CSEC 490 Project Report

Project 17: Security Club Ecosystem

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1 Introduction & Motivation

1.1 Motivation

Cybersecurity is facing a critical skills gap, posing a critical threat to the global economy [1]. The longer this gap persists, the greater the danger it becomes. Therefore, there is an urgent need for an effective and scalable approach to cybersecurity training. A survey conducted by the Brookings Institute aimed to understand why many types of job training programs fail [2]. The survey found that hands-on experience is the best way to train people for technical roles. This project's group members, who have all had close involvement with RITSEC—Rochester Institute of Technology's (RIT) cybersecurity club—have seen first-hand the transformational power of cybersecurity extracurriculars in a university environment.

One problem with cybersecurity extracurriculars is the time involved in their creation and operation. Other schools—such as the New Jersey Institute of Technology and the University of Tulsa—are beginning to form their own clubs based on the RITSEC's structure due to the power that extracurriculars offer. Both of these schools have reached out, and received extensive mentorship from RITSEC leadership. Yet, RIT's model has taken over twenty years to develop across its predecessors and current organization, so it could take other schools a substantial time to recreate the model themselves. Even if other clubs are based on RIT's offerings, replicating RIT's model by themselves may be inefficient and complex, given RITSEC's monetary corporate sponsorship, large membership population, and accumulated experience.

This project aims to create a scalable model for security education across schools. It will emphasize hands-on learning and the community that is central to RITSEC. Additionally, the project will address shortcomings in RITSEC's offerings by making a more engaging and collaborative experience through gamified lessons. The capstone aims to combine Capture the Flag (CTF) competitions, with an engaging live environment similar to Kahoot, a gamified quiz platform. CTFs are widely recognized as an effective way to teach cybersecurity concepts [3]. In these competitions, participants solve puzzles, complete tasks, and exploit vulnerabilities to capture and submit flags: secret codes that are revealed when challenges are completed correctly. When a competitor or team submits a correct flag, points are added to their score; the competitor or team with the most points wins the CTFs.

1.2 Purpose

RITSEC heavily uses technical demonstrations ("demos") as a hands-on component of weekly meetings, and the capstone group consists entirely of present or past RITSEC members. This project aspires to make the demo model more scalable to other schools, and build an education ecosystem around it. It aims to build a network of affiliated clubs to increase RIT's reach. These affiliates will have access to a demo platform: a web application this group is developing. The focus on developing a single platform intends to lower entry barriers for clubs, scale cybersecurity education, and foster community building, addressing the skills gap in cybersecurity.

The project will benefit RIT, other educational institutions, and the security community at large. For other schools, it offers resources for clubs to form quickly and deliver high-quality experiences, fostering community building, and narrowing the cybersecurity skills gap. If adopted, it will increase the efficacy of the demo experience at RIT. Additionally, it may lead to more people with security expertise, backed with meaningful hands-on learning, for the security community more broadly. This project will have a meaningful and practical effect on reducing the talent gap.

The capstone project demonstrates technical and nontechnical expertise. It involves developing training materials, a secure web application, and automation, showcasing transferable skills relevant to enterprise security settings. Additionally, the project involves marketing, organizational management, and scalability, highlighting nontechnical skills essential for the success and growth of the security education ecosystem.

The deliverables include an integrated education application with a demo platform. The project also creates potential for partnerships with other schools, internal training, and documentation for sustained operation and development. Addressing the need for a better engagement experience, the project aims to increase engagement through collaborative demos inspired by successful educational software, like Kahoot.

2 Background & Significance

Researchers have studied the effect of gamification on education over the last decade. While results vary slightly, a meta-analysis of 22 studies found a "moderate level positive effect on learner motivation" [4]. Furthermore, another study found that gamification correlated with better answer quality in educational settings [5].

However, gamification is a broad topic, and there are many ways gamified elements can be integrated into this project. Massive Online Open Courses (MOOC) are of particular interest to this project. These are online courses that are highly efficient to scale, such as RITx. However, they struggle with retention. A study from Leibniz University found that students who studied for a quiz with an individual gamified method had a 22.5% increase in scores over their peers who studied with non-gamified methods. Additionally, they found a 40% increase in quiz scores when students engaged in an environment with social gamification, rather than in a traditional MOOC environment [6]. Based on this research, this project assumes that social gamification is the best strategy to scalably drive high levels of retention.

The ultimate goal of this capstone project is to reach intrinsic motivation to study cybersecurity. Gamification and extrinsic rewards are highly effective mechanisms to cultivate initial interest and continued exploration of new subjects [7]. Other elements, such as quests, can then be leveraged to build curiosity and shift participation from extrinsic motivation to intrinsic [7].

CTF-style competitions are well suited to gamification. A cybersecurity training organization, Avatao, found that CTFs encourage healthy teamwork and competition, and help retention through practical training [8]. The healthy teamwork and competition align closely with the Leibniz study, which emphasized the importance of social gamification, providing a practical path to realizing those desired gains.

Additionally, Morgan State University (MSU) has seen direct success in outreach through CTF competitions. At the American Society of Engineering Education 2021 conference, MSU highlighted that its CTF participation helped make underrepresented groups more interested in cybersecurity. The CTF also effectively taught cybersecurity concepts to students who lacked a technical background [9]. These results map closely to the desired goals for this project.

3 Related Works

3.1 Hedonics

Hedonics is the study of happiness and unhappiness. The Objective Happiness model describes what makes people happy. It proposes that there is an "experiencing self," which encompasses emotions experienced while experiencing events, and the "remembering self," which encompasses emotions experienced while reflecting on past experiences. He proposes that "objective happiness" is the cumulative result of happiness or unhappiness felt in any given moment [10].

Hedonics also addresses the influence of motivational forces on individual behavior. The Self Determination Theory models behavior on the assumption that people are self-acting agents that, and are guided by intrinsic and extrinsic motivations. Intrinsic motivations involve doing something for its inherent satisfaction. Intrinsic motivations include a desire to learn or improve one's skills. Extrinsic motivations involve doing something for external rewards or punishments [11]. Extrinsic motivations include awards, grades, or professional opportunities, among others. Intrinsic motivations, when present, tend to be stronger than extrinsic motivations. Intrinsic is particularly effective since it tends to encourage challenge, curiosity, and mastery [12].

Emotions are feelings based on experience that are motivational and informational. They are a highly effective mechanism to motivate rapid changes in behavior [13]. However, emotions are responsive to environments, and therefore difficult to control [14]. Emotional responses can be approximated across a population group through Semantic Differential (SD). SD relies on people scoring concepts along a bipolar scale of emotions; for instance, a scale from happy to sad [15]. The SD model is central to hedonics research, since it can approximate characteristics that are difficult to quantify. However, it can be subject to bias and will primarily be used through relative rankings [15].

Gamification exploits the emotional reward system to encourage external behaviors. The combination of the extrinsic and intrinsic motivation correlates with higher engagement and desire to return to a gamified system than systems with a single type or no type of motivation [12]. Crucially, it will use a subset of game design elements, such as interface design, mechanics, heuristics, models, and design methods to drive behavior in non-game contexts [16].

Student engagement can be described as one of three forms: behavioral, emotional, or cognitive. Gamification systems primarily focus on emotional engagement. Emotional engagement can be difficult to evaluate, but there are two primary models [17]. One model looks at self-reported scoring, similar to the SD. The other model builds qualitative representations from third-party observers, such as the relationships between teachers and students observed in the classroom.

Form	Description
Behavioral Engagement	Positive conduct including adhering to rules and absence of disruptive behavior
Emotional Engagement	Affective reactions such as interest, boredom, happiness, sadness, and anxiety
Cognitive Engagement	Self regulation and strategic thinking, such as a desire to exceed requirements, flexible problem solving, or a desire for hard work

Figure 1: Forms of Student Engagement [17]

Generally, the first model would be preferred for the same population set given inter-rater variability, which is when two people rate the same outcome differently. The second model would be preferred for comparisons between population sets given that the same observers would score both studies, reducing the impact of inter-rater variability. However, both models are difficult to attribute feelings to a specific reason outside of a controlled experiment. Studies have repeatedly and consistently found strong correlation between behavioral engagement and academic success [17].

Three longitudinal studies that explored early-semester student emotions against end of semester grades found that positive emotions early in the semester were reasonably strong predictors of overall course success [18]. Conversely, boredom correlated with poor course success, far worse than other feelings like test anxiety [18]. One study examined emotions as students learned with three different educational applications, and found that boredom is exceedingly difficult to break, suggesting that learning systems should prioritize reducing boredom before other negative emotions like frustration [19].

3.2 Gamification

Gamification is a technique that refers to "the use of design elements and characteristics for games in non-game contexts" [16]. Gamified applications differ from video games in that they are not built on game-based technologies and serve a primary purpose other than entertainment [16]. Gamification builds on a long history of applying hedonics to machine interfaces, and is unique in its emphasis of playfulness as a desirable characteristic.

Studies on the effects of gamification generally investigate psychological or behavioral outcomes [20]. While results vary, these studies typically find positive results for some, but not all, of their gamification techniques. While the cause is uncertain, it is likely due to confounding variables such as the context and qualities of the users [20].

Gamification research often focuses on educational research. Educational settings often lend themselves to gamification as they are assessment-centric and may struggle with student engagement. Gamification in educational settings leverage three mechanisms for scoring:

External assessments are one of the best ways to evaluate the effectiveness of gamification training techniques, as they can be deployed in controlled studies [21]. However, there is a separate question of what elements should be used to guide user behavior. The most common elements are points, performance graphs, badges, leaderboards, avatars, teammates, and meaningful stories. These mechanisms should be chosen based on the desired feedback mechanism.

A simulation explored the relationship between these elements and desired outcomes [22]. The simulation was of someone picking items from storage shelves, similar to a fulfillment warehouse. The simulation found that people

Mechanism	Characteristics
Game Scoring	Grading is based on targets acquired, obstacles overcome, or time to complete
External Assessment	Assessments take place independently of the game, often using more traditional methods
Embedded Assessments	Assessments take place during gameplay but do not rely on mechanisms that would be commonly present in games

Figure 2: Scoring Mechanisms in Educational Settings [21]

in the gamified environment that focused on competence (e.g., points, performance graphs, badges, and leaderboards) found much greater levels of competence for participants who experienced gamification. Those with the competence elements also felt greater meaningfulness in their actions relative to those who did not. Simulation participants who had social relatedness gamification elements (e.g., avatars and teammates) felt a much greater degree of social relatedness than those who did not.

A study from Unisinos University examines the effects on students in areas of introversion and extroversion [5]. It concludes that students with low extroversion, low openness, or low agreeableness benefited most from gamified systems. Extroverted students thrive with collections of badges as well, with both groups scoring higher when utilizing gamification models between a baseline exam and a final exam. Extroverted groups saw a significant decline in performance when they were directly ranked with peers [5].

Gamification research has expanded to include social gamification research. As mentioned before, the "teammates" design element correlates strongly with an increase in performance. A study from the University of Alcalá isolated the impact of social environments and gamification on e-learning performance [23]. They ran a "quasi-experiment" in an information and communication technologies course with a blended learning model. The study found significant improvements for students who were assigned to the social or gamification methods compared to the control, regardless of how often they used those benefits, on practical assessments. However, the traditional study method outperformed both the social and gamified study methods on

Design Element	Descritpion	Mechanism
Points	A number that is awarded for successful accomplishment of an activity	Granular feedback
Performance Graphs	A graph that shows progression of points or other indicators over time	Sustained feedback
Badges	A visual representation of an achievement that can be earned and collected in an environment	Cumulative feedback
Leaderboards	A ranking of players based on relative success, as defined by a certain criteria	Cumulative feedback
Avatars	Customizable visual representations of a player in a game	Decision freedom
Teammates	Real or non-player characters that can add conflict, competition, or cooperation	Volitional engagement
Meaningful Stories	The narrative context that a player's actions take place in	Shared Goal

Figure 3: Elements for Gamification [22]

written exams. This finding suggests that the social and gamification treatments overemphasized skill acquisition at the expense of knowledge acquisition. This project's goal focuses on skill acquisition, making social learning and gamified learning effective strategies.

3.3 Technology Acceptance Model

The goal for this project, as an educational application, is to have an intuitive user interface. The project's users should spend more time solving problems, rather than learning how to navigate the app. There is extensive academic research to make applications easy to use; one effort to apply the scientific method to user experience design is the Technology Acceptance Model (TAM) by IBM [24].

The model focuses on two objectives: perceived usefulness and perceived ease of use [24]. Perceived usefulness is how likely someone who uses an application will say that it enhances their productivity [24]. Perceived ease of use is how likely a user of an application will say it is "free of effort" [24]. IBM developed TAM from a study of 66 industrial salespeople who found that perceived productivity had the strongest correlation with application adoption ($p<0.001$) [25]. The TAM is also backed by the Theory of Reasoned Action which says that people are more likely to perform an action if they perceive said action positively, or if they perceive it as important to people in their social circle [26].

While designed for productivity systems, TAM is often used in research for educational software. In a review of 68 papers investigating learning management system (LMS) adoption, 38 of them use TAM because of how flexible the model is [27]. However, over time, more factors were incorporated into user experience research to model behavior beyond usefulness and ease of use [27]. For example, a study of 484 students at the University of Malaga investigated the impact of playfulness—an "individual's tendency to interact spontaneously, inventively and imaginatively with computers"—on LMS system usage [28]. While not directly affecting application adoption, playfulness indirectly increased application adoption through increased perceived ease of use and usefulness [29].

These compounding factors have caused the TAM model to be reevaluated over time [30]. The TAM2 model (2000) includes the following as factors that can influence perceived usefulness:

1. Perceived Ease of Use: if a user thinks that a system will be easy to use
2. Subjective Norm: if a user's social circle thinks they should use or not use a system
3. Image: if using or not using a system will help a user's social status
4. Job Relevance: how relevant a system is in helping a user complete their job
5. Output Quality: how good of a job a user perceives the system will do
6. Result Observability: the degree to which someone believes that the benefits will be visible and tangible

Characteristics of the TAM2 model [30]

Then, the TAM2 model was redesigned based on further research, creating the TAM3 model (2008), which focuses on perceived ease of use:

1. Computer Self-Efficacy: the degree to which someone thinks they can perform a task on the computer
2. Perception of External Control: the degree of which a person believes organizational support for a system exists
3. Computer Anxiety: the degree of fear someone feels when using a computer
4. Perceived Enjoyment: the degree to which someone feels an activity will be enjoyable, regardless of actual productivity
5. Objective Usability: comparisons of systems based on actual complexity, rather than perceived complexity

Characteristics of the TAM3 model [30]

TAM3 also focuses on having its characteristics moderated by experience, rather than perception [30]. In other words, it is not just how someone perceives a system before they use a system, but also how they learn to use a system. However, studies have found that TAM3 could explain "between 52% and 67% of the variance in perceived usefulness across... time periods and models," meaning that it can theoretically be effective for nearly all applications [30].

4 Project Outline

4.1 Goals

Our project goals were organized by priority level:

1. High
   a) Build a simple interface to complete CTF challenges
   b) Streamline the development process for lesson authors
   c) Eliminate the necessity for Virtual Machines (VMs) on end-user devices, such as school computers and personal laptops
   d) Create an environment where almost anyone with a web browser can participate
2. Medium
   a) Reduce the network strain when large groups of people need to utilize VMs to complete challenges
   b) Minimize operational and computational costs for student clubs
   c) Make the codebase readable and accessible to ease maintenance, lessen adoption pains, and speed up the contributor onboarding process
   d) Documentation of backend code and its structure
   e) Self-documenting and intuitive frontend code structure
3. Low
   a) Improve the in-person event experience for students during club meetings
   b) Scale the system to other student clubs
   c) Establish a multi-club unified curriculum
   d) Add continuous integration and continuous deployment (CI/CD), unit tests, and code coverage to the development process

4.2 Technical Overview

The project is a web application to ease the process of accessing and completing demos. With this, the capstone project aims to ensure that the game aspect is well-structured to encourage members to participate and compete. The backend of the application is written in Python with the Flask framework. This provides a modern and simple code structure that will be easy for individuals to contribute to. As Python is often one of the first languages introduced to computing students, it is anticipated that they will be able to transition their skill sets from that into this project [31]. Flask also provides numerous plugins to assist in the development process, such as a login feature and a fully functional Object-Relational Mapping (ORM) system. An ORM converts relational databases into functional classes, restricting the need to write Structured Query Language (SQL) statements. This makes understanding data queries more intuitive and limits direct access to SQL, which can cause bugs and vulnerabilities if not properly managed.

The frontend of the application is written using SvelteJS and TailwindCSS. Svelte handles many of Javascript's traditional complexity, such as state management and reactivity. Svelte abstracts the details of Javascript development, and the intent of using this technology is to ease the burden of onboarding new contributors. This project also makes extensive use of Lottie, a web animation library. Lottie allows developers to programmatically trigger animations. Svelte, Tailwind, and Lottie combine to make a visually appealing and highly animated website. The end result is a hybrid between a website and a game, which may lead to greater engagement.

To allow users to access demos remotely, this project uses NoVNC to give console access. NoVNC is an open source project that utilizes the Virtual Network Computing (VNC) protocol over websockets to obtain a console view in a web browser. This protocol is supported by many major virtualization platforms, such as ESXi, Proxmox, OpenStack, and AWS. The protocol gives groups the ability to use this project with whatever infrastructure they are comfortable with. To limit computing resources, the capstone group implemented a timer on the VMs. When a demo VM is created, users will have a one-hour window allocated before the VM is destroyed. At any time before the timer ends, users can click a button to reset the time to one hour. This allows members to take their time to complete a challenge, while also giving the power to shut down machines that are no longer in use.

All development is being done on GitHub. Once complete, the project will be made public for anyone to access the source code, post suggestions, and contribute changes. This capstone project has established GitHub Actions to ensure proper linting on the backend codebase.

These give maintainers the ability to ensure that key aspects of the project are not impacted by new changes, while also showing where more tests may be needed.

5 Project Outcomes

5.1 Backend

The backend contains create, read, update, and delete functions for all of the key data types in the program. Due to the multiple parent-to-children relationships present in this model, the API structure functions in a similar manner. For example, the API routes for a specific class's lessons are children of the class's main route. Furthermore, the Python Flask framework has been integrated as the primary web provider to serve the frontend files along with API data. This reduces total processes needed to run the application, as a proxy is not needed to direct requests to the API or the served frontend files. This also allows administrators to compress the entire application into one Docker image, enabling the application to deploy quickly, as there is not a separate API and frontend image.

The VM allocation process uses a standardized class structure. By doing this, different providers can be used without changing any code other than the provider's plugin. With the test resources available to the project, this capstone only provides a plugin for the OpenStack virtualization platform. Yet, the modularity of this API component allows other providers to be quickly developed and added. The plugin used and accompanying values, such as API keys, are provided to the application through environment variables.

To manage VMs in use, both the PostgreSQL database and a Redis cache are used. Data on VM templates and pairing exact machines to users is stored via the PostgreSQL database. Redis is used to manage time remaining before expiration. This is done via the Time-To-Live (TTL) feature in Redis, giving a key a time before being deleted. The API application has a notification thread running that will immediately be triggered upon a VM's expiration. This allows administrators to automatically remove machines that are no longer in use. If a user is still using their VM and is approaching the expiration time, they can make a request to the API to extend it to the original time.

5.2 Database Structure

PostgreSQL operates as the primary data storage. To manage changes to the schema, Flask's Alembic system was used. This feature detects modifications in the ORM classes, and will create migration files to represent those changes in the database. These files are generated in Python, which is then executed by the Flask command line tool. Then, these migrations are dependent on the ones previous to them, allowing for a straight timeline for debugging past versions and upgrading from any previous version.

Redis was utilized for live storage of VM expiration time due to its notification system. Clients on the database can "subscribe" to different events, such as the expiration of a key due to reaching the end of its time to live. Any time a VM is created, a key-value pair of the machine's UUID and the owner's username is created. If the machine expires, the backend is notified with the machine's UUID, which will trigger the function to delete that machine from the provider.

5.3 Frontend

The web app uses modern, maintainable technologies. The platform is built on the SvelteKit library, since it offers a good balance of efficiency and maintainability. Svelte also allows developers to offer greater interactivity, such as animations when a flag is correct.

The capstone group began by designing for mobile devices, then adding modifications for medium-sized screens (e.g., tablets and small laptops) and then further modifications for large screens. This allows the platform to offer a high quality experience regardless of a user's device. This focus on mobile-first was essential, as there is a meaningful opportunity to scale this application into environments with Chromebooks and other low-powered computers. The project follows the Web Content Accessibility Guidelines 2.0 (WCAG2) accessibility guidelines whenever possible, further reducing the barriers to security education.

The application also uses a modular lesson system. Lessons are composed of "blocks" which include, but are not limited to, CTF blocks. This system allows for integration of CTF questions within other content, such as text, images, PDFs, or YouTube videos. While less crucial for the in-person environment used at RIT, it allows for the development of self-guided content which offers other clubs greater flexibility in the modality of their meetings.

The application, including the modular lesson system, adopts a component-centric design. This structural paradigm makes iteration much faster. When each entity has a dedicated component type, it can be guaranteed to render the same way in different parts of an application. It also reduces the amount of code reuse. This structure was particularly helpful to build similar but separate student and administrator portals, with over 70% of code shared between both, enabling faster development times and greater cross-application consistency.

5.4 Documentation

To ensure that the API is maintainable and able to be easily tested by developers, all routes have been documented using the OpenAPI v3 specification. This standard creates a YAML file. This file can then generate the code for the front-end to communicate to the back-end, reducing the chance for errors. All functions have also been documented with docstrings within the codebase for easier future development.

5.5 Platform

The application was developed as a platform that many organizations can use. While some of the API endpoints are organization specific, the project has others that are accessible to environments outside of RIT. These open endpoints allow for clubs to develop resources, such as lessons and VMs, and share them with other clubs.

Lesson development consumes resources and time that clubs might be better used elsewhere. Larger clubs can absorb these costs without too much impact, but it is a significant barrier for new clubs. Thus, large clubs can learn from each other and take less time while new clubs can offer a better experience than they otherwise could deliver.

One barrier new clubs face is how to form and attract members. It can be difficult to learn how to manage a club without prior experience: marketing, writing a constitution, structuring meetings, delivering value to members, and more. This project includes a curriculum, available as a "class," to guide new clubs through their formation and first-year of operation. This will help leaders of new clubs become acclimated to the platform, and streamline the formation of their club.

5.6 Gamification

The development of gamification in this project strategically focuses on awards and scoring, as the system pushes students to reach certain milestones. The challenges grow in difficulty as students progress, naturally causing completion to decrease further into lessons. Awards—in the case of this project, bronze, silver, and gold achievements—for each lesson push students to continue. The awards are given when a student submits an answer (or "flag") through a check on the backend.

6 Future Work

6.1 Adoption

Future work focuses on expanding the CTF platform's reach beyond RIT. Specifically, the widespread adoption of the CTF platform by other educational institutions will foster a collaborative environment where schools can leverage and build upon this project's foundational work. One strategy involves marketing to institutions outside of RIT and promoting the platform as a tool for gamified cybersecurity education. In addition, future work includes creating an open curriculum encompassing demos and lessons crafted from adopters' and contributors' experiences, enabling schools to kickstart cybersecurity clubs. Lastly, this project aims to create a community where multiple schools actively contribute to the platform's development, adhering to open-source community standards and driving collective growth.

6.2 Funding

Funding is another area for future work. First, adopters should routinely search and apply for any grants that might be interested in funding this project. Additionally, adopters should determine if there is a way to integrate sponsorships into the project or platform. Cloud hosting providers and cash exchanges to help build infrastructure or content may be especially lucrative areas.

6.3 Live Competition Mode

Another future development includes a live competition mode, where a group would have a central scoreboard with real-time scoring, similar to that in competitive video gaming. Here, points would be added to a person's score on the scoreboard when they complete a challenge in the CTF platform. This would improve participation among members and create a more collaborative environment for students who attend in-person events.

7 Conclusion

In conclusion, this capstone project made significant strides in addressing the skills gap in cybersecurity education. By creating a scalable model for security education across schools and emphasizing hands-on learning, this project aims to have a lasting impact on the cybersecurity community.

The project seeks to enhance engagement and foster curiosity among students by integrating gamified elements into the educational platform. Through gamification and its effects on motivation and learning, the project aims to make security education more accessible and effective.

The technical aspects of the project—the development of a web application with a user-friendly interface, well-managed database, dynamic backend, and extensive documentation—demonstrate the team's dedication to creating a long-term, maintainable, and scalable solution.

Overall, the project's efforts contribute significantly to narrowing the cybersecurity skills gap by building excitement and rewarding exploration. By creating a collaborative ecosystem for security education, this project lays the foundation for a more secure digital future.

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