Understanding security mistakes developers make: Qualitative analysis from Build It, Break It, Fix It

Abstract
Secure software development is a challenging task requiring programmers to consider many possible threats and mitigations. This paper investigates how and why programmers, despite having a baseline of security experience, make security-relevant errors. To do this, we conducted an in-depth analysis of 76 submissions to a secure programming contest designed to mimic real-world constraints: correctness, performance, and security. In addition to writing secure code, participants were asked to search for vulnerabilities in other teams’ programs; in total, teams submitted 866 exploits against the submissions we considered. We found that simple mistakes were least common: only 26% of projects introduced such an error. Conversely, vulnerabilities arising from a misunderstanding of security concepts were significantly more common: 84% of projects introduced at least one such error.

Author Keywords
Secure Software Development; Vulnerability Discovery; Security Competitions

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Introduction
Producing secure programs is a difficult task. NIST’s National Initiative for Cybersecurity Education framework highlights the size of the challenge developers face, outlining 44 distinct areas of knowledge necessary for secure development [4]. Developers’ limited time and attention — e.g., for security training, or for learning about and using new programming and testing tools — implies the importance of identifying the most critical and effective security interventions to prioritize.

Research Questions:
RQ1: What types of vulnerabilities do developers introduce? Are they conceptual flaws in their understanding of security requirements or coding mistakes?

RQ2: How severe are the vulnerabilities? If exploited, what is the effect on the system?

RQ3: How exploitable are the vulnerabilities? What level of insight is required and how much work is necessary?

Simple mistakes, in which the developer attempts a valid security practice but makes a minor programming error, were least common: only 26% of projects introduced such an error. However, vulnerabilities arising from misunderstanding of security concepts were significantly more common: 84% of projects introduced at least one such error. Although these vulnerabilities were common, they proved difficult to exploit: only 76% were exploited by other teams (compared to 97% of simple mistakes), and our qualitative labeling identified 32% as difficult to exploit (compared to none of the simple mistakes).

Methods
We are interested in characterizing the vulnerabilities developers introduce when writing programs with security requirements. In particular, we pose several research questions as can be seen in the sidebar on page 2.

Answers to these questions can provide guidance about which interventions—tools, policy, and education—might be (most) effective, and how they should be prioritized. To obtain answers, we manually examined a sample of 76 BIBIFI projects (54% of all BIBIFI projects) and the 866 breaks submitted against them. The ultimate codebook we developed provides labels for vulnerabilities—their type, severity, and exploitability—and for features of the programs that contained them.

Codebook
To measure the types of vulnerabilities in each project, we characterized them across three variables as can be seen in the sidebar on page 4.

Results
Our manual analysis of 76 BIBIFI projects identified 172 unique vulnerabilities. We categorized each based on our
codebook into 23 different Types. We also saw some interesting relationships between vulnerability class and prevalence, severity, and likelihood to be exploited.

**Classes**

**No Implementation** A vulnerability type was classed as *No Implementation* when a team failed to even attempt to implement a necessary security mechanism, presumably because they did not realize it was needed. This class is further divided into the sub-classes *All Intuitive*, *Some Intuitive*, and *Unintuitive*. In the first two categories teams did not implement all or some, respectively, of the requirements that were either directly mentioned in the problem specification or were intuitive. The *Unintuitive* category was used if the security requirement was not directly stated or was otherwise unintuitive.

**Misunderstanding** A vulnerability type was classed as *Misunderstanding* when a team attempted to implement a security mechanism, but failed due to a conceptual misunderstanding. We sub-classed these as either *Bad Choice* or *Conceptual Error*. An example of this can be seen in figure 1.

**Mistake** Finally, some teams attempted to implement the solution correctly, but made a mistake that led to a vulnerability. The mistake class is composed of five subclasses: insufficient error checking (P=12, V=12), uncaught runtime error (P=5, V=9), control flow mistake (P=5, V=10), skipped algorithmic step (P=5, V=7), and null write (P=1, V=1). An example of this can be seen in figure 3.

**Prevalence**

We observed a clear trend that teams often struggled to completely understand security concepts.

**Teams often did not understand security concepts** We found that both classes of vulnerabilities relating to a lack of security knowledge—*No Implementation* and *Misunderstanding*—were significantly more likely to be introduced than vulnerabilities caused by programming mistakes. These results indicate that efforts to address conceptual gaps should be prioritized. Focusing on these issues of understanding, we make the following observations.

**Unintuitive security requirements are commonly skipped** Of the *No Implementation* vulnerabilities, we found that the *Unintuitive* subclass was much more common than its *All Intuitive* or *Some Intuitive* counterparts. This indicates that developers do attempt to provide security—at least when incentivized to do so—but struggle to consider all the unintuitive ways an adversary could attack a system.
Teams often used the right security primitives, but did not know how to use them correctly. Among the Misunderstanding vulnerabilities, we found that the Conceptual Error sub-class was significantly more likely to occur than Bad Choice. This indicates that despite knowing the correct primitives to use, developers do not always conform to the assumptions of “normal use” made by the library developers.

**Complexity breeds Mistakes** We found that complexity within both the problem itself and also the approach taken by the team has a significant effect on the number of Mistakes introduced. Mistakes were most common in the multiuser database problem and least common in the secure log problem. Teams were $5.79 \times$ more likely to introduce Mistakes in multiuser database than in the baseline secure communication case. This effect likely reflects the fact that the multiuser database problem was the most complex, requiring teams to write a command parser, handle network communication, and implement nine different access control checks.

**Effect of Exploitation** To answer RQ2 and RQ3, we compare the severity and likelihood of exploitation of the identified vulnerabilities. Misunderstandings are hard to find Identifying Misunderstanding vulnerabilities often required the attacker to determine the developer’s exact approach and have a good understanding of the algorithms, data structures, or libraries they used. As such, we coded Misunderstanding vulnerabilities as hard to find significantly more often than both No Implementation and Mistake vulnerabilities.

No Implementations are easy to find Unsurprisingly, a majority of No Implementation vulnerabilities were coded as easy to find ($V=41, 60\%$ of No Implementations). None of the All Intuitive or Some Intuitive vulnerabilities were coded as difficult to exploit; however, $42\%$ of Unintuitive vulnerabilities were ($V=19$).

Mistakes are easy to find and exploit We coded Mistakes as easy to exploit significantly more often than either No Implementation or Misunderstanding vulnerabilities. Further, all Mistakes were coded as easy to exploit. Fortunately, code review may be sufficient to find many of these vulnerabilities: Mistakes were also found and exploited during the Break It phase significantly more often than either Misunderstanding or No Implementation with only one Mistake ($0.03\%$) not found by any Break It team.

**Conclusion** With the goal of understanding which security errors programmers tend to make and why, this paper has presented a systematic, qualitative study of 76 program submissions to the build it, break it, fix it secure programming contest. Considering the 866 exploits against these submitted programs, we labeled 172 unique security vulnerabilities, according to type, severity, and ease of exploitability as well as security aligned project features. We found implementation mistakes were comparatively less common than failures in security understanding. Our results have implications for improving APIs and documentation, vulnerability-finding tools, and security education.

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**REFERENCES**

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