Real-World Study of the Security of Educational Test Systems

Stefan Gast*, Sebastian Daniel Felix*, Alexander Steinmaurer†, Jonas Juffinger*, Daniel Gruss*
*Graz University of Technology, Graz, Austria
Email: {stefan.gast, jonas.juffinger, daniel.gruss}@tugraz.at, sebastian.felix@student.tugraz.at
†Interdisciplinary Transformation University Austria, Linz, Austria
Email: alexander.steinmaurer@it-u.at

***Abstract*—Computer science education has a unique setting where students write code commonly automatically tested in so-called "test systems". While best practices for sandboxing are known in the academic community, the security of real-world test systems remains unclear.**

In this work, we evaluate the security of 11 real-world test systems from computer science university classes, including computer security classes. We studied these systems between October 2023 and February 2024 and provide a systematic overview of the typical approaches these systems follow. We identify 3 categories of systems: GitLab Runners with a Docker registry, GitLab Runners with custom pipelines, and entirely custom test systems that do not rely on a CI system as a basis. We identify 13 types of security issues, the most widely spread ones affecting 5-6 of the test systems in our analysis. We practically show that all test systems in our analysis can be compromised and develop new techniques to exfiltrate secret and privileged information, including the use of side channels. We present 3 cases studies, demonstrating specific bypasses possible in these systems. Finally, in a user study, we assess the impact a potential breach together with the educators using these test systems. Our work shows that educational test systems are particularly critical, as a compromise can lead to the exposure of highly sensitive student and research data, and even embargoed vulnerabilities. Our results highlight that the real-world challenges to run and maintain secure test systems are not solved in practice. While we discuss best practices, our study reveals the need for new systematic security approaches to secure this very common type of software system.

1. Introduction

A crucial element of university computer science education is that students also practically write code. Educators review this code and often also used to grade the students [1]. Practical programming courses range from introductory courses to programming languages to advanced courses requiring direct hardware access or courses for practicing the development of secure code and exploitation of insecure code. Especially for larger institutions with thousands of students, reviewing student code can accumulate to a significant workload [2].

A solution to this resource problem is the partial or full automation of the code reviews [2], [3]. For this purpose, an automated "test system" [4] runs student code with test inputs and analyzes the behavior and output. Especially for classes with thousands of users, this is a unique setting where large amounts of untrusted code are run on university computer systems. There are different approaches on how to run the untrusted student code, ranging from simple scripts that execute one program after another to the use of containers and virtual machines. Wilcox [4] already noted that security is a crucial aspect of these systems and advised the use of `chroot` or virtual machines. Similarly, Paiva et al. [3] argue that virtual machines and containers are among the most comprehensive solutions to run student code securely. As the students are also often provided with Git repositories via university GitLab instances, one can consider GitLab Runners (the continuous-integration system integrated in GitLab) [5] for testing student code. GitLab Runners can be configured to use a container or a virtual machine. While under normal use, the output would be provided to the developer, educators can restrict the information they hand to students, e.g., via customized interfaces that communicate with GitLab through an API. However, CI systems are intended for trusted environments, whereas in malware analysis, where the fundamental assumption is that the code under analysis is malicious, other tools, such as virtual machines [6], are used to fully isolate the malicious code from the rest of the system.

In this work, we show that despite following the recommendations of prior work, e.g., using containers or virtual machines, several security issues can persist in educational test system environments. We evaluate the security of 11 test systems used in computer science university classes during the time frame from October 2023 to February 2024, including computer security classes.[1] We studied these systems and provide a systematic overview of the typical approaches these systems follow. We identify 3 categories of systems: GitLab Runners with a Docker registry, GitLab Runners with custom pipelines, and entirely custom test systems that do not rely on a CI system as a basis. We identify 13 types of security issues, the three most widely spread ones affecting 5-6 of the test systems in our analysis.

We practically show that all test systems in our analysis can be compromised and develop new techniques to exfiltrate secret and privileged information, including the usage of side channels. We present 3 case studies, showing specific bypasses possible in these concrete systems. Finally, in a user study, we assess the impact of a

1. We note that one of the systems was set up by one of the authors of this paper.

potential breach together with the educators using these test systems. Based on our results, we derive best practices that educators should follow to minimize security risks and prevent exposure of confidential data and malicious data integrity breaches in the context of testing untrusted student code.

Contributions. We summarize our contributions as follows.

1) We systematically analyze the security of 11 independently developed test systems in computer science education that were practically used from October 2023 to February 2024.
2) We identify 3 categories of systems and 13 types of security issues tied to these systems. We showcase 3 case studies where we show the specific security bypasses possible.
3) We assess the impact of potential breaches in a user study involving the educators of these systems.
4) We discuss best practices for educators to minimize the risk of security breaches that would compromise the confidentiality and integrity of sensitive data but also the practical limitations.

Ethical Considerations. We responsibly disclosed our findings to the maintainers of the examined test systems in December 2023. We received permission to publish our findings from the test system maintainers and invited them to take part in our user study. In our experiments, we have not extracted any personal identifiable information from the affected systems.

Outline. The rest of the paper is organized as follows. Section 2 provides background. Section 3 presents our systematic analysis of the 11 test systems we study and categorizes them into 3 categories. Section 4 presents the 13 types of security issues we identified and how they are tied to the design choices of the systems. Section 5 showcases 2 case studies of concrete test systems and how they can be exploited. Section 6 presents our user study with educators to assess the impact of potential breaches. Section 7 contextualizes our work and discusses best practices to minimize security risks. Section 8 concludes.

2. Background

In this section, we overview computer science education, focusing on higher education, educational aspects of test systems in coding classes, principles of related continuous integration systems, and misconfiguration of those.

2.1. Programming Education at Universities

In almost all computer science-related study programs around the globe, programming is one of the core concepts within the curricula. Even though these programming courses are building the central foundation for the students' programming education, the learned concepts are part of many follow-up classes. Traditionally, courses that involve programming, especially early in the academic education, have specific characteristics: For example large, they often comprise a heterogenous groups of students, continuous assessment, and large performance differences between students [7]. In a comprehensive literature review, Medeiros et al. [8] report that scalability is one of the major challenges that educators are faced with. This can be traced back to diverse backgrounds of students enrolled in computer science classes, including varying levels of prior programming experience, academic preparation, and mindset.

Xia [9] found that well-defined learning goals and a deeper cognitive understanding are relevant factors for a successful learning process, especially in programming education. One central concept related to learning and motivation is self-efficacy, introduced by Bandura [10], which is part of the *social cognitive theory*. Self-efficacy means that an individual's belief in their own ability to accomplish tasks directly influences their actions and persistence in the face of challenges. The theory implies that students with high self-efficacy in their programming abilities are more likely to engage in learning and persevere through difficulties.

Another challenge related to scalability is a lack of feedback and communication between educators and students due to a mismatch in the staff-student ratio. Koulouri et al. [11] discuss the role of formative feedback, which is not always positive, as students may find feedback challenging to understand. Additionally, the complexity of coding assignments in computer science education, particularly in advanced courses, poses challenges for educators.

2.2. The Need for Automated Test Systems

Automated testing systems play a crucial role in accommodating this complexity by providing personalized feedback, assessment, and support to students at different skill levels in many computer science courses. Educators carefully design test suites and evaluation criteria to assess students' mastery of key concepts, problem-solving skills, and software development practices, ensuring that assessments are meaningful and relevant to the course objectives. Wrenn et al. [12] show that this widely used approach may negatively impact the quality of the assessment of students due to cases not fully considered in the test suites. However, in a recent study, Mitra [13] showed that it still supports students to develop independent testing skills and positively impacts their work, especially for underrepresented student groups. The nature of coding assignments in computer science education varies widely, from simple exercises in introductory courses to complex projects in advanced topics. Consequently, test systems must be flexible enough to accommodate different programming languages, environments, and testing requirements. Basic input-output testing is the most common approach, where the output of a student's solution is compared against the output of a reference solution. While this approach is simple for both educators and students, it can have an impact on students' skills to write test cases [14], as this is excluded from the learning path.

2.3. Continuous Integration Systems

Continuous integration (CI) refers to the widespread [15], [16] practice of frequently integrating software changes into a shared mainline code repository.

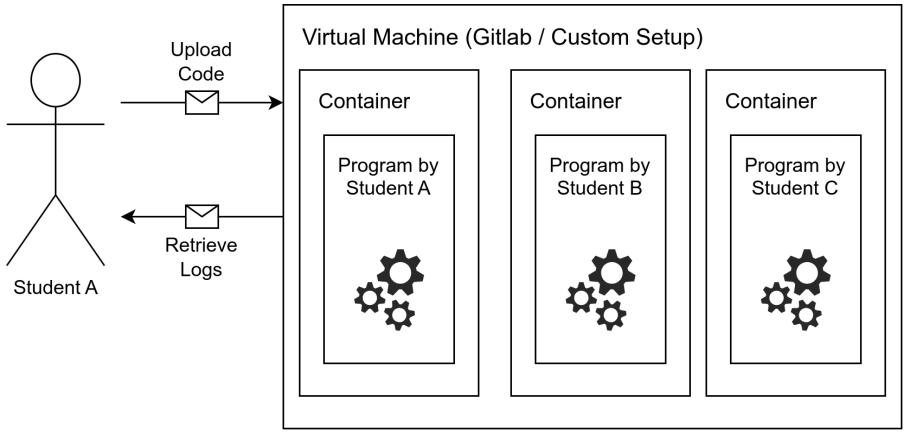


Figure 1: A typical test system setup. Multiple student solutions are tested in separate containers. Students provide code via Git and get the results via a web interface.

Instead of postponing the integration task to a later development phase, integration is performed regularly, at least once per day [17]. By this, CI aims to reduce and simplify integration conflicts, as changes do not accumulate over an extended period, making conflicts more manageable and easier to resolve.

In addition to a shared and frequently updated mainline code base, CI includes automated builds and tests triggered by every mainline code update [17]. This ensures quick feedback about programming and integration errors, minimizing the effort to narrow them down to specific changes.

Continuous integration systems, such as Jenkins [18], Travis CI [19], or GitLab Runner [20], enable development teams to set up automated build and test pipelines. When triggered by a code update, these systems fetch the current source code from the repository, run the project-defined build and test pipeline, and report back the result via email or a web interface. Pipelines are usually run on specialized executors, either hosted by the vendor of the CI system or on a project-managed instance.

The actions to be executed during a pipeline run are defined by scripts. These can be stored in the code base, together with the code of the project itself, or in a separate code repository. Executors run these scripts and, during testing, also the code of the project. Effectively, anyone with write access to the code base can run arbitrary code on the executor. However, in usual development settings, only development team members have write access. Consequently, executors do not run untrusted code in these settings.

Furthermore, as best practices recommend [21], [22], pipelines are typically executed within ephemeral containers or virtual machines. With this, pipelines are always executed within the same environment, without any potential traces of prior runs influencing the results. In addition, when configured correctly [22], this also enhances security, as potentially dangerous code is restricted to interacting with its ephemeral sandbox.

2.4. Security Misconfigurations

To support a wide variety of programming languages, project management styles, application domains, and test cases, CI systems have to provide a large degree of flexibility. In addition to the ability to execute arbitrary code within the pipeline, these systems also have a rich set of configuration options. In GitLab, for example, the overall execution of the pipeline is controlled by a configuration file within the code base [5], whereas the web interface is used to assign executors (*i.e.*, runners in GitLab terms) to specific projects, pass environment variables to the executor and set up access tokens. Especially in the context of isolating workloads, e.g., with Docker, or container orchestration tools like Kubernetes, security misconfigurations can compromise the entire system setup [23], [24]. However, misconfigurations can occur on any layer of the software stack, especially for use cases with a wide range of configuration options [25], including the application level [26]. Based on their analysis, Dietrich et al. [27] conclude that there are *countless undiscovered* security issues in systems connected to the Internet. In educational test systems, misconfiguration issues can occur on all layers, e.g., within the container, the runner, and the virtual machine hosting the runner. Finally, misconfiguration can also be a reason for deferred software updates, among other reasons, again leading to vulnerable applications [28].

3. Threats of Executing Untrusted Code in Educational Contexts

In this section, we systematically analyze the typical approaches of test systems with respect to their security properties. We focus on 11 test systems from computer science university classes, including computer security classes. All test systems were in productive use in the time frame from October 2023 to February 2024 at a university.

3.1. Decentral Development of Test Systems

A solution to the resource problem of reviewing student code is automation [2], [3] with so-called “test systems” [4]. However, test systems are often developed and deployed by educators of the courses rather than professionals aware of security best practices. Several of the test systems we analyzed were developed over the past 3 years and, in some cases, moved away from previously

TABLE 1: Overview of the analyzed test systems.

System	Educational Context	Languages	User Interface	Students
GD1	Introductory	C	Git	770
GD2	Introductory	C	Git	366
GD3	Introductory	C++	Git	547
C4	Systems	C, C++, Assembly	Git, Web	134
GD5	Formal Methods	Python	Git	125
GD6	Privacy	C++, Python	Git	57
GC7	Software Development	Java	Git	413
C8	Systems	C++	-	547
GD9	Security	Python	Git	413
C10	Systems	C, C++, Assembly	Git, Web	374
C11	Security	C	Web	75

unified and centralized test systems due to the specific requirements the different courses have. Hence, there are different strategies to develop such systems. Among the 11 test systems[2] we analyzed, 6 opted for GitLab Runners with Docker registries. This is in line with the best practices recommended by Paiva et al. [3], using containers to run student code in isolation.

One test system used GitLab Runners but with a custom pipeline. In this testing system, each push triggers the execution of a Python script. The script builds and spawns three separate Docker containers that communicate with each other. This approach allows for more precise management of the container spawning process and isolation between different parts of the test system and untrusted code, e.g., checks are not performed within the same container and also not directly on the host system but run in another container, to also mitigate exploitation of this code. However, this approach requires significantly more upfront development and maintenance.

Four test systems were not based on CI systems and developed from scratch. The first (**C4**) is testing student code inside virtual machines, that are run inside a `chroot` environment, following the recommendations by Paiva et al. [3] and Wilcox [4]. This is also the case for the other three: System **C8** is testing student code by compiling it and running unit tests within a reference Ubuntu virtual machine without any further isolation. Systems **C10** and **C11** are testing student code with custom **bash** and **python** scripts inside Docker containers.

Table 1 provides an overview of the test systems, programming languages, and educational context. The four systems-related courses use custom test systems (prefixed with a **C**), whereas all others rely on a GitLab-based approach (prefixed with a **G**). Language-wise, there is a focus on C and C++, and in about half of these systems, the build environment is also controlled by the user. Finally, for the interfaces, most test systems expose an interface via Git, e.g., commit hooks or CI pipeline triggers, and to the web to check the results. Most test systems directly rely on the GitLab interface for the students.

3.2. Threat Model of Running Untrusted Code

In our threat model, illustrated in Figure 2, we assume malicious users intentionally submitting code intended to exploit the test system. We assume the user has no knowledge about the test system other than publicly available to all participants. We assume that the host system spawning the test containers is running on the most recent kernel and that it uses the most recent packages from its distribution. Furthermore, we assume established software security features to be enabled, e.g., KPTI [29], ASLR and KASLR [30], [31], hardware-assisted control-flow integrity [32], [33]. We assume the educators' credentials are appropriately chosen, secure against unpermitted access, and possibly even protected with second-factor authentication.

For both GitLab Runners with Docker registries and GitLab Runners with custom pipelines, we assume that the student code is run inside a container and not running directly under the user account of the educator on the host machine. We also assume that GitLab itself is fully up-to-date and no software bugs are known about the GitLab instance.

The malicious user can obtain information such as the total runtime, log files, and other custom artifacts the test system provides. The goal of the malicious user is to extract information about the test system, the test cases, and access confidential data and configurations.

4. A New Approach to Identify Security Issues in Educational Test Systems

Educational test systems face unique security challenges: First, they execute untrusted code, submitted by potentially malicious students. Second, they also process a variety of sensitive information, such as test cases, solutions and privacy related information. This contrast between execution of potentially dangerous code and the sensitivity of the processed information makes hardening these systems more difficult than it is the case for more typical CI systems.

In the following, we suggest a 3-step approach: First, the security-critical assets on the test system are identified (Section 4.1). Secondly, intentional features of the educational test system that may facilitate attacks are examined (Section 4.2). Finally, the test system has to be assessed for security vulnerabilities, with the unique setting of educational test systems in mind (Section 4.3). While hijacking of the test system is a critical concern, unauthorized access to the data processed by the test system is an even bigger risk. Educational test systems process a variety of sensitive information, such as test cases or solutions of the exercise tasks. In Section 4.1, we

2. We note that one of the systems was set up by one of the authors of this paper.

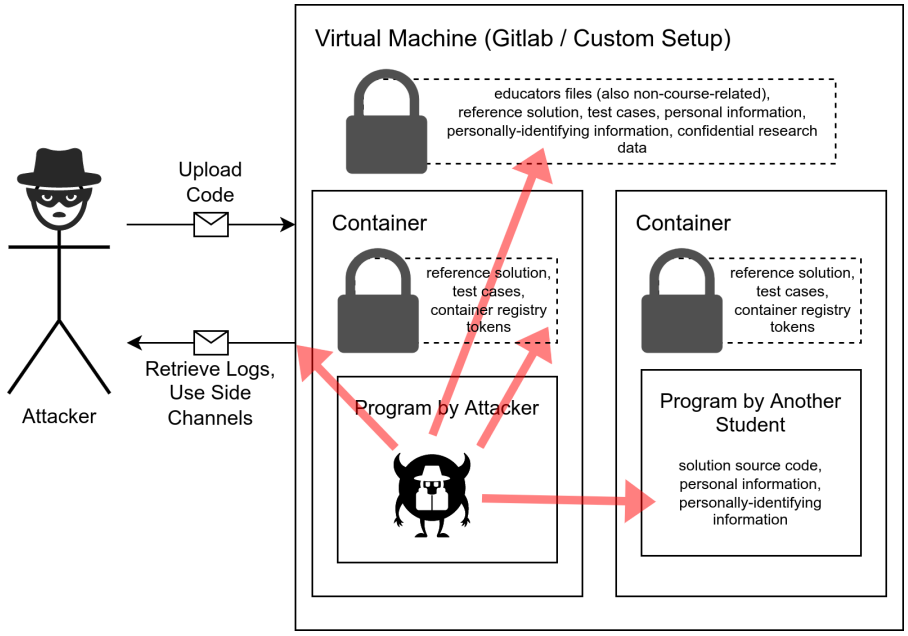


Figure 2: The threat model we consider for the test systems in this work.

identify a set of critical assets that require special security evaluation.

4.1. Asset-oriented Security Evaluation

In this section, we discuss which assets might be of interest to an attacker. We want to emphasize that this discussion is not comprehensive. However, there are not only assets that are of direct interest to the attacker (primary interest assets) but also assets that are useful in intermediate steps (secondary interest assets).

4.1.1. Primary Interest Assets. We consider assets to be of primary interest if they contain information the attacker is directly interested in: Such information includes everything that gives the attacker an unfair grading advantage, as well as everything that directly breaks user privacy and confidentiality.

To gain a grading advantage, the attacker might want to exfiltrate non-publicly available test cases, reference solutions, or other students' solutions. The attacker might develop against the test cases in a trial-and-error manner without properly understanding what the program is supposed to do. Exfiltrated solutions can be directly plagiarized.

A test system storing grades or points might leak other students' grades to the attacker, infringing privacy and breaking confidentiality. Test systems might also store real names, email addresses, contact data, or other personally-identifying information of the students or the educator.

4.1.2. Secondary Interest Assets. We consider assets to be of secondary interest if they provide an intermediate step to obtain primary interest assets. Such assets include credentials or access tokens protecting confidential data, e.g., private repositories or container registries. While they do not contain the critical information *directly*, the attacker can use them in a subsequent step to gain access.

For example, if test cases are provided in a private docker container that is supposed to be accessed only by the test executor, the test system might leak the access token for the container registry, enabling the attacker to download the container and extract the test cases. If, due to misconfiguration, the access token even grants write access, the attacker can perform unauthorized modifications to the container. Similar attacks can be imagined for access tokens protecting external test case repositories.

As another example, code execution as root might also be used to bypass permission checks and, in turn, to obtain a primary interest asset. The same argument applies to container-to-host escapes. Furthermore, injecting malicious code into the test pipeline might lead to primary interest assets.

4.2. Continuous Integration for the Attacker

Using CI systems for testing student code has the major advantage of providing feedback quickly. Usually, within minutes after submitting their code, most systems give students visual feedback and a log file, indicating which tests passed and which of them failed. However, while such short feedback loops are desired under normal circumstances, these might also be helpful to an attacker. Attackers, too, get immediate feedback from the test system, allowing them to test their exploits frequently and quickly.

The feedback usually includes a log file of the test run. Student code usually is permitted and often even required to generate some output, which is also written to the log file. If attackers gain unauthorized access to security-critical information, they can directly print it and exfiltrate it through the log. Similarly, information might also be exfiltrated via other artifacts the pipeline creates. In addition, if Internet access is not blocked, the attacker might send critical data to a web server they control.

Even without log files, artifacts, or Internet access, the attacker can exfiltrate data via covert channels, e.g.,

by encoding a byte in delayed execution time dependent on the numeric value of the byte to leak. A multi-byte secret could be transmitted in multiple pipeline executions, allowing the attacker to reconstruct the secret byte-by-byte from the execution times.

4.3. Categorization of Security Issues

To identify the issues in test systems, we analyze the systems with respect to the following four categories of security issues:

4.3.1. Output sanitization. As Paiva et al. [3] note, a secure test system should block any attempt to leak sensible test data, e.g., "output data", to the outside. However, for virtually all systems we analyzed, the output data is intended to be seen by the students. This setup introduces a significant challenge, requiring filtering illegitimate output from legitimate output. This challenge is far from trivial to solve, as an attacker can choose an arbitrary encoding for the secrets.

4.3.2. Permission issues. The test system must protect sensitive information from the execution of student-provided code, *i.e.*, access to critical assets should be denied to untrusted code. The operating system supports this by enforcing file access permissions or limiting access to other resources, such as processes. However, this requires that the permissions are set correctly by the test system. For example, if student code runs under the same system account as the test case owner, a malicious student could exfiltrate the test cases.

While it is challenging to design a test system with correct separation, the confidentiality of the test cases and the integrity of the test system is still crucial.

4.3.3. Misconfiguration issues. Misconfiguration is a common source of security problems. One of the most efficient ways to leak information about the system or data is to use the Internet. If the test system allows Internet access, the attacker can exfiltrate data to a web server under their control.

Another common misconfiguration is the use of outdated software. While we assume the host system running the test containers to be up to date, this might not necessarily be the case for the container images, where outdated software might also be exploited. A large-scale study by Shu et al. [34] showed that about 30 % of the Docker images available on Docker Hub have not been updated within 400 days when that study was performed. Container images might also ship custom software that is no longer maintained, making updating the images challenging. Educators may be negligent with updating containers.

4.3.4. Environment sanitization issues. The test system must prevent students from modifying the environment in a way that would yield unauthorized access to the system or test cases. For instance, students should not be able to modify the build system by modifying the `Makefile`. Therefore, build files are often replaced with a reference file or checked for modifications by the test system.

Similarly, with GitLab Runners, the `.gitlab-ci.yml` file defines the pipeline. However, this file should not be modifiable by the student, as this would allow the student to modify the pipeline. Consequently, students can change pipeline variables such as the entry point or add additional steps to the pipeline.

5. Case Studies

Following the methodology described in Section 4, we analyzed 11 test systems. As Table 2 shows, each of them was affected by at least one vulnerability. In this section, we briefly summarize our most critical findings before we continue by discussing 3 case studies in more detail. As the analyzed test systems were in productive use, we focus on analyzing their vulnerabilities, without performing full end-to-end exploitation.

Out of the 11 systems, 6 systems did not sanitize their output. At least 4 of them allowed the tested code to establish outbound Internet connections, and none of them fully mitigated timing side channels. Consequently, on all of these, if student code has access to sensitive information, it can also exfiltrate it from the test system, as we discuss in all our 3 case studies in more detail.

All of the 6 systems based on GitLab runners and Docker registries exposed credentials for the registry to untrusted student code via the `DOCKER_AUTH_CONFIG` environment variable. Effectively, this gives an attacker read access to the entire Docker container, possibly including reference solutions and test cases. In at least 3 cases, the exposed credentials even granted write permissions to the Docker registry, enabling an attacker to modify the container image persistently. For instance, this misconfiguration issue affects the test systems **GD5** and **GD1**, discussed in Section 5.1 and Section 5.2, respectively.

On 5 of the test systems, the reference solutions were accessible for an attacker, either directly by examining the docker container or during the execution of the tests (e.g., due to misconfigured file permissions). Examples of this are provided in Section 5.1 and Section 5.2 for the **GD5** and **GD1** test systems.

Furthermore, on 4 test systems, attackers could manipulate the test pipeline, enabling them to inject arbitrary commands and run unauthorized code. For instance, we found this environment issue in the **GD1** test system, as discussed in Section 5.2. Similarly, on at least 5 systems, attackers could inject arbitrary commands into the build process by modifying the `Makefile` or other build scripts. For instance, the **GD1** and **C4** test systems discussed in Section 5.2 and Section 5.3 both had this issue.

5.1. Case Study 1: Test System GD5

Our first case study is **GD5**, and we investigated the 4 categories of security issues outlined in Section 4. **GD5** is a system based on GitLab Runners, combined with a Docker registry, which is not publicly accessible. Students can push code into their GitLab repository, which is then tested within a Docker container by the GitLab Runner. Subsequently, the log file is available as an artifact to the students. Notably, the test cases and runtime are not

TABLE 2: Test systems and what attack vectors they mitigated. ✗ means vulnerable, ✓ means not vulnerable, ~ means inconclusive.

Security Issue	GD1	GD2	GD3	C4	GD5	GD6	GC7	C8	GD9	C10	C11
Unsanitized Output	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓
Timing Side Channels	✗	✗	✗	~	✗	✗	~	~	✗	~	~
No Container	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓
Privileged Git Tokens	✗	✗	✗	✓	✓	✓	✓	✗	✓	✓	✓
Reference Solution	✗	✗	✗	✓	✗	✓	✓	✗	✓	✓	✓
Exec as Root	✓	✓	✓	✓	✗	✓	✓	✓	✓	✗	✗
`DOCKER_AUTH_CONFIG`	✗	✗	✗	✓	✗	✗	✓	✓	✗	✓	✓
`ptrace`	✓	✓	✓	✗	✗	✗	~	✗	✓	✗	✓
Internet Access	✗	~	~	✗	✓	✓	✗	✗	✓	✓	✓
Outdated Software	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓
Docker Socket Mount	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓
Modify Pipeline	✗	✗	✗	✓	✓	✓	✗	✓	✓	✓	✓
Build System Takeover	✗	✗	✗	✗	✓	~	✓	✓	✓	✓	✓

randomized and highly stable, *i.e.*, 6 seconds with an empty submission where no tasks have been solved.

5.1.1. Output Sanitization. As a first category, we analyzed the system's output sanitization. Given the intention to provide users with the output, we observe that system **GD5** does not sanitize the output at all. However, this introduces significant security issues, as a malicious user can print any data of interest into the log file, which is then accessible through GitLab's web interface, *i.e.*, as an artifact. While this does not imply that leakage of valuable information is possible, it is a direct path to information leakage when combined with any misconfiguration, permission issue, or missing environment sanitization.

For completeness and going beyond the issues Paiva et al. [3] identified, we also tested the timing channel as a possible output vector. In our timing side channel, we leak environment variables or user credentials. These are often stored as `base64`-encoded strings (typically 26 characters), and hence, we focus on leaking such `base64` strings. We encode and transmit character by character, one per test run. For a single character, we let the GitLab Runner sleep between 0 and 64 seconds, depending on the `base64` character to leak. Thus, after deducing the base runtime, the attacker can infer the specific character transmitted from within the GitLab Runner. Consequently, we can leak a GitLab authentication token within 156 s to 1820 s, with an average around 988 s.

5.1.2. Permission Issues. Primary assets for a malicious user are test cases and the reference solution. We analyzed system **GD5** and discovered three main issues: First, the reference solution was accessible to the malicious user from within the Docker container, *i.e.*, it was bundled into the Docker container. It is not clear why this is necessary for testing, as the test system uses test cases. Hence, a solution is to not include unnecessary secret data in the Docker containers. Second, however, the test cases were also accessible to the malicious user from within the Docker container, also bundled into the Docker container. In line with Paiva et al. [3], neither the reference solution nor the test cases should be available to the user. A solution could be to restrict the permissions, e.g., provide not read permissions to the user executing the student code. Finally, even if these permission issues were fixed, the student-provided submission is executed with root privileges inside the Docker container. Consequently, the student effectively has unrestricted access to all data within the Docker container, regardless of other restrictions, e.g., file permissions, made. Furthermore, root privileges within containers are particularly dangerous when combined with misconfiguration issues, e.g., unnecessary provision of capabilities to the container.

5.1.3. Misconfiguration Issues. As a third attack vector, misconfiguration issues could expose confidential information, including secret test cases or a reference solution. We identified two main issues in system **GD5**: The first issue is the provision of the `ptrace` capability. As we already noted, in system **GD5**, untrusted code runs with root privileges within the containers. However, this combination of root privileges and the `ptrace` capability effectively allows the student code to attach (*i.e.*, like a debugger) to any process within the container including the parent process responsible for running the tests and evaluating the output of the student-provided code, *i.e.*, the process with full access to the test cases. The second issue is the **implicit** provision of the `DOCKER_AUTH_CONFIG` environment variable by the GitLab runner. GitLab runners use the `DOCKER_AUTH_CONFIG` to access an image from a private container registry [5]. However, it is not documented that containers **implicitly** inherit this environment variable, exposing the credentials to authenticate against the private container registry. Consequently, neither **GD5** nor any of the other test systems we tested unset this environment variable. We emphasize the significance of this issue, as the `DOCKER_AUTH_CONFIG` credentials often include both read and write permissions to the container registry. Thus, this misconfiguration not only exposes the confidentiality of the test cases of the educators: A malicious user could overwrite the existing image in the container registry with their own image, running arbitrary code on every subsequent push of every student.

5.1.4. Environment Issues. For completeness, we also investigated the environment issues but did not identify any particular issues that would allow for a takeover of the build system or pipeline modifications.

5.2. Case Study 2: Test System GD1

Our second case study is system **GD1**, which we analyzed as described in Section 4. **GD1** is similar to our first case study test system, **GD5**, which is also based on GitLab runners combined with a Docker registry.

With each `git push`, the student code is tested inside a Docker container by the GitLab Runner. Once the test run is complete, students can view the corresponding pipeline log. Additionally, students are provided with a `testreport.html` document that includes both public and a select few redacted private test cases, along with their corresponding inputs and outputs for the public test cases.

5.2.1. Output Sanitization. The first category we analyze is the output sanitization of the test system. The output data is intended for students to receive feedback on their submissions. In system **GD1**, the output data for each public test case can be obtained from the `testreport.html` document. In addition, the pipeline offers metrics during runtime, such as testing times. We observe that no output sanitization occurs for the output data in the `testreport.html` document. Consequently, a user with malicious intent can print any data of interest, such as environment variables and the file system structure.

We also tested the timing side channel as a possible output vector. The test cases have a constant runtime, which allows us to leak environment variables such as the `DOCKER_AUTH_CONFIG` environment variable encoded in the runtime. The approach we follow, is the same as the one described in the first case study: We encode and transmit character by character, one per test run, where each character is represented by 1 second of timing delay. More efficient leakage is possible if sub-second runtime information is available.

5.2.2. Permission Issues. In test system **GD1**, grading is based on the passed test cases. There are both public and private test cases. Students have access to the input and output data for all public test cases, but private test cases are always redacted in the test report. Therefore, the test cases and the reference solutions are the most interesting resources for a potential attacker. Based on this assumption, we identified two issues in **GD1**:

Before building and testing the student's submission, the test pipeline retrieves the latest test cases from private repositories. Authentication is required to pull from a private Git repository. Hence, in **GD1**, GitLab API tokens are provided via files, accessible to the unprivileged user. An attacker can leak an API token through unsanitized output or side channels. The attacker can then use these tokens to access and inspect repositories on a local machine. This cannot only result in data leakage but also more severe security issues: API tokens often have not only read but also write privileges. As a result, by modifying files in the private repository, a student with malicious intent could delete or add test cases, or even execute arbitrary code. In combination with misconfiguration errors, this can lead to more devastating security compromises.

Secondly, the private Git repositories contain not only the test cases but also the reference solution to the assignments. As the test system does not require the reference solution, it should also not be present while testing the student's submission with the test cases. This is a significant issue, as the reference solution is the most valuable resource for a potential attacker in our scenario.

5.2.3. Misconfiguration Issues. System **GD1** suffers mainly from two misconfiguration issues. The first issue is yet again the presence of the `DOCKER_AUTH_CONFIG` environment variable. As we noted earlier, the `DOCKER_AUTH_CONFIG` credentials often include both read and write permissions to the container registry. Combined with the fact that the test system did not sanitize the output data, the leakage of the `DOCKER_AUTH_CONFIG` credentials is a significant problem. We also verified that the credentials provided had write permissions to the container registry. As a result, a malicious user could have overwritten the existing image in the container registry with their new image.

The second issue is that outbound Internet connections are not blocked throughout the entire pipeline. Internet connections are only blocked during the build and test stages. As mentioned before, the pipeline requires this connectivity to retrieve the latest test cases from private repositories. Once the test cases are retrieved, the Internet connection is blocked for the duration of the tests. After the tests are completed, the pipeline can connect to the Internet and upload artifacts to a dedicated server.

5.2.4. Environment Issues. The fourth category of attack vectors are environment issues. System **GD1** also suffers mainly from two environment-related security issues: First, students receive a `.gitlab-ci.yml` file containing the pipeline configuration for the test system. This file defines the pipeline stages, the jobs executed in each stage, and their order. The `.gitlab-ci.yml` file is stored in the student's repository and executed by the GitLab Runner. It is a critical asset for a potential attacker, as it can be modified to manipulate the pipeline. For instance, an attacker can modify the entrypoint of the Docker container to run unauthorized code. Additionally, the attacker obtains a command injection vulnerability since the script sections of the `.gitlab-ci.yml` file are executed as shell commands following the Docker container entrypoint.

Secondly, the build process relies on the `Makefile` provided by the student. The `Makefile` contains the build instructions for the student's submission. However, the test system does not check the integrity of the `Makefile` or the commands it contains. This is a significant issue, as the `Makefile` can be altered to execute arbitrary commands instead of compiling the student's code.

5.3. Case Study 3: Test system C4

For our third case study, we investigated **C4**. **C4** is a completely custom and independently developed system for testing low-level system code.

After students push their code into a GitLab repository, a web hook triggers the system to pull the submission and to execute the following two steps: First, the student code is built in a `chroot` environment following the best practices described by Paiva et al. [3]. The `chroot` environment is a separate root file system that contains all the necessary tools and libraries to build and test the student's submission. Secondly, the resulting binary is tested within a customized QEMU fork to obtain specific low-level event metrics. From each test run, students get the build log and a report of unintended behavior or crashes.

5.3.1. Output Sanitization. We again first analyze the system's output sanitization. The system performs output sanitization in several places, yet not in all stages of the test pipeline. For example, an attacker can write arbitrary text during the build and startup phases. As the test cases reside in the `chroot` tree of the build process, an attacker can directly exfiltrate them by writing them to the log. Furthermore, the test cases are included in the built image, allowing the attacker to dump them into the log during the startup phase.

5.3.2. Permission Issues. For completeness, we checked for permission issues but did not identify any particular security-relevant issues.

5.3.3. Misconfiguration Issues. We observed three major misconfiguration issues:

Firstly, outbound Internet connections are unrestricted while running the entire pipeline. This allows an attacker to exfiltrate arbitrary information to a server, enabling similar attacks as with incomplete output sanitization.

Secondly, **C4** uses outdated software versions in multiple places. The custom QEMU fork is outdated and,, unpatched against multiple published vulnerabilities [35], [36], allowing the tested code to escape the virtual machine. Furthermore, the software within the `chroot` environment has also not been updated for more than 3 years. For example, the `sudo` binary in the `chroot` environment is vulnerable against CVE-2021-3156 [37], enabling an attacker to gain root privileges and escape the `chroot` environment.

Thirdly, **C4** runs pipelines from different students always under the same user and does not prohibit `ptrace` across different processes of the same user. Thus, an attacker can embed code into the build phase, attaching itself to the pipeline of another student. Hence, the attacker can read memory or files within the victim's `chroot`, obtaining the solution of other students. The attacker can also hijack the victim's pipeline process to execute arbitrary shell code, e.g., to disrupt the victim's process and manipulate the test results.

5.3.4. Environment Issues. Our investigation of environment issues yielded two command injection vulnerabilities. First, the system executes several helper programs during the build process. These are built from source files, which can be overwritten by an attacker to execute arbitrary code in the `chroot` environment, enabling the attacks discussed above. Secondly, an attacker can also overwrite the `Makefile`, enabling similar attacks.

6. User Study: Severity Assessment

To assess the severity of the found security vulnerabilities, we performed a user study with the people in charge of the test systems. The people responsible for 6 of the systems participated on all questions regardless of whether their test system was vulnerable or not.

The severity assessment of the read access (Figure 3a) is strongly connected with the frequency with which student assignments change. For courses where the assignments change every semester, the severity is assessed as low. The main reason given was that there can always be communication between students leading to plagiarism. Therefore, solutions must always be checked for plagiarism, uncovering copied solutions from the test system. The medium-high assessment of one participant was reasoned by possible access to the solutions of assignments and because it is difficult to detect plagiarism.

The severity of write access (Figure 3b) to the solutions of other students was assessed low because the manipulation of other students' solutions could easily be detected, and also, there is no reason to do it.

The severity of read access to the test cases (Figure 3c) is assessed low for courses where the test cases are public and use randomized inputs on the test system. In this case, there is no advantage for an attacker. Most participants assessed the severity medium because access to the test cases could allow them to reverse engineer the solution. For courses where the test cases do not change frequently, accessing them would have high severity.

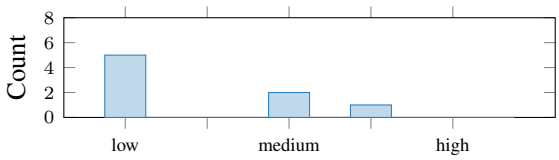
Manipulating test cases with write access (Figure 3d) would be detected, *i.e.*, has a low severity. Still, it could be used to interfere with other groups.

The severity assessments of read or write access to all files in the test container (Figure 3e and Figure 3f) are very similar to the assessment of accessing the test cases. The reason is that the test systems do not contain other secret data that an attacker could exploit. One participant notes that modifications of student grades would be evident in log files.

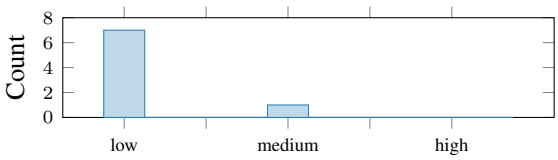
In most cases, read access to the container registry (Figure 3g) gives an attacker access to the test cases. This may be a security issue if the test cases are private and not frequently changed. On the test system of one participant, read access to the container registry gives an attacker access to the reference solution. On one test system, the container does not contain the test cases.

The severity of a write access (Figure 3h) is assessed based on a few factors: In some courses, the containers from the registry are also run locally on student's systems. A modified container would be started carelessly in privileged mode this could cause a complete exploitation of a student's system. Medium severity was assessed because modified containers could leak all student solutions.

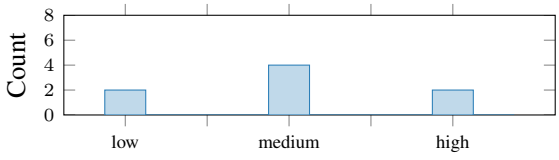
Access to the host system (Figure 3i and Figure 3j) provides an attacker access to personal information of students, and databases with students' points and grades.



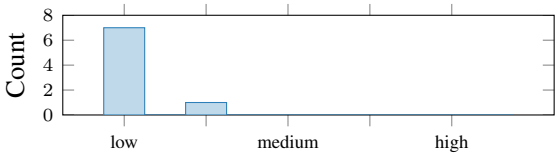
(a) Reading solutions of other students.



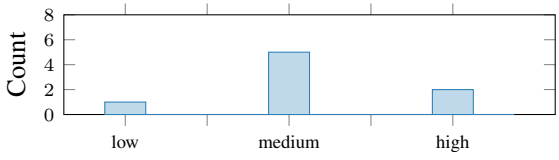
(b) Writing solutions of other students.



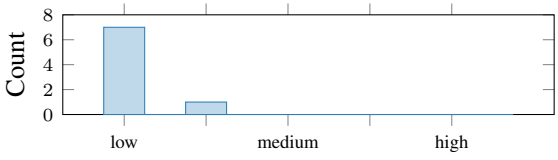
(c) Read access to the test cases.



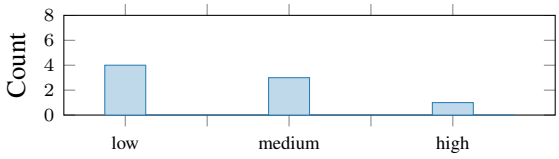
(d) Write access to the test cases.



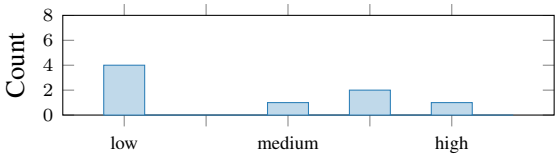
(e) Reading any file in the test container.



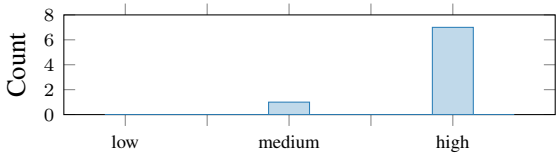
(f) Writing any file in the test container.



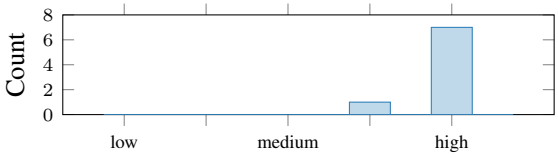
(g) Read access to the container registry.



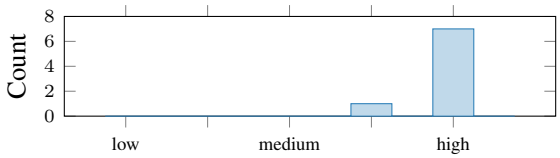
(h) Write access to the container registry.



(i) Read access on container host.



(j) Write access on container host.



(k) Execute permission on container host.

Figure 3: Severity assessment by the participants.

Educators typically do not know or are in charge of the host system and they expressed the concern that access to the host will give an attacker also access to other information not related to their course. The severity assessment for execution permission (Figure 3k) is the same as for write access on the host system, as they ultimately give an attacker the same capabilities.

7. Discussion and Limitations

Hardening educational test systems against security vulnerabilities is challenging, given that they have to execute untrusted code while they also process a variety of security-critical information. Furthermore, resources to develop and maintain these test systems are often limited. In the following, we therefore want to give some guidelines to improve the security of these systems.

First of all, security-critical assets have to be identified (see Section 4.1), and it is crucial to reduce these to a minimum. For example, reference solutions should not be stored on the test system if they are not required for testing the submissions. Each required asset must be protected from the student code.

Secondly, typical CI systems are not designed to test completely untrusted code. If such a system is used, its security has to be evaluated with regard to the changed threat model (Section 3.2). Even some desired properties of the CI system may be helpful to an attacker (Section 4.2).

Thirdly, derived from the previous steps, concrete attack vectors have to be identified. Several of the issues we have discussed could be mitigated by following best practices: For instance, providing users with the precise execution time of their tests, inherently opens a timing side channel. Therefore, test system maintainers should consider **hiding the execution time** from the students. Permission issues generally align with best state-of-the-art security practices and the **principle of least privileges** that test system maintainers should follow: On the container level, untrusted code should not be run without a container, data that is not required should not be made accessible to untrusted code, root privileges should not be granted by default. On the level of interaction with Git and GitLab, it is important to set up GitLab access tokens only with the least privileges required, *i.e.*, read access to clone student or testcase repositories. Common misconfiguration errors include access to Internet or communication sockets, but also setups that implicitly lead to outdated software, e.g., manually patched software or environment configurations that prevent automatic updates. Another common error here are container capabilities that are not required for testing, such as the `ptrace` capability. As these capabilities usually configure the interaction between processes inside the container and the host kernel, they implicitly allow bypassing the sandbox boundaries in certain ways. It is crucial that test system maintainers carefully **review the capabilities** granted to a container. Furthermore, environment issues allow an attacker to take over the build process or the entire test pipeline. Test system maintainers should **ensure critical control files are not overwritten** by student code.

Our investigation shows that these best practices are not followed in several cases. This indicates that test system maintainers are often unaware of the many ways their systems might be exploited. We hope this paper will raise the general awareness of the security problems of educational test systems.

While we found a large variety of vulnerabilities, additional issues might exist, or future changes in the test systems might introduce new issues. Hence, the security of the test systems has to be evaluated periodically. To support this, educators should encourage their students to find and disclose security issues in their test systems. This not only helps hardening these systems but also teaches the students to engage in responsible disclosure.

8. Conclusion

We evaluated the security of 11 practically used test systems from computer science university classes, including computer security classes. We studied these systems during the time frame from October 2023 to February 2024 and provide a systematic overview of the typical approaches these systems follow. We identified 3 categories of systems: GitLab Runners with a Docker registry, GitLab Runners with custom pipelines, and entirely custom test systems that do not rely on a CI system as a basis. We identified 13 types of security issues, the most widely spread ones affecting 5-6 of the test systems in our analysis. We practically showed that all test systems in our analysis can be compromised and develop new techniques to exfiltrate secret and privileged information, including the use of side channels. We presented 3 case studies where we show the specific bypasses possible in these concrete systems. Finally, in a user study, we assessed the impact a potential breach together with the educators using these test systems. Based on our results, we derived best practices that educators should follow to minimize security risks and prevent exposure of confidential data and malicious data integrity breaches, in the context of testing untrusted student code.

Acknowledgments

This research is supported in part by the European Research Council (ERC project FSSec 101076409) and the Austrian Science Fund (FWF SFB project SPyCoDe 10.55776/F85) Additional funding was provided by generous gifts from Red Hat and Google. Some results are from the CodeAbility Austria project, funded by the Austrian Federal Ministry of Education, Science and Research (BMBWF). Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the funding parties.

References

[1] Z. Kubincová and M. Homola, "Code review in computer science courses: Take one," in *Advances in Web-Based Learning (ICWL)*. Springer, 2017.

[2] C. Wilcox, "The role of automation in undergraduate computer science education," in *Computer Science Education (CSE)*, 2015.

[3] J. C. Paiva, J. P. Leal, and Á. Figueira, "Automated assessment in computer science education: A state-of-the-art review," *ACM Transactions on Computing Education (TOCE)*, vol. 22, no. 3, pp. 1–40, 2022.

[4] C. Wilcox, "Testing strategies for the automated grading of student programs," in *Computing Science Education (CSE)*, 2016.

[5] Gitlab, "Run your CI/CD jobs in Docker containers," 2024. [Online]. Available: https://docs.gitlab.com/ee/ci/docker/using_docker_images.html

[6] M. Yong Wong, M. Landen, M. Antonakakis, D. M. Blough, E. M. Redmiles, and M. Ahamad, "An Inside Look into the Practice of Malware Analysis," in *CCS*, 2021.

[7] D. Capovilla, M. Berges, A. Mühling, and P. Hubwieser, "Handling heterogeneity in programming courses for freshmen," in *Learning and Teaching in Computing and Engineering*, 2015.

[8] R. P. Medeiros, G. L. Ramalho, and T. P. Falcão, "A systematic literature review on teaching and learning introductory programming in higher education," *IEEE Transactions on Education*, vol. 62, no. 2, pp. 77–90, 2019.

[9] B. S. Xia, "An In-Depth Analysis of Teaching Themes and the Quality of Teaching in Higher Education: Evidence from the Programming Education Environments," *Journal of Teaching and Learning in Higher Education*, vol. 29, pp. 245–254, 2017.

[10] A. Bandura, *Self-efficacy : the exercise of control*. W.H. Freeman and Company New York, 1997.

[11] T. Koulouri, S. Lauria, and R. D. Macredie, "Teaching Introductory Programming: A Quantitative Evaluation of Different Approaches," *ACM Trans. Comput. Educ.*, vol. 14, no. 4, dec 2015.

[12] J. Wrenn, S. Krishnamurthi, and K. Fisler, "Who tests the testers?" in *International Computing Education Research (ICER)*, 2018.

[13] J. Mitra, "Studying the impact of auto-graders giving immediate feedback in programming assignments," in *ACM Symposium on Computer Science Education (SIGCSE)*, 2023.

[14] J. Gao, B. Pang, and S. S. Lumetta, "Automated Feedback Framework for Introductory Programming Courses," in *Innovation and Technology in Computer Science Education (ITiCSE)*, 2016.

[15] M. Hilton, T. Tunnell, K. Huang, D. Marinov, and D. Dig, "Usage, Costs, and Benefits of Continuous Integration in Open-Source Projects," in *ASE*, 2016.

[16] D. Ståhl and J. Bosch, "Automated software integration flows in industry: a multiple-case study," in *ICSE Companion*, 2014.

[17] M. Fowler, "Continuous Integration," 2024. [Online]. Available: https://martinfowler.com/articles/continuousIntegration.html

[18] Jenkins, "Jenkins," 2024. [Online]. Available: https://www.jenkins.io/

[19] Travis CI, "Home," 2024. [Online]. Available: https://www.travis-ci.com/

[20] GitLab, "GitLab Runner," 2024. [Online]. Available: https://docs.gitlab.com/runner/

[21] M. Hilton, N. Nelson, T. Tunnell, D. Marinov, and D. Dig, "Trade-offs in Continuous Integration: Assurance, Security, and Flexibility," in *ESEC/FSE*, 2017.

[22] GitLab B.V., "Security for self-managed runners," 2024. [Online]. Available: https://docs.gitlab.com/runner/security/

[23] A. Y. Wong, E. G. Chekole, M. Ochoa, and J. Zhou, "On the Security of Containers: Threat Modeling, Attack Analysis, and Mitigation Strategies," *Computers & Security*, vol. 128, p. 103140, 2023.

[24] A. Rahman, S. I. Shamim, D. B. Bose, and R. Pandita, "Security misconfigurations in open source kubernetes manifests: An empirical study," *ACM Transactions on Software Engineering and Methodology*, vol. 32, no. 4, pp. 1–36, 2023.

[25] J. Zhang, L. Renganarayana, X. Zhang, N. Ge, V. Bala, T. Xu, and Y. Zhou, "Encore: Exploiting system environment and correlation information for misconfiguration detection," in *ASPLOS*, 2014.

[26] B. Eshete, A. Villafiorita, and K. Weldemariam, "Early detection of security misconfiguration vulnerabilities in web applications," in *ARES*, 2011.

[27] C. Dietrich, K. Krombholz, K. Borgolte, and T. Fiebig, "Investigating system operators' perspective on security misconfigurations," in *CCS*, 2018.

[28] D. Ferrari, M. Carminati, M. Polino, and S. Zanero, "Nosql breakdown: A large-scale analysis of misconfigured nosql services," in *ACSAC*, 2020.

[29] T. Gleixner, "x86/kpti: Kernel Page Table Isolation (was KAISER)," 2017. [Online]. Available: https://lkml.org/lkml/2017/12/4/709

[30] PaX Team, "Address space layout randomization (ASLR)," 2003. [Online]. Available: http://pax.grsecurity.net/docs/aslr.txt

[31] J. Edge, "Kernel address space layout randomization," 2013. [Online]. Available: https://lwn.net/Articles/569635/

[32] M. Abadi, M. Budiu, U. Erlingsson, and J. Ligatti, "Control-Flow Integrity," in *CCS*, 2005.

[33] Intel, "Control-flow Enforcement Technology Preview," 6 2017, revision 2.0.

[34] R. Shu, X. Gu, and W. Enck, "A Study of Security Vulnerabilities on Docker Hub," in *CODASPY*, 2017.

[35] NIST National Vulnerability Database, "CVE-2019-14378," 2019. [Online]. Available: https://cve.mitre.org/cgi-bin/cvename.cgi?name=CVE-2019-14378

[36] ——, "CVE-2020-24165," 2019. [Online]. Available: https://cve.mitre.org/cgi-bin/cvename.cgi?name=CVE-2020-24165

[37] ——, "CVE-2021-3156," 2021. [Online]. Available: https://cve.mitre.org/cgi-bin/cvename.cgi?name=CVE-2021-3156