How Developers Diagnose Potential Security Vulnerabilities with Static Analysis

Justin Smith, Brittany Johnson, Emerson Murphy-Hill, Bill Chu, and Heather Richter Lipford

Abstract—While using security tools to resolve security defects, software developers must apply considerable effort. Success depends on a developer's ability to interact with tools, ask the right questions, and make strategic decisions. To build better security tools and subsequently help developers resolve defects more accurately and efficiently, we studied the defect resolution process — from the questions developers ask to their strategies for answering them. In this paper, we report on an exploratory study with novice and experienced software developers. We equipped them with Find Security Bugs, a security-oriented static analysis tool, and observed their interactions with security vulnerabilities in an open-source system that they had previously contributed to. We found that they asked questions not only about security vulnerabilities, associated attacks, and fixes, but also questions about the software itself, the social ecosystem that built the software, and related resources and tools. We describe the strategic successes and failures we observed and how future tools can leverage our findings to encourage better strategies.

1 Introduction

Software developers are a critical part of making software secure, a particularly important task considering security vulnerabilities are likely to cause incidents that affect company profits as well as end users [5]. When software systems contain security defects, developers are responsible for fixing them. In fact, a recent survey by Christakis and Bird found that developers cared more about security issues than other reliability issues [6].

Static analysis tools, like Find Security Bugs (FSB) [46] and many others [42]–[44], [50], [52], promise to help developers remove security defects early in the development life cycle. These tools locate and report on potential software security vulnerabilities, such as SQL injection and cross-site scripting even before the code executes.

Unfortunately, these tools are confusing for developers to use. Researchers cite several related reasons why these tools do not help developers resolve defects, for instance, the tools: "may not give enough information" [18]; produce "bad warning messages" [6]; and "miscommunicate" with developers [17].

Our work investigates this tool understanding problem by advancing our knowledge of how developers use a security-focused static analysis tool to resolve security defects, including their information needs, defect resolution strategies, and assumptions. No prior study has specifically investigated these facets of security tool usage.

To that end, we conducted an exploratory think-aloud study with ten developers who had contributed to iTrust [48], a security-critical Java medical records software system. We observed each developer as they assessed potential security vulnerabilities identified by FSB. We operationalized developers' information needs by measuring questions — the verbal manifestations of information needs. Using a card sort methodology, we sorted 559 questions into 17 categories. We report the questions participants asked throughout our study, discuss the strategies participants used to answer questions in each category, and also describe the assumptions participants made.

In non-security domains, work that identifies information needs has helped toolsmiths both evaluate the effectiveness of existing tools [1], and improve the state of program analysis tools [24], [38], [41]. Similarly, we expect that categorizing developers' information needs while using security-focused static analysis tools will help researchers evaluate and toolsmiths improve those tools.

An earlier version of this work appeared as a conference paper [40]. The contribution we presented in that paper was a categorization of questions developers asked while resolving security defects. While that contribution explains the information needs of developers, it did not explain how developers *answer* those questions. In this work we explore how developers acquire the information they need either actively (through strategies) or passively (through assumptions).

Consequently, this paper elaborates on the earlier work with the following two additional contributions:

- A catalog of developers defect resolution strategies, organized by the information need each strategy addresses (Section 3). For example, to understand how to implement a fix, participants strategically surveyed multiple sources, including the web, the tool's notification, and other modules in the code.
- A description of the common assumptions that undermined those strategies (Section 4). For example, participants incorrectly assumed input validation had been handled securely.

2 Methodology

We conducted an exploratory study with ten software developers. In our analysis, we extracted and categorized the questions developers asked during each study session. Section 2.1 outlines the

- *J. Smith is with North Carolina State University, Raleigh, NC 27603. E-mail: jssmit11@ncsu.edu*
- *B. Johnson is with North Carolina State University, Raleigh, NC 27603. E-mail: bijohnso@ncsu.edu*
- *E. Murphy-Hill is with North Carolina State University, Raleigh, NC 27603. E-mail: emerson@csc.ncsu.edu*
- *B. Chu is with University of North Carolina at Charlotte, Charlotte, NC 28223. E-mail: billchu@uncc.edu*
- *H. Richter Lipford is with University of North Carolina at Charlotte, Charlotte, NC 28223. E-mail: heater.lipford@uncc.edu*

research questions we sought to answer. Section 2.2 details how the study was designed and Sections 2.3, 2.4, and 2.5 describe how we performed our three phases of data analysis. Study materials can be found online [45] and in the appendices.

2.1 Research Question

We want to answer the following research questions:

- **RQ1**: What information do developers need while using static analysis tools to diagnose potential security vulnerabilities?
- **RQ2**: What strategies do developers use to acquire the information they need?
- **RQ3**: What assumptions do developers make while executing these strategies?

We measured developers' information needs (RQ1) by examining the questions they asked. The questions that we identified are all available online [45]. We list several exemplary questions throughout Section 3 along side the strategies (RQ2) developers used to answer those questions. Where appropriate, we also describe how participants' strategies led to successes or failures. Finally, in Section 4 we discuss the correct and incorrect assumptions (RQ3) developers made while executing their strategies.

2.2 Study Design

To ensure all participants were familiar with the study environment and Find Security Bugs (FSB), each in-person session started with a five-minute briefing section. The briefing section included a demonstration of FSB's features and time for questions about the development environment's configuration. During the briefing section, we informed participants of the importance of security to the application and that the software may contain security vulnerabilities.

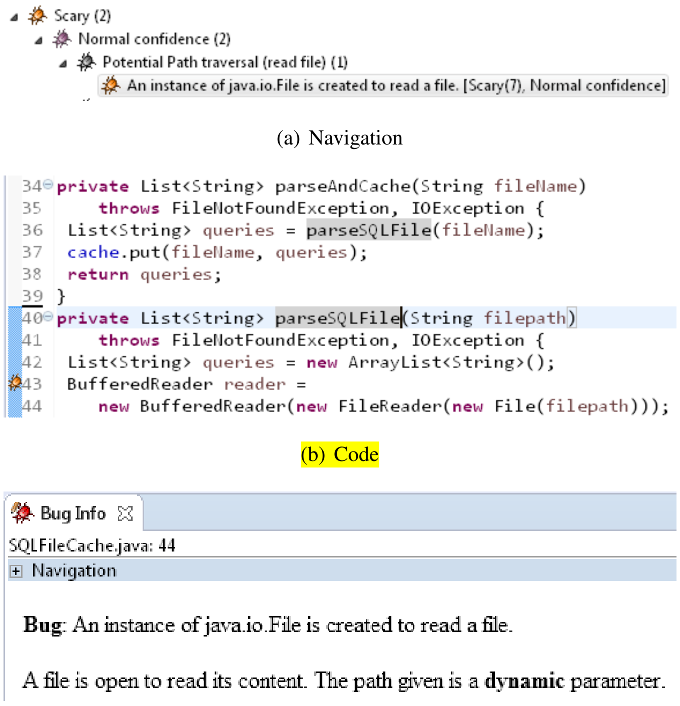
Additionally, we asked participants to use a think-aloud protocol, which encourages participants to verbalize their thought process as they complete a task or activity [35]. Specifically, they were asked to: "Say any questions or thoughts that cross your mind regardless of how relevant you think they are." We recorded both audio and the screen as study artifacts for data analysis.

Following the briefing period, participants progressed through encounters with four vulnerabilities. Figure 1 depicts the configuration of the integrated development environment (IDE) for one of these encounters. All participants consented to participate in our study, which had institutional review board approval, and to have their session recorded using screen and audio capture software. Finally, each session concluded with several demographic and open-ended discussion questions.

2.2.1 Materials

Participants used Eclipse to explore vulnerabilities in iTrust, an open source Java medical records web application that ensures the privacy and security of patient records according to the HIPAA statute [47]. Participants were equipped with FSB, an extended version of FindBugs.

We chose FSB because it detects security defects and compares to other program analysis tools, such as those listed by NIST, [42] OWASP, [50] and WASC [52]. Some of the listed tools may include more or less advanced bug detection features. However, FSB is representative of static analysis security tools with respect to its user interface, specifically in how it communicates with its users.



Scary (2)
Normal confidence (2)
Potential Path traversal (read file) (1)
An instance of java.io.File is created to read a file. [Scary(7), Normal confidence]

(a) Navigation

```
private List<String> parseAndCache(String fileName)
    throws FileNotFoundException, IOException {
 List<String> queries = parseSQLFile(fileName);
 cache.put(fileName, queries);
 return queries;
}
private List<String> parseSQLFile(String filepath)
    throws FileNotFoundException, IOException {
 List<String> queries = new ArrayList<String>();
 BufferedReader reader =
    new BufferedReader(new FileReader(new File(filepath)));
```

(b) Code

Bug Info
SQLFileCache.java: 44
Navigation

Bug: An instance of java.io.File is created to read a file.

A file is open to read its content. The path given is a **dynamic** parameter.

(c) Short Notification Text

Fig. 1. The study environment.

TABLE 1
Participant Demographics

Participant	Job Title	Vulnerability Familiarity	Experience Years
P1*	Student	●●◐○○	4.5
P2*	Test Engineer	●●●○○	8
P3	Development Tester	●●○○○	6
P4*	Software Developer	●●○○○	6
P5*	Student	●●●●○	10
P6	Student	●○○○○	4
P7	Software Developer	●●●●○	4.5
P8	Student	●●●○○	7
P9	Software Consultant	●●●○○	5
P10	Student	●●●○○	8

FSB provides visual code annotations and textual notifications that contain vulnerability-specific information. It summarizes all the vulnerabilities it detects in a project and allows users to prioritize potential vulnerabilities based on several metrics such as bug type or severity.

2.2.2 Participants

For our study, we recruited ten software developers, five students and five professionals. Table 1 gives additional demographic information on each of the ten participants. Asterisks denote previous use of security-oriented tools. Participants ranged in programming experience from 4 to 10 years, averaging 6.3 years. Participants also self-reported their familiarity with security vulnerabilities on a 5 point Likert scale, with a median of 3. Although we report on experiential and demographic information, the focus of this work is to identify questions that span experience levels. In the remainder of this paper, we will refer to participants by the abbreviations found in the participant column of the table.

We faced the potential confound of measuring participants questions about a new code base rather than measuring their questions about vulnerabilities. To mitigate this confound, we required participants to be familiar with iTrust; all participants either served as teaching assistants for, or completed a semester-long software engineering course that focused on developing iTrust. This requirement also ensured that participants had prior experience using static analysis tools. All participants had prior experience with FindBugs, the tool that FSB extends, which facilitated the introduction of FSB.

However, this requirement restricted the size of our potential participant population. Accordingly, we used a nonprobabilistic, purposive sampling approach [15], which typically yields fewer participants, but gives deeper insights into the observed phenomena. To identify eligible participants, we recruited via personal contacts, class rosters, and asked participants at the end of the study to recommend other qualified participants. Although our study involved only ten participants, we reached saturation [11] rather quickly; no new question categories were introduced after the fourth participant.

2.2.3 Tasks

First we conducted a preliminary pilot study ($n = 4$), in which participants spent approximately 10 to 15 minutes with each task and showed signs of fatigue after 60 minutes. To reduce the effects of fatigue, we asked each participant to assess four vulnerabilities. We do not report on data collected from this preliminary study.

When selecting tasks, we ran FSB on iTrust and identified 118 potential security vulnerabilities across three topics. To increase the diversity of responses, we selected tasks from mutually exclusive topics, as categorized by FSB. For the fourth task, we added a SQL injection vulnerability to iTrust by making minimal alterations to one of the database access objects. Our alterations preserved the functionality of the original code and were based on examples of SQL injection found on OWASP [51] and in open-source projects. We chose to add a SQL injection vulnerability, because among all security vulnerabilities, OWASP ranks injection vulnerabilities as the most critical web application security risk.

For each task, participants were asked to assess code that "may contain security vulnerabilities" and "justify any proposed code changes." Table 2 summarizes each of the four tasks and the remainder of this section provides more detail about each task.

Task 1
The method associated with Task 1 opens a file, reads its contents, and executes the contents of the file as SQL queries against the database. Before opening the file, the method does not escape the filepath, potentially allowing arbitrary SQL files to be executed. However, the method is only ever executed as a utility from within the unit test framework. The mean completion time for this task was 14 minutes and 49 seconds.

Task 2
The method associated with Task 2 is used to generate random passwords when a new application user is created. FSB warns `Random` should not be used in secure contexts and instead suggests using `SecureRandom`. `SecureRandom` is a more secure alternative, but its use comes with a slight performance trade-off. The mean completion time for this task was 8 minutes and 52 seconds.

Task 3
The method associated with Task 3 reads several improperly validated string values from a form. These values are eventually redisplayed on the web page exposing the application to a cross site scripting attack. The mean completion time for this task was 13 minutes and 19 seconds.

Task 4
In the method associated with Task 4, a SQL Statement object is created using string interpolation, which is potentially vulnerable to SQL injection. FSB recommends using `PreparedStatements` instead. The mean completion time for this task was 8 minutes.

2.3 Data Analysis — Questions

To analyze the data, we first transcribed all the audio-video files using oTranscribe [49]. Each transcript, along with the associated recording, was analyzed by two of the authors for implicit and explicit questions. The two question sets for each session were then iteratively compared against each other until the authors reached agreement on the question sets. In the remainder of this section, we will detail the question extraction process and question sorting processes, including the criteria used to determine which statements qualified as questions.

2.3.1 Question Criteria

Participants ask both explicit and implicit questions. Drawing from previous work on utterance interpretation [29], we developed five criteria to assist in the uniform classification of participant statements. A statement was coded as a question only if it met one of the following criteria:

- **The participant explicitly asks a question.**
  Ex: *Why aren't they using* `PreparedStatements`*?*
- **The participant makes a statement and explores the validity of that statement.**
  Ex: *It doesn't seem to have shown what I was looking for. Oh, wait! It's right above it...*
- **The participant uses key words such as, "I assume," "I guess," or "I don't know."**
  Ex: *I don't know that it's a problem yet.*
- **The participant clearly expresses uncertainty over a statement.**
  Ex: *Well, it's private to this object, right?*
- **The participant clearly expresses an information need by describing plans to acquire information.**
  Ex: *I would figure out where it is being called.*

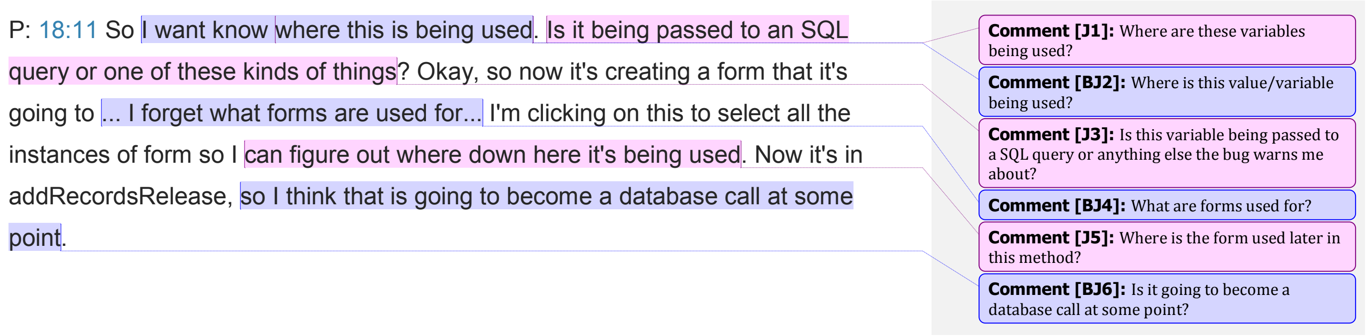
2.3.2 Question Extraction

To make sure our extraction was exhaustive, the first two authors independently coded each transcript using the criteria outlined in the previous section. When we identified a statement that satisfied one or more of the above criteria, we marked the transcript, highlighted the participant's original statement, and clarified the question being asked. Question clarification typically entailed rewording the question to best reflect the information the participant was trying to acquire. From the ten sessions, the first coder extracted 421 question statements; the other coder extracted 389.

It was sometimes difficult to determine what statements should be extracted as questions; the criteria helped ensure both authors only highlighted the statements that reflected actual questions. Figure 2 depicts a section of the questions extracted by both authors from P8 prior to review.

TABLE 2
Four vulnerability exploration tasks

Vulnerability	Short Description	Severity Rank
Potential Path Traversal	An instance of java.io.File is created to read a file.	"Scary"
Predictable Random	Use of java.util.Random is predictable.	"Scary"
Servlet Parameter	The method getParameter returns a String value that is controlled by the client.	"Troubling"
SQL Injection	[Method name] passes a non-constant String to an execute method on an SQL statement.	"Of Concern"



P: 18:11 So I want know where this is being used. Is it being passed to an SQL query or one of these kinds of things? Okay, so now it's creating a form that it's going to ... I forget what forms are used for... I'm clicking on this to select all the instances of form so I can figure out where down here it's being used. Now it's in addRecordsRelease, so I think that is going to become a database call at some point.

Comment [J1]: Where are these variables being used?

Comment [BJ2]: Where is this value/variable being used?

Comment [J3]: Is this variable being passed to a SQL query or anything else the bug warns me about?

Comment [BJ4]: What are forms used for?

Comment [J5]: Where is the form used later in this method?

Comment [BJ6]: Is it going to become a database call at some point?

Fig. 2. Question merging process

2.3.3 Question Review

To remove duplicates and ensure the validity of all the questions, each transcript was reviewed jointly by the two authors who initially coded it. During this second pass, the two reviewers examined each question statement, discussing its justification based on the previously stated criteria. The two reviewers merged duplicate questions, favoring the wording that was most strongly grounded in the study artifacts. This process resulted in a total of 559 questions.

Each question that was only identified by one author required verification. If the other author did not agree that such a question met at least one of the criteria, the question was removed from the question set and counted as a disagreement. The reviewers were said to agree when they merged a duplicate or verified a question. Depending on the participant, inter-reviewer agreement ranged from 91% to 100%. Across all participants, agreement averaged to 95%. The agreement scores suggest that the two reviewers consistently held similar interpretations of the question criteria.

It is also important to note that participants' questions related to several topics in addition to security. We discuss the questions that are most closely connected to security in Sections 3.2.1, 3.3.6, and 3.5.3. Although our primary focus is security, we are also interested in the other questions that participants posed, as those questions often have security implications. For example, researchers have observed that developers ask questions about data flow, like *What is the original source of this data*, even outside security [27]. However, in a security context, this question is particularly important, because potentially insecure data sources often require special handling to prevent attacks.

2.3.4 Question Sorting

To organize our questions and facilitate discussion, we performed an *open* card sort [16]. Card sorting is typically used to help structure data by grouping related information into categories. In an *open* sort, the sorting process begins with no notion of predefined categories. Rather, sorters derive categories from emergent themes in the cards.

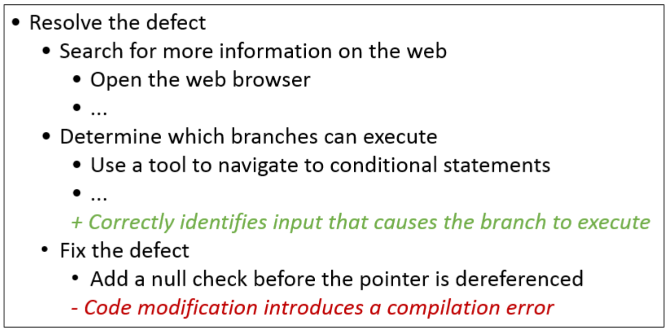
We performed our card sort in three distinct stages: clustering, categorization, and validation. In the first stage, we formed question clusters by grouping questions that identified the same information needs. In this phase we focused on rephrasing similar questions and grouping duplicates. For example, P1 asked, *Where can I find information related to this vulnerability?* P7 asked, *Where can I find an example of using `PreparedStatements`?* and P2 asked, *Where can I get more information on path traversal?* Of these questions, we created a question cluster labeled *Where can I get more information?* At this stage, we discarded five unclear or non pertinent questions and organized the remaining 554 into 155 unique question clusters.

In the second stage, we identified emergent themes and grouped the clusters into categories based on the themes. For example, we placed the question *Where can I get more information?* into a category called ***Resources/Documentation***, along with questions like *Is this a reliable/trusted resource?* and *What information is in the documentation?* Table 3 contains the 17 categories along with the number of distinct clusters each contains.

To validate the categories that we identified, we asked two independent researchers to sort the question clusters into our categories. Rather than sort the entire set of questions, we randomly selected 43 questions for each researcher to sort. The first agreed with our categorization with a Cohen's Kappa of $\kappa = .63$. Between the first and second researcher we reworded and clarified some ambiguous questions. The second researcher exhibited greater agreement ($\kappa = .70$). These values are within the $.60 - .80$ range, indicating substantial agreement [25].

2.4 Data Analysis — Strategies

To answer RQ2 the first author performed two additional passes through the transcripts and recordings. In the first pass, we focused on identifying each participant's defect resolution strategy for each task. We define a defect resolution strategy as all the actions a developer takes to validate and resolve a defect. Such actions include invoking additional tools, modifying the source code, and searching the web.



- Resolve the defect
  - Search for more information on the web
    - Open the web browser
    - ...
  - Determine which branches can execute
    - Use a tool to navigate to conditional statements
    - ...

    + Correctly identifies input that causes the branch to execute
  - Fix the defect
    - Add a null check before the pointer is dereferenced

    - Code modification introduces a compilation error

Fig. 3. Example strategy tree for a null dereference defect.

To represent these defect resolution strategies we drew from the notion of attack trees [32]. Attack trees encode the actions an attacker could take to exploit a system, including the idea that he may combine multiple actions to achieve a higher-level goal. Much like attack trees, our representation organizes actions hierarchically. We refer to this representation as a strategy tree. Whereas attack trees describe an attacker's actions, we use strategy trees to represent the hierarchical set of actions a developer takes to resolve a security defect. Figure 3 depicts an example strategy tree. To identify participants' actions and construct the strategy trees, we used the screen recordings and participants' think-aloud verbalizations.

During the second pass we added annotations to each strategy tree. As depicted in Figure 3 (lines prefixed with $+/-$), we annotated the trees whenever an action led to a success or a failure. To best understand which strategies contributed to success, we measured success/failure as granularly as possible. Rather than annotating the entire tree as successful or not, we annotated the sub-strategies that compose the tree. Participants could succeed with some strategies while failing with others. For example, participants could succeed in locating relevant information, but fail to interpret it correctly. Some sub-strategies were not observably successful/failure-inducing and were, therefore, not annotated.

2.5 Data Analysis — Assumptions

To answer RQ3, we identified participants' assumptions and analyzed each assumption to determine if it was correct. Because implicit assumptions are pervasive [8], it would be intractable to identify them all. Participants likely made many assumptions silently. For example, they may have implicitly assumed the Eclipse environment was configured correctly and all the relevant source files were accessible. Instead of speculating about all of these assumptions, we only consider the assumptions participants explicitly stated.

To identify the explicit assumptions participants made, we searched the transcripts for keywords. To derive the search set, we started with the following base words: *assume*, *presume*, *reckon*, *believe*, and *guess*. Next, we applied lemmatisation to identify all the inflected forms of these words, such as *hypothesize*, *speculate*, *suppose*, etc. Finally, we searched the transcripts for the stems of all the words identified by the lemmatisation process. This search process returned some false-positives. For example, one participant referred to the interviewer's assumptions rather than making an assumption of his own asking, "Am I *assumed* to have some prior knowledge?" To filter only the assumptions participants made about the task or the code, the first author inspected each search result.

After determining the result was an assumption, we evaluated its correctness. For example, one participant's assumed an external library was implemented securely. We determined this assumption was incorrect by locating a vulnerability in the library using the common vulnerability and exposures database.[1]

3 Results

3.1 Interpreting the Results

In the next four sections, we discuss our study's results using the categories we described in Section 2.3. Due to their large number, we grouped the categories to organize and facilitate discussion about our findings. Table 3 provides an overview of these groupings.

For each category, we selected several questions to discuss. A full categorization of questions can be found online along with the full descriptions of participants strategies [45]. The numbers next to the category titles denote the number of participants that asked questions in that category and the total number of questions in that category — in parenthesis and brackets respectively. Similarly, the number in parenthesis next to each question marks the number of participants that asked that question.

The structure of most results categories consists of four parts: an overview of the category, several of the questions we selected, a discussion of those questions (RQ1), and a discussion of participants' strategies for answering the questions in that category (RQ2). Some sections contain less discussion than others either because participants' intentions in asking questions were unclear, or participants asked questions without following up or attempting to answer them at all.

The strategies for answering individual questions often overlap, especially within a given category. Accordingly, to present a coherent discussion and avoid duplication, we discuss strategies for each category rather than for each question.

When discussing the questions participants asked for each category, we will use phrases such as "*X* participants asked *Y*." Note that this work is exploratory and qualitative in nature. Though we present information about the number of participants who ask specific questions, the reader should not infer any quantitative generalizations.

3.2 Vulnerabilities, Attacks, and Fixes

3.2.1 *Preventing and Understanding Attacks (10){11}*

Unlike other types of code defects that may cause code to function unexpectedly or incorrectly, security vulnerabilities expose the code to potential attacks. For example, the Servlet Parameter vulnerability (Table 2) introduced the possibility of SQL injection, path traversal, command injection, and cross-site scripting attacks.

Is this a real vulnerability? (7)
What are the possible attacks that could occur? (5)
Why is this a vulnerability? (3)
How can I prevent this attack? (3)
How can I replicate an attack to exploit this vulnerability? (2)
What is the problem (potential attack)? (2)

[1] cve.mitre.org

TABLE 3
Organizational Groups and Emergent Categories

Group	Category	Clusters	Location in Paper
Vulnerabilities, Attacks, and Fixes	Preventing and Understanding Potential Attacks	11	Section 3.2.1
	Understanding Alternative Fixes and Approaches	11	Section 3.2.2
	Assessing the Application of the Fix	9	Section 3.2.3
	Relationship Between Vulnerabilities	3	Section 3.2.4
Code and the Application	Locating Information	11	Section 3.3.1
	Control Flow and Call Information	13	Section 3.3.2
	Data Storage and Flow	11	Section 3.3.3
	Code Background and Functionality	17	Section 3.3.4
	Application Context/Usage	9	Section 3.3.5
	End-User Interaction	3	Section 3.3.6
Individuals	Developer Planning and Self-Reflection	14	Section 3.4.1
	Understanding Concepts	6	Section 3.4.2
	Confirming Expectations	1	Section 3.4.3
Problem Solving Support	Resources and Documentation	10	Section 3.5.1
	Understanding and Interacting with Tools	9	Section 3.5.2
	Vulnerability Severity and Rank	4	Section 3.5.3
	Notification Text	3	Section 3.5.4
	Uncategorized	10	

Participants sought information about the types of attacks that could occur in a given context. To that end, five participants asked, *What are the possible attacks that could occur?* For example, within the first minute of his analysis P2 read the notification about the Path Traversal vulnerability and stated, “I guess I’m thinking about different types of attacks.” Before reasoning about how a specific attack could be executed, he wanted to determine which attacks were relevant to the notification.

Participants also sought information about specific attacks from the notification, asking how particular attacks could exploit a given vulnerability. Participants hypothesized about specific attack vectors, how to execute those attacks, and how to prevent those attacks now and in the future. Seven participants, concerned about false positives, asked the question, *Is this a real vulnerability?* To answer that question, participants searched for hints that an attacker could successfully execute a given attack in a specific context. For example, P10 determined that the Predictable Random vulnerability was “real” because an attacker could deduce the random seed and use that information to determine other users’ passwords.

Strategy Analysis Results: Participants used various strategies to answer questions about attacks. When available, participants read FSB’s vulnerability information. When FSB did not provide sufficient information, participants turned to the web, searching on sites like Google and StackOverflow.

These strategies for getting information about different types of attacks were prone to two types of failures. First, because web search engines were not fully aware of participants’ programming contexts, they returned information about a superset of the relevant attacks. For example, P2 searched for attacks that exploit unvalidated input vulnerabilities. Searching the web returns results about cross site scripting attacks, injection attacks, and buffer overflow attacks. However, due to Java’s automatic array bounds checking, buffer overflow attacks are not feasible in the vast majority of Java programs, including iTrust. Devoting more effort to buffer overflow attacks would have distracted P2 from the other more relevant attacks.

Secondly, by executing these strategies some participants erroneously considered only a subset of the possible attacks. This failure was especially evident for the Servlet Parameter vulnerability, where a cross site scripting attack was feasible, but a SQL injection attack was not. Some participants correctly determined the data was sanitized before reaching the database, dismissed SQL injection, and prematurely concluded the vulnerability was a false positive. By failing to consider cross site scripting attacks, participants overlooked the program path that exposed a true attack.

3.2.2 Understanding Alternative Fixes and Approaches (8){11}

When resolving security vulnerabilities, participants explored alternative ways to achieve the same functionality more securely. For example, while evaluating the potential SQL Injection vulnerability, participants found resources that suggested using the `PreparedStatement` class instead of Java `Statement` class.

Does the alternative function the same as what I’m currently using? (6)
What are the alternatives for fixing this? (4)
Are there other considerations to make when using the alternative(s)? (3)
How does my code compare to the alternative code in the example I found? (2)
Why should I use this alternative method/approach to fix the vulnerability? (2)

Some notifications, including those for the SQL Injection and Predictable Random vulnerabilities, explicitly offered alternative fixes. In other cases, participants turned to a variety of sources, such as StackOverflow, official documentation, and personal blogs for alternative approaches.

Three participants specifically cited StackOverflow as a source for alternative approaches and fixes. P7 preferred StackOverflow as a resource, because it included real-world examples of broken code and elaborated on why the example was broken. Despite the useful information some participants found, often the candidate alternative did not readily provide meta-information about the process of applying it to the code. For example, P9 found a suggestion on StackOverflow that he thought might work, but it was not clear if it could be applied to the code in iTrust.

While attempting to assess the Servlet Parameter vulnerability, P8 decided to explore some resources on the web and came across a resource that appeared to be affiliated with OWASP [51]. Because he recognized OWASP as "the authority on security," he clicked the link and used it to make his final decision regarding the vulnerability. It seemed important to P8 that recommended approaches came from trustworthy sources.

Strategy Analysis Results: Participants' strategies for acquiring information about alternative fixes centered around three information sources — FSB, the web, and other modules in the code. Even when FSB informed participants about a specific alternative, participants sought supplementary information from the other two external sources.

For example, during Task 4, FSB suggested using `PreparedStatements`. In search of information about `PreparedStatements'` syntax, participants navigated to the project's related code modules they suspected would contain `PreparedStatements`. Participants largely found examples from these related modules helpful, because they were easy to translate back to the original method.

For Task 2, participants similarly sought examples of `SecureRandom`, but were ultimately less successful. Unaware that the project contained examples of `SecureRandom`, in this case, participants turned to online resources. Although some participants understood the relevant online API documentation, others struggled to compare the online documentation to the original method.

3.2.3 Assessing the Application of the Fix (9){9}

Once participants had identified an approach for fixing a security vulnerability (Section 3.2.2), they asked questions about applying the fix to the code. For example, while considering the use of `SecureRandom` to resolve the Predictable Random vulnerability, participants questioned the applicability of the fix and the consequences of making the change. The questions in this category differ from those in ***Understanding Alternative Fixes and Approaches*** (Section 3.2.2). These questions focus on the process of applying and reasoning about a given fix, rather than identifying and understanding possible fixes.

Will the notification go away when I apply this fix? (5)
How do I use this fix in my code? (4)
How do I fix this vulnerability? (4)
How hard is it to apply a fix to this code? (3)
Is there a quick fix for automatically applying a fix? (2)
Will the code work the same after I apply the fix? (2)
What other changes do I need to make to apply this fix? (2)

When searching for approaches to resolve vulnerabilities, participants gravitated toward fix suggestions provided by the notification. As noted above, the notifications associated with the Predictable Random vulnerability and the SQL Injection vulnerability both provided fix suggestions. All participants proposed solutions that involved applying one or both of these suggestions. Specifically, P2 commented that it would be nice if all the notifications contained fix suggestions.

However, unless prompted, none of the participants commented on the disadvantages of using fix suggestions. While exploring the Predictable Random vulnerability, many participants, including P1, P2, and P6, decided to use `SecureRandom` without considering any alternative solutions, even though the use of that suggested fix reduces performance. It seems that providing suggestions without discussing the associated trade-offs appeared to reduce participants' willingness to think broadly about other possible solutions.

Strategy Analysis Results: Although participants were not asked to make any modifications to the code, they did describe their strategies for applying and assessing fixes. Many participants looked for ways to apply fixes automatically. However, none of the FSB notifications included quick fixes. Still, some participants unsuccessfully attempted to apply quick fixes by clicking on various interface elements.

To assess whether the fix had been applied correctly, participants commonly described one particular heuristic. P1, for instance, would make the change and simply "see if the bug [icon] goes away." This strategy typically ensures the original vulnerability gets fixed, but fails when the fix introduces new defects.

3.2.4 Relationship Between Vulnerabilities (4){3}

Some participants asked questions about the connections between co-occurring vulnerabilities and whether similar vulnerabilities exist elsewhere in the code. For example, when participants reached the third and fourth vulnerabilities, they began speculating about the similarities between the vulnerabilities they inspected.

Are all the vulnerabilities related in my code? (3)
Does this other piece code have the same vulnerability as the code I'm working with? (1)

Strategy Analysis Results: Participants asked a few passing questions about the relationships between vulnerabilities, but were not explicitly asked to relate the vulnerabilities to each other across tasks. As a result, we did not observe the emergence of any predominant strategies in this category.

3.3 Code and the Application

3.3.1 Locating Information (10){11}

Participants asked questions about locating information in their coding environments. In the process of investigating vulnerabilities, participants searched for information across multiple classes and files. Unlike Sections 3.3.2 and 3.3.3, questions in this category more generally refer to the process of locating information, not just about locating calling information or data flow information.

Where is this used in the code? (10)
Where are other similar pieces of code? (4)
Where is this method defined? (1)

All ten participants wanted to locate where defective code and tainted values were in the system. Most of these questions occurred in the context of assessing the Predictable Random vulnerability. Specifically, participants wondered where the potentially insecure random number generator was being used and whether it was employed generate sensitive data like passwords.

In other cases, while fixing one method, four participants wanted to find other methods that implemented similar functionality. They hypothesized that other code modules implemented the same functionality using more secure patterns. For example, while assessing the SQL Injection vulnerability, P2 and P5 both wanted to find other modules that created SQL statements. All participants completed this task manually by scrolling through the package explorer and searching for code using their knowledge of the application.

Strategy Analysis Results: For the majority of participants, scrolling through the source file was a key component of their strategies for locating information. Eclipse provides many tools designed to help users locate specific types of information. For example, OPEN DECLARATION locates method declarations, FIND REFERENCES locates references. More generally Eclipse provides a customizable SEARCH tool for locating other information. Despite the availability of such dedicated tools, many participants unsuccessfully scrolled through the package explorer and open files before using tools.

3.3.2 Control Flow and Call Information (10){13}

Participants sought information about the callers and callees of potentially vulnerable methods.

Where is the method being called? (10)
How can I get calling information? (7)
Who can call this? (5)
Are all calls coming from the same class? (3)
What gets called when this method gets called? (2)

Participants asked some of these questions while exploring the Path Traversal vulnerability. While exploring this vulnerability, many participants eventually hypothesized that all the calls originated from the same test class, therefore were not user-facing, and thus would not be called with tainted values. Three participants explicitly asked, *Are all calls coming from the same class?* In fact, in this case, participants' hypotheses were partially correct. Tracing up the call chains, the method containing the vulnerability was called from multiple classes, however those classes were all contained within a test package. Even though all participants did not form this same hypothesis, all ten participants wanted call information for the Path Traversal Vulnerability, often asking the question, *Where is this method being called?*

Strategy Analysis Results: Participants used various strategies to obtain information about control flow. The most basic strategy was simply skimming the file for method calls, which was error-prone because participants could easily miss calls. Other participants used Eclipse's MARK OCCURRENCES tool (code highlighting in Figure 1), which, to a lesser extent, was error-prone for the same reason. Further, it only highlighted calls within the current file.

Participants additionally employed Eclipse's FIND tool, which found all occurrences of a method name, but there was no guarantee that strings returned referred to the same method. Also, it returned references that occurred in dead code or comments. Alternatively, Eclipse's FIND REFERENCES tool identified proper references to a single method. Eclipse's CALL HIERARCHY tool enabled users to locate calls and traverse the project's entire call structure. That said, it only identified explicit calls made from within the system. If the potentially vulnerable code was called from external frameworks, CALL HIERARCHY would not alert the user.

3.3.3 Data Storage and Flow (10){11}

Participants often wanted to better understand data being collected and stored: where it originated and where it was going. For example, participants wanted to determine whether data was generated by the application or passed in by the user. Participants also wanted to know if the data touched sensitive resources like a database. Questions in this category focus on the application's data — how it is created, modified, or used — unlike the questions in Section 3.3.2 that revolve around call information, essentially the paths through which the data can travel.

Where does this information/data go? (9)
Where is the data coming from? (5)
How is data put into this variable? (3)
Does data from this method/code travel to the database? (2)
How do I find where the information travels? (2)
How does the information change as it travels through the programs? (2)

Participants asked questions about the data pipeline while assessing three of the four vulnerabilities, many of these questions arose while assessing the Path Traversal vulnerability.

Strategy Analysis Results: While exploring this vulnerability, participants adapted tools such as the CALL HIERARCHY tool to also explore the program's data flow. As we discussed in *Control Flow and Call Information*, the CALL HIERARCHY tool helped participants identify methods' callers and callees. Specifically, some participants used the CALL HIERARCHY tool to locate methods that were generating or modifying data. Once participants identified which methods were manipulating data, they manually searched within the method for the specific statements that could modify or create data. They relied on manual searching, because the tool they were using to navigate the program's flow, CALL HIERARCHY, did not provide information about which statements were modifying and creating data.

Some participants failed because they used aggregation strategies, rather than tracing individual data elements. This was particularly evident for Task 3, where 12 variables were aggregated in a form object. By tracing individual variables, some participants uncovered the incorrect validation function. Others, like P6, grew tired of tracing each variable and instead considered the form as a whole. As a result, he overlooked the validation function and incorrectly concluded the vulnerability was a false positive.

3.3.4 Code Background and Functionality (9){17}

Participants asked questions concerning the background and the intended function of the code being analyzed. The questions in this category differ from those in Section 3.3.5 because they focus on the lower-level implementation details of the code.

What does this code do? (9)
Why was this code written this way? (5)
Why is this code needed? (3)
Who wrote this code? (2)
Is this library code? (2)
How much effort was put into this code? (1)

Participants were interested in what the code did as well as the history of the code. For example, P2 asked about the amount of effort put into the code to determine whether he trusted that the code was written securely. He explained, "People were rushed and crunched for time, so I'm not surprised to see an issue in the servlets." Knowing whether the code was thrown together haphazardly versus reviewed and edited carefully might help developers determine if searching for vulnerabilities will likely yield true positives.

Strategy Analysis Results: To answer questions in this category, participants relied primarily on their prior knowledge of the system. We observed relatively few instances where participants executed additional strategies to substantiate their existing knowledge. This strategy, or lack thereof, was susceptible to failures when participants overestimated their knowledge of the system. For example, while assessing the Path Traversal vulnerability, P2 incorrectly assumed that the methods in the DBBulder module were only called during development and deployment when iTrust first starts up.

3.3.5 Application Context and Usage (9){9}

Unlike questions in Section 3.3.4, these questions refer to system-level concepts. For instance, often while assessing the vulnerabilities, participants wanted to know what the code was being used for, whether it be testing, creating appointments with patients, or generating passwords.

What is the context of this vulnerability/code? (4)
Is this code used to test the program/functionality? (4)
What is the method/variable used for in the program? (3)
Will usage of this method change? (2)
Is the method/variable ever being used? (2)

Participants tried to determine if the code in the Potential Path Traversal vulnerability was used to test the system. P2, P4, P9, and P10 asked whether the code they were examining occurred in classes that were only used to test the application. To answer this question, participants sometimes used tools for traversing the call hierarchy; using these types of tools allowed them to narrow their search to only locations where the code of interest was being called.

Strategy Analysis Results: Participants were particularly interested in differentiating between two contexts — test code and application code. As P4 explained, test code does not ship with the product, so it is held to a different standard from a security perspective.

Participants' strategies for this task were undermined by the FSB "Bug Explorer" view, because it obscured many of the usual cues participants would have used to differentiate between contexts. In iTrust, tests are organized into a test package, which is separate from the application code. By default, the "Bug Explorer" view closes the package explorer and omits package names from the notification text. Without visible package names or the package explorer, unfortunately some participants were mislead. For instance, P9 incorrectly inferred the code for Task 3 was contained within a test class before eventually correcting his mistake, "This one I would be more inclined to ignore, because it's a test method I believe... Wait no, it's not a test method. No, it's not." Had P9 not corrected his mistake, he would have misdiagnosed the error and ignored a true positive.

3.3.6 End-User Interaction (8){3}

Questions in this category deal with how end users might interact with the system or a particular part of the system. Some participants wanted to know whether users could access critical parts of the code and if measures were being taken to mitigate potentially malicious activity. For example, while assessing the Potential Path Traversal vulnerability, participants wanted to know whether the path is sanitized somewhere in the code before it is used.

Is there input coming from the user? (4)
Does the user have access to this code? (4)
Does user input get validated/sanitized? (4)

When assessing the Potential Path Traversal vulnerability, P1 and P6 wanted to know if the input was coming from the user along with whether the input was being validated in the event that the input did come from the user. For these participants, finding the answer required manual inspection of surrounding and relevant code. For instance, P6 found a `Validator` method, which he manually inspected, to determine if it was doing input validation. He incorrectly concluded that the `Validator` method adequately validated the data.

When assessing the Potential Path Traversal vulnerability, four participants asked whether end-user input reached the code being analyzed. P2 used CALL HIERARCHY to answer this question by tracking where the method the code is contained in gets called; for him, the vulnerability was a true positive if user input reached the code. P1 and P6 searched similarly and determined that because all the calls to the code of interest appeared to happen in methods called `testDataGenerator()`, the code was not vulnerable.

Strategy Analysis Results: Participants' strategies for answering questions about end-user interaction typically included strategies from other categories. In other words, participants gathered evidence by Locating Information (Section 3.3.1), examining Control Flow (Section 3.3.2), retracing Data Flow (Section 3.3.3) information, and recalling information about the Code Background (Section 3.3.4). Participants successfully answered questions in this category when they successfully synthesized the results of these other efforts.

3.4 Individuals

3.4.1 Developer Planning and Self-Reflection (8){14}

This category contains questions that participants asked about themselves. The questions in this category involve the participants' relationship to the problem, rather than specifics of the code or the vulnerability notification.

Do I understand? (3)
What should I do first? (2)
What was that again? (2)
Is this worth my time? (2)
Why do I care? (2)
Have I seen this before? (1)
Where am I in the code? (1)

Participants most frequently asked if they understood the situation, whether it be the code, the notification, or a piece of documentation. For instance, as P6 started exploring the validity of the SQL Injection vulnerability, he wanted to know if he fully understood the notification before he started exploring, so he went back to reread the notification before investigating further. These questions occurred in all four vulnerabilities.

Strategy Analysis Results: Compared to other categories, the strategy analysis results in this category are sparse. Although we asked participants to think-aloud, they seemed to resolve questions in this category internally.

3.4.2 Understanding Concepts (7){6}

Some participants encountered unfamiliar terms and concepts in the code and vulnerability notifications. For instance, while parsing the potential attacks listed in the notification for the Servlet Parameter vulnerability, some participants did not know what a CSRF token was.

What is this concept? (6)
How does this concept work? (4)
What is the term for this concept? (2)

Participants often clicked links leading to more information about specific concepts. For example, while assessing the Potential Path Traversal vulnerability, P2, unsure of what path traversal was, clicked the link labeled "path traversal attack" provided by FSB to get more information. If a link was not available, they went to the web to get more information or noted that the notification could have included more information on those concepts. While parsing the information provided for the Predictable Random vulnerability, P7 and P8 did not know what CSRF token was. The notification for this vulnerability did not include links so they searched the web for more information. When asked what information he would like to see added to the notification for the Servlet Parameter vulnerability, which also did not include any links, P4 noted he would have liked the notification to include what a servlet is and how it related to client control.

Strategy Analysis Results: As mentioned above, participants' strategies for finding information about concepts included clicking the links provided by FSB. However, this strategy failed when the hyperlink text poorly described the links' contents. Unable to determine the quality and type of information hidden behind FSB's links, some participants preferred to search the web for information about concepts.

We observed participants using several noteworthy substrategies while searching online. To find information pertaining to their particular situation, several participants copied and pasted content directly from the FSB notification into their web browser. Participants also demonstrated the simple, yet successful, strategy of iteratively refining their search terms. For example, after performing a search that failed to return relevant results, P1 added specificity to his search by adding the term 'Java'. Finally, we noticed some consistency in the strategies participants were using to find information about concepts — several different participants used the exact same search terms.

3.4.3 Confirming Expectations (4){1}

A few participants wanted to be able to confirm whether the code accomplishes what they expected. The question asked in this category was, *Is this doing what I expect it to?*

Strategy Analysis Results: We did not observe many overarching strategies in this category, in part because participants rarely signaled to us when they were testing their expectations. When we did observe participants questioning their expectations, their strategies varied situationally.

3.5 Problem Solving Support

3.5.1 Resources and Documentation (10){10}

Many participants indicated they would use external resources and documentation to gain new perspectives on vulnerabilities. For example, while assessing the Potential Path Traversal vulnerability, participants wanted to know what their team members would do or if they could provide any additional information about the vulnerability.

Can my team members/resources provide me with more information? (5)
Where can I get more information? (5)
What information is in the documentation? (5)
How do resources prevent or resolve this? (5)
Is this a reliable/trusted resource? (3)
What type of information does this resource link me to? (2)

All ten participants had questions regarding the resources and documentation available to help them assess a given vulnerability. Even with the links to external resources provided by two of the notifications, participants still had questions about available resources. Some participants used the links provided by FSB to get more information about the vulnerability. Participants who did not click the links in the notification had a few reasons for not doing so. For some participants, the hyperlinked text was not descriptive enough for them to know what information the link was offering; others did not know if they could trust the information they found.

Some participants clicked FSB's links expecting one type of information, but finding another. For example, P2 clicked the first link, labeled "WASC: Path Traversal," while trying to understand the Potential Path Traversal vulnerability hoping to find information on how to resolve the vulnerability. When he did not see that information, he attempted another web search for the same information. A few participants did not know the links existed, so they typically used other strategies, such as searching the web.

Other participants expressed interest in consulting their team members. For example, when P10 had difficulty with the Potential Path Traversal vulnerability, he stated that he would normally ask his team members to explain how the code worked. Presumably, the code's author could explain how the code was working, enabling the developer to proceed with fixing the vulnerability.

Strategy Analysis Results: Participants' primary strategy involved consulting the code (i.e. variable and class names) along with its sparse comments. Participants seemed to successfully use this information to understand basic code constructs (i.e. control structures, variable types, method calls, and which variables were being stored in which data structures). However, these strategies sometimes failed to convey security-relevant semantic information. For example, as we discuss more in the surrounding sections, participants struggled to determine whether variables containing user input had been sanitized (3.3.6). Further, this strategy fell short when participants sought documentation for IDE tools or external APIs, when the information was not readily available within the code itself.

Supplementing their primary strategy, participants gathered additional information from web resources. Additionally, participants described their plans to contact team members for help, although they could not do so within the confines of the study.

3.5.2 Understanding and Interacting with Tools (8){9}

Throughout the study participants interacted with a variety of tools including FSB, CALL HIERARCHY, and FIND REFERENCES. While interacting with these tools, participants asked questions about how to access specific tools, how to use the tools, and how to interpret their output.

Why is the tool complaining? (3)
Can I verify the information the tool provides? (3)
What is the tool's confidence? (2)
What is the tool output telling me? (1)
What tool do I need for this? (1)
How can I annotate that these strings have been escaped and the tool should ignore the warning? (1)

Participants asked questions about accessing the tools needed to complete a certain task. Participants sometimes sought information from a tool, but could not determine how to invoke the tool or possibly did not know which tool to use. The question, *What tool do I need for this?* points to a common blocker for both novice and experienced developers, a lack of awareness [34].

Strategy Analysis Results: We observed two types of strategies in this category, tool selection strategies and tool evaluation strategies. While selecting tools, participants often knew what functionality they wanted to achieve, but were unsure how to find a tool to achieve that functionality. For example, P2 knew he wanted to navigate to methods up the call hierarchy, but struggled to identify an appropriate tool. His tool selection strategy involved first Ctrl-hovering over the current method's name followed by right clicking the method name. This strategy failed because the tool was not available in the Ctrl-hover menu and he failed to recognize the tool in the right-click menu.

Rather than search for the ideal tool, some participants opted to opportunistically invoke tools and evaluate the appropriateness of their output. Unfortunately, these strategies were susceptible to misinterpretations. For example, one participant opened, closed, and reopened the CALL HIERARCHY tool several times, unable to determine whether it was appropriate.

3.5.3 Vulnerability Severity and Ranking (5){4}

FSB estimates the severity of each vulnerability it encounters and reports those rankings to its users (Table 2). Participants asked questions while interpreting these rankings.

How serious is this vulnerability? (2)
How do the rankings compare? (2)
What do the vulnerability rankings mean? (2)
Are all these vulnerabilities the same severity? (1)

Most of these questions came from participants wanting to know more about the tool's method of ranking the vulnerabilities in the code. For example, after completing the first task (Potential Path Traversal), P1 discovered the tool's rank, severity, and confidence reports. He noted how helpful the rankings seemed and included them in his assessment process for the following vulnerabilities. As he began working through the final vulnerability (SQL Injection), he admitted that he did not understand the tool's metrics as well as he thought. He wasn't sure whether the rank (15) was high or low and if yellow was a "good" or "bad" color. Some participants, like P6, did not notice any of the rankings until after completing all four sessions when the investigator asked about the tool's rankings.

Strategy Analysis Results: Severity ratings typically help developers triage vulnerabilities. Due to the limitations of our controlled study, we preselected the vulnerabilities and the order in which they would appear. As a result, working with the severity rankings was not critical for participants to complete their tasks. Therefore, we observed relatively shallow strategies in this category; some participants asked questions about the rankings, but most did not follow up with an investigation.

3.5.4 Notification Text (6){3}

FSB provided long and short descriptions of each vulnerability (Figure 1). Participants read and contemplated these notifications to guide their analysis.

What does the notification text say? (5)
What is the relationship between the notification text and the code? (2)
What code caused this notification to appear (2)

Beyond asking about the content of the notification, participants also asked questions about how to relate information contained in the notification back to the code. For example, the Predictable Random vulnerability notes that a predicable random value could lead to an attack when being used in a secure context. Many participants attempted to relate this piece of information back to the code by looking to see if anything about the code that suggested it is in a secure context. In this situation, the method containing the vulnerability was named `randomPassword()`, which suggested to participants that the code was in a secure context and therefore a vulnerability that should be resolved.

Strategy Analysis Results: Participants' defect resolution strategies appeared to include reading portions of the notification text. The three participants (P3, P4, and P6) who reported the lowest familiarity with vulnerabilities started 11 of 12 tasks by immediately reading the notification text. Conversely, the participants (P5 and P7) who reported the most familiarity with vulnerabilities only started by reading the notification text for 2 of 8 tasks.

The distinctions between these two workflows affected how participants built hypotheses. Low-familiarity participants built their initial hypothesis from the notification and tested that hypothesis against the code. On the other hand, high-familiarity participants used the notification to refine their already-formed hypotheses. It remains an open question whether tool notifications currently support one of these workflows more than the other; the presence of two distinct workflows suggests tools should support both.

Participants' strategies also varied in terms of how much of the notification they read. Some participants read the entirety of the message before proceeding, whereas others only read the short descriptions. Several participants read the visible parts of the long description, but neglected to scroll further to reveal the rest of the message. Often, this lead to problems. For instance, P3 struggled with the Predictable Random vulnerability because he initially failed to find documentation for `SecureRandom`. P3 started the task by reading only the first half of the long description. After finally finding the documentation online and completing the task, the interviewer directed his attention to the overlooked second half of the long description. P3 read the rest of the description and realized it contained the information he sought, "I didn't scroll down that far. I see it even has a link to generating strong random number. I could have clicked on this link."

4 ASSUMPTIONS

While performing their tasks, participants made different types of assumptions. Overall, we observed 73 total assumptions —

27 incorrect and 46 correct. We identified assumptions across all participants, except for P3. Additionally, we found at least one assumption during each task. In this section we will describe different types of correct and incorrect assumptions as well as elaborate on how those assumptions contributed to defect resolution.

iTrust inherits functionality from many external libraries. Participants commonly made assumptions about these external libraries, their correctness, and their usage. Some assumptions centered around the proper usage of an external library. For instance, while skimming `SecureRandom`'s documentation during Task 2, P8 incorrectly assumed `SecureRandom` does not provide a `nextInt` method. Based on that assumption, P8 proposed a workaround that was valid, but duplicated the functionality nextInt already provided. Other assumptions pertained to the security of external libraries. For example, P7 correctly assumed that `SecureRandom` handles the secure seeding of random number generators. In contrast with P8, P7's correct assumption lead him to propose the most valid and readable solution.

Tools attempt to communicate information about the location and type of defect in the code. When FSB failed to effectively communicate that information to participants, they made assumptions. For Task 3, P10 incorrectly assumed FSB was indicating an issue with the DAO objects. Based on that assumption, he proposed adding a sanitization method to those objects, which is an incorrect fix. Sanitization methods already existed in another class and just needed to be modified.

As we discussed in Section 3.3.3, tracing the sources of data was an important part of participants' tasks. Participants made assumptions about where data comes from, whether it be from a user or hard-coded test data. For Task 1, P1 incorrectly assumed data was passed in from a user. He followed up on this weakly-held assumption by further investigating the origin of the data. His successful investigation strategy, which included him using the CALL HIERARCHY tool, led him to correct his initial assumption and resolve the defect correctly.

5 Discussion

In this section we discuss the implications of our work.

5.1 Flow Navigation

When iTrust performed security-sensitive operations, participants wanted to determine if data originated from a malicious source by tracing program flow. Similarly, given data from the user, participants were interested in determining how it was used in the application and whether it was sanitized before being passed to a sensitive operation. Questions related to these tasks appear in four different categories (Sections 3.3.1, 3.3.2, 3.3.3, 3.3.6). We observed participants using three strategies to answer program flow questions, strategies that were useful, yet potentially error-prone.

First, when participants asked whether data comes from the user (*a user-facing source*), and thus cannot be trusted, or if untrusted data is being used in a sensitive operation, participants would navigate through chains of method invocations. When participants navigated through chains of method invocations, they were forced to choose between different tools, where each tool had specific advantages and disadvantages. Lightweight tools, such as FIND and MARK OCCURRENCES, could be easily invoked and the output easily interpreted, but they often required multiple invocations and sometimes returned partial or irrelevant information. For example, using MARK OCCURRENCES on a method declaration highlights all invocations of the method within the containing file, but it does not indicate invocations in other files. On the other hand, heavyweight tools, such as CALL HIERARCHY and FIND REFERENCES, return method invocations made from anywhere in the source code, but were slower and clumsier for participants. Moreover, even heavyweight tools do not return all invocations when looking for tainted data sources; for instance, CALL HIERARCHY does not indicate when methods are being called from outside the system by a framework.

Second, when participants asked whether a data source was user-facing, participants would make inferences based on class names. For instance, any class that started with `Test` participants assumed was as JUnit test case, and thus was not user-facing, and therefore not a potential source of tainted data. When participants made inferences based on class names, their inferences were generally correct that the class name accurately described its role. However, this strategy fails in situations where the word "Test" is overloaded; this happens in iTrust where "Test" can also refer to a medical laboratory test.

Third, a common strategy for participants was to rely on their existing knowledge of sensitive operations and data sources in the application. When participants relied on existing knowledge of sensitive operations and data sources, such reliance may be failure-prone whenever the code has been changed without their knowledge. Indeed, prior research suggests that developers are less knowledgeable about unstable code [10]. Additionally, when a developer only contributes to a portion of the system, as is often the case in the open source community [33], he may be unable to reason about the system-wide implications of a change.

Much like work that examines more general programming tasks [27], we observed that participants would have benefited from better program flow navigation tools while investigating security vulnerabilities. Although researchers have proposed enhanced tools to visualize call graphs [28] and trace control flow to its origin [3], in a security context, these tools share the same limitations as the existing heavyweight tools. Existing tools like CodeSonar [43] and Coverity provide source-to-sink notifications for analyzing security vulnerabilities, but take control away from the programmer by forcing the developer into a tool-dictated workflow.

We envision a new tool that helps developers reason about control flow and data flow simultaneously, by combining the strengths of existing heavy and lightweight tools. We imagine such a tool could use existing heavyweight program analysis techniques, but still use a lightweight user interface. For example, such a tool might use a full-program, call hierarchy analysis technique in the back end, but use a MARK OCCURRENCES-like user interface on the front end. To indicate calls from outside the current class, additional lightweight notifications would be needed. Such a tool could support both lightweight and systematic investigation of the flow of potentially tainted data.

5.2 Structured Vulnerability Notifications

FSB provided explanatory notifications of potential vulnerabilities. However, to completely resolve vulnerabilities, participants performed many cognitively demanding tasks beyond simply locating the vulnerability and reading the notification, as is evidenced by the breadth of questions they asked. To resolve potential vulnerabilities, we observed participants deploying a mix of several high-level strategies including: inspecting the code; navigating to other relevant areas of the code; comparing the vulnerability to previous vulnerabilities; consulting documentation and other resources; weighing existing knowledge against information in the notification; and reasoning about the feasibility of all the possible attacks. Yet, these strategies were limited in three respects.

Participants used error-prone strategies even when more reliable tools and strategies were available. For example, in Section 3.5.1, we noted that participants, unaware of the relevant hyperlinks embedded within the notification text, searched for links to external resources using web search tools. The web searches often returned irrelevant results. However, when the interviewer pointed out the embedded links after the session, participants stated that they probably should have clicked them.

Second, even after choosing an effective strategy, participants were often unaware of which tools to use to execute the strategy. For example, while assessing the Servlet Parameter vulnerability, participants wanted to determine whether certain input parameters were ever validated, but were not aware of any tools to assist in this process. Previous research suggests that both novice and experienced developers face problems of tool awareness [34].

Third, regardless of the strategies and tools participants used, they had to manually track their progress on each task. For example, the Servlet Parameter vulnerability involved twelve tainted parameters and introduced the possibility of several types of attacks. Participants had to reason about each of those attacks individually and remember which attacks they had ruled out. In a more general programming context, researchers have warned about the risks of burdening developers' memories with too many concurrent tasks — overburdening developers' attentive memories can result in *concentration failure* and *limit failure* [36].

We envision an approach that addresses these limitations by explicating developers' strategies in the form of hierarchically structured checklists. Previous research suggests that checklists can effectively guide developers [37]. We propose a structure that contains hierarchical, customizable tasks for each type of notification. For example, the structure would contain high-level tasks, such as "Determine which attacks are feasible," and subsequently more actionable nested subtasks, such as "Determine if a SQL injection attack is feasible" or "Determine if an XSS attack is feasible." This structure would also include a checklist-like feature that allows users to save the state of their interaction with a particular notification — for example, checking off which attack vectors they have already ruled out — diminishing the risk of *concentration failure* and *limit failure*. Additionally, each task could include links to resources that relate specifically to that task and tool suggestions that could help developers complete the task.

5.3 Context-Informed Web Search

Accessing web resources was an important element of participants' strategies across several categories (Section 3.2.1, Section 3.2.2, Section 3.4.2, Section 3.5.1). To find success, participants sought information that was scattered around different sites. Depending on the task and an individual's approach, participants found critical clues hidden on StackOverflow, official documentation pages, and personal blogs, for instance.

To reach these helpful web resources, participants either (1) followed the links that FSB had curated, or (2) used an online search engine. As we will discuss, both of these approaches are failure-prone. However, by drawing inspiration from the positive aspects of each of these approaches, we will propose a new tool-assisted approach for gathering resources from the web while diagnosing a static analysis defects. We will refer to this approach as *context-informed web search*.

(1) FSB includes links to web resources in its description of some defects under the header "References." FSB's designers supposedly deem these references relevant and helpful, and, when references to the right types of information were available, participants tended to agree. Unfortunately, the links in each references section cover a limited number of topics. For example, the references might describe the defect and how to exploit it, but not how to remedy the vulnerability. In practice participants sought information and visited sites beyond what was available in the finite reference sections. In summary, the references encapsulate the tool *designer's* expertise and knowledge of a specific defect pattern, but are not tailored to the user's needs.

(2) Participants also used search engines to locate web resources, sometimes as a primary means, other times after having exhausted the FSB links. With this approach, participants had to sift through long lists of irrelevant results to find useful information. As described in Section 3.4.2, some participants iteratively refined their search terms to filter out as many irrelevant results as possible. Others simply tested link after link until they found something useful or gave up.

The two approaches for accessing web resources described so far exist at opposite ends of a spectrum and fail in complementary ways. The tool's list of links (1) only cover a narrow set of topics, with each link highly relevant to the defect reported. Conversely, search engines (2) over-approximate the set of relevant resources, but cover far more topics of interest.

We envision a new way for developers to access web resources while resolving defects with static analysis, *context-informed web search*. This approach improves on existing approaches by combining the breadth of web search with the relevance afforded by a tool's contextual awareness. Users would perform a *context-informed web search* just as they would any other web search, but enter their query into a specialized search engine, rather than a general-purpose search engine. The specialized search engine would work in tandem with the developers' static analysis tool and would start by fetching results just like a general-purpose search engine. Before returning those results to the user, the specialized search engine would query the static analysis tool for details about the developers context — information the tool has already computed in order to detect defects. Finally, the specialized search engine would only display context-relevant results.

Consider, for example, a developer who searches for 'secure random number.' A general-purpose search engine would return results targeted at Ruby, Javascript, Android, and Java developers. The specialized search engine could conclude from the static analysis tool that the developer was using Java and importing java.util.Random and filter out irrelevant results pertaining to other languages.

6 Related Work

We have organized the related work into three subsections. Section 6.1 outlines some of the current approaches researchers use to evaluate security tools, Section 6.2 references other studies that have explored developers' information needs, and Section 6.3 relates our work to the other work on strategies.

6.1 Evaluating Security Tools

Using a variety of metrics, many studies have assessed the effectiveness of the security tools developers use to find and remove vulnerabilities from their code [2], [30], [31].

Much research has evaluated the effectiveness of tools based on their false positive rates and how many vulnerabilities they detect [2], [7], [19]. For instance, Jovanovic and colleagues evaluate their tool, PIXY, a static analysis tool that detects cross-site scripting vulnerabilities in PHP web applications [19]. They considered PIXY effective because of its low false positive rate (50%) and its ability to find vulnerabilities previously unknown. Similarly, Livshits and Lam evaluated their own approach to security-oriented static analysis, which creates static analyzers based on inputs from the user [30]. They also found their tool to be effective because it had a low false positive rate.

Austin and Williams compared the effectiveness of four existing techniques for discovering security vulnerabilities: systematic and exploratory manual penetration testing, static analysis, and automated penetration testing [2]. Comparing the four approaches based on number of vulnerabilities found, false positive rate, and efficiency, they reported that no one technique was capable of discovering every type of vulnerability.

Dukes and colleagues conducted a case study comparing static analysis and manual testing vulnerability-finding techniques [7]. They found combining manual testing and static analysis was most effective, because it located the most vulnerabilities.

These studies use various measures of effectiveness, such as false positive rates or vulnerabilities found by a tool, but none focus on how developers interact with the tool. Further, these studies do not evaluate whether the tools address developers' information needs. Unlike existing studies, our study examines a security tool through the lens of developers' information needs and, accordingly, provides a novel framework for evaluating security tools.

6.2 Information Needs Studies

Several studies have explored developers' information needs outside the context of security. Similar to our work, some existing studies determine these needs by focusing on the questions developers ask [21], [26], [27], [39]. These three studies explore the questions developers ask while performing general programming tasks. In contrast to previous studies, our study focuses specifically on the information needs of developers while performing a more specific task, assessing security vulnerabilities. Unsurprisingly, some of the questions previously identified as general programming questions also occur while developers assess security vulnerabilities (e.g., Sections 3.3.2 and 3.3.3).

Much of the work on answering developer questions has occurred in the last decade. LaToza and Myers surveyed professional software developers to understand the questions developers ask during their daily coding activities, focusing on the hard to answer questions [27]. Furthermore, after observing developers in a lab study, they discovered that the questions developers ask tend to be questions revolving around searching through the code for target statements or reachability questions [26]. Ko and Myers developed WHYLINE, a tool meant to ease the process of debugging code by helping answer "why did" and "why didn't" questions [22]. They found that developers were able to complete more debugging tasks while using their tool than they could without it. Fritz and Murphy developed a model and prototype tool to assist developers with answering the questions they want to ask based on interviews they conducted [9].

6.3 Defect Resolution Approaches

Prior work has noted the importance of strategies. In their inspirational work, Bhavnani and John observed that knowledge of tasks and tools for complex computer applications such as CAD were insufficient for developers to be efficient; they found that users needed to learn good strategies [4]. Additionally, they argue that the identification of efficient strategies should be a key research goal. Our work furthers progress toward that goal by identifying successful strategies for resolving security vulnerabilities. Further, Katz and Anderson, found that a developer's choice of bug-location strategy affects his or her ability to asses the correctness of a line of code [20]. Our work extends that of Katz and Anderson by focusing on the defect resolution process after a potential bug has been located.

Several studies have explored the effects of strategies and assumptions in end-user programming environments. Grigoreanu and colleagues examined gender differences in debugging strategies for spreadsheet end-user programmers [12], [13]. Through a think-aloud study, they found that women and men employed different strategies. For example, women tended to use comprehensive information processing styles, where they overview the task before making changes; in contrast, men tended to selectively process information. Gross and colleagues conducted an exploratory study in which end-user programmers were asked to find and modify code for specific functionality with unfamiliar programs, which they classified into models [14]. Ko and colleagues categorized six types of learning barriers faced by end-user programmers [23]. They discussed how end-user programmers can overcome learning barriers by making simplifying assumptions, but incorrect assumptions often lead to errors.

7 THREATS TO VALIDITY

In this section we discuss the internal and external threats to the validity of our study.

We faced the internal threat of recording questions that participants asked because they lacked a basic familiarity with the study environment. We took two steps to mitigate this threat. First, we required participants to have experience working on iTrust. Second, at the beginning of each session, we briefed participants on FSB and the development environment. During these briefing sessions, we gave participants the opportunity to ask questions about the environment and study setup, though we cannot say for certain that participants asked all the questions they had at that time.

Thus, some of the questions we identified may reflect participants' initial unfamiliarity with the study environment and FSB. Since we are interested broadly in developers' information needs, the initial questions they ask about a new tool and environment still are an important subset to capture.

Because this study was conducted in a controlled environment rather than an industrial development setting, our results also face a threat to their external validity. Though we cannot and do not claim that we have identified a comprehensive categorization of all security-related questions all developers might ask, we have made several efforts to mitigate this threat. First, we included both students and professionals in our sample, because developers with more or less experience might ask different questions. Further, participants were equipped with FSB, a representative open source static analysis tool with respect to its user interface. Finally, we chose iTrust, an industrial-scale open-source project as our subject application.

Relatedly, participants may have spent an unrealistic amount of time (either too much or too little) on each task due to working outside their normal work environment. To counteract this threat, we did not restrict the amount of time alloted for each task. Further, whenever a participant asked the interviewer what to do next, the interviewer provided minimal guidance, typically prompting the participant to proceed as she would in her normal work environment.

8 Conclusion

This paper reported on a study that explored how developers resolve security defects while using static analysis. During the study, we asked ten software developers to describe their thoughts as they assessed potential security vulnerabilities in iTrust, a security-critical web application. We presented the results of our study as a categorization of questions and a catalog of strategies for answering those questions. Our findings have several implications for the design of static analysis tools. Our results suggest that tools should help developers, among other things, search for relevant web resources.

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Appendix A
Recruitment Email

Hi [Name],

My name is Justin Smith. I am a PhD student working with Dr. Murphy-Hill on doing a study with iTrust. I am looking for students who have worked on this system in the past. Participation in this study will help improve the design of security related software engineering tools.

The study will take approximately 45 – 60 minutes to complete. Participants must perform the study at NC State University, Room [TBD]. Familiarity with iTrust is required.

If you have any questions about the study or would like to schedule a time to participate, please respond to me at this email address (jssmit11@ncsu.edu). Participants must be 18 years of age or older.

Thanks!
Justin Smith

Appendix B
Procedure

Introductory Script: This experiment is designed to evaluate how you approach security vulnerabilities. This session will be recorded using screen and audio capture software. I will present you with some code that FindBugs has analyzed and ask you to explain what is going on.

This experiment is not designed to test your ability as a developer. Instead, we are attempting to understand how you approach code vulnerabilities. During the experiment, you can use any web resource. I have opened a web browser, which you are welcome to use at any point.

For the purposes of this experiment, imagine that you are in charge of security for iTrust, which is nearing release. You must justify any proposed code changes that you make. Currently, the software may contain security vulnerabilities. FindBugs has been configured to direct you to 4 areas of concern. For each area, Ill ask you about 10 questions.

Do you have any questions before we begin?

1) Navigate to first warning message

2) Read through the code/warning message

3) Try to think aloud. So, say any questions or thoughts that cross your mind regardless of how relevant you think they are.

Experimental Questions:

- Can you explain what this warning is trying to tell you?
- What are you exploring/trying to figure out right now?
- What information do you need to proceed?
- For the sake of time, explain to me what you would keep doing?
- Would you normally do this in your work?
- How does the wording effect the process?
- Based on your understanding of this error message, what is the percentage likelihood you would modify this section of the code?
- How would you fix the problem? Where would you start?
- On a scale of 1-5, how confident are you in your understanding of this error message?
- On a scale of 1-5, how confident are you that you are making the correct judgment?
- What part of the message is most helpful?
- What information would you like to see added to the error message?
- Look at the error message one last time. Is there any information that you initially disregarded?
- Anything else I should know?

Post-Experiment Questions:

- What is your current job title (if student, indicate so here)
- How many years have you been programming?
- How many years of professional programming experience do you have?
- Over the last year, about how many hours per week would you say you spend programming, on average?
- When programming, do you typically use security tools? Y/N
  - If Y, Which tool(s) do you use? Why do you use these security tool?
  - If N, can you tell me the reasons why you don't use security tools?
- On a scale form 1 to 5, how familiar are you with security vulnerabilities? (1 = not at all, to 5 = very familiar)
- In general how effectively did the FindBugs communicate information to you? What did you or didnt you like?
- What security related questions could the tool answer better?

[2] research.csc.ncsu.edu/dlf/

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