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Review

Solving the Chemistry Puzzle—A Review on the Application of Escape-Room-Style Puzzles in Undergraduate Chemistry Teaching

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Abstract: Active learning techniques are taking the classroom by storm. Numerous research articles have highlighted the benefits of active learning techniques on student understanding, knowledge retention, problem solving, and teamwork. One avenue to introduce active learning into the classroom is the gamification of course learning content. Educational escape rooms are one such example in which students solve a series of puzzles related to course content to "escape" within a set time frame. Escape games play an interesting role in motivating students, building communication skills and allowing for multimodal learning, having been shown to increase students' test results and enjoyment of the course content. In lieu of the traditional escape room format, a fully immersive room(s) with classical escape room puzzles (finding items, riddles, alternative locking mechanisms) is used alongside learning activities, and educators have begun to develop truncated activities for easier applications in larger classrooms. In this review, we explore several escape room activities: immersive, paper-based, Battle Boxes, condensed escape activities, and online/virtual, providing examples of the types of puzzles included therein. We similarly discuss the creation of escape room materials and recommendations for the interested educator, as well as the learning benefits of engaging in puzzle development. Finally, we provide an overview on methods to assess active learning through escape rooms, establishing an overview of empirical evidence towards their effectiveness as a learning tool.

Keywords: gamification; escape room; humor/puzzles/games; active learning; chemistry education; undergraduate/general; applications of chemistry

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1. Introduction

The revised Bloom's Taxonomy of Learning suggests that higher learning, involving procedural and metacognitive knowledge, is engaged when students can interact with learning processes. This includes carrying out a procedure (apply), detecting how parts of a process or theory relate to one another (analyze), making judgements based on criteria (evaluate), and designing an original product (create) [1]. In order to engage with these higher levels of learning, classroom structures must move beyond classical lecturing (passive learning) to provide students with organized experiences in which they can interact with course content more directly (active learning). The Learning Pyramid provides a simplified view of the success of learning strategies on knowledge retention, showcasing that active learning techniques, flipped classrooms (teaching), or laboratories (practice) lead to better knowledge retention (Figure 1). While the percentages of knowledge retention reported within the Learning Pyramid are debated [2], the framework highlights that active learning strategies are in line with achieving higher learning, as described by Bloom. In general, active learning techniques can be categorized into four themes: (1) individual nonpolling (e.g., concept maps); (2) in-class polling (e.g., iClickers or TopHat); (3) whole-class discussions (e.g., case studies or worked problems); and (4) collaborative team-based activities (e.g., worksheets, games, or hands-on activities) [3]. In all cases, the goals within a learning experience are centralized on providing students with new knowledge, creating opportunities for skill development, challenging preconceived notions, and developing beneficial behaviors.

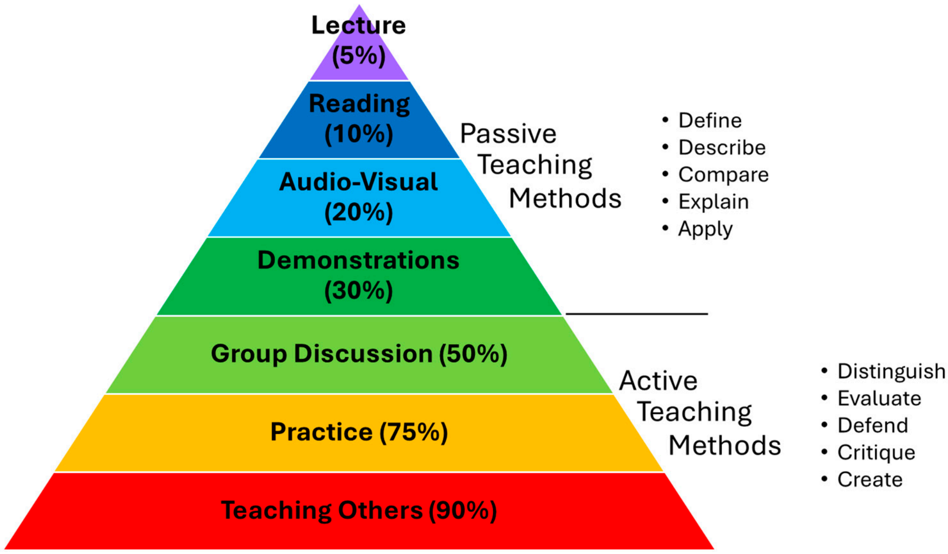


Figure 1. The Learning Pyramid (adapted from National Training Laboratories, Bethel, ME, USA). Teaching and learning method (% average knowledge retention rate).

Active learning in science, technology, engineering, and math (STEM) classrooms is a well-established, and now commonly used, practice to increase student performance [4–8]. For example, research by Freeman et al. showcases that active learning can increase the average student examination performance by a half a letter grade while, similarly, lowering the failure rate by 55%, compared to lecture-only courses [4]. In first-year general chemistry, Mutambuki et al. have shown that a combination of metacognition (ability to plan, monitor, and evaluate one's own understanding and performance [9]) and active learning significantly increases students' exam performance, lowers the number of "D" and "F" letter grades, and lowers the number of course withdrawals [10]. Similar work has shown that active learning in other undergraduate chemistry courses significantly improves student outcomes, most noted in students with lower academic achievement levels [11] and underrepresented groups [12]. Despite the benefits of active learning, student perceptions of active learning techniques as efficient tools for teaching can be mixed depending on the technique chosen [7,13–15]. For example, in-person discussion-based activities or team-based activities are often well received by chemistry students [16] compared to online discussion forums where student engagement can be low [17–19]. The benefits of active learning highlight the need to develop thoughtful engagement opportunities in which students can explore learning together through guided discussion-based activities [14,15]. The application of gamified learning materials is an excellent method to engage students, incorporating opportunities for hands-on application of learning objectives, allowing for multimodal learning and team communication. The benefits of gamified learning and the application of escape rooms as immersive learning experience are outlined herein. The unique design of escape rooms not only allows for discussion-focused engagement but provides an avenue for students to apply key learning objectives in a "real-world" experience.

In this review, we present an overview of the current literature around the use of escape-room-style puzzles in chemical education and provide practical guides for instructors looking to incorporate these tools. Additionally, we provide context about the pedagogical value of escape-room-style puzzles, a summary of assessment methods which can be used for active learning techniques (such as this one), and a future outlook on using these tools.

1.1. Gamification of Learning

> "The "holy grail" for training professionals is to harness the motivational properties of [games] to enhance learning and accomplish instructional objectives."
>
> —Thatcher and Robinson [20].

The Kolb's Experiential Learning Cycle defines that learning takes place when individuals engage with concrete experiences, are provided with the opportunity for reflective observation, explore abstract conceptualization, and perform active experimentation [21]. This learning cycle is often reflected in experimental development in which learners draw on knowledge gained in previous experiences to develop or improve new processes and gameplay, taking place multiple times as the game proceeds [22]. Gamification of learning is defined as the application of gaming components into non-gaming environments. The desire to improve problem solving and increase student motivation [23], has grown in popularity in recent years [24]. Gamification of learning and game-based learning, learning in which participants achieve educational targets by playing games, are often considered to be synonymous; however, it has been argued that gamification is embedded into the learning process and cannot be replaced by games alone, while game-based learning relies on the thoughtful development of a game itself [23]. For example, utilization of leaderboards or badges in pedagogical activities would be considered gamification but not game-based learning as no game has been developed. However, using a game to teach a topic would be considered both gamification of learning and game-based learning.

Self-Determination Theory, a widely adopted theory in the study of gamified learning, highlights that student's sense of autonomy, competence, and material relatedness are three key factors influencing intrinsic motivation [24]. Work by Buil, Catalán, and Martínez provides empirical evidence that specific game design elements can help to improve student motivation by meeting students' need for autonomy, competence, and material relatedness [25]. For example, developing avatars, meaningful stories, and quests can increase feelings of autonomy. Similarly, design elements like teamwork, leader boards, and background development can better relate game content to course content [24,26,27], while competition-based learning components such as point boards, levels, badges, and timed trials can give students a stronger sense of competence [28]. Research by Atherton et al. has also shown that games can have a beneficial impact for autistic individuals, providing an alternative platform for group discussion [29]. For a systematic review of empirical evidence towards the effectiveness of gamification of learning, we turn readers to work by Zainudden et al., highlighting the utility of specific gamified approaches as well as learning theories and models applied in gamification studies [24].

The effectiveness of games and simulations in teaching and learning depends on the debriefing that takes place following the activity [30]. The debriefing creates opportunities for reflection and discussion on the impacts of the experience on individuals. This includes the processes developed during gameplay, clarification of facts, concepts, and principles utilized, identifying emotions during gameplay (this can affect learning outcomes), and identifying views formed by participants throughout the experience [22,31]. To achieve desired learning outcomes, games should be motivating, encouraging learners to persistently reengage with the content, leading to an unpromoted return to Kolb's Experiential Learning Cycle [26,31]. The idea is that the student will showcase desirable emotional or cognitive reactions in response to feedback from gameplay [27]. Educators play an important pedagogical role in the implementation of educational games: planning, orientation, gameplay, and debriefing [32]. Here, regardless of the effectiveness of game design, educators act as a facilitator working to lead students to content topics, act as a tutor, and create opportunities for reflection. Often, "teachable moments" can be key to engaging critical thinking and learning during gameplay, lending to the idea of educators as co-learners in the process [33].

1.2. Escape Rooms for Learning in STEM

Utilizing games as a means to promote learning and engagement in chemistry is no new concept [34]. Chemistry games such as The Game of the Name, in which players ask questions to determine the identify of prominent organic chemists, emerged as early as 1971 [35]. Since then, chemistry games have become more elaborate, incorporating course learning objectives into the game design to better tailor to student learning. A list of recent chemistry games, their format (card game, boardgame, online game, etc.), and chemistry topic(s) can be found in Appendix A.

Using escape rooms as learning tools is a more recent emergence in gamified learning for teaching STEM [36]. A popular global phenomenon, escape rooms consist of a series of themed puzzles, riddles, and tactile components that must be solved in order to exit the room within a set time frame [36]. Before the game begins, teams are introduced to the storyline, safety considerations, and general considerations—how to unlock the various lock types, for example. During gameplay, the game master observes players and provides hints when requested. Common escape room elements include hidden items and clues, sound puzzles, light puzzles, math puzzles, word puzzles, ciphers, riddles, electrical current, magnets, jigsaw puzzles, repeating numbers, keys, matching puzzles, physical puzzles, visual design puzzles, maps and coordinates, Sudoku and crossword puzzles, and labyrinth puzzles [37]. While not inherently educational, many escape rooms allow participants to leverage prior knowledge in order to complete the tasks within. For example, math-themed puzzles will have players solve basic math problems, associated with learning in elementary school. Similarly, escape rooms provide a unique tactile component to gameplay in which numerous items within the room can be manipulated to reveal clues, hidden rooms, and secret compartments. Electrical current puzzles, for example, require players to place their hands in a specific area in order to complete a circuit and engage a locking mechanism. In the height of their popularity, several at-home escape games were developed utilizing single-use objects (cutting or folding paper-based puzzle components) such as "ESCAPE ROOM: THE GAME" [38]. Other escape games such as "Unlock! Escape Adventures" combine the use of playing cards, maps, and mobile apps to deliver clues, hints, and other content [39]. Due to the breadth of entertainment-focused escape rooms, their tailorable contents, and the intrinsic motivation they create, it is unsurprising to see the rise in development of educational tools reminiscent of this format [40–44].

Educational escape rooms are uniquely primed for application in STEM classrooms, allowing students to leverage their knowledge of course content as well as technical laboratory skills in puzzle solution [45]. In many ways, exploring scientific learning through an escape room is similar to the research process. Here, the educator takes a side role in the activity, proving guidance (clues) when requested and students work in teams to develop their own independent ideas, strategies, and solutions, partaking in active experimentation to evaluate theories [41–44,46]. This learning process is highlighted in Figure 2. Educators implement specific course content and gaming characteristics into the escape activity, and students then participate in a cycle of conceptualization, reflective observation, experimentation, and behavioral self-reflection. Finally, educators perform a final debriefing, highlighting expected learning outcomes and addressing misconceptions to solidify student understanding. Escape rooms, in this sense, mimic laboratories creating a sequence of experiences as a part of a coherent whole to engage in higher learning [47].

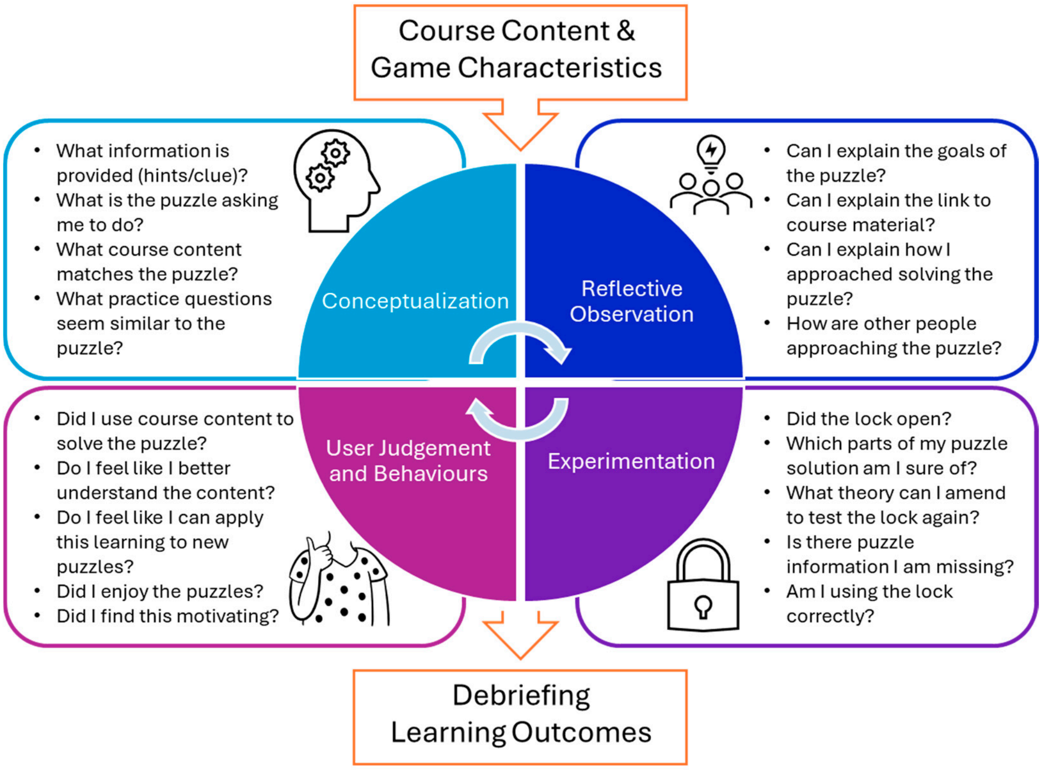


Figure 2. The Kolb's Experiential Learning Cycle [21] and model of game-based learning [30] in relation to educational escape room games.

2. Chemistry Escape Rooms

A 2021 survey of 93 educational escape rooms in STEM showcased that courses focused on medicine (35), chemistry (15), math (13), and computer science (13) had the most developed escape room activities [47]. The review suggested that in order for escape rooms to remain relevant in STEM teaching and learning, activities should be able to be more readily implemented (easily adaptable, less time-consuming, flexible interactivity). Similarly, reviewers highlighted that utilization of current escape rooms should be more systematic to provide a clear overview of available escape activities as well as empirical evidence towards their effectiveness at improving student understanding, motivation, and problem-solving skills [47]. Herein, we examine the landscape of chemistry-focused escape room activities in teaching and learning at post-secondary institutions.

In the landscape of advancements in gamified learning for chemistry education, chemistry escape rooms are at the forefront of new developments in educational tools. This active learning technique has been implemented in a variety of ways, from escape rooms which fully immerse students in their interactive puzzles to those administered online. The range of approaches have varying pros and cons to implementation and overall student learning. The following sections explore not only the styles of escape room puzzles and their content but also their benefits to learning and how student learning is assessed during their administration.

This section will outline a diversity of escape room puzzle designs including immersive escape rooms (Section 2.1), paper-based puzzles (Section 2.2), Battle Boxes and condensed escape activities (Section 2.3), and online escape activities (Section 2.4).

2.1. Immersive Escape Rooms

The term escape room predominantly elicits imagery of a small team working in a space filled with elaborate, stepwise, thematic puzzles of all varieties to achieve a common goal against the clock [43]. This classic escape room format has been realized in secondary and post-secondary chemistry classrooms to increase student engagement and understanding. Ranging from introductory chemistry content to upper-year analytical research development, this immersive tool is sufficiently flexible to adapt to an instructor's needs, providing opportunities for hands-on laboratory-style learning.

Participants: 2–10 per room.
Time: 60–90 min.
Room Requirements: room(s), laboratory.
Set-Up Time: hours–days.
Cost: $$$.
Recommended Implementation: laboratories, tutorials, workshops, outreach events.
Subjects: general, analytical (see Appendix A).

A chemistry-themed escape room experience, "Escape ClassRoom CSI 1.0", created by Barbero et al., was featured at the European Researchers' Night 2017 in Cadiz (Andalusia, Spain) [48]. Participants included undergraduate and graduate students as well as postdoctoral researchers. A total of 43 participants attempted the activity in groups of six to ten individuals of varying educational backgrounds. Approximately 50% of teams escaped in the 60 min time frame with 67% of participants rating the experience as difficult/very difficult. The outreach activity, themed around solving a murder mystery using analytical tools, featured three scenarios: one in which student teams worked to collect the required analytical instrumentation needed to complete the room, the second a crime scene sampling zone, and the final a forensics laboratory in which the collected samples could be tested (Figure 3). While not all puzzles were chemistry-focused, for example, two locks in the first room (scientific police station) required participants to solve a mathematical riddle and attempt a logic game focused on historical scientists, analytical chemistry techniques were reflected throughout. Room three, the forensics laboratory, featured two key mock experiments: (1) toxicological analysis in which students performed a series of acid–base reactions to determine the presence of a "poison" in a mock blood sample and (2) analysis of chromatography–mass spectrometry data to match the poison in the "blood" sample to known poisons. Unfortunately, little supporting information is provided by the authors detailing the set-up, contents, and solutions to each of the puzzles, limiting the use of the activity in other classrooms.

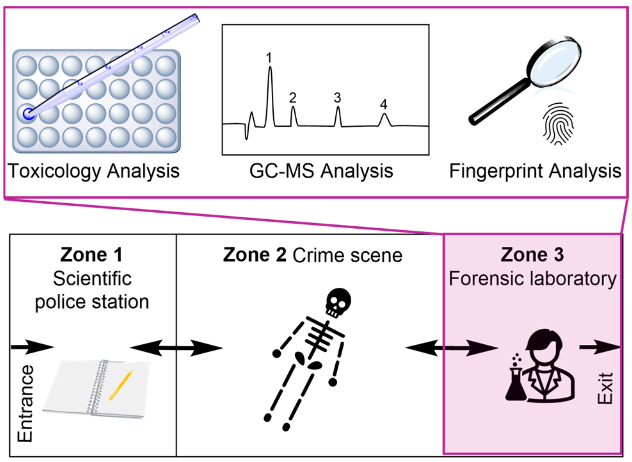


Figure 3. "Escape ClassRoom CSI 1.0" content layout and analytical puzzles included in area 3 (forensics laboratory); arrows indicate direction of intended movement through the zones [48].

In 2021, Avargil and co-workers reported an immersive chemistry escape room experience for high school students [49]. The complete experience was originally piloted by 12 experienced high school chemistry instructors, with the aim that high school students would be able to utilize the activity following the COVID-19 pandemic. Later in 2022, the experience was implemented as an undergraduate general chemistry learning tool (58 participants) [50]. The escape room, consisting of four rooms equipped with recording equipment, was established within the Faculty of Education at the Israel Institute of Technology (Haifa, Israel). The activity was designed to provide a complementary teaching tool for basic chemistry concepts, to prepare students for final exams, to practice laboratory techniques, and to allow students to develop 21st-century skills such as teamwork, leadership, and communication [51,52]. Self-described as a "hands-on, heads-on, hearts-on" experience, participants engaged with 19 unique puzzles, including "wet" experimental activities mimicking laboratory-style learning [53,54]. Hints are provided by facilitators throughout the experience when participants appeared frustrated or motivation to solve the puzzle appeared low. One "wet" puzzle (#102) required participants to prepare four solutions (aspirin, discovered in another puzzle, sodium bicarbonate, laundry detergent, and milk), measure the pH of each solution, and organize the solutions in ascending order of pH. Each sample solution holder is equipped with a radio frequency identification device (RFID) and, when placed in the correct position, triggers an electromagnetic lock to open (Figure 4A).

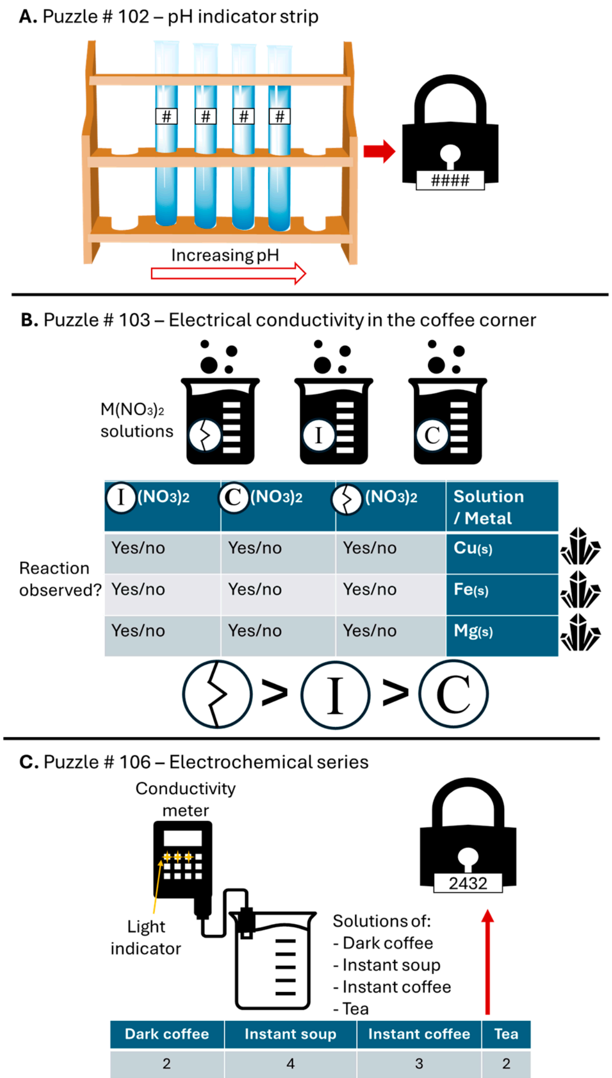


Figure 4. Example "wet" puzzle experiments from the "Break Dalton's Code and Escape!" activity. (**A**). Puzzle #102, ordering samples by increasing pH opens the corresponding lock. (**B**). Puzzle #103, reacting metal nitrate solutions with metal reagents allows students to rank the reducing abilities of metals and correlate these with a Dalton symbol. (**C**). Puzzle #106, measuring the conductivity of four solutions provides combination for lock [49].

Puzzle #103, an electrochemical series, considered a high-level knowledge puzzle, challenges participants to determine which metal (Mg, Cu, or Fe) is a stronger reducing agent. Participants are provided with metal strips of Mg and Cu as well as Fe powder. Unknown solutions of $M(NO_3)_2$, each with a Dalton symbol corresponding to one of the metals (Figure 4B), are tested with each metal to see if a reaction occurs. A reaction would be indicated by the formation of a gas (bubbles), a color change, or disintegration of the metal strip/powder. Based on these observations, participants will determine that Mg is the strongest reducing agent, reacting with both $Cu(NO_3)_2$ and $Fe(NO_3)_2$, followed by Fe and Cu, respectively. By determining the reactivity of the metals, participants can assign a metal to each of the Dalton symbols for use in later puzzles.

Another "wet" puzzle, #106—electrical conductivity in the coffee corner—requires students to measure the electrical conductivity of four prepared solutions (tea, dark coffee, instant coffee, and instant soup). The solutions are tested using a conductivity meter. The conductivity is then correlated to a series of LED lights where more LED lights illuminating corresponds to higher solution conductivity. By filling out the associated conductivity table (Figure 4C), participants discover the numerical code for the corresponding lock.

Despite the complex locking mechanism utilized within the escape room, the "Dalton's Code" activity represents an excellent example of hands-on experimental-focused puzzles that can be readily incorporated into a more simplistic room set-up, laboratory, or condensed escape activity (Section 2.3). Similarly, each of the "wet" puzzles described can be utilized individually, with many aligning to course content in undergraduate general chemistry classrooms [55]. The authors provide a detailed overview of puzzle set-up, solutions, learning objectives, and prior knowledge requirements, as well as recommendations for more simplistic locking mechanisms. Print files for each puzzle are likewise provided for the interested educator.

A pilot of the activity, utilizing low-budget materials in a laboratory setting, was run in 2019 for 22 chemistry teachers in groups of 5–6 individuals. On average, teams completed the activity within 60–90 min. As is the case with most escape rooms, whether educational or entertainment-based, participants struggled to connect clues to specific puzzle activities without some guidance. For example, educators solving puzzle #106 recognized that four solutions must be prepared but not how to use the conductivity measurements to determine a code for the corresponding lock. Providing more guidance to participants by reducing the number of interactive components and false leads, or coupling the activity to a workbook (see Section 3), helped to reduce participant confusion while still exploring learning objectives. Following the activity, participants completed a reflective questionnaire to determine the expected impact of this experience on student learning. These results indicated that educators believed students would display stronger communication and collaboration skills and high-order problem solving, as well as increased motivation to learn the chemistry content covered [49]. This belief was later reflected in undergraduate students' feedback surveys in which group communication and teamwork in problem solving was most often cited as a tool utilized by student teams to complete the puzzles [50].

"Escape the Lab", designed by Vergne et al., was implemented in an upper-level instrumental methods of analysis course, featuring a 12-step solution to escape [56]. The series of challenges, tackled by groups of 4–6 over 1 h, were tactfully designed to revisit instrumental analytical chemistry techniques and concepts students had been exposed to in earlier course content and laboratory sessions. This encompassed an array of spectroscopic, spectrometric, and chromatographic techniques with an overall goal of identifying an unknown compound. Riddles and "search for item" puzzles were limited, ensuring students focused on the main puzzles pertaining to utilization of the analytical techniques rather than wandering the rooms. For example, puzzle A requires students to locate a faux pop can. Inside the faux can is a sample vial containing an unknown sample (20 mg/L aqueous caffeine solution). A second puzzle revealed a UV-Vis cuvette, a description of the Beer's Law equation, and the molar absorptivity of the unknown liquid, indicating to students that they must collect an absorption spectrum of the unknown liquid and determine the concentration of the sample using a calibration curve (provided). The last two digits of the calculated concentration were used to open a numerical lock (Figure 5A), revealing another unknown sample (0.5%, w/v, ethanol in water) in a gas chromatography (GC) vial and a color-coded key. The key opened the instrumentation room in which the GC was housed. Puzzle B required students to run the unknown GC sample and determine the retention time in minutes, the first two digits of which were used to open a second locked box (Figure 5B). The puzzle solution continued in this manner, allowing students to likewise utilize their understanding of infrared (IR) spectroscopy.

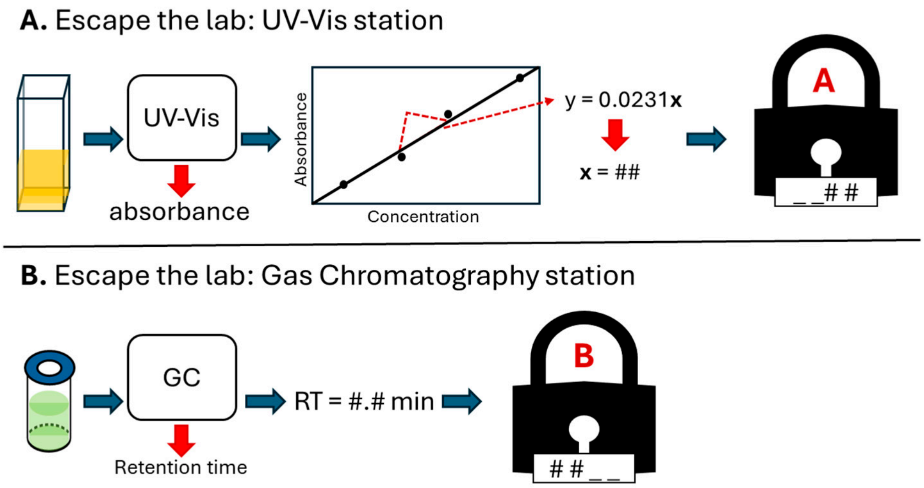


Figure 5. (**A**). UV-Vis and (**B**). gas chromatography puzzles in the "Escape the Lab" activity [56].

The set-up time required for this escape room is similar to a typical analytical chemistry laboratory. Instructors must prepare standard solutions and generate a calibration curve prior to entering the lab as well as arrange several puzzles and lockboxes around the room. After completion of the activity, students reset the escape room (placing items back in lockboxes, hiding clues) for the following team, minimizing the work required for activity turnover. As a result of this escape room activity, students, as self-reported through a questionnaire, indicated that the experience was not only fun but additionally provided an effective review of key techniques related to the associated course content. While the utilization of the described escape room is limited to analytical laboratories with access to UV-Vis, GC, and FT-IR, the puzzle components requiring the analysis of spectra and corresponding calculations can be readily implemented as a paper-based puzzle.

The "Quant Escape Game" (QEG), pioneered by Musgrove et al., was implemented in tandem with an upper-level undergraduate quantitative analysis laboratory class [57]. Uniquely, this game was a central focus of the course, acting as a final project, emphasizing the importance of course content to successful solution of the QEG. The escape room was run during the 3 h laboratory time over the course of four weeks and was designed to accommodate groups of six students. Prior to the escape room experience, students engaged in scaffolded laboratory sessions providing them with the foundational characterization skills that would be required for later puzzle solution. The laboratories steadily increased the level of student learning in accordance with Bloom's taxonomy, with later laboratories mimicking elements of classical research (analyze, compare, evaluate, create) [58,59]. The authors provide an overview of the preparatory laboratory experiments in their supporting information.

The QEG experience requires students to use course knowledge of spectroscopic, electrochemical, and titrimetric methodologies. Uniquely, the QEG was designed to allow students to not only solve puzzles related to course content but to design their own experimental methods of analysis. The storyline is focused on identifying a copper smuggler who is utilizing chocolate syrup as a transport material. In the first puzzle set, students must design a method to identify which chocolate sample (1 of 3) has been tampered with by analyzing the copper content. Students proposed several analytical methods including external calibration with atomic adsorption (AA), standard addition with AA, UV-Vis followed by AA, a displacement reaction with a calcium ion-specific electrode (ISE), a quick test with a copper ISE, and colorimetric titration with ethylenediaminetetraacetic acid (EDTA). The choice of analytical method did not affect puzzle solution but rather allowed students to utilize their understanding and confidence with their proposed method to identify the contaminated sample. In this way, the escape room was designed to reflect the realities of conducting real-life research, equipping students with the critical thinking skills necessary for future success. While this style of immersive escape room can be time-intensive and difficult to implement outside of a laboratory, it represents a unique method that can be leveraged to allow students to develop research confidence and self-efficacy while providing rapid formative feedback (facilitator approval of reasoning and opening locks).

Unlike other escape room activities, typically graded on a participation basis, the QEG lab was graded based on completion of the activity. Students were provided with chemistry questions/prompts in this case. Partial credit was assigned based on the completion of the prompts: one complete, 33%; two complete, 66%; all prompts and puzzles complete, 100%. To add an element of competition-based learning, the first group to complete the experience received extra credit. While students felt anxious initially, this dissipated as the QEG laboratories continued. This problem-based learning technique, as assessed by pre- and post-game surveys, significantly improved students' perceptions and feelings surrounding teamwork. Moreover, 100% of students indicated that this activity helped their learning, citing reasons such as greater critical thinking and increased understanding of course content. The increase in student learning is further supported by the difference in class average on pre-assessment and post-assessment quizzes, where a marked increase in test score average (0 to 1000%) is reported following course completion.

"Spectroscopy Unlocked", an undergraduate escape room activity reviewing classical analytical and spectroscopic techniques, IR and nuclear magnetic resonance (NMR) spectroscopy, GC, and thin-layer chromatography (TLC), was cocreated by a team of two final-year undergraduate students and two faculty members [60]. The activity, aimed at developing skills such as time management, problem solving, teamwork, communication, laboratory techniques, and general subject understanding, was implemented during a laboratory session (2 h). Prior to the activity, an introductory briefing was performed, informing students of general laboratory procedures, health and safety considerations, and the storyline for the escape room. Similarly, a debriefing followed the activity in which facilitators worked to consolidate student learning, promoting reflective discussions on the problem-solving process and influences on student understanding (see Figure 2; reflective observations and user judgements and behaviors).

The escape room consists of four activity stations: IR spectroscopy, TLC, NMR spectroscopy, and mass spectrometry. Each station consists of an experiment or task alongside a puzzle to be solved using experimental data. The activities are interrelated with the solution of station 1 providing key information to solve the puzzle at station 2 and so on. For example, station 2—thin-layer chromatography—has students analyze a mixture of unknown, colored compounds (Waxoline Victoria Blue, Sudan IV (red), and *p*-nitroanaline dissolved in acetone) by TLC using several solvent systems (ethyl ethanoate, dichloromethane, toluene). Students must calculate the retention factor (R_f) of each colored compound and arrange the eluents in order of decreasing polarity (Figure 6A). Students communicate their findings to the facilitator. If correct, the students are provided with a "letter cross" puzzle featuring two perpendicular lines of numbered letters and a series of number combinations. By relating the number combinations to the letter cross, students uncover the clue "They say the most polar is purple", indicating that a purple box located in the room contains the information required to begin the next station. In station 3—NMR spectroscopy—students are provided with an alphabet wheel, a binary decoding book, seven unassigned NMR spectra, and the names of the compounds to which the spectra are related (Figure 6B). The names of the compounds are doubly encrypted, meaning that students must first translate a series of binary numbers into a capital letter, then students must use the alphabet wheel to relate the capital letter to a lowercase letter (the true letter in the name). Once the names of the compounds are deciphered, students must match the chemical to the corresponding NMR spectrum. Again, students provide their answers to a facilitator who will in turn provide them with a key to access the next station.

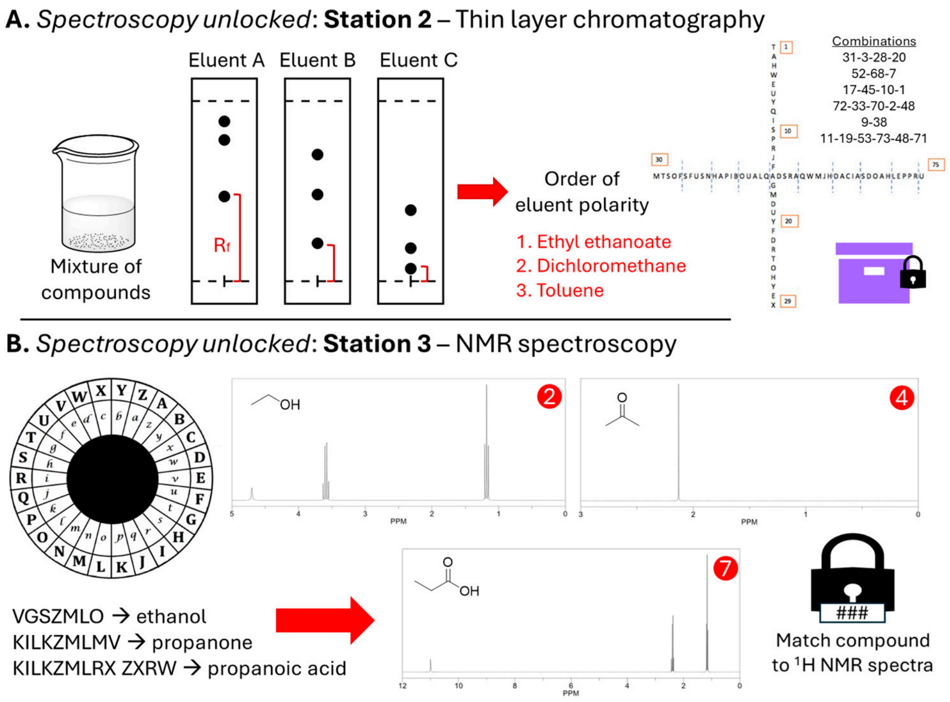


Figure 6. "Spectroscopy Unlocked" (**A**). thin-layer chromatography station and (**B**). NMR spectroscopy station [60].

A mobile escape room, developed by Peleg et al., was implemented at the secondary school level (grades 11 and 12) and featured 13 distinct puzzles for student teams to interact with [61]. These puzzles, designed to support four groups of 4–6 students, were completed within 40–60 min. The puzzles consist of both "wet" (4) and "dry" (9) activities, ranging in complexity. The activities are non-linear and span varying levels of knowledge, giving students multiple avenues for successful completion and "escape". The instructor labor required to run this escape room was lessened as teachers received pre-assembled escape room kits. Teachers similarly received 2 h of training several weeks before the activity was run to learn about the room itself as well as associated set-up, operation, and take-down. The activity requires 3–4 h to set up the room, 1.5 h for the complete escape room experience (introduction, activity, and debriefing), and 2 h for take-down. This time requirement is reflective of the immersive experience, complete with thematic elements such as caution tape and signs. The puzzles included were designed to challenge students' knowledge of acid–base chemistry, balancing chemical equations, identifying solution pH, and neutralizing a mystery solution. For example, a paper-based puzzle, pH envelope, provides students with three chemical formulas (1 M HBr, H_2O, and 1 M KOH). Using a clue on the front of the envelope (an arrow labeled "pH" with 14 at the end of the arrow), students must organize the chemicals in order of increasing basicity to reveal the combination. The "wet" puzzles have students perform simple reactions in order to reveal corresponding combinations or keys. For example, puzzle 5, the pink jar, has students add an acid sample (revealed in an earlier puzzle) to a jar containing base and phenolphthalein labeled "needs acid". Adding the acid neutralizes the solution, changing the color to clear, and revealing a code at the bottom of the jar (Figure 7A). This puzzle requires low chemical knowledge but can be exciting for students to perform due to the discovery of the hidden combination. A similar puzzle, release the key, features a key placed in a Styrofoam ball inside of a sealed jar with a small opening at the top. Students must add acetone (revealed in an earlier puzzle) to dissolve the Styrofoam ball and release the key (Figure 7B). Unfortunately, three of the "wet" puzzles described do not require specific chemical knowledge to complete the activity; however, they provide exciting methods for clue discovery and puzzle solution (e.g., making conductive dough to complete a circuit). The benefits of the experience were apparent in feedback collected from students. The results indicated that students felt they employed both course content and teamwork for successful completion of puzzles. Additionally, students reported they were fully engaged in the activity, creating an environment for personal growth and learning.

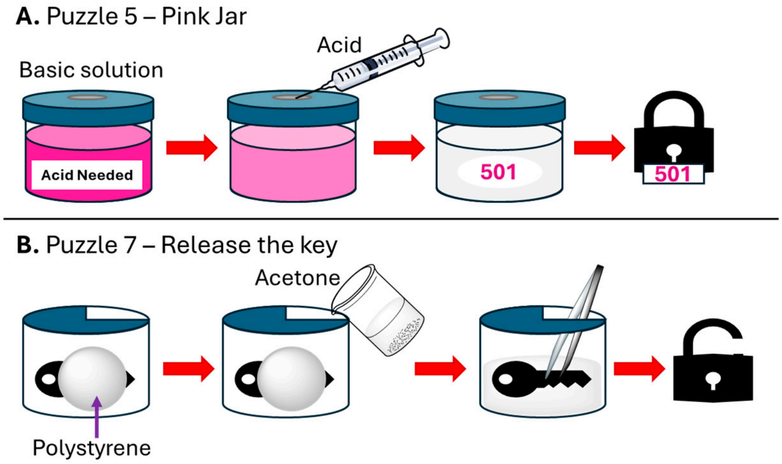


Figure 7. Select "wet" puzzle examples from the mobile escape room described by Peleg et al. (**A**). Puzzle 5—pink jar. (**B**). Puzzle 7—release the key; arrows indicate order of stepwise interaction with puzzles [61].

The above examples provide insight into the plethora of ways in which immersive escape rooms can be utilized in chemistry classrooms to increase student learning. These rooms can be leveraged to not only increase comprehension and enjoyment of course content but to develop key laboratory skills through active experimentation [49,50,56,57,60]. Rather than following a prescriptive procedure, developing laboratory skills through puzzle solution can be used to mimic real-world research practices in which the outcomes of experimentation are unknown, and data must be collected to confirm research postulations [57]. In the examples above, we can see two common themes emerging in the design of immersive escape rooms: puzzle solution that requires data collection to determine a lock combination [49,56,57] and more traditional laboratory experimentation paired with "classical" puzzle activities [37] to unlock new experiences [48,60]. Both methods are valid and have been shown to increase student learning and motivation, although, as mentioned by Vergne et al., it is important to balance traditional escape room puzzles (riddles, codes, "search for" tasks) with puzzle solutions related to course learning objectives [56].

The versatility of immersive escape rooms is similarly reflected in the varying complexities of room set-up and total activity time. This flexibility allows educators to simplify escape room immersion or complexity to fit their instructional needs. For example, many long-format immersive escape rooms can be truncated by using fewer puzzles. We can likewise take inspiration from these total escape rooms to develop smaller puzzles that can be implemented in more classical classroom formats. Regardless of the complexity, or commitment to immersion, these escape rooms garner positive student feedback and contribute to student learning. Post-activity assessments indicate students feel a sense of improved self-efficacy and research confidence [57,62], express improved critical thinking skills, and have increased interest in chemistry as a whole [48,50]. Moreover, administrators of these escape rooms note the activities encouraged teamwork, analysis capabilities, critical discussion of results, and problem solving [49]. Additional examples of interactive chemistry escape rooms are provided in Appendix A, Table A1.

2.2. Paper-Based Puzzles

A widely used derivative of escape rooms are paper-based puzzles. In contrast to immersive escape rooms, this educational tool can be used to promote critical thinking and team building with less labor for activity set-up, instruction, and take-down on the part of the instructor. As in the name, these escape rooms rely primarily on logic-based puzzles and activities rather than employing "wet" lab techniques. This allows for ease of implementation into more classical, high-enrolment, lecture-focused classroom set-ups.

Participants: 2–8 per puzzle set.
Time: 20–60 min.
Room Requirements: Desks, tables.
Set-Up Time: 5–20 min.
Cost: $.
Recommended Implementation: lectures, tutorials, workshops.
Subjects: general, medicinal, green, organic, polymers (see Appendix A).

Perhaps one of the better-known examples of escape room puzzle activities developed for teaching undergraduate chemistry, "Escape Classroom: The Leblanc Process", created by Dietrich, was used with high school and undergraduate students [63]. Groups of 5–7 students were given 1 h to complete three "enigma sheets" which require use of the periodic table, balancing chemical equations, and determining a missing synthetic step. The puzzles are centered around the Leblanc process and walk students through the scientific method as used by Nicolas Leblanc [64]. Enigma Sheet 2, for example, requires students to balance the formula for the formation of sodium carbonate and calcium sulfide (Figure 8A). Enigma Sheet 3 requires students to choose the synthetic tools required for each step of the Leblanc process where each reaction tool is assigned a corresponding letter to be utilized with an alphabet lock (Figure 8B). While introducing simplistic learning objectives, this activity highlights the ease at which chemistry content can be adapted to an escape room format. All of the necessary equipment to administer this activity can be printed and easily purchased, which minimizes cost and labor on the instructor's behalf. Similarly, this activity is easily modifiable and could be used to highlight various famous chemical processes or historical figures to emphasize the applications of chemistry to students. After performing the activity, participants agreed that this tool promoted team building, increased motivation, and improved students' communication skills.

Ang et al. describe a physical and digital escape room for teaching chemical bonding in a first-year general chemistry course [65]. The activity was originally designed to be implemented in an active learning space (tables, movement around the room); however, it was translated to be an online escape room due to the COVID-19 pandemic. The original activity featured five puzzles to be solved by groups of eight students. These interconnected games were designed to deepen students' understanding of chemical bonding and took on average 20–25 min for groups to complete and reset the puzzles. Within the groups of eight, students are further divided into pairs, and each pair is assigned one of the first four puzzles in the series to solve. Each of the four puzzles provides a number to be used on a combination lock, revealing the final puzzle. Each student pair is provided with a superhero avatar alongside the storyline for the escape room containing a cipher clue. The puzzles described are mainly paper-based for implementation in a decorated room. These were translated into an online format using Google Forms. The paper-based puzzles are described herein. Puzzle 1 challenges students to apply their understanding of molecular dipoles (Figure 9).

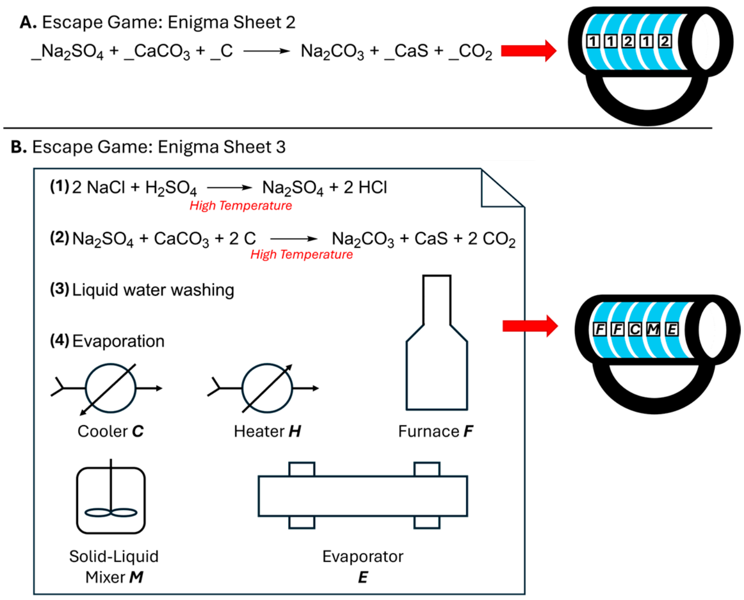


Figure 8. Example enigma sheets from "Escape Classroom: The Leblanc Process": (**A**). balancing the reaction for the formation of black ash (sodium carbonate and calcium sulfide); (**B**). reaction conditions puzzle; arrows indicate lock code determined from puzzle solution [63].

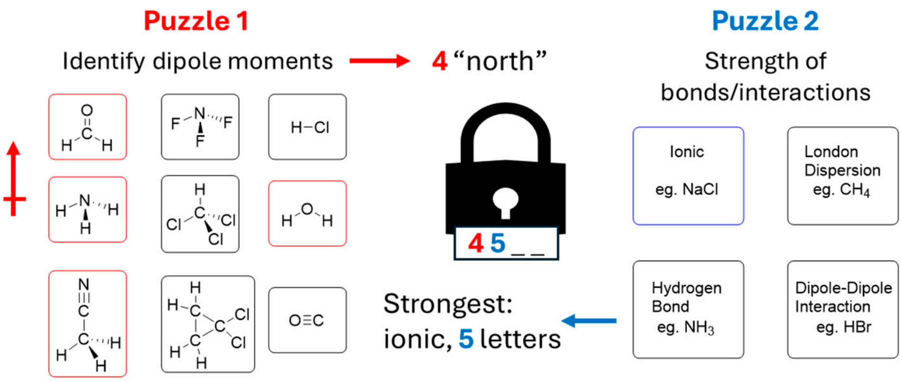


Figure 9. Puzzles 1 (molecular dipole) and 2 (bonding interactions) developed for the superhero-themed escape room by Ang et al [65].

Here, students are provided with nine chemical structures alongside a "North Pole" diorama and must determine the direction of molecule dipole. The diorama provides students with directions of a pole (in this case, north) and students are to determine how many of their nine structures have a molecular dipole in that direction. Once students determine that four structures point in the northern direction, they have solved the puzzle. Puzzle 2 is focused on determining the strength of different bonding interactions (ionic, London dispersion, hydrogen bonding, and dipole–dipole interactions). Students are provided with small packages labeled with each of the bonding interactions. Sealed inside of the packages are magnets of varying strength. Students can use the packages to lift paperclips; the number of paperclips the package can hold is related to the strength of the interaction. When the strongest bonding interaction is determined, the number of letters used to spell the name of the interaction corresponds to the combination number (e.g., ionic = 5). Other puzzle themes include relative bond strengths of metallic, covalent, and ionic bonds (puzzle 3) and terminology relevant to chemical bonding (puzzle 4). The final puzzle, completed collaboratively, asks students to determine the presence and relative strength of hydrogen bonds. Because each student pair only interacts with one puzzle, authors suggest providing students with copies of the other puzzles following completion of the experience.

Each puzzle makes use of boxes with supplies including magnets, safety pins, a black light, and a crossword puzzle, amongst others. The total cost reported for this escape room is ~USD 250. While the authors drive home the importance of the immersive atmosphere (decorations), the scene is not required to solve any of the puzzles described and therefore could be readily adapted to more lecture-hall-style learning spaces. The ease of this implementation is reflected in the transfer of the escape room puzzles to an online format.

Doughty describes the development and implementation of "Project: Lockbox", an escape activity for teaching general chemistry content which was later expanded to include concepts such as equilibrium, gas law, thermodynamics calculations, point groups, and reaction types [66]. This activity was designed with the intention of offering students, and educators, access to the teaching and learning benefits of escape-style puzzles while minimizing the workload associated with tailoring and implementing these initiatives. The experience was run during the discussion sections of a first-year general chemistry course; the classroom was divided into six teams of 2–3 students each. Each member of a team was given the same worksheet, consisting of four questions, and students were instructed to work on problems independently but come to an agreement on a problem prior to moving on to the next one. Teams had distinct worksheets which covered one of the above-mentioned topics in a given discussion section and were given 40 min to complete the activity. Following the successful solution of all four questions on a given worksheet, a team would then use these answers to determine the combination required to open their respective padlock on the lockbox (Figure 10). Worksheets were labeled A–F and corresponded to labeled locks on the lockbox which was placed at the center of the classroom. As such, the lockbox could only be opened once all six teams had successfully completed their worksheets, unveiling prizes inside the box.

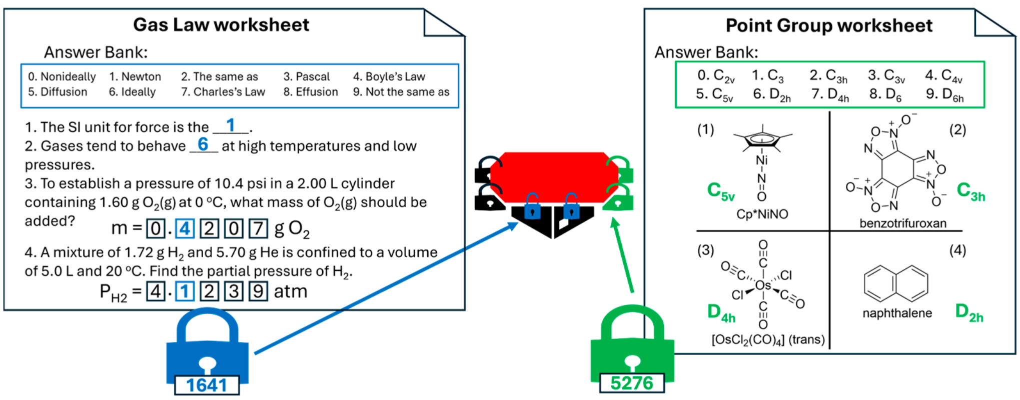
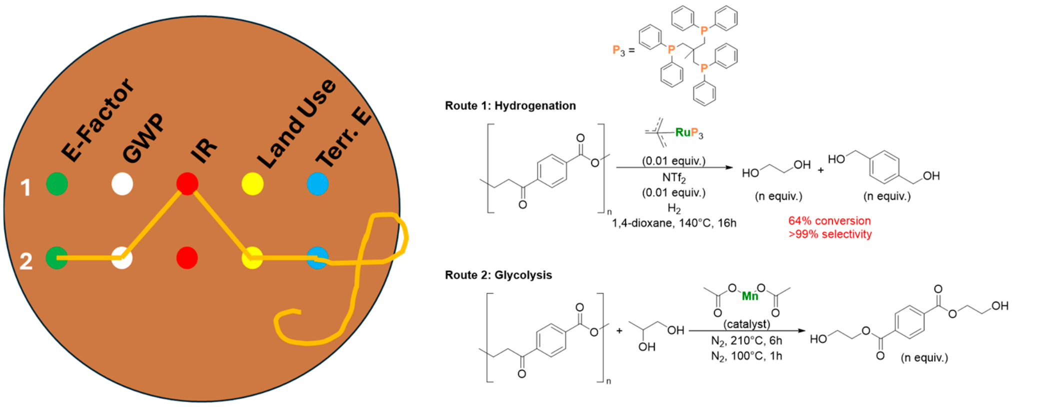
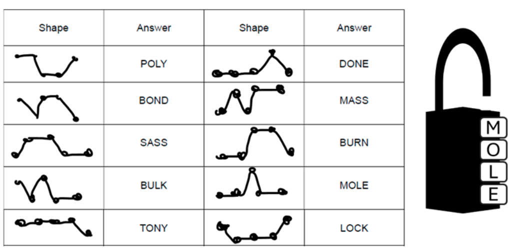


Figure 10. Selected puzzles from "Project: LockBox". The gas law worksheet (**left**) and point group worksheet (**right**) [66].

The worksheets consisted of both qualitative and quantitative problems pertinent to a given review topic. When answering qualitative questions, worksheets included either a numbered answer bank or multiple choice. As such, the correct answer to these questions corresponded to one digit on the physical lock. The point group worksheet employed this technique and presented students with structures which, when associated with the correct point group, provided a padlock digit (Figure 10 (right)). To answer quantitative questions, students were provided with a "hangman-style" answer guide indicating which digit corresponded to a padlock digit upon its solution. The gas law worksheet utilized this method of puzzle solution and primarily featured questions about partial pressure determination (Figure 10 (left)). All supplies needed to construct the lockbox can be purchased online (lockbox and padlocks), totaling ~USD 70, and this box can be repurposed many times for use across multiple classrooms or with different worksheets. While student feedback reported high levels of enjoyment and greater mastery of the material reviewed, often there was significant pressure placed on the last team to finish. To mitigate this, and prevent high-stress situations, it is recommended that students who finish their worksheets earlier are given another worksheet to complete during activity time, or that these students be distributed amongst the slower teams to convey their understanding of the material in helping the final teams succeed.

Recent publication by Clapson et al. describes a paper-based escape room developed for introducing concepts of sustainable development and green chemistry to early-career chemistry professionals at the 2024 Canadian Chemistry Conference and Exhibition [67]. Participants took approximately 20 min to complete the activity, requiring minimal hints from facilitators. The puzzles explore the synthesis, and later depolymerization, of a series of bio-derived polymers as sustainable plastic alternatives. Puzzle 1 features a series of riddles to which participants must match the corresponding bio-based starting material (corn, petroleum, sugar cane, crab (chitin)). Each material has a corresponding number, leading participants to open the correct paper file and look under a table to find additional materials for puzzle 2. Puzzle 2 asks participants to answer a series of questions related to green chemistry metrics comparing petroleum/fossil fuel, hybrid, and biological feedstock-based polymers; each polymer chosen corresponds to a combination number. Finally, puzzle 3 compares the life cycle analysis of two poly(ethylene terephthalate) depolymerization catalysts. Participants are provided with a corkboard labeled with different green metrics, yarn, and a puzzle key. Using the life cycle analysis, participants compare the green metrics for each system, selecting which reaction is greener to provide a final design in the yarn (Figure 11).





Route	PM Form.	FRS	F. ecotox.	F Eutrop.	GWP	HNC Tox.	IR	LU	M. Ecotox.	M. Eutr.	OF, HH	Terr. A.	Terr. E.	WC
1	0.0081	2.4761	0.2026	0.0016	5.7834	2.8348	0.2129	0.1066	0.2623	0.0003	0.0119	0.0177	5.0171	0.1705
2	0.0057	1.7969	0.173	0.0016	4.3357	2.5899	0.441	0.0658	0.2243	0.0001	0.0083	0.0112	4.3355	0.3394

Endpoint Category Abbreviations

PM Form. = Particle matter formation (kg PM 2,5 equiv.)	FRS = Fossil resource scarcity (kg oil equiv.)
F. ecotox. = Freshwater ecotoxicity (kg 1,4-DCB)	F. Eutroph. = Freshwater eutrophication (kg P equiv.)
GWP = Global warming potential (kg CO_2 equiv.)	HNC Tox. = Human non-carcinogenic toxicity (kg 1,4-DCB)
IR = Ionizing radiation (kBq Co-60 equiv.)	LU = Land use (m^2a crop equiv.)
M. Ecotox. = Marine ecotoxicity (kg 1,4-DCB)	M. Eutroph. = Marine eutrophication (kg 1,4-DCB)
OF,HH = Ozone formation, human health (kg Nox equiv.)	Terr. A. = Terrestrial acidification (kg SO_2 equiv.)
Terr. E. = Terrestrial ecotoxicity (kg 1,4-DCM)	WC = Water consumption (m^3)

Figure 11. Life cycle analysis puzzle comparing two synthetic routes for the depolymerization of poly(ethylene terephthalate). GWP = global warming potential (kg CO_2 equiv.), IR = ionizing radiation (kBq Co-60 equiv.), LU = land use (m^2a crop equiv.), Terr. E. = terrestrial ecotoxicity (kg 1,4-DCM) [67].

Overall, paper-based escape room activities represent an easily implemented gamified learning tool for variable class sizes. The ease of development and implementation is clear, requiring little room set-up or space to complete the activities. Similarly, the length of time to complete the activities can be largely reduced compared to immersive escape rooms, as no active experimentation is required, and numerous groups can solve the puzzles in tandem. However, many current examples of paper-based puzzles do not engage students in high levels of learning (see Bloom's Taxonomy of Learning), focusing rather on the recall of course material to describe, compare, or explain puzzle concepts [42,44,47]. The careful design of puzzle content and questions can tailor learning to better engage students in the analysis and expansion of course knowledge, allowing students to defend, integrate, and critique content—all skills associated with higher learning [1]. Methods to design puzzle materials are further explored in Section 3. While not offering the same immersive atmosphere as the full escape rooms described previously, paper-based puzzles still result in positive impacts on student learning, increasing engagement, teamwork, and communication by offering a low-cost entry point for educators to access a new and enriching student experience.

2.3. Battle Boxes and Condensed Escape Activities

While fully immersive escape rooms facilitate deep learning and understanding of concepts, providing hands-on experience with chemistry content, they require significant labor and expenses by the instructor to prepare and facilitate [42,44,47,68]. On the other hand, paper-based escape rooms are more easily accessible to educators, can accommodate larger classes of students, and can similarly increase student engagement; however, they lack tactile elements which further promote deeper learning. Battle Boxes and condensed escape activities offer a middle ground, including tactile experience while requiring less set-up by facilitators. These escape games employ many of the same tactile elements as an immersive escape room, as well as paper-based logic puzzles, but are designed to be mobile to minimize set-up and take-down. Many of the previously highlighted escape rooms do not include adaptations to improve mobility and ease of implementation in large classrooms. As such, the subsequent development of explicitly mobile, tactile, cost-effective, escape rooms serves to expand on this need, allowing for wider classroom applications. Battle Boxes and condensed escape activities are comparatively new to the field of educational escape rooms. This section explores the few examples available, highlighting a new avenue to educational escape room development.

Participants: 2–4 per puzzle set.
Time: 20–60 min.
Room Requirements: tables.
Set-Up Time: 5–20 min.
Cost: $$.
Recommended Implementation: laboratories, tutorials, workshops, outreach events.
Subjects: general, organic, polymers (see Appendix A).

The term Battle Box is used to describe a mobile puzzle unit which applies concepts of competition-based learning [69]. A Battle Box is a puzzle box, the size of a small shelving unit, which contains four escape room puzzles per side [69]. Each side of the Battle Box contains the same puzzles, often in the same order, allowing groups of students to compete with one another in the completion of the puzzles within a specific time frame. The first puzzle is located in an open compartment at the top left-hand side of the Battle Box. Each puzzle compartment contains all the information (clues and storyline) and materials to solve the puzzle. The solution to puzzle 1 opens a combination lock allowing students access to puzzle 2 (top right-hand side of the Battle Box unit). Puzzle solution continues clockwise around the Battle Box with the final combination (puzzle 4) opening a small, locked box located on the top of the Battle Box. The small, locked box typically contains prizes such as a congratulatory message, bonus marks, or candy.

Similarly, condensed escape activities (CEAs), often contained within small boxes or Tupperware containers, consist of 3–4 puzzles with all supplies for each puzzle provided to the student immediately. Battle Boxes and CEAs often contain scaffolded puzzles developed under a common theme. Here, puzzles must be solved in a specific order, in which learnings achieved from earlier puzzle solution(s) may be leveraged in later puzzles. This scaffolded learning, featuring a background storyline, is reflective of many immersive escape rooms [42,44]. Battle Boxes and CEAs may not always include puzzles featuring "wet" experimentation, requiring laboratory space and MSDS considerations, however all puzzles considered in this category do feature tactile components, mock experimental results, and visuals. For example, the "ChemEscape General Chemistry" Battle Box (Figure 12) developed by Clapson et al. features puzzles that can be implemented outside of a laboratory setting as they utilize household materials [55]. In one puzzle, students prepare a working water-based electrochemical cell with Zn and Cu electrodes (active experimentation), which is utilized to light up an LED panel, light by light, revealing the lock combination. Alternatively, in a second puzzle, students analyze mock TLC plates by visualizing them with a UV flashlight (mock experiment). Students are provided with a riddle requiring them to select the correct combination numbers from the TLC plates using the relative retention factor (R_f) values of the chemical unknowns. The authors proposed altering the TLC plate puzzle to be an active experiment by allowing students to prepare and run their own TLC plates using chemical unknowns. However, for safety reasons, this limits applications of the puzzle to laboratory settings.

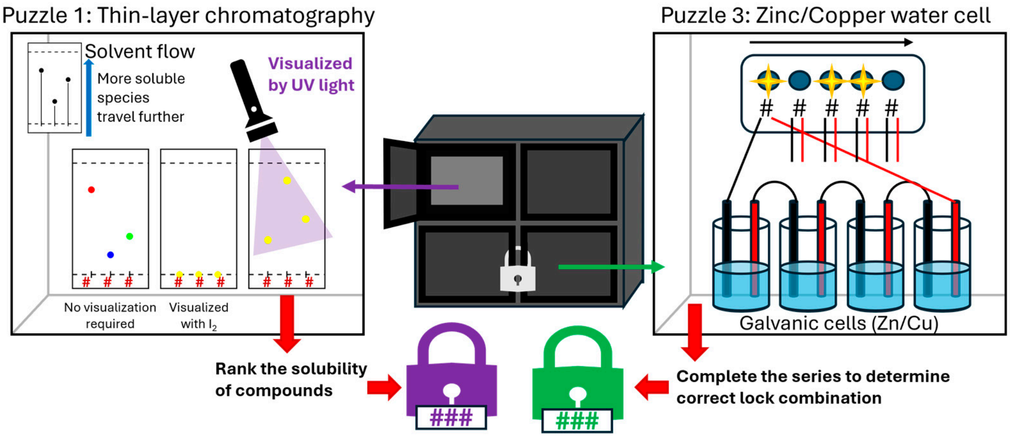


Figure 12. "ChemEscape Battle Box" featuring general chemistry puzzles: puzzle 2: zinc/copper water cell (**right**) and puzzle 4: thin-layer chromatography (**left**) [55].

The use of the Battle Box framework has since been expanded upon by Clapson et al. to include puzzles focused on polymer chemistry in "ChemEscape: Polymer Chemistry"; in [70], it has been applied as on outreach tool as well as a learning activity in a second-year materials chemistry course, redox and thermodynamics (general chemistry) in "ChemEscape: Redox and Thermodynamics"; in [55], it was developed for applications in a first-year general chemistry tutorial and organic chemistry in "ChemEscape: Organic Synthesis"; and in [71], common introductory organic reactions (substitution and elimination) are explored alongside IR and NMR spectroscopy. Examples of the puzzles' contents are described below.

"ChemEscape: Polymer Chemistry" (Figure 13), applied in a second-year materials chemistry for engineers course, focused on developing students understanding of polymer structure–property relationships including tacticity, elasticity, and hydrophobicity [70]. Puzzle 1: tacticity, provided students with a series of polymer fragments as well as a visual clue displaying the functional group pattern for isotactic, syndiotactic, and atactic polymers. The fragments can be combined using Velcro attachments to form the three different polymer tacticity patterns, hung from two hooks on the side of the Battle Box, and their strength was tested using sandbag weights. The polymer tacticity patterns are then rated strongest to weakest, revealing the lock combination. Puzzle 3: hydrophobicity, in comparison, requires students to perform a small "wet" experiment. Here, students are provided with three polymer samples and their corresponding chemical structures. The chemical structures are color-coded to indicate the polar and non-polar regions of the polymer. Students must place a droplet of water onto each polymer sample and compare the contact angle. Polymer samples with more hydrophobic functional groups result in a large contact angle. Using this observation, students must rank the polymers in order of hydrophobicity to reveal the combination.

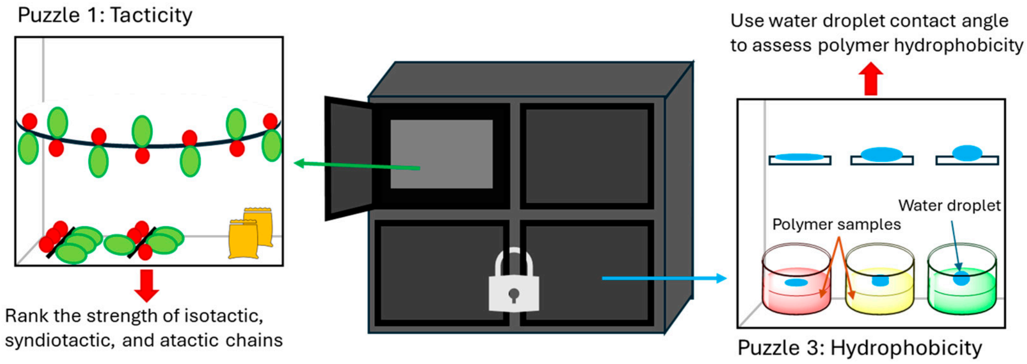


Figure 13. "ChemEscape: Polymers" Battle Box featuring puzzle 1: tacticity (**left**) and puzzle 3: hydrophobicity (**right**) [70].

Unique to "ChemEscape: Polymers", puzzles were scaffolded, requiring an understanding of the first three puzzles to complete puzzle 4: designing a polymer for applications as a wetsuit. The puzzle activity was accompanied by a worksheet, providing students with additional information related to course content as well to record their puzzle solutions and reasoning. The worksheet was similarly adapted for public outreach, providing participants with less chemistry jargon and more real-world comparisons. The polymer puzzles were also adapted as a CEA, in which students were provided with a cardboard puzzle backdrop and most of the required materials to solve the puzzles. Here, students needed to identify which components belong to which puzzle, guided by the workbook, to unlock boxes at the front of the room containing components to solve the next puzzle. Introduction of the CEA version of the activity improved mobility, lowered time for puzzle set-up, and eliminated the need for several lock combinations (all student groups' puzzles resulted in the same combination used to open the communal lock boxes).

In both iterations, students in groups of 2–4 worked to solve the four distinct polymer puzzles. Primary school students (outreach), grades 4–9, were given 30 min and a simplified guiding workbook to complete the puzzles. Post-secondary students were given 50 min to complete the activity, with a workbook tailored to course learning objectives. This included providing additional background information and tactile elements used to make observations to polymer properties, fewer explicit hints or guiding questions, and less obvious differences in polymer chemical structure. With primary students, facilitators noted student success in identifying the puzzle learning objectives and instructors indicated this format, while challenging, allowed students to apply their scientific knowledge towards solving the puzzles. Facilitators noted similar positive experiences with post-secondary students, including high student engagement and the successful solution of puzzles which required both previously covered course content and those which introduced new material.

A series of redox and thermodynamics-themed puzzles, applied in the Battle Box framework, were implemented in a first-year general chemistry class for engineers [55]. Students completed the activity during their tutorial section (50 students on average) in groups of 2–4. Student groups were given 30 min to complete two of the four puzzles, one puzzle on content already covered during the lecture (A) and one puzzle on new course content (B). The puzzles covered learning objectives related to chemical equilibrium (A), Gibbs free energy (B), metal redox properties (B), and electrochemistry and spontaneity (A). For example, puzzle 1: equilibrium constants, requires students to perform a mini "wet" experiment (Figure 14). Students are provided with a cup of hot and cold water and three sealed samples of $[CoCl_4]^{2-}$ in water with which to experiment. Through their experimentation, students must determine in which direction the reaction is exothermic (uniquely, the reaction in endergonic in the forward direction), the external stimuli that causes an increase in the equilibrium constant, and the corresponding reaction coordinate diagram. Students were quick to recognize that the sample tubes must be tested in the hot and cold water as well as shaken; however, they struggled to relate the color changes observed upon heating and cooling to the directionality of the equilibrium.

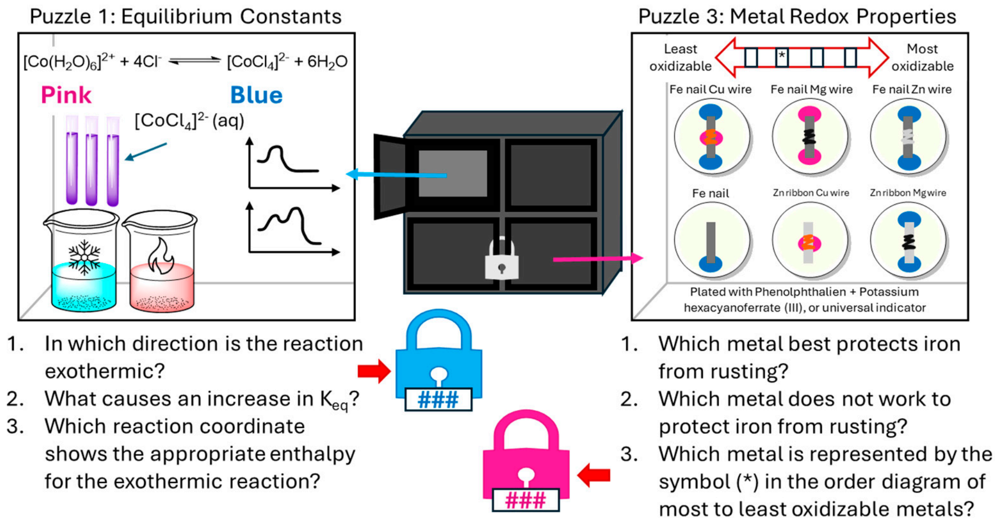


Figure 14. "ChemEscape: Redox and Thermodynamics". Puzzle 1: equilibrium constants (**left**) and puzzle 3: metal redox properties (**right**) [55].

Puzzle 3: metal redox properties, alternatively, has student examine a series of mock reaction set-ups (Figure 14). Six samples of metal combinations in agar are visualized with phenolphthalein, universal indicator, or potassium ferricyanide. Students must determine that (1) $K_3Fe(CN)_6$ turns blue in the presence of Fe(II), indicating when iron has been oxidized, (2) phenolphthalein is pink in the presence of a base and will indicate the location where oxygen, in the presence of water, is reduced to form hydroxide anions, (3) universal indicator can be used in place of phenolphthalein and will turn blue in the presence of hydroxide anions, and (4) the location where hydroxide ions are produced (center of the wrapped metal or tip of the metal wire) indicates which metal is being reduced. Color at the wrapped metal wire indicates the nail/ribbon metal is being oxidized, while color at the tips of the nail/ribbon suggests the wrapped metal wire is oxidized. Combining this information, students are able to rank the metals in order of most to least oxidizable as well as determine which metal may be applied to protect iron from rusting.

In this iteration of puzzles, clues were presented in the form of exam-style questions, closely relating the puzzle contents to course learning objectives. Compared to previous "ChemEscape" puzzles, facilitators noted that students better understood the goals of each puzzle, likely a result of the more direct line of questioning (exam questions vs. riddles). Despite a better understanding of what needed to be provided to solve each puzzle, students were confused by distractor items, such as the color of the universal indicator matching the color of $K_3Fe(CN)_6$, classical to entertainment-focused escape rooms [42,44,47,68]. Students, however, enjoyed the experience, displaying high degrees of engagement, teamwork, and critical thinking.

A unique, single-puzzle CEA is presented by Strippel, Schröder, and Sommer [72]. A locked clear box is equipped with a voltmeter, an electrical motor tethered to a door on the box, and two beakers (Figure 15). The electrical equipment is connected via an LCD to an external computer program. The program controls the general motor mechanism. The puzzle stipulates that a voltage must be generated to open the box, requiring students to build a working galvanic cell. The difficulty of the puzzle is regulated by the number of elements in the galvanic cell that are already set up. For example, both beakers are already in the box, meaning students must determine the appropriate electrodes and electrolyte solution. The puzzle can likewise be modified so that specific voltages are required in order to engage the opening mechanism, challenging students to determine the appropriate metal electrode combinations. The puzzle mechanism can likewise be repurposed to teach concepts such as acid–base chemistry by exchanging the voltmeter for a pH meter and altering the programing.

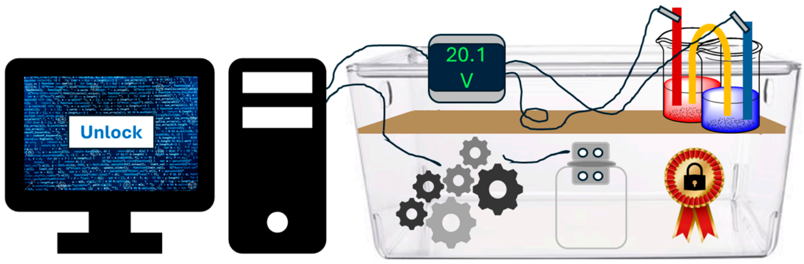


Figure 15. Galvanic cell escape box developed by Strippel, Schröder, and Sommer [72].

The Royal Society of Chemistry (RSC) has prepared a series of miniature escape room puzzles, "Escape the Classroom" [73], open to RSC members. Six topics are available: exam escape (general chemistry, primary school), perplexing puddles (microscale reactions to explore chemical equilibria), basic puzzles (general chemistry, primary school), advanced challenges (general chemistry), materials science (liquid crystals, alloys, thermochromism, polymers), and color changes (general chemistry), featuring a mixture of "wet", paper-based, and online puzzles. For example, the materials science puzzles, six total, are focused on introducing students to the interesting properties of modern materials. Puzzle 1, a memory test, introduces memory metals (stents, robotics) as well as the chemistry of nickel and its various alloys (Figure 16A–C). Students must decipher a series of clues related to a wiregram and playing card puzzle. The wiregram is made of nitinol (an alloy of nickel and titanium) that changes into a set shape when heated. When students heat the wiregram, it will reveal a number and shape corresponding to a specific playing card. On the card, written in UV-active ink, is the combination of the lock which can be revealed using UV light. Puzzles two and three explore the use of thermochromic paper and ink. In puzzle two, a code is written in black ink on a black thermochromic liquid crystal sheet. Heating the sheet above 27 °C causes a color change to red, green, or blue, revealing the code (Figure 16B). To solve puzzle three, students must heat a piece of paper. Written on the paper is the combination coated with thermochromic ink of the same color (Pilot Frixion). By heating the paper, the thermochromic ink changes color, revealing the code. Together, puzzles two and three can be used to introduce concepts of liquid crystals and their uses. Finally, puzzle four introduces students to hydrogels. Here, students reveal a code at the bottom of a glass beaker filled with hydrated aqua beads by adding water (Figure 16C). The aqua beads and water have the same refractive index, causing the code to be revealed. Together, these puzzles offer a method to capture students' interest in a topic before exploring deeper learning objectives.

Battle Boxes and condensed escape activities, relatively new to escape room activity development, provide a helpful solution to the problems associated with implementation of fully immersive escape rooms: room requirements, set-up time, take-down time, class size, etc. These escape activities are mobile and require little advanced set-up on the part of the instructor. Similarly, as the contents of the "wet" experimentation within are often household supplies, the activities can be implemented outside of laboratories. Compared with paper-based escape activities, Battle Boxes and CEAs are better able to immers students in a hands-on chemistry experience, allowing for "wet" experiments, analysis of mock experiments, and classical numerical puzzles and riddles [69]. An additional benefit to the Battle Box framework is that once the box is assembled, numerous puzzle activities can be exchanged in the box, allowing for easy storage of alternative puzzles in Tupperware containers, meaning several activity topics can be utilized throughout the year or between courses with minimal additional set-up. ChemEscape Consulting Inc. [74] currently provides educational consultation and Battle Box puzzle development, tuning puzzles for specific course objectives. More on activity design consideration and tools can be found in Section 3.

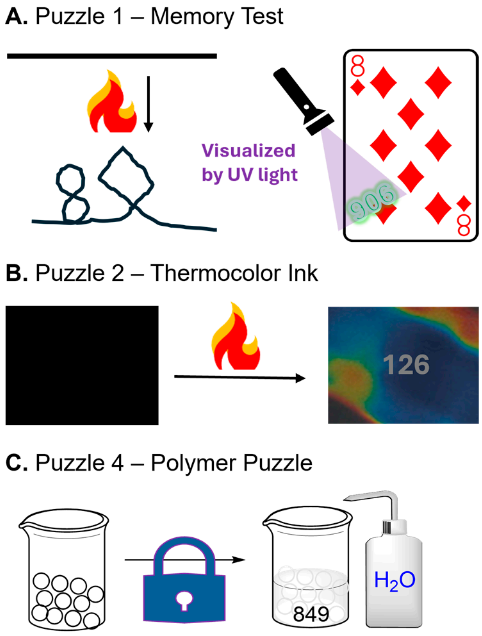


Figure 16. (**A**–**C**) Royal Society of Chemistry "Escape the Classroom" materials science puzzles [73].

2.4. Online Escape Rooms

In considering educator and student needs, both in the context of administrative hours and resources, and with the recent need for virtual teaching [19,75], online escape rooms are of interest [76]. This section encompasses escape rooms which can be fully administered and performed virtually, requiring only access to a computer or mobile device. These puzzles, while providing, arguably, the least immersive student experience, are the most easily implemented in classrooms (in person and online) and as a result have been widely studied as an accessible active learning tool.

Participants: infinite.
Time: 20–60 min.
Room Requirements: internet access.
Set-Up Time: <5 min.
Cost: free–$$$ depending on the requirement for app development.
Recommended Implementation: lectures, tutorials, online learning.
Subjects: general, organic, green (see Appendix A).

"Escape the (Remote) Classroom", designed by Vergne et al., was implemented in a class of upper-year chemistry and biochemistry students [77]. This online alternative employed easily accessible virtual tools such as Zoom and Google Forms for its creation and administration. The class of eight students met over Zoom and were divided into pairs. These pairs then worked through a Google Form consisting of four distinct puzzles which required them to enter the correct solution into the answer field before moving on to the next. The puzzles consisted of molecular weight determinations, acid–base chemistry, chromatography, and linear regression, and took students at most 5 min per puzzle to complete. Here, a chocolate factory was used as a thematic setting from which puzzle design was constructed. For example, the first station tasked students with determining the molecular weight of theobromine, a xanthine found in chocolate (Figure 17). A "gift shop" involved students completing a linear regression task where they determined the concentration of an unknown compound using a UV calibration curve. Total run times for pairs ranged from 10 to 20 min. Students reported that pairs worked together, with no issues dividing work or tasks, towards the common goal of escaping. Compared to a classical worksheet in which students would answer the same types of questions, the online escape room format provides a more engaging experience through inclusion of a storyline. Similarly, compared to a worksheet, online escape rooms provide instantaneous formative feedback on whether the question is correct.

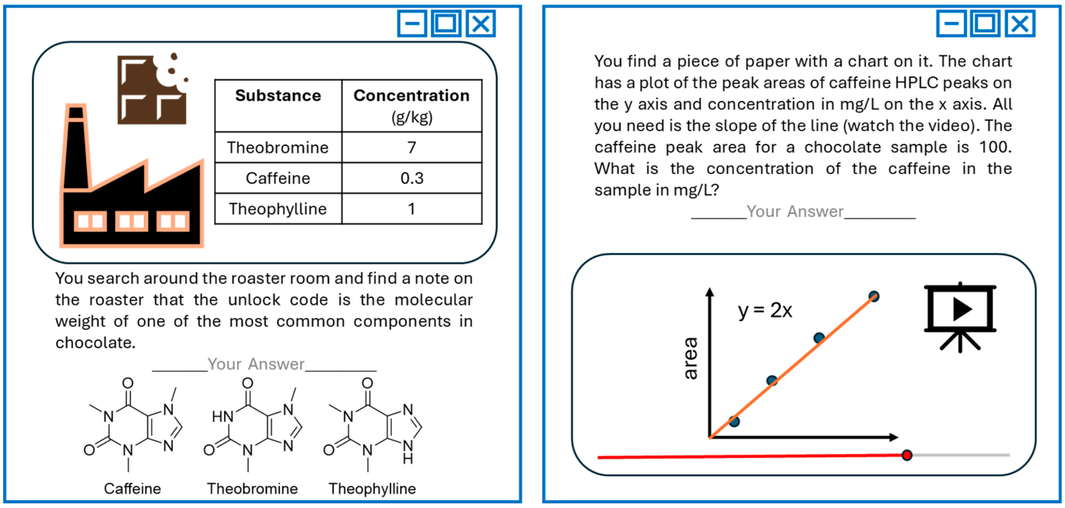


Figure 17. Select examples from "Escape the (Remote) Classroom: Chocolate Factory". Determination of molecular weight puzzle (**left**). Linear regression puzzle (**right**) [77].

"Stereoisomers, Not Stereo Enigmas", a stereoisomer-themed virtual escape room, was developed by Elford et al. for use with first-year undergraduate students to improve their understanding of stereochemistry [78]. In this, instructors developed escape rooms which used either a virtual reality (iVR) learning environment, augmented reality (AR), or a molecular model kit which students interacted with to solve the stereochemistry-based puzzles and escape. These puzzles were designed to take groups of three students 1 h to complete. The escape room featured puzzles of varying levels of difficulty which could be completed in parallel, rather than sequentially, to prevent students from becoming stuck on a more difficult puzzle early on. The four distinct puzzles, which utilize ciphers, intel image markers, molecular modeling kits, AR, and iVR, required students to differentiate between stereoisomers, assign metal oxidation states, determine metal stereochemistry, and more. Depending on the participant group, physical molecular modeling kits, AR, or iVR are incorporated to assist with identification. For example, puzzle 2 provides students with twelve intel image markers, placed throughout the room, each relating to a different metal complex. Students must extract information pertaining to the central metal atom, bound ligands, geometrical isomerism, and molecular geometry. Together, students identify the metal complexes and determine the corresponding passcodes. Following the completion of the escape room, students reported greater levels of engagement and interest in stereochemistry. Moreover, they expressed that this escape room method was a better avenue for consolidating course knowledge, a testament to the benefits of active and collaborative learning experiences.

"The Masked Scientist" virtual escape room, pioneered by Haimovich et al., was used with high school and first-year undergraduate students [79]. The authors aimed to reinforce general chemistry knowledge and concepts such as radioactive decay, stoichiometry, and common elements found in everyday items. The nine distinct puzzles were designed using the publicly available WIX site, and groups of 3–4 students were given 90 min to escape the virtual room, averaging a completion time of 31 min. Some examples, shown in Figure 18, included the "Elements Attracted to the Magnet" and "Smoke Detector" puzzles. In the first example, students use a magnet, found lying on the floor, to test four unique Nobel Prize medals. Medals containing a metal which exhibits magnetic properties (Ni, Co, Fe) will attract the magnet. The medal stands and the locks become colored upon use of the magnet, which allows the metal to be associated with the appropriate lock (Figure 18A). The lock combination corresponds to the highest energy level when determining the electronic configuration (e.g., Fe = $1s^22s^22p^63s^23p^64s^23d^6$ = 4) and the element's atomic number. In "Smoke Detector", a figure appears on the screen which shows an open detector, ^{237}Np and α symbols, and a calculator that implies that a reaction should be formulated (Figure 18B). Students successfully solve the puzzle when they determine the chemical reaction. Due to the flexibility offered by WIX, much more elaborate and thematic puzzles were able to be created in a virtual format. Additionally, through the application of experimental videos, authors were able to include experiments and procedures which would be unsafe for students to perform in an actual lab setting. For example, the storyline proceeds such that a series of lasers must be revealed before students can "enter the next room". To do this, students balance the reaction equations for the decomposition of NI_3 to N_2 and I_2, resulting in the formation of iodine vapor which visualizes the lasers.

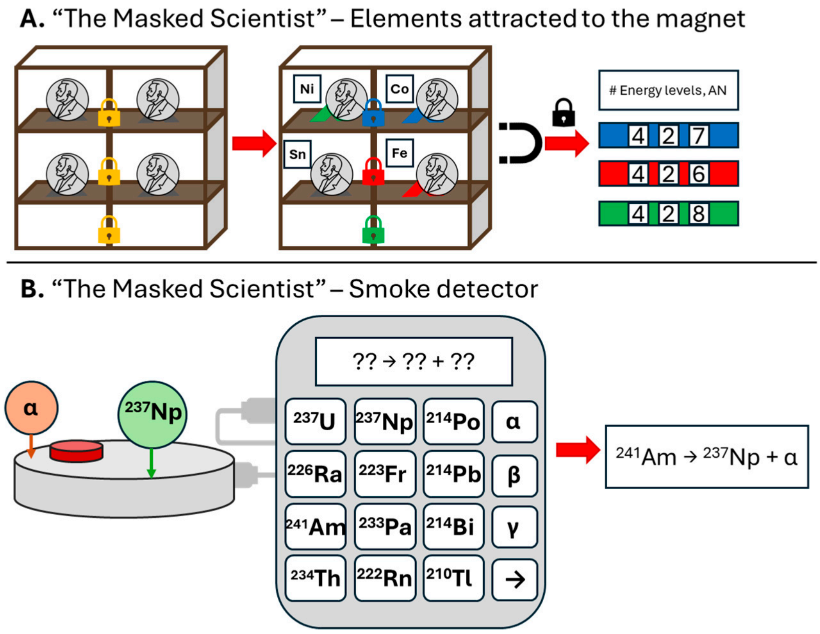


Figure 18. Select puzzle examples from "The Masked Scientist" activity. (**A**). Elements attracted to the magnet puzzle. (**B**). Smoke detector puzzle [79].

Importantly, if used unchanged (access to WIX site available upon request), this escape room requires minimal set-up labor on the instructor's behalf. Administration of these puzzles can be carried out both in a classroom setting, where students share a computer or printed puzzles, or in a fully virtual setting using video conferencing applications. Student and teacher feedback highlighted the value added by use of an immersive and tailored online environment, rather than simply a Zoom call, and demonstrates that virtual escape rooms can offer similar benefits to fully immersive experiences. However, when administered through Zoom, 75% of students indicated their experience would have been greater had the escape room been administered in person [80]. Regardless of the administration format, students noted the benefits of the activity, mentioning how the puzzles allowed them to assess their understanding, providing feedback on what content they needed to review.

Online/virtual escape rooms are a recent advancement and as such have received much attention in chemistry education literature. Their prevalence may be a function of the low-cost options available virtually (slide decks, videos, etc.), although we recognize that other options such as app development may be more costly. Online tools of this nature have the added benefit of giving students new methods for visualizing structure and bonding [81], noting that stereochemistry is a common topic in these puzzles [78,82].

Uniquely, online escape rooms offer the opportunity for students to participate in experiments which they would not otherwise be able to due to concerns of safety or lack of access to equipment [79]. However, in reports which directly compare in-person and online escape rooms, student satisfaction is generally higher for the hands-on iterations [79,80]. Due to the teamwork-intensive nature of escape rooms, it is possible that communication was impaired in activities which were administered entirely online (i.e., via Zoom). This can be remedied by having students share a computer in class, when possible, similarly easing instructor involvement in the activity. Despite this, online escape rooms still show considerable benefit to student learning.

3. Designing Escape Room Activities

Within the literature, there is no shortage of escape rooms designed for science education [42,44,46,79,83]. These designs have many considerations for educators looking to adopt theories of gamification or experiential learning with escape rooms [46,84,85]. These design considerations can be broken down into different questions that an educator can use to design their own puzzle activity. In the following section, we will break down these questions, provide examples of what has been achieved in the literature, and give a worked example utilizing these questions. These guiding questions are summarized in Table 1. Within this section, we explore some of the many considerations for designing educational escape rooms. The examples provided are meant to highlight current trends in educational escape room design, various theoretical frameworks (i.e., learning theory), and logistical decisions in designing escape rooms. To be clear, there are many ways to design gamified learning activities, and the examples provided are meant to show breadth over standardization.

Table 1. Questions to guide educators in the development of chemistry escape room activities.

Section	Questions
3.0 Logistics (i.e., *What practical considerations do I need to consider?*)	1. How many people need to participate in the activity? 2. What is the time frame (i.e., class time or event length) to complete the activity? 3. How much time do students need to settle in the space and reset or clean up the escape room? 4. What is the cost of the supplies that are not currently accessible? 5. Who resets the puzzles after they are completed?
3.1. Audience (i.e., *Who is participating?*)	1. Who is the audience (i.e., students, adults, children)? 2. Is this activity being designed for a specific subject or classroom? 3. What is the audience experience with the content knowledge and/or skills being explored in the activity? 4. Do participants need training or protective equipment to fulfill any safety requirements of the activities? 5. How can the accessibility of the activity be improved?
3.1 Purpose (i.e., *What is the goal of the activity?*)	1. What is the purpose of implementing the activity? 2. Is the purpose of the activity informed by course learning outcomes? 3. Is the purpose of the activity based on skill development, engagement, or community building instead of content knowledge? 4. How are you going to understand if participants have the experience related to the purpose of the activity? 5. To achieve the purpose, do students need to complete all, some, or none of the activity?
3.2 Location and Space (i.e., *Where is the activity being completed?*)	1. What type of room is the activity being completed in (i.e., lecture hall, classroom with tables, laboratory or outside)? 2. What is the layout of the room?
3.2 Instructor or Designer Workload (i.e., *What is the workload of the preparation?*)	1. Can the activities be related to pre-existing experiments or material in the course? 2. How much time do you have to develop the activity? 3. Do you require funding to complete the activity? 4. What supplies are already accessible to you (chemical, equipment or technology)? 5. Are the materials reusable or do they need to be replaced after each iteration?

Table 1. *Cont.*

Section	Questions
3.2 Interactivity and Tactility (i.e., *If desired how can these be added to an activity*)	1. Is interactivity and/or tactility a goal of designing the activity? 2. What elements of your activities are tactile? 3. Why does a particular element need to be tactile? 4. What types of locks are being used to design the activity? 5. How could different types of locks be used in the design of the activity? 6. What are the potential hazards in the activities?
3.3 Learning Theories and Game Elements (i.e., *What are the theoretical commitments required to design the activity?*)	1. Is the purpose of using an escape room aligned with a specific learning theory? 2. Is there a specific learning theory or taxonomy that you want the escape room to be modeled after? 3. What assumptions do you need to hold to implement this learning theory in the activity? 4. How does the design of the activity align with the assumptions of the learning theory or taxonomy you are using? 5. Is the goal of the activity to define the activity as gamified learning? 6. How is gamification defined in your activity? 7. What game elements are being incorporated into the design of your specific activity?
3.4 Adaption Based on Feedback (i.e., *How did participants and facilitators respond to the goal of the activity?*)	1. How do you plan to test the activity before it is implemented? 2. How does the feedback asked for align with the purpose of the activity? 3. How did students enjoy the activity? 4. How did students engage with the activity? 5. Where did students need the most facilitator support or feedback? 6. Did anything not work as expected that you want to change next time? 7. Are you looking to assess students learning from the activity? 8. How might the feedback for engagement look different than for content knowledge? 9. What did you learn from running the activity?

3.1. Defining Your Audience: Purpose, Knowledge, and Outcomes

The broadest considerations in the design of any gamified activity are the audience and the resources available [86–88]. In terms of audience, we consider who will be participating in the escape room and what knowledge they have or need to complete the activity. For example, some escape rooms are designed for high school [89], introductory chemistry [49], or even elementary school [90]. The intended audience of the escape room activity is often communicated in an article's title, abstract, keywords, and the design choices within the activity itself. For example, an escape activity targeting the public as an outreach tool might utilize household chemicals to introduce "wet" experimentation while an escape room targeting a first-year undergraduate class may host the experience in a laboratory with more hazardous materials. An important consideration in designing an escape room experience is the participants' safety knowledge and, if required, how safety considerations will be communicated within the activity. For example, if students are completing this as part of a laboratory component of the course, safety might be communicated during the introduction of the activity as is the case when entering a laboratory. Alternatively, safety training might be provided in an activity outside of the laboratory environment such as helping participants understand safety signage or discussing the rules. Prior knowledge can also include participants' familiarity with a skill or piece of knowledge. Their knowledge informs the purpose of the activity, the design of clues, and the role of the facilitator.

The goal or purpose of the educational escape room highlights what educators want students to take away from the activity. There is a variety of outcomes for these activities such as increasing engagement and learning specific content knowledge or disciplinary skills. Escape rooms focusing on engagement might be interested in knowing if their students enjoyed the activity, their feedback, and what they took away [63,66,79,91,92]. In other contexts, there is a desire to have the escape room teach students a specific concept or skill [56,70,78]. In this case, content can be tailored to achieve course learning outcomes [55,70]. Learning outcomes can also extend beyond chemistry content, to build 21st-century skills or influence the affective domain such as engagement, communication, and self-regulation [50,87,93–95]. Regardless of the desired goals of the activity, having a clear purpose for the escape room is important for successful design, as it informs the feedback you solicit and the design components included such as tactility, learning theories, and game elements [42,44,76].

Connecting the purpose of the escape room activity with specific learning objectives requires the educator to define the knowledge essential to complete the puzzles, both previous knowledge and information to be provided within the activity. The knowledge requirements shift depending on whether the activity will be used to introduce, reinforce, or assess a concept [96,97]. These considerations are incorporated into the puzzle design by carefully tailoring the hints/clues provided, background information, and general facilitation. An escape room introducing or reinforcing a concept provides more background information in the opening story or within the hints and clues. For example, Clapson et al. in the implementation of "ChemEscape: Polymer Puzzles" used a workbook to provide the storyline and introductory information to two separate audiences, the public (grade 4+) and a second-year introductory materials chemistry course, allowing the content to be readily tailored without changing the puzzle components [70]. The workbook provided context to the four puzzles for each learning level as well as guided students' progression through each of the puzzles. Another approach is incorporating exam-style questions to solve alongside clues on how to open the lock. "Project Lockbox", for example, pairs qualitative questions (with numbered or multiple-choice options) and quantitative questions (numerical answers with a box indicating which number is to be utilized in opening a lock) in a worksheet that guides students in puzzle solution [66]. As an alternative to a worksheet approach, the opening story of an escape room activity can be verbally communicated to participants and the individual puzzles can be presented on different sheets of paper. Additionally, worksheets can communicate safety hazards, supplies, and provide a spot to write the lock combination as seen in "Spectroscopy Unlocked" [60]. Worksheets provide a versatile option in gameplay, shaping the game elements and the difficulty of puzzles in accordance with the audience.

For activities that have engagement and other affective outcomes, considering the participants' familiarity with the topic can shape the activity design. For example, escape room activities targeted at engaging wide audiences to improve enjoyment of chemistry may provide little background information tailored to specific learning objectives but rather focus on storytelling and room exploration. The mobile escape room developed by Peleg et al., for example, includes several puzzles that require little chemistry knowledge to complete but have exciting reveals (color changes, physical changes) for combinations and keys [61]. "Escape ClassRoom CSI 1.0" similarly incorporates several entertainment-focused puzzles such as hidden doors, puzzles requiring participants to search the room for materials, and riddles [48]. As highlighted by Verge et al. and others, finding a balance when employing classical escape room puzzles (riddles, hidden clues, ciphers, etc.) is imperative to the development of an educational escape room, ensuring that course learning objectives are being effectively highlighted through the activity [50,56,86,87,94,95]. For a more comprehensive review on activity design elements for effective hands-on and active learning, we turn readers the following references [86,98,99].

3.2. Escape Room Design and Educator Resources

To support the inclusion of game elements in the design of activities, having a clear definition of gamification and learning game design skills is an asset. Several articles highlight the importance of game design, working to align learning objectives with storylines and specific game tasks [100,101]. A clear alignment between the task performed and their relationship to coursework can help educators to reduce ludonarrative dissonance, improving student understanding during gameplay. There are many excellent resources to support educators in learning about game design [102–106], incorporating interactive game components and moving beyond quiz-style formats where applicable.

A major consideration in the design and implementation of an escape room activity is the available resources for the educator. The time to run the activity, course size, supplies, and funding shape the resources required [42,44]. As seen within the literature, escape rooms can range from fully immersive rooms, condensed escape activities, individual puzzles, and online games to paper-based puzzles. Each, as previously discussed, has pros and cons associated with assembly and implementation. When choosing the best escape room approach for your content, it is recommended not only to consider the time and space available for the activity but also the reusability of the activity itself, if components of the activity can be repurposed, and the available funding for the activity both within and outside of the institution. Below, we outline some of the considerations and examples for each style of escape room experience.

Immersive rooms are often limited based on supply costs, number of participating students, time to complete the activity, and room layout [107]. Part of the cost can include the supplies for having multiple puzzles contained within the room [49,108], specific laboratory equipment [56,57], and decorations for the room to develop the story and game elements within the space. Some immersive escape rooms can contain anywhere from 2 to 18 puzzles; the number of puzzles employed is dictated by the complexity of the puzzles themselves as well as the time allotted for the activity. For example, puzzles by Vergne et al. required specific laboratory instrumentation such as gas chromatography mass spectrometry (GCMS), limiting both the space in which the escape room can be performed (requiring a lab equipped with a GCMS), number of students, and time to be completed (as each group is required to collect their own GCMS spectrum) [56]. The incorporation of laboratory spaces, equipment, and chemicals additionally adds safety considerations that educators and students completing the escape room must consider. In many cases, hazards can be readily communicated to students during the introduction of the experience, through safety signage, and facilitator feedback. The safety requirements can similarly differ depending on if the activity is being completed in a laboratory space, as part of class/course, or as outreach [60].

In most cases, immersive escape rooms are practical for use with small course sizes, outside of lecture hours, in a teaching space such as those used for tutorials or laboratories, as these allow for group work between students and movement throughout the room. The number of students that can be accommodated is determined based on the time to complete the escape room, available instruction time, and the amount of equipment. Additionally, escape rooms can be completed over multiple sessions, allowing for longer puzzles [57]. To help determine the time required for the activity, individuals may find it beneficial to test run the activity with other educators [49,108] or teaching assistants [60,66]. For example, Doughty, in the design of "Lockbox", had teaching assistants complete the activity and gave students double the time it took the TAs to complete the activity plus an additional 10–15 min of buffer time to become acquainted with the components [66]. Part of the focus of an immersive escape room is prioritizing the inclusion of game elements (gamification) and interactivity, often lengthening the preparation time for educators and limiting the number of participants.

Condensed escape activities are a helpful tool incorporating both the tactility and experimentation of an immersive escape room with the mobility of paper-based experiences. An interesting box design described by Veldkamp et al. features a hexagonal-shaped box in which six puzzles are housed [41]. Three puzzles are initially exposed, with solution of the three puzzles unlocking the second three (dropping a small panel). Solving puzzles 4–6 provides a combination allowing for a "bomb", held inside the box, to be diffused. The boxes are enriched by including covers and drawers which can contain clues and puzzle materials, mimicking the "hidden element" component common to immersive rooms. Similarly, Battle Box, the hexagonal escape box can be readily adapted to new puzzle content and assembled in advance, leading to fast and easy handling. Mobile escape rooms such as that described by Peleg et al. provide a similar benefit, providing educators with pre-developed puzzles for implementation into laboratories [61]. The reusability of these activities is a particular benefit as it lowers the cost of implementing subsequent escape activities. Educators choosing to utilize this escape room method should prepare puzzle materials for high-traffic environments—the puzzles must be built to last. This means laminating paper components, securing structural components to the box, and having spare pieces where possible. In comparison to an immersive experience, condensed escape activities have a lower barrier to implementation, often requiring less time to complete, to develop, and to facilitate making them a useful active learning technique that can be readily implemented over several iterations. Similarly, the current CEAs described have thorough supporting information files, allowing educators at other institutions to readily build and tailor the activities described. Blueprints, printable files, and instructions outlining the set-up, solution, and recommended facilitator interventions for these activities are integral in the success of condensed escape rooms.

Conversely, paper-based escape rooms have significantly lower associated costs and allow for a larger number of participants, requiring little active experimental space. However, this format often lacks elements of gamification and tactile components to make them engaging escape rooms [46]. Paper-based escape rooms are often implemented to focus on defining, describing, and comparing puzzle content and questions; however, allowing students to engage with one another as a team during puzzle solution can create opportunities for discussion and feedback from peers, enriching the experience. The ability for students to work in teams during puzzle solution is often key to the success of the active learning technique [40,46,50,68,95]. The strength of paper-based escape rooms is the ease in which they can be scaled-up for applications in larger introductory courses as they are easy to reset by the facilitator and do not require as many supplies beyond locks and instructions [63,91]. Depending on the educator's goals for an escape room, the number of game elements and the outcomes for the escape room will vary. For example, the introduction of locks to a worksheet may not necessarily be implemented to apply gamification but rather as an opportunity for students to receive immediate formative feedback [46,66]. "Lockbox", for example, includes numerical locks to provide instant feedback on worksheet questions but lack hints, experiences, storylines, and other game elements built into its design [106,107].

Digital escape rooms provide increased flexibility as they can be completed anywhere with access to the internet [76]. Online games can likewise allow for the integration of greater student choice in the solution of puzzles [109,110]. Different platforms have been leveraged to design digital escape rooms such as Zoom paired with a Google Form [111], augmented reality (metaverse) [112], WhatsApp [92], and Flippity [113,114]. Depending on the platform used, different digital escape rooms are logistically more feasible for large classrooms. Most students have personal electronic devices such as computers or phones which can be used for gameplay, whereas VR or AR headsets would need to be provided to participants. With escape activities being developed using a platform such as Google Forms, educators are often familiar with the interface, so puzzle design is less time-intensive. However, these activities have limitations similar to those of worksheet-style escape rooms. Specifically, these often feature a lack of game elements in favor of mass distribution for large classes and instant feedback. Additionally, escape rooms applied solely in an online environment may suffer from reduced team communication compared to those applied in class [80]. More immersive games may also require coding and programming expertise to create exploratory, open-ended designs; a feature that may be daunting to educators not well versed in this area [115]. While several online chemistry escape rooms have been developed, there is no current bank of activities that can be easily accessed by other educators, limiting their implementation at other institutions.

3.3. Learning Theories

In the design of any game-based learning intervention, the narrowest consideration is having the design be informed by learning theories and general gamification practices [28,116]. Learning theories support an educator's beliefs about teaching and learning in their classrooms including pedagogy [117], assessments [11], and learning activities [32,118]. Additionally, a theoretical lens can also be applied, centering in on universal design for learning and equity, diversity, and inclusion (EDI) [119]. Educators' beliefs may likewise include ideas regarding the role of the students, the role of the educator, what is learning, and what is knowledge [21,118,120]. Some approaches to learning that educators have linked to escape rooms are experiential learning [78,121,122], Bloom's Taxonomy [55,70,123], and gamification [93,124,125], as mentioned in Section 1. For escape rooms informed by Bloom's taxonomy, educators prioritize the development of higher-order thinking skills, such as applying or evaluating instead of recalling information [1]. Game elements which provide learners with choices, challenges, instantaneous feedback, world-building, hints, and point systems [85,124,126] can help to achieve these higher-order problem-solving skills. Similarly, concepts such as educational scaffolding have been shown to be beneficial in gamified learning [127].

3.4. Participant Feedback

As part of the experience, participants receive instantaneous feedback. Educators can frame how this feedback is presented to participants. Escape rooms as a means for competition-based learning have also been shown to improve interactivity, collaborative teamwork, and active participation, create a sense of challenge versus duties, and improve motivation for learning [28,113]. Important however in the application of competition-based learning is assuring students that "poor" results, such as taking longer than another team to complete a set of puzzles, will not affect their overall grades but rather the experience itself is meant for learning. "Winners" may optionally see improvements to grades or small awards such as congratulatory messages, candy, or bonus marks. In this sense, there is no penalty for engaging in the escape room activity, but there is motivation to participate in hopes of receiving a bonus [28].

A final, but important, aspect in designing escape rooms is the solicitation of feedback from participants. Feedback should not only include participants' enjoyment of the activity, or its motivational effects on learning, but also recommendations for improvement on the overall design. This may include feedback on which puzzles were the most repeatable experimentally, or simple feedback such as providing written instructions on how the locks work rather than verbal instructions. With each iteration, educators can learn new approaches to design the puzzles and common areas of student confusion. Section 5 explores methods for soliciting student feedback and its use in assessing active learning strategies.

While there are many methods for designing escape room puzzles, Table 1 provides additional examples of guiding questions that may be utilized by interested educators. As escape rooms have become more popular in education, numerous resources have likewise been compiled to help educators in their development [98,99,128–130]. Similarly, several educational design and consulting companies have emerged, which are able to create escape room content for educators based on supplied course learning objectives [74,131–134]. Individuals wishing to implement escape room activities may find it beneficial to experience an entertainment-focused commercial escape room to better explore gaming elements. This can help in the brainstorming of new puzzles but also provides a better sense of where and how confusion can develop during puzzle solution, lending to better clue and hint design. We also turn readers to the book *Escape the Game: How to Make Puzzles and Escape Rooms* by Clare for further information and examples [135]. Additionally, in the development of all activities, we strongly encourage educators to probe the accessibility of the design and turn readers to the following articles [136–139]. For example, does puzzle solution require the implementation of fine motor skills? Does the design utilize small text, hidden text, or hard-to-read text? In considering these questions, we can develop activities that allow all students to participate.

4. The Benefits of Puzzle Development on Learning

Much of the literature on escape rooms focuses on students solving or playing with the escape rooms. A less explored avenue for escape room applications in learning is students developing their own puzzles. As anyone who has designed an escape room might know, a great deal of learning takes place as you link course content knowledge to the puzzle being designed [7]. This aligns with theories of learning such as active learning and experiential learning [21,107]. With active learning, students have the autonomy to make choices in their own learning and participate. Experiential learning has students reflect and design as a part of their learning experience [21]. Both learning theories, when incorporated within the classroom, have led to improved learning and engagement [89]. We might expect some learning benefits when linking active learning and escape room design. In a study by Schechtel et al., students in an introductory chemistry course for engineers designed their own puzzles for applications in a Battle Box [140]. During the semester, students were asked to design two puzzles, one focused on material covered earlier in the semester, and one including material from later in the semester. To design their puzzles, students were given access to supplies such as combination locks, simple glassware, eyedroppers, a select list of aqueous solutions (for electrochemical cells, acids/bases, or indicators), gloves, and electrochemical cell set-ups. Prior to the experience, students were able to engage with the "ChemEscape: General Chemistry" puzzles [69]. Feedback was provided to students during an early-semester tutorial and midsemester when they submitted their puzzle proposals to TAs for approval of design and supplies. Any additional supplies were provided by the students such as paper, calculators, blocks, or paper puzzle pieces as required. At the end of the semester, student groups solved one another's puzzles and provided feedback. The activity was likewise assessed by instructors using a general rubric, containing marks for creativity, clarity of learning objective, and providing a sound answer to the puzzle based on their chemistry content knowledge. This study is a steppingstone showcasing that puzzle creation can happen in large introductory courses and that students can identify the learning objectives from instructor-designed puzzles. A logistical challenge reported by the authors is ensuring students have adequate resources to support the puzzle development [140]. An additional consideration that was overlooked was the workload on students, which led some students to design their puzzles based off the examples provided in the project instructions or to just provide a piece of paper and a pencil as a puzzle.

One example from engineering had 105 students develop boardgames related to their course work, namely kinetics, process safety, and instrumentational control, over three weeks [123]. Similarly to the previous example, students were assessed based on creativity, course content understanding, topics selected, and peer evaluations. The students in this study built a stronger sense of community and were pushed to engage in deeper learning. Other studies have shown improved student engagement and learning from students creating their own games [141]. In the digital sphere, student game design has taught students new skills like coding, created stronger communities, improved peer teaching, and improved literacy. In another study, students felt empowered in their learning and noted improvements to their critical thinking [142]. While some examples of game creation lean on digital applications, their findings provide a promising path forward to inviting students to engage more deeply with their learning.

"Spectroscopy Unlocked" similarly employed two undergraduate students in the development of the escape room activity as part of their research studies in chemistry education [60]. Faculty members supported the students in designing the course-based puzzle components, as well as the practical aspects required for completion of the activity (how does each puzzle help students to escape?), mainly ensuring the content was appropriate for the learning audience. The activity was designed over the course of 10 weeks and later implemented into an introductory undergraduate chemistry classroom. When probed about their experience, the students noted the high level of skill development associated with preparing the activity, requiring time management, organization, and creative problem solving. Developing the puzzles also provided the students with a deeper understanding of the subject matter and allowed them to hone their communication skills. Sentiments such as this have likewise been reported for junior organizers assisting in the development of gamified learning materials for applications in the Societal Impacts of Inorganic Chemistry symposium hosted at the 2023 Canadian Chemistry Conference and Exhibition. Here, students also highlighted the importance of engaging in activity development on their self-efficacy and feelings of belonging within the chemistry community [143]. The development of course materials, specifically gamified components such as escape rooms, provides a unique avenue for students to showcase their content understanding as well as develop a stronger sense of self-efficacy as a member of the scientific community. Coupling together puzzle solution and puzzle development yields a unique experience in which students can actively engage in higher learning.

5. Assessing Active Learning and Escape-Room-Based Puzzles

As outlined in Section 1, active learning in the STEM classroom is a well-established practice to increase student academic performance [4]. A 2018 report by Stains et al. indicated that active learning methodologies had found use in 40% of large college STEM courses in the United States [144]. A further 2024 report from Stains indicated that tenure status and institution type, as well as personal characteristics of the instructor, are good indicators of active learning uptake for introductory general chemistry classes [145]. Five principles underlie active learning including constructivism, problem solving, knowledge transfer, collaboration, and explanation articulation [4]. Here, we are considering puzzles and escape-room-type activities as active learning tools; however, the suite of active learning methodologies can be expanded to include classroom discussions, iClicker questions, practice problems to be completed individually or in small groups, team-based learning, and further educational games.

There are meaningful ways in which the effect of using active learning techniques can be measured with respect to student performance, student persistence in STEM fields, and the sense of social supports as a function of this research-based instructional strategy. Overall, active learning is well understood to lead to higher student performance; a 2014 meta-analysis of 225 publications indicated classes with active learning strategies had 6% higher scores [4]. Additionally, students in traditional lecture courses were 1.5 times more likely to fail. This meta-analysis also revealed the active learning strategies were most efficacious with classes of 50 students or less [4]. Use of active learning can also reduce the achievement gaps for underrepresented minorities in STEM fields [12]. Active learning techniques have been shown to significantly narrow achievement gaps for underrepresented minorities using both remote and in-person instruction [146]. Additionally, a particular 2022 study found that active learning strategies used in a General Chemistry I class reduced attrition of female-identifying students by 7% [147]. A validated instrument is available to measure the perception of social support during active learning (called the Perception of Social Supports for Active Learning or PSSALI); this self-reported survey tool is used to understand students' perceptions of the support they are receiving from learning assistants (commonly known as teaching assistants) to engage in active learning during chemistry courses [148]. This tool, which assesses appraisal support, emotional support, and informational support, can be particularly useful when considering the support that students are being provided by teaching (or learning) assistants in large courses where active learning is used.

With respect to escape-room-style puzzles, there are many ways to assess students both in terms of performance and perception. Unsurprisingly, all reports of escape-room-style puzzles reported in the chemical education literature assessed whether (and how many) students successfully completed the puzzle. Students may complete a pre- and post-test or quiz on the content that is being incorporated into these escape room activities; one such report in 2024 using a battle card game for chemical tests found that students showed improved scores on this test after the escape room activity than before [149]. Another use of a pre- and post-test survey was reported in 2022 to investigate the effect of a digital escape room to challenge student misconceptions about stoichiometry [150]. Groups were controlled, with one group receiving only online instruction, one group participating in the digital escape room only, and one group receiving online instruction in addition to the digital escape room. The results from this study implied that a digital escape room was just as effective as a typical online lesson with a collaborative learning method in addressing misconceptions around stoichiometry. Some educators may choose to measure the time to complete a puzzle as part of their assessment. While this cannot accurately measure student understanding (i.e., just because a group completes a puzzle quickly does not mean they learned something more robustly than a group that finished in more time and vice versa), it can provide insight into student engagement and puzzle feasibility.

Student surveys remain an powerful and informative tool to probe the efficacy of the escape-room-style puzzle; therefore, virtually all reports of escape room activities in chemistry classrooms include some kind of student survey with a variety of questions being asked. Some major themes emerge when assessing these survey tools. Survey questions addressed student enjoyment of the activity, frequently, using a 4-point or 5-point Likert-style model [65]. Many survey questions also asked about student confidence and perceived competency in the chemistry content as a result of completing the activity [111]. Many survey questions also chose to explore the idea of teamwork in escape-room-style puzzles; whether students enjoyed working in teams and if they felt they benefited from the teamwork element of this active learning [61]. Beyond the quantitative survey questions, many surveys also chose to ask qualitative (textual) questions to gather additional information and to ask if and why they found the teaching material(s) meaningful [151]. Survey question themes emerged, as did themes around student responses. Across reports of escape-room-style puzzles, regardless of whether students were asked for quantitative or qualitative responses, and regardless of what questions they were asked, responses were positive. Students felt they learned the chemistry content as a function of completing the puzzle with increased confidence, an appreciation for teamwork and communication, and when asked deliberately, students reported they would like to see more escape-room-style puzzles included in other classes [152].

6. Future Perspectives

Despite the explosion of educational escape rooms within the literature, one of the biggest critiques is the incorporation of full-room, immersive components, such as active experimentation and tactility, into large classrooms [42,44,47,68]. Targeting these high-enrolment courses requires a more purposeful design of tactile components, considering not only the space in which the activity can be performed (lecture hall, tutorial room, etc.) but the reusability of puzzle components, aiming to reduce supply costs and puzzle reset time if multiple student groups are using the puzzles. For example, "ChemEscape" Battle Boxes have been implemented at large-scale outreach events as well as in large-enrolment chemistry courses [55,69,70]. The multi-day use of the puzzles as well as the high turnover required the puzzles to be designed for integrity, so that puzzles are not easily broken, as well as for rapid reset. To accomplish this, paper components were laminated, consumables were prepared in duplicates in advance, puzzle components and locks were labeled with the puzzle number and Battle Box number, several puzzle features were affixed to the Battle Box to avoid their removal, and facilitators were pre-trained on puzzle solution and provided with a list of lock combinations [55,69,70]. Similar designs such as hexagonal escape boxes [41], condensed escape activities [72], and paper-based puzzles incorporating small tactile components [65] have emerged, helping to increase applicability and mobility of the escape rooms while retaining tactile components—an important feature in chemistry escape rooms—mimicking research-style exploration and experimentation.

While hands-on experimentation is an asset, it is important to remember that not every aspect of a puzzle needs to be a "wet" experiment. Mock experiments may be incorporated, challenging students to utilize research observation-based clues in puzzle solution. Tactility can also be incorporated by utilizing different types of locks such as directional locks, color-coded locks, key locks, and combination locks [63,66]. If the code is a shape, such as a reaction coordinate diagram or graph, a directional lock could be considered. Similarly, color-based locks can be helpful in puzzles following reaction kinetics such as the iodine clock [153] or those focused on the utilization of acid–base indicators. By tailoring our activity design approach to target larger-enrolment courses and activity reuse, escape room activities are more likely to remain prevalent as a gamified learning approach in future years. We expect that as educators move away from the traditional view of escape rooms and immersive rooms, we will begin to see more activity development applicable to larger course sizes. In pursuit of this goal, we have included Section 3, exploring design considerations during escape room activity development. We hope that this, and the references within, can act as a guide for the interested educator.

Similarly to concerns noted by Lathwesen and Belova in their review of STEM escape rooms [47], chemistry-focused escape rooms are still limited in their interdisciplinary nature as well as divisional content, with most activities focused on learning objectives in general chemistry. An overview of available chemistry escape activities is located in Appendix A. For example, there is a noticeable lack of puzzles focusing on inorganic chemistry (0), upper-year physical chemistry (0), and organic chemistry (3), specifically, synthesis (1) and environmental/green chemistry (2). However, of the existing escape rooms, there appears to be a good balance between fully immersive rooms, condensed escape activities, paper-based puzzles, and online content, showcasing the community efforts to design more applicable and accessible escape room strategies. Similarly, there is a balance between laboratory-style learning (experimentation, analysis of results) and applications of lecture-based learning to exam-like problems. The development of digital and VR-based escape rooms in chemistry has likewise opened doors for online learning focused on experimentation that might not be possible in a laboratory space, or the 3D visualization of chemical species, a benefit to students that struggle with concepts such as symmetry and stereochemistry.

We also find, compared to previous reviews, that there is a larger body of literature and empirical evidence on the effectiveness of active learning techniques, gamified learning, and escape-room-style activities. Overall, evidence suggests that chemistry-focused escape room activities are effective in developing stronger student understanding of course content, enhancing student laboratory skills, increasing student motivation, and increasing student self-efficacy, as well as promoting student collaboration, teamwork, and communication. For the latter, in-person escape rooms provide a more effective learning environment for teamwork, although online platforms such as Zoom and Teams have been shown to be effective for collaboration. We envision that research on the effectiveness of escape room activities will continue, although we hope to see more evidence on the specific gaming components that increase student understanding and engagement. For example, are "wet" or mock experimentation-focused puzzles more effective then ciphers or riddles? Does removing classical escape-room-style puzzles (hidden items, surprise reveals) decrease students' sense of immersion or motivation to complete the activity? By attempting to answer these questions we will be able to better design condensed escape room activities.

Ultimately, what do we recommend based on this literature review? For instructors with limited infrastructure (i.e., time, costs, learning technologies, or spaces are prohibitive), there are a multitude of existing escape-room-style puzzles outlined that vary in materials needed. This is especially true of escape-room-style puzzles designed for students in general chemistry courses. For instructors across chemical sub-disciplines under-represented in escape-room-style puzzles, there is much opportunity to develop new escape rooms with various demands and sophistication. These escape rooms can be delivered electronically or in person. We recommend that instructors who develop new escape-room-style puzzles use our guiding questions centered around audience, purpose, and accessibility in their design, and assess the efficacy of their new teaching tool as outlined in Section 5. We envision that in alignment with improving the applicability of escape room activities in large-enrolment classrooms that we will see an influx of condensed escape activities, laboratory-focused activities, and online platforms. In the development of these materials, it is imperative that educators share not only the preliminary puzzles but provide blueprints, printable files, puzzle solutions, and facilitation guides, allowing for the ready implementation of these activities at other institutions. Similarly, while there is a small repository of escape activities provided by the Royal Society of Chemistry [73], educators and educational journals should work to develop an online repository of activities, aiming for open access, to allow for a consolidate list of available escape rooms, their type, the size of participant groups, cost, time, and topic.

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Appendix A

Table A1. Overview of recent chemistry escape rooms.

Name	Division	Topic	Type	Students	Time to Play	Ref
Escape ClassRoom	General	Analytical chemistry | scientific method | acids and bases | chromatography	Full Room	Groups of 6–10	60 min	[48]
Break Dalton's Code and Escape!	General	Conductivity | acids and bases | structure and reactivity | thermodynamics | periodic table	Full Room	Groups of 5–6	60–90 min	[49]
Escaping Boredom	General	Chemical reactions | kinetics | thermodynamics | structure and bonding	Full room	Groups of 4	20 min	[62]
Quantum Escape Game	General	Analytical chemistry | electrochemistry | spectroscopy | quantitative analysis | titration | calorimetry	Full Room	Groups < 7	180 min	[57]
Chemical Escape	General	Acids and bases | stoichiometry | periodic table	Full Room	Groups of 4–6	40–60 min	[61]
Physical and Digital Educational Escape Room	General	Structure and bonding | molecular interactions | periodic trends	Paper-based	Groups of 8	25 min	[65]
Periodic Table of Elements Chemical Escape Room	General	Periodic table | chromatography | optical properties	Paper-based	Groups of 6	90 min	[108]
Escape Classroom: The Leblanc Process	General	Stoichiometry | Leblanc process | chemical reactions	Paper-based	Groups of 5–7	60 min	[63]
Escape the Desert Island	General	Pharmaceutical chemistry | acids and bases | kinetics | thermodynamics | nomenclature	Blended	Groups of <7	160 min	[154]
ChemEscape: General Chemistry	General	Density | buoyancy | thin-layer chromatography | electrochemical cells	Battle Box	Groups of 2–4	30–60 min	[69]
ChemEscape: Redox and Thermodynamics	General	Thermodynamics | redox | chemical equilibria | equilibrium constants | Gibb's free energy | electrochemical cells | indicators	Battle Box	Groups of 2–4	30–60 min	[55]
The Masked Scientist	General	Stoichiometry | radioactive decay | chemistry applications	Online	Groups of 3–4	30 min	[79]

Table A1. *Cont.*

Name	Division	Topic	Type	Students	Time to Play	Ref
Harry Potter Themed Digital Escape Room	General	Stoichiometry | chemical formulae | structure and bonding | periodic table	Online	Groups of 3–6	30 min	[150]
Mirror Mirror on the Wall	General	Structure and bonding | stereochemistry | pharmaceutical chemistry	Online	Groups of 2	50 min	[82]
AR Escape Classroom: The Leblanc Process and the Solvay Process	General	Periodic table | stoichiometry | Leblanc process | Solvay process	Online	Groups of 5–7	60 min	[112]
Escape the Lab	Analytical	Analytical chemistry | spectroscopy | chromatography | periodic table	Full Room	Groups of 4–6	60 min	[56]
Nonsterile Compounding Escape Room	Medicinal	Pharmaceutical chemistry | compounding medications | conversions	Paper-based	Groups of 2–3	40 min	[155]
ChemEscape: Organic Reactions and Spectroscopy	Organic	NMR spectroscopy | IR spectroscopy | mass spectrometry | substitution reactions (SN1, SN2) | elimination reactions (E1, E2)	Battle Box	Groups of 2–4	30–60 min	[71]
Chemistry Escape–Find the Way	Organic	Alcohols | aldehydes | carboxylic acids | coloring agents | esters	Paper-Based	Groups of 2–4	30–60 min	[156]
Chem'Sc@pe	Organic	Organic chemistry | nomenclature | stereochemistry | hybridization | chromatography	Online	Groups of 3–4	60 min	[83]
Plastic and Recycling for Arts and Fashion Students	Polymers	Material properties | manufacturing processes | sustainability	Blended	Groups of 6	50–70 min	[157]
ChemEscape: Polymer Chemistry	Polymers	Polymer chemistry | structure and properties |	Battle Box	Groups of 2–4	30–60 min	[70]
Break Out Safety	Safety	Laboratory safety training	Full Room	Groups of 3	30 min	[158]
Waving the Green Flag: LCA Escape	Green	Polymers | catalysts | biopolymers | sustainability | green metrics | life cycle analysis	Paper-based	Groups of 2–3	20 min	[67]
Saving the Earth	Green	Environmental chemistry | atmospheric chemistry | chemistry applications | polymer chemistry | inorganic and organic compounds	Online	Groups of 3	35 min	[159]
Can You Make It Back to Earth?	Green	Green chemistry | renewable materials | waste | pollution | green metrics | catalysis	Online	Groups of 2–4	30–50 min	[152]
Escape the Environmental Crisis	Green	Spectroscopy | symmetry | elemental analysis | nanomaterials	Online	Groups > 2	60 min	[111]

Table A2. Overview of recent chemistry games (card games, boardgames, etc.).

Name	Division	Topic	Game Type	Reference
Families of Chemical Elements	General	Chemical elements | periodic table	Card Game	[160]
SeArCH	General	Periodic table	Card Game	[161]
Rare Earth Elements	General	Rare earth elements	Card Game	[161]
Periodica	General	Periodic table	Card Game	[162]
Groupica	General	Elements	Card Game	[162]
Mendeleev's Cards	General	Periodic table	Card Game	[163]
CountQuest	General	Effective atomic number concept	Card Game	[164]
ChemMend	General	Periodic table	Card Game	[96]
Acid–Base Poker	General	Acid–base chemistry	Card Game	[165]
Compoundia	General	Compounds	Boardgame	[162]
Fun with Flags and Chemistry	General	Chemical complexes	Boardgame	[166]
Orbital Battleship	General	Orbitals | Hund's rule | quantum numbers	Boardgame	[167]
Chemical Pursuit	General	Elements | structures | thermodynamics | acid–base	Boardgame	[168]
CHEMTrans	General	Stoichiometry | balancing equations	Boardgame	[169]
Chemistry and Chaos	General	Elements | structures | thermodynamics | acid–base	Role Play	[170]
BingOrbital Game	General	Orbitals | quantum numbers	Online Game	[171]
Organic Chemistry Cassino	Organic	Synthesis | functional group transformation	Card Game	[172]
Go Fischer	Organic	Nomenclature | functional groups | preliminary reactivity	Card Game	[173]
Retrosynthetic Rummy	Organic	Synthesis | retrosynthesis	Card Game	[174]
Synthesis (Solitaire)	Organic	Synthesis | retrosynthesis	Card Game	[175]
Synthetic Dominos	Organic	Synthesis | organic reactions	Card Game	[175]
Carbohydeck	Organic	Bonding in carbohydrates	Card Game	[176]
Act, Draw, Explain Your Science	Organic	Naming | geometry | bonding	Card Game	[151]
Prediction! The VSEPR Game	Organic	VSEPR diagrams	Card Game	[177]
LINK	Organic	Amino acids	Card Game	[161]
^{1}H NMR Spectrum	Organic	^{1}H NMR spectroscopy	Boardgame	[178]
Texas Carbon	Organic	Bonding	Boardgame	[161]
Tap It Fast!	Organic	Molecular symmetry	Boardgame	[179]
Insulin–Glucagon Game	Organic	Metabolic effects | hormone action	Boardgame	[180]
18 Electron Rule	Inorganic	Electron counting in transition metals	Card Game	[181]
Complex	Inorganic	Transition metal complexes	Card Game	[181]
SALC	Inorganic	Orbital arrangement	Boardgame	[181]
Slap Count	Inorganic	Electron counting in transition metals	Boardgame	[181]
Catalyst Towers	Inorganic	Green chemistry principles | catalyst development | ligands | reaction conditions	Boardgame	[114]

Table A2. *Cont.*

Name	Division	Topic	Game Type	Reference
Race to the Reactor	Materials	Polymers | functional group–physical properties relationships	Boardgame	[151]
Tetris	Materials	Crystal growth	Online Game	[182]
Bioanalytical Murder Mystery	Biochemical	Analytical techniques | protein separation | mass spectrometry | HPLC	Boardgame	[183]
Quantum Tic-Tac-Toe	Computational	Quantum chemistry | superposition in movement | entanglement | state of collapse	Online Game	[184]
Chemical Kinetics	Computational	Chemical kinetics | algorithms	Boardgame	[185]
Green Machine	Green	Polymers | sustainability | recycling	Card Game	[186]
Life Cycle Analysis Puzzle	Green	Green chemistry metrics | life cycle analysis	Boardgame	[114]
Polizzies	Green	Sustainability | policy	Boardgame	[67]
Conflicts in Chemistry	Green	Polymers | sustainability | policy	Role Play	[187]
The Safer Chemical Design Game	Green	12 principles of green chemistry	Online Game	[188]

Note: this list is not comprehensive.

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