypt      | Freelance Smart Contract Dev | 3-5        | Full-Stack                                | Blockchain based project                                    |
| P15        | Male    | Iran       | Software Developer     | 3-5          | Backend                                   | Application for health sector                                |
| P14        | Male    | UK         | Co-Founder, dev, DeFi Company | 2-3        | Backend                                   | Developed DAO, solidity projects                             |
| P15        | Male    | India      | Software Developer     | 2-3          | Backend                                   | Machine learning and AI project                              |
| P17        | Male    | India      | Software Developer     | 2-3          | Backend                                   | Smart contract for donations                                 |
| P18        | Male    | USA        | Dev, Defi Company      | 2-3          | Full-stack                                | Research and architecture in DeFi                           |
| P19        | Male    | USA        | CTO, DeFi Company      | 3-5          | Backend                                   | Snapchat and DeFi token                                     |
| P21        | Male    | India      | Bachelor Student       | 2-3          | Backend                                   | Hyperledger and Ethereum related project                     |
| P22        | Male    | Germany    | PhD Student, CSE       | 3-5          | Backend                                   | Blockchain for data storage                                 |
| P23        | Male    | Australia  | Developer, DeFi Industry | 2-3          | Backend                                   | Financial smart contracts (Tracer)                          |
| P25        | Male    | Greece     | Developer and Researcher | 2-3         | Backend                                   | Gaming / betting smart contract                             |
| P26        | Male    | Germany    | Developer, DeFi Industry | 2-3          | Backend                                   | Auditing Smart Contract                                     |
| P27        | Male    | Canada     | Developer, De-Fi Industry | 3-5          | Backend                                   | Layer 2 project in smart contract                           |
| P29        | Male    | New Zealand| Developer, De-Fi Industry | 3-5          | Backend                                   | De-Fi Project                                                |

experienced (2-5 years of experience) in Solidity smart contract development. We had 10 early-stage developer participants and 19 experienced developer participants.

5.2 Programming and Development Background

Programming background. Our participants reported using multiple programming languages. Besides Solidity, other languages mentioned are Python (55%), Javascript (39%), C++ (24%), Java (13%), and C (13%). Besides smart contract development, they also reported other expertise such as backend development (69%), front end development (7%), full-stack (21%) and research (4%).

Information resources used for smart contract development. Our participants mentioned a number of information resources that they used for smart contract development. Common sources are Solidity documentation (34%), Google search (31%), Stack Overflow (17%), YouTube (14%), as well as documents published by the Ethereum Foundation (14%), OpenZeppelin28 (14%), and ConsenSys29 (14%).

Tools for smart contract development. Participants mentioned a large set of tools they used to develop, deploy, and test their smart contracts. Most frequently used tools included Truffle (76%), Remix (55%), Ganache (38%), HardHat(34%), and Waffle (21%).

Practices of code re-use. 52% (15) of our participants (5 early-stage and 10 experienced developers) talked about using code from open source libraries such as OpenZeppelin, a popular implementation of the ERC-20 and other ERC standards. For instance, P24 said “I try to use the libraries from OpenZeppelin because they are kind of best practice, for example, for access control and things like that.”

Experience in code review. 76% of our participants had different levels of Solidity code review experience. Some conducted code review by pen and paper (P1,P6,P20, P25), some used automated test scripts/tools (e.g., OpenZeppelin ERC20 library) for code review (P2, P24, P26, P27), and some used both techniques (P14, P19, P24, P26). Seven out of 10 early-stage developers had prior code review experience in Solidity. P1, P3 and P7 indicated that they had experience but are not experts. Four out of 15 experienced developers did not have prior code review experience.

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28https://openzeppelin.com/
29https://consensys.net/
in Solidity. However, among the seven participants who did not have code review experience in Solidity, three of them had much code review experience in other languages, such as Python (P3), RUST (P8) and Golang (P22). Four participants (P4, P5, P13, P17) did not have any prior code review experience in any language.

5.3 Perceptions of Smart Contract Security

Is security a priority in their smart contract development? We asked our participants their priorities in smart contract development, most participants (83%) did not claim security as a top priority and cited three main reasons: (1) they need to ship projects fast and security becomes secondary, (2) their projects forked other popular projects (e.g., Uniswap), which are often already vetted by the community, and (3) someone else internally or externally will conduct security audits. However, the majority of participants considered functional correctness (66%) and gas optimization (48%) as important priorities. Both are actually closely relevant to security. We saw functional correctness as a form of security earlier. Gas optimization saves transaction cost but also reduces the possibilities of economic security issues such as front-running (e.g., attackers observe a user’s buy transaction in the mempool and submit another buy transaction with a higher gas fee to outbid the user’s transaction).

One early stage and 11 experienced developer participants mentioned security as one of the factors they considered in smart contract development. Figure 6 in the Appendix presents the different factors our participants mentioned. However, only five participants (P3, P11, P14, P26, P27) said that they considered security as a priority during development. Except P3, all other four participants were experienced developers. They evaluated different aspects of security. For instance, P11 explained: “I considered security the most important factor because you need to know the address in the blockchain to send and receive, […] the address should be unique and it’s secure and cannot be changed by someone else.” P14 instead paid more attention to the reentrancy and front-running issues, and explained “[...] a lot of security thought, can someone front run this? Can they reenter it?”

Why (Solidity) smart contract security is hard? Five participants (P25, P14, P18, P19, P24) pointed out that the Solidity language design has some inherent limitations for maintaining security. P25 (as well as P14, P18, P19, P24) noted the ambiguity of Solidity programming language where function definition is not explicit: “It is very limited and so this requires you to go through hoops to do very basic things like access that you could do easily in [a] mainstream language”. He suggested that adopting functions like in Python. P19 spoke about another issue with Solidity: “Contract work[s] like state machine when you send a transaction. It only appears like state changes. But in regular program, you can differentiate read only calls and state changes. Solidity can not do that.” He also added the difficulties of performing proper string and array manipulations due to a lack of direct language/library support in Solidity. To fill this gap, this participant created his own assembler to correspond between Solidity instructions and machine code instructions.

5.4 Practices of Smart Contract Security

Our participants explained their practices of ensuring smart contract security. They shared their methods and their experiences in working with other team members. We start by discussing the different strategies they followed.

Manual inspection of smart contracts. Eight (28%) participants reported using manual code inspection as the main method for identifying security issues in their smart contracts. For instance, P28 tried to think as an attacker while he read through the code. “Reading through the code and then thinking of how to steal everyone’s money or do something
malicious.” As an other example, P6 combined flow charts with manual code inspection: “I think step one always is to draw flow chart of where information are flowing and where [...] coins can get stuck and protocols. To find places where reentrancy can happen. So, having a graph of good representation can solve a lot of logical issues. And then trying to look at problems how calls are being made? Is there contracts gonna run out of gas? All that is just manual code inspection.” As P6 read through the code, he created flow charts to help track the system logic but also identify issues of reentrancy and gas cost.

**Use of smart contract testing or security tools.** Nine (31%) participants reported using smart contract tools for security purposes. Testing or security tools, such as static analysis tools (17%), Truffle testing suite (14%), Remix security plugins (14%), MythX (7%) and Slither (3%).

**Limitations of current smart contract security tools.** About one third of our participants (P4, P6, P7, P12, P14, P19, P22, P24, P25) spoke about the limitations of existing security tools for smart contracts. For example, P6 explained: “I don’t think there are any automated tools [...] Even once you deploy the contract, having to write a constructor, then testing that contract is a really cumbersome activity. It’s non-trivial, and there really exists no tool to help. Even truffle testing is quite hard to use in my experience.” P25 also complained about the Truffle tool being slow: “I didn’t like truffle because it was a little slow. I had to rely on global imports into Files and then had to run all files from command line using truffle suit for testing which make iterative development complex.” P24 similarly stressed the importance of better integration of security tools into the development process, saying “I don’t like to write code in an IDE and use another tool to test. I like my compiler to do everything for me. I don’t like to use extra tool for checking bugs and security.” Better understanding and improving the usability of smart contract security tools is a direction for future research.

After presenting how our participants self-reported their security practices, next we will cover how they actually behaved in identifying security issues in the code review task.

### 5.5 Findings from The Smart Contract Code Review Task

In this task, we asked our participants to review a smart contract to identify any security issues or areas of improvement. We also asked their rationale for any code modifications.

**Task performance of identifying security vulnerabilities.** Overall, 55% of participants found at least one security issue in the smart contract. 28% (N=8) of participants identified both (all) vulnerabilities in the smart contract. More specifically, Reentrancy had the highest identification success rate (53%), followed by improper access control (43%), unchecked low-level call (40%) and lastly integer overflow (29%).

Figure 1 shows our participants’ performance (success rate) in identifying different security vulnerabilities. We observe that experienced developers had much higher success rate (55%) than their early stage counterparts (15%). Table 3 summarizes each participant’s task performance as well as the method they used to identify the security issues.

In addition, we recorded and calculated how long participants took in successfully identifying each security issue, as summarized in Table 4. We observed that for reentrancy early stage developers spent more time. None of the early stage developers identified the low-level call vulnerability. Only one early stage developer (P28) identified the overflow (about 7 minutes) and insecure access control issues (about 8 minutes). Code Review task time is detailed in Table 4, Appendix E.4 For participants who failed to identify any security issues, they all used up the 25-minute period we gave them.

**Developers with formal training in smart contracts were associated with better task performance.** We also explored how our participants learned to code smart contracts and observed a trend that those participants who had formal educational training in smart contracts tended to do better in the code review task and had more awareness of security practice. We found six out of eight participants (who identified both security vulnerabilities in code review task) had formal training for writing smart contracts. Some of them (P12, P25, P27) designed courses on smart contract and has been teaching in universities and community groups. P27 said - “I learned smart contract coding as a part of my research in school. Then I helped design and develop the technical content to lecturer where I was the one to initiate that course in a college in Canada.” P28 mentioned formal learning for smart contract coding is important to avoid known vulnerabilities. “There’s always new developers who are just throwing code out there as quickly and fastly with very little testing, no peer code review, no security considerations, and no experience and learning. So they’re introducing problems. A lot of seasoned developers with awareness stopped doing this ages ago, and there’s always new developers popping up, launching code with known vulnerabilities in them.” We also found 10 out of 13 participants (who failed to identify any security vulnerabilities in code review task) relying on informal learning (e.g., YouTube, Stack Overflow, adhoc google search, Solidity docs) for smart contract coding. Future research can further investigate the relationship between formal training and security practices of smart contracts.
Different approaches to code review. Participants used different ways to identify security issues during the task. Most of them manually read through the code. Only four of them used security assessment plugins and/or static analysis tools.

For instance, P14 used linting and static analysis tools in his code review. He successfully identified both vulnerabilities (reentrancy and unchecked low-level call) in the contract. We did a hierarchical task analysis to break down how a participant conducted the code review into detailed steps. Figure 3 illustrates P14’s code review process.

P14 started by quickly setting up his development environment, where he created a folder with a package manager and installed development dependencies so he could compile the contract. He stressed the importance of having the folder ready to compile first. He explained, “Let’s get some scripts, dev dependencies and I’m going to run that here and run yarn. Things that will allow me to compile, check coverage, test, clean it. I will make sure that it’s linting as well. ”

After compilation, he started looking for possible security issues. He also manually went through the Open Zeppelin implementation of ERC20, “I would literally track this whole thing and I’d use Open Zeppelin implementation. I can go through this implementation and see if it’s good or not.” Importantly, he did not blindly take or trust the Open Zeppelin implementation even though it is widely used. After manually checking the code, he explained some of the possible vulnerabilities. For instance, he pointed out a potential reentrancy vulnerability in the withdraw function: “it is withdrawing if the amount is less than the amount to just return false and subtracts the amount before it does the accounting before it’s actually sending anything out, which is pretty crucial for preventing someone re-entering the function, which would be really bad.” He then ran static analysis with Slither to confirm his suspicion. He interpreted the Slither output: “we can see if there’s any fatal errors. Yeah, so exactly- state variables written after the re-entering pool. That’s only if it’s not successful. so I mean there’s reentrancy in over here.”

Unlike P14, many participants just did manual inspection of the code without using any security tools. For instance, P6 only did manual inspection. But he also searched information resources such as security best practices in the official Solidity documentation and the Open Zeppelin documentation. He also successfully identified both vulnerabilities (integer overflow and improper access control) in the contract (task2) he reviewed. For instance, upon manual inspection, he found that the amount of a local variable is calculated as the product of two other variables _cat and _value. The later can have an extremely large value which can overflow the product and make it zero (as shown in Figure 5). He suggested using the Safe Math library.

P2, an early stage developer, was one of the 13 participants who did not find any security vulnerabilities in the code review task. He was assigned the same task (task 1) as P14. Figure 4 illustrates P2’s code review process. He started by skimming through different functions of the code. After almost five minutes, he said, “This seems like a security flaw here in “transferfrom” function. I will look deeper later.” Then, he went through a few functions randomly, such as “transferfrom”, “allowance,” and put another comment on the transfer function: “I did misread the “transferform” before. I was looking at in a wrong direction. Now it makes a lot more sense and then you’re verified with a certain amount of tokens.” At this point, he was not sure about vulnerabilities. For confirming some of his suspicion, he searched “ERC-20 code” and “Reentrancy,” in the Open Zeppelin contract example. He also read through some code examples in GitHub repos that included ERC-20 code example. As the time was close to 25 minutes, he concluded: “I don’t see anything major. Not really seen doing much wrong.”

What is interesting here is that even though P2 found and read some reference documentations about ERC20 (e.g., Open Zeppelin) similar to P14, P2 was still not able to identify the security issues. A similar example is P22 (whose
review process flowchart is Figure 9 in the Appendix). In addition, many of our participants (e.g., P3, P15, P20, P21) who did use security tool(s) also missed some security issues. These observations suggest that just by accessing standard documentation, reference implementations and security tools is not sufficient in helping developers (especially early stage developers) identify security issues. We included a few more examples of how other participants performed the code review task in the Appendix 8.3.

**Code modifications for improvement.** For the 16 participants who have successfully identified at least one vulnerability, seven of them modified the contract code for improvement and six (21% of all participants) correctly fixed the vulnerabilities. The modified code snippets are included in the Appendix 8.4. Due to the time constraints, the other nine participants did not modify the code but verbally commented on how the contract code could be improved. Conceptually, all the comments would fix the security vulnerabilities.

**False positives.** We also observed that sometimes our participants incorrectly thought they identified security vulnerabilities, which were actually not vulnerabilities (i.e., false positives). Four (14%) participants had false positives and they tended to have less prior experience with smart contract development. For instance, P1 thought there was a security issue in the “approve” function (Figure 15 in Appendix). He explained, “it is possible for adversary to call the function in StandardToken and this would bypass ‘whennotpaused’ modifier.” However, there was a “Pausable” base contract, which can implement an emergency stop mechanism where “whenNotPaused” modifier was only callable when the contract is not paused. Also when it is called by the owner to pause, it triggers the stopped state. Hence, one cannot bypass the “whennotpaused” modifier. P1 googled different keywords related to ERC20 and finally found the Open Zeppelin ERC20 contracts for reference.

**Resources used during the task.** During the code review task, participants were told that they could use any resources or tools. Most frequently searched resources include Solidity documentation (28%), Open Zeppelin (17%), and Google search with keywords (17%). Some of the search terms used were “parent contract call,” “safe math parent class,” “fallback function,” “emit in solidity,” “reentrancy vulnerability example,” “example of transfer and withdraw function,” “constructor example,” and “solidity version specific details.”

**Tools/Frameworks used in the task.** After sharing the GitHub link of our smart contracts for the code review task, participants were initially using Remix (48%), VS code (28%), Sublime Text Editor (14%) and IntelliJ IDEA (3%), or manually conducting code review on GitHub (7%) for the task. In addition, 24% of participants used a static analysis tool, such as Remix static analyzer plugin, Slither, and Oyente, during the task. One participant used a dynamic analysis tool, MythX during the code review task.

```solidity
function batchTransfer(address[] _receivers, uint256 _value) public
whenNotPaused returns (bool) {
    uint cnt = _receivers.length;
    require(cnt > 0 && cnt <= 20);
    uint256 amount = mul(uint256(cnt), _value);

    // below is possible taken care of by super.transfer
    require(_value > 0 && balances[msg.sender] >= amount);

    // balances[msg.sender] = balances[msg.sender].sub(amount);
    for (uint i = 0; i < cnt; i++) {
        // checks if receivers are address(0x0) --> revert if true
        super.transfer(_receivers[i], _value);
        // balances[_receivers[i]] = balances[_receivers[i]].add(_value);
        // emit Transfer(msg.sender, _receivers[i], _value);
    }
    return true;
}
```

Figure 5: Part of the contract code P6 reviewed and modified. The first few lines had a overflow vulnerability where local variable is calculated as the product of `cnt` and `_value`. By having two `_receivers` passed into `batchTransfer`, with that extremely large `_value`, attacker can overflow amount and make it zero.
6 Discussion

6.1 Recap of Major Findings

Our study aimed to understand the security practices and challenges of smart contract developers. Overall, we found that our participants had diverse perceptions and behaviors regarding smart contract security.

While the majority (83%) of all participants did not mention security as a priority in their smart contract development, a large portion of all participants mentioned functional correctness (66%) and gas optimization (48%) as important priorities, both of which are closely relevant to smart contract security.

Five participants said that they considered security as a priority in their smart contract development. Among the five participants, only one of them was an early stage smart contract developer while the other four were experienced developers. Early stage developers tended to think security is not important for their projects since they felt their projects have little impact in part because they are not deployed in the mainnet and thus are not an interesting target for attackers. As a result, they often lack awareness of smart contract security issues as well as resources and tools about smart contract security. While the impact of security vulnerabilities in smart contracts deployed on the testnet is limited, there is a missed opportunity to motivate and educate (early stage) developers about smart contract vulnerabilities and corresponding best practices. Prior research in traditional software development suggests that this kind of perception can have a long-term negative effect on development practice [41]. Prior work on software security has also shown the value of improving security education and awareness [55, 49].

In comparison, our experienced developer participants indicated that their companies or projects have faced security issues, including known and edge cases. For security practices, they mentioned using best practices and resources, such as Open Zeppelin contracts (reference implementations) and Solidity official documentation. However, their responses also suggested that they tended to rely on security audits as the final security evaluation.

In terms of their actual behavior in the code review task, early stage developer participants had a much lower success rate (15%) of identifying security vulnerabilities in the reviewed code than their experienced counterparts (55%). The majority (72%) of all participants only did manual inspection of the code where they tried to run through possible execution traces to find out vulnerabilities as well as edge cases. 20% of early stage developers used security tool(s) in the code review, compared with a higher percentage (32%) of their experienced counterparts. The early stage developers only used Remix with its security plugin whereas the experienced developers used more tools such as static and dynamic analysis tools (e.g., Slither, MythX). Our hierarchical task analysis of their code reviews implies that just by accessing standard documentation, reference implementations and security tools is not sufficient. Many developers checked those materials or used a security tool but still failed to identify the security issues.

In addition, one third of the participants pointed out many limitations of smart contract security tools, such as lack of comprehensive libraries, integration of these tools as part of the IDE as well as complex user interfaces. How to make existing smart contract security tools more usable is an important direction for future work.

6.2 Smart Contract Security vs Traditional Software Security

There exists systematic software security guidelines, NIST[30] and OWASP[31] to facilitate secure software development practices amongst business owners and software developers for traditional software. These help software producers to mitigate the potential impact of exploitation, and address the root causes of vulnerabilities to prevent future recurrences. Compared with traditional software, smart contract development is a relatively new landscape. With the recent boom of the DeFi industry (since 2020), a new pool of developers joined this industry and started writing smart contracts. Their knowledge of and experience with smart contract security vary widely, as observed in our study. There are some information resources on smart contract security, such as ConsenSys and Solidity documentations, which provide design patterns that developers should follow. However, we are not aware of a framework for organizations to properly assess and communicate smart contract security during the development life cycle.

Apply software security solutions in smart contracts. Our results suggest some similarity of practices and challenges between smart contract and general software security. Thus some security strategies of software development can be applied to smart contracts. For instance, some participants indicated the importance of relevant documentations within the IDEs which can support their learning in smart contract development. The literature on secure software engineering has made similar suggestions (e.g., [56, 55]). Our participants also desired well-structured, context-specific security warnings. This aligns with prior literature that suggests effective security warning to reduce cryptographic

[30]https://csrc.nist.gov/Projects/ssdf
[31]https://owasp.org/www-project-security-knowledge-framework/
API misuse [49]. The prior literature on cryptographic APIs [55] suggests that simplified libraries can promote security. However, it might not be the case in the domain of smart contracts. Many participants in our study explicitly requested the security/testing libraries to be more comprehensive in covering most if not all security issues. Further research is needed to investigate this idea. Our study also highlights the inconvenience of using different tools and plugins to detect different vulnerabilities.

Why is smart contract security different and difficult? Smart contract security have some fairly unique or more prominent characteristics and often have a significant financial impact, especially for DeFi projects. It is fairly easy to monetize the attacks (e.g., “stealing” tokens and passing them to a mixer before selling them). In addition, the system states are visible on public blockchains and the smart contract code is often open-sourced, thus the public nature makes them targets for attacks. Besides, the additional economic considerations (e.g., incentive mechanisms, gas cost) add more complexities to smart contract security (i.e., economic security) [57]. Furthermore, in the smart contract development ecosystem, there is wide reuse of library code or interactions with other smart contracts (DeFi projects known as “money lego” because they can be created by composing smart contracts from different projects) [58]. This composability, however, also opens the door for trusting and calling untested and potentially vulnerable or even malicious smart contracts.

6.3 Implications for Smart Contract Security

Our study results provide a number of implications for smart contract security education and tools. Specifically, we will discuss the implications for smart contract education, compilers, libraries, development frameworks, IDEs, and testnets.

Education. Our results suggest that accessing documentations, reference implementations and security tools is not enough in helping developers identify smart contract security vulnerabilities. Education that improves their motivation, knowledge and awareness regarding smart contract security is crucial. While there are many reading materials for educational purposes, we believe what is missing is hands-on exercises or labs for smart contract security, similar to the SEED projects for computer security in general [59]. Once these educational materials (e.g., hands-on labs) are created, they should be brought up when corresponding security issues are detected (i.e., teachable moments) in the various components of the smart contract ecosystem (e.g., compilers, security tools, IDEs, testnets).

Compilers. Our results indicate that most of our early-stage developer participants were not familiar with the basic smart contract security concepts and common vulnerabilities. Some suggested integrating security analyses (e.g., static analysis) directly into the Solidity compiler, so that they can obtain the security assessment without any extra step.

Code libraries. Some participants commented that current security libraries fall short of covering edge cases. Most of the recent tools work on the byte code for identifying security vulnerabilities. The parser and symbolic execution engine work solely on the byte code, so if developers see a potential integer under/overflow, they will report it, but they do not know where it occurs in the source code. A direct mapping between security vulnerabilities and source code would be valuable.

Error / warning messages. Many participants noted the error messages from current testing libraries can be overwhelming and hard to understand. For instance, P23 felt the error messages lack actionable insights. The (security) error messages can be improved by including links to detailed explanations, known incidents, and how to correct the issues. Since many early-stage developers did not see the importance of security in smart contracts, connecting their own code (vulnerabilities) to past incidents of security vulnerabilities might improve their awareness of smart contract security. Some participants also suggested having better GUIs to present those information. For instance, P7 compared the Solidity tools to that of another language Python, which has a nice graphical user interface to show where exactly the problems are in the code and how significant the effect can be. Creating hierarchical GUIs where developers can see an outline of issues and can then zoom into specific issue or information would make the security assessment outputs less overwhelming.

Formal verification. In addition to static analysis, some participants also felt that many vulnerabilities could have been avoided with the help of formal analysis and verification, which were not built into Solidity. They believed that formal verification can enhance code coverage in terms of correctness, because they are based on mathematical proofs. Future research and development could create more formal verification tools for smart contract security.

Integrated Development Environments (IDEs). Our study suggested integrating security concepts into IDEs. A checklist of common smart contract security issues inside IDEs would be useful. The security tools (e.g., static analysis) can show which common security issues from the list are present in the code. Many participants liked the convenience of the web-based Remix IDE but wished its features can match those in the desktop-based IDE (e.g., Visual Studio Code) where more security plugins are available. Some of them also desired the security plugins can be
more discoverable, either by enabling them by default or providing better search capability (e.g., creating a list of all security-related plugins).

**Development frameworks.** Some participants mentioned existing development frameworks to be heavy-weighted and difficult to learn and use the security functionalities. For instance, P6 noted Truffle, a popular smart contract development framework is “unwieldy” to learn and run security tests. One possibility is for these development frameworks to include a “security mode” where security analyses are automatically done as part of the compilation process.

**Testnets.** Many of our early stage developer participants said they did not consider security as a priority in their smart contract development because they mostly deployed their projects in testnets where the (security) bugs have no real impact. While this sentiment might be understandable, this observation raises the question of whether a separate testnet could be designed specifically for smart contract security education and testing. For instance, the testnet is deployed with hands-on labs, which include smart contacts that purposefully embed existing smart contract vulnerabilities (imagine a vulnerable version of OpenZeppelin ERC20 contracts) and developers need to reuse or interact with these contracts. This testnet could help developers experience and learn how to mitigate these security vulnerabilities.

### 6.4 Limitations and Future Research

Our exploratory qualitative study has many limitations. First, we have a small sample size (29 participants), and thus we cannot claim our results can necessarily be generalized to the broader smart contract developer population. However, our participants were smart contract developers with diverse levels of experience and backgrounds, and our findings do present the real practices in this community. Future research can conduct large-scale follow-up surveys to help answer more quantitative questions such as the frequency of different types of smart contract security practices.

Our sample included many students, which one may wonder if they can represent some of the smart contract development practices. We note that “smart contract developers” are not bound to those who have a formal title as a (full-time) smart contract developer. All of our participants had experience in developing smart contracts and thus met our criteria of smart contract developer. In addition, the emerging smart contract (and DeFi) space has developers from very diverse backgrounds and with different levels of experience (including students), not just full-time developers. Many students are indeed creators of DeFi projects. In popular DeFi hackathons such as ETHGlobal and Encode, most participants were students. We see our diverse sample as a strength since it fits with the diversity of the smart contract developer population.

Our study focused on Solidity, the most popular programming language for smart contracts. There are other smart contract languages such as Viper and RUST. Further studies are needed to smart contract security practices in other languages. In addition, we only tested four common smart contract vulnerabilities in our code review task. Future research is needed to investigate other smart contract vulnerabilities such as front running, flash loan attacks, upgradable proxy and delegate calls which may require developers to have a good understanding of the economic aspects of DeFi projects (e.g., incentive mechanisms of Ethereum, token economics, how token prices interplay with automatic market makers in decentralized exchanges).

Last but not least, our participants were asked about security practices in the interviews before doing the code review task. Therefore, the interviews could prime our participants to think more about security in the code review and did better than they would otherwise. We also noticed a positive association between years of experience and successfully identifying security vulnerabilities in the code review task, this hypothesis however needs to be tested in future large-scale studies.

### 7 Conclusion

To understand smart contract developers’ security perceptions and practices, we conducted an exploratory qualitative study consisting of a semi-structured interview and a code review task. We found that many developers rely on others or external audits to ensure security of their projects. When they do assess smart contract security, they often do it manually and find a lack of security resources and tools. Given the recent rise of smart contract projects (e.g., decentralized finance) and their associated security attacks, providing better educational materials and tool support especially for novice developers is paramount for the healthy growth of this domain.
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8 appendix

8.1 Pilot Study

We conducted a pilot study with 4 smart contract developers to test our study design including interview questions and code review tasks. For the code review task, first we implemented five smart contracts, each including one common smart contract security vulnerability (e.g., reentrancy, under/overflow, access control). We present details of these smart contracts in Section 4.3.1.

First round pilot. In the first two pilot sessions, we had participants who were doctoral student researchers in the blockchain and smart contract security area. We conducted the interview and provided three contracts to each participant for review. They felt the interview questions were good. For second part of study (code review tasks), we gave...
the pilot participants 10 minutes for each task (30 minutes in total for all 3 tasks). They provided suggestions on how to improve the code review task to make it more realistic. For instance, they felt the time was too tight to review three contracts, and suggested having each participant review only one contract, which should be more comprehensive and realistic by having common functionalities. They mentioned that code review takes an effort, and might be distracting without a realistic contract. Therefore, we created two basic smart contracts based on ERC20 token standard, which have basic functionalities to transfer tokens as well as allow tokens to be approved so they can be spent by another on-chain party. ERC20 is the most common token standard on Ethereum and should be familiar to smart contract developers. The length of smart contract code varies significantly: some library/interface code can be 20 lines, while other more complicated contracts (e.g., Uniswap router code) can be several hundreds of lines. Practically, to fit into the time frame of our study, the code cannot be too long. Therefore, our 2 newly created smart contracts contain 80 lines of code on average. We chose an average of 80 lines of code based on this 1st round of pilot, which was sufficient to contain common vulnerabilities in the ERC20 form. We then embedded at least two common smart contract security vulnerabilities in each contract.

Second round pilot. To test the updated study materials, we had a second round of pilot with another two participants who were blockchain researchers/developers. The estimated time for the interview session was 30 minutes and 25 minutes for code review tasks and 5 minutes for exit interview. Specifically, we gave them 20 minutes to review the code (each participant was assigned only one task). They were asked to: a) review the contract code; b) update the code if necessary; c) can search for any resources online during the task. In addition, we gave them 5 minutes to discuss the area of improvement and their rationale after the task.

They made suggestions on the interview questions. For instance, they suggested that we add questions to understand what role(s) the participant played in their smart contract projects. Therefore, we added questions to learn: a) what types of role they play in smart contract projects, and b) if they have any experience in deploying smart contracts in a production system or mainnet/testnet. They thought the smart contracts for review were good, but suggested making them ready to go compile from GitHub, which we did in the final study.

8.2 Figure: Factors considered in Development and Tools/Programming Languages

We include figures representing different factors considered by early stage and experienced developers (Figure 6), and their programming language background (Figure 7).

8.3 Figure: Task Flowcharts of Participants

This section includes flowcharts of code review process which were most common among participants.

8.4 Code Review Improvement Suggestions: Task 1 and 2

This section includes examples of modified code snippets by participants who were able to identify security vulnerabilities.
Figure 8: Code Review Task Flowchart for P22 who manually reviewed smart contract for Task 2 and failed to identify any vulnerabilities

Figure 9: Code Review Task Flowchart for P6 who manually reviewed the code and successful in identifying both vulnerabilities in Task 2
**Figure 10:** Security vulnerability identification (access control) and modification by P6 during the task. Tools used: Remix, manual inspection.

```solidity
modifier onlyOwner() {
    require(msg.sender == address(owner)) ;
}
```

**Figure 11:** Security vulnerability identification (low-level call) and modification by P10 during the task. Tools used: VS Code, manual inspection.

```solidity
function transferFrom(address from, address to, uint256 tokens) override public returns (bool success) {
    if (balanceOf[from] >= tokens && allowance[from][msg.sender] >= tokens) {
        // no use of safemath
        // todo: is this safe, with the caveat that total supply of 15e23 +
        // all ether < type(uint256).max
        balanceOf[to] += tokens;
        balanceOf[from] -= tokens;
        allowance[from][msg.sender] -= tokens;
        emit Transfer(from, to, tokens);
        return true;
    } else {
        // typically a lot of contracts revert in this case
        // revert('Insufficient allowance' ); instead of 'return false'
        return false;
    }
}
```

**Figure 12:** Security vulnerability identification (re-entrancy) and modification by P10 during the task. Tool used: Remix.

```solidity
function withdraw(uint256 amount) public returns (bool success) {
    if (balanceOf[msg.sender] < amount) return false;
    balanceOf[msg.sender] -= amount;
    totalSupply -= amount;
    // There is some danger in using send: check
    // https://docs.soliditylang.org/
    if (!msg.sender.send(amount)) {
        // vulnerable to reentrancy attack:
        // https://docs.soliditylang.org/
        balances[msg.sender] += amount;
        _totalSupply += amount;
        return false;
    }
    return true;
}
```

**Figure 13:** Security vulnerability identification (re-entrancy) and modification by P12 during the task. Tool used: Remix.
function transferFrom(address from, address to, uint256 tokens)
override public returns (bool success) {
    // modification: adding require here
    require(from != address(0), "Empty address is not allowed");
    require(to != address(0), "Empty address is not allowed");
    if (balances[from] >= tokens && allowed[from][msg.sender] >= tokens &&
        tokens > 0) {
        balances[to] += tokens;
        balances[from] -= tokens;
        allowed[from][msg.sender] -= tokens;
        emit Transfer(from, to, tokens);
        return true;
    } else { return false; }
}

Figure 14: Security vulnerability identification (low-level unchecked calls) and modification by P12 during the task.
Tools used: VS Code, manual inspection.

// Might be a vulnerability - something to do with miners reordering approve txs
// I kinda remember approve functions having a "set to 0" kinda logi
// look deeper later
function approve(address spender, uint256 tokens) override public
returns (bool success) {
    allowed[msg.sender][spender] = tokens;
    emit Approval(msg.sender, spender, tokens);
    return true;
}

Figure 15: False positive Security vulnerability identification for task1 by P1
Table 3: Summary of participants’ task performance in the code review task where success rate (i.e., Rate) denotes the percentage of participants who correctly identified a particular vulnerability; 0: the participant did not identify the vulnerability; 1: the participant identified the vulnerability. The middle section of the table shows the early-stage (<1 year of experience) Solidity developer participants, whereas the bottom section of the table shows the experienced (2-5 years of experience) Solidity developer participants. Every participant either did Task 1 or Task 2. Task 1 includes two vulnerabilities: reentrancy and unchecked low-level call. Task 2 includes two vulnerabilities: integer overflow and improper access control. We also show the review method each participant used during the task. Most participants did manual inspection of the code using an IDE or a test editor such as Remix, VS Code, Sublime, IntelliJ, or simply viewing the code on GitHub. Remix and Hardhat are development/testing frameworks for smart contracts. Three participants (P3, P15, P20) used Remix with a security plugin (sp), which does Solidity static analysis. Slither is a static analysis tool and Oyente is an analysis tool based on symbolic execution.

| ID  | Reentrancy | Low-Level Call | Review Method | ID  | Overflow | Access Control | Review Method |
|-----|------------|----------------|---------------|-----|-----------|----------------|---------------|
| Early | Rate: 53.3% | Rate: 40% | Manual | P1  | 0 | 0 | Manual |
|      | Rate: 25%  | Rate: 0%  | Manual | P3  | 0 | 0 | Remix (sp) |
|      | Rate: 0%   | Rate: 0%  | Manual | P9  | 0 | 0 | Manual |
|      | Rate: 16.7%| Rate: 16.7%| Manual | P24 | 0 | 0 | Manual |
|      | Rate: 16.7%| Rate: 16.7%| Manual | P16 | 0 | 0 | Manual |
|      | Rate: 16.7%| Rate: 16.7%| Manual | P28 | 1 | 1 | Manual |
| Exp. | Rate: 63.6%| Rate: 54.5%| Manual | P8  | 1 | 1 | Manual |
|      | Rate: 37.5%| Rate: 62.5%| Manual | P6  | 1 | 1 | Manual |
|      | Rate: 37.5%| Rate: 62.5%| Manual | P13 | 0 | 0 | Manual |
|      | Rate: 37.5%| Rate: 62.5%| Manual | P15 | 0 | 0 | Manual |
|      | Rate: 37.5%| Rate: 62.5%| Manual | P17 | 1 | 1 | Manual |
|      | Rate: 37.5%| Rate: 62.5%| Manual | P21 | 0 | 0 | Manual |
|      | Rate: 37.5%| Rate: 62.5%| Manual | P22 | 0 | 0 | Manual |
|      | Rate: 37.5%| Rate: 62.5%| Manual | P26 | 0 | 0 | Manual |
|      | Rate: 37.5%| Rate: 62.5%| Manual | P27 | 1 | 1 | Manual+Oyente |
|      | Rate: 37.5%| Rate: 62.5%| Manual | P29 | 1 | 1 | Manual+Remix (sp) |
|      | Rate: 37.5%| Rate: 62.5%| Manual | P20 | 18.18 | 8.31 | Manual+Remix (sp) |
|      | Rate: 37.5%| Rate: 62.5%| Manual | P21 | 14.54 | 14.40 | Manual+Oyente |
|      | Rate: 37.5%| Rate: 62.5%| Manual | P22 | 10.37 | 10.37 | Manual+Remix (sp) |
|      | Rate: 37.5%| Rate: 62.5%| Manual | P26 | 15.47 | 15.47 | Manual+MythX |
|      | Rate: 37.5%| Rate: 62.5%| Manual | P27 | 12.13 | 11.56 | Manual+Remix (sp) |
|      | Rate: 37.5%| Rate: 62.5%| Manual | P29 | 10.37 | 10.37 | Manual+Remix (sp) |

Table 4: Average time for identifying each vulnerability by early stage and experienced developers. *avg*: Average Time

| ID  | Reentrancy | Low-Level Call | ID  | Overflow | Access Control |
|-----|------------|----------------|-----|-----------|----------------|
| Early Stage | 18.18 | 18.18 | Experienced | 18.18 | 18.18 |
| P20 | 18.18 | 18.18 | P28 | 7.07 | 8.31 |
| P20 | 5.08 | 8.08 | P6 | 9.08 | 14.15 |
| P10 | 8.16 | 12.44 | P12 | 10.12 | P8 | 9.17 | 14.01 |
| P12 | 10.07 | P14 | 12.44 | P18 | 9.13 | P15 | 11.45 | P19 | 13.50 |
| P19 | 10.53 | P25 | 6.23 | P27 | 12.13 | P26 | 15.47 |
| P27 | 11.56 | 10.37 | P26 | 15.47 |
| P29 | 10.37 | 10.37 | P29 | 10.37 |
| avg: 10.0 | avg: 10.4 | avg: 10.1 | avg: 14.4 |