Using Pop-Culture to Engage Students in the Classroom

Nicolas Dietrich, Mélanie Jimenez, Manuel Souto, Aaron Harrison, Christophe Coudret, Éric Olmos

USING POP-CULTURE TO ENGAGE STUDENTS IN THE CLASSROOM

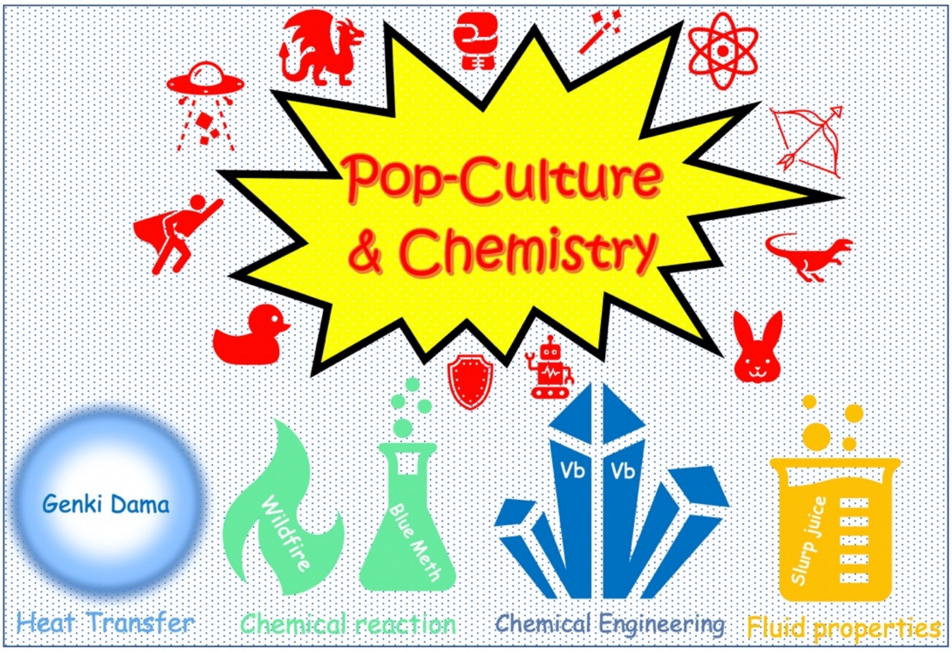
Nicolas DIETRICH[1], Mélanie JIMENEZ[2], Manuel SOUTO[3], Aaron W. HARRISON[4], Christophe COUDRET[5] & Eric OLMOS[6]

1. Toulouse Biotechnology Institute (TBI), Université de Toulouse, CNRS, INRA, INSA, Toulouse, France
2. Biomedical Engineering Division, James Watt School of Engineering, University of Glasgow, Glasgow, United Kingdom
3. CICECO-Aveiro Institute of Materials, Department of Chemistry, University of Aveiro, Aveiro, Portugal
4. Schmid College of Science and Technology, Chapman University, Orange, California, USA
5. Interactions Moléculaires et Réactivité Chimique et Photochimique (IMRCP), Université de Toulouse, CNRS, UPS, Toulouse, France.
6. Laboratoire Réactions et Génie des Procédés (LRGP), Université de Lorraine, CNRS, LRGP, Nancy, France

■ ABSTRACT

Herein, we describe how video games, TV shows or movies have been used to provide an innovative framework for students to think about chemistry and chemical engineering. The main objective of this paper is to show how science can be linked with pop culture, to provide educators with recent materials to use in classrooms, and to discuss the benefits and limitations of such tools. The videogames Fortnite, Spiderman and Angry Birds, the TV shows Game of Thrones and Breaking Bad, the Marvel movies, and the animated programs Raving Rabbids and Dragon Ball are used to illustrate different approaches to engage with students and encourage them to learn in a more recreational environment.

■ GRAPHICAL ABSTRACT



■ KEYWORDS

General Public, Chemical Engineering, Collaborative / Communication / Writing, Humor / Puzzles / Games, Reactions /History, Philosophy/ Inquiry-Based/Discovery Learning, Physical Properties, Student-Centered Learning

■ INTRODUCTION

Attracting a general audience to chemistry and chemical engineering topics is a significant challenge[1,2] and developing stimulating, alternative teaching methods is important for educators in all disciplines. In several articles, authors describe aspects of popular culture[3] to teach chemistry using resources that are part of everyday life to engage students more effectively. Chemistry classes have been supplemented with material from arts such as music[4–7] (including jazz[8] and opera[9,10]) and paintings[11–13] (including fashion art[14]), history[15–18], archaeology[19–21], or literature[22–27]. As examples, educators illustrated chemistry with a Shakespeare's play[28] while others found inspiration in detective cases where chemistry was used by the perpetrator of a crime or in their identification[29,30]. The chemical references from Ian Fleming's *James Bond*[31] series of novels were used to illustrate chemical reactions and substances (sedatives, rocket fuels, *etc.*). The *Harry Potter* novel series also offered an opportunity to reproduce wizardry experiments[32] in a chemistry lab (*e.g.* with invisible and color-changing inks, colored flame in a jam-jar). Famous characters from the *Sherlock Holmes* stories (from Conan Doyle's novels) have been used to create a fictional mystery based on chemistry[33–35], as has a murder novel of Agatha Christie[36]. Michael Crichton's novel *Jurassic Park*[37] has been an inspiring source of discussions on the chemical defense of plants or chemicals used by animals for communication. Cartoons[38,39] and comic books[40] can also illustrate chemical principles (*e.g.* microscale chemistry in *Archie*'s comic book[41] or general chemistry in *Dick Tracy*[42–45], *DC Comics*[46] or Marvel comics[40]). Recently, lab safety rules have been presented to students with comics[47], graphic novels and mangas[48]. Beyond novels and comics, movies are currently one of the biggest providers of pop-culture[49,50]. The list of movies used to illustrate chemistry is impressive, including for example *Apollo 13*[51], *October Sky*[52], *Star Trek*[53] and many others[54–58]. The omnipresent Marvel franchises often invoke various areas of chemistry and chemical engineering such as nanotechnology in the suits of *Iron Man*[40], properties of the fictional metal vibranium in *Black Panther*[59], the quantum realm in *Ant-Man*[60], or material sciences in *Spider-Man*[61]. Television is also a good way to illustrate chemistry[62] and famous shows used for this purpose include *The Price is Right*[63], *The Big Bang Theory*[64], *CSI*[65], *The Simpsons*[66], *Bones*[67], *ER* and *House*[68]. Trending games[69–89] are also an interesting pathway to involve students in general chemistry courses[90–97]. Educators have included pop-culture elements to solve educational escape games, *e.g.* to unveil the name of a super hero (Clark Kent from *Superman*) or famous gimmicks of a character[88,98] such as "Bazinga" from the TV series *The Big Bang Theory*. Moreover, while many educators have successfully used pop-culture themes to introduce their students to scientific concepts, educators have continually tried to use new techniques to engage their students, such as the creation of a Science Café on the pop-culture theme[99]. Video games[100] have become an increasingly important part of the entertainment industry, and they are also considered a form of art[101]; surprisingly the use of videogames to illustrate chemistry or chemical engineering[102] is relatively unexplored in the literature even though pedagogical videogames exist[103–105]. Video games being used directly in education is an increasingly popular research topic and even just playing commercial video games has been shown to benefit important skills in adult learners like effective communication, executive function, and resourcefulness[106–108]. Though these examples have been focused on skills-based learning, using video games for content-based learning in chemistry such as described below is beginning to be explored. The most notable example can be seen in the recent work by Smaldone, *et al.* where the authors presented a modified version of the popular video game *Minecraft* called *PolyCraft World.* In the game, the player collect resources and uses chemical refinement and synthesis techniques to craft equipment and materials in the game[109]. Initial results indicated that students who played the game learned advanced chemistry even without grading incentive or traditional classroom instruction. Given the difficulty of creating an engaging game content *de novo*, finding existing popular games to modify or for insight into how games can be used for educational purposes like *PolyCraft World* is an important resource. The main objective of this paper is to explore recent pop-culture references and the untapped potential of videogames for teaching purposes and more broadly propose new approaches to link chemistry/chemical engineering and pop culture. We present a range of activities inspired by videogames but also TV shows and recent movies, with their context and materials for implementation by the wider community. In a first section, three different activities that have been applied with students will be presented and the feedbacks from students' are discussed; in a second section, some additional activities used for outreach events are described.

■ ACTIVITIES

We report here activities related to the videogames Fortnite, the TV shows Games of Thrones and Breaking Bad and the movie Black Panther. All these activities were tested and evaluated with students' (see supplementary information for more details about the activities).

FORTNITE

Fortnite is an online video game developed in 2017 by Epic Games. The game mode includes a free-to-play battle royale game where up to 100 players fight in increasingly smaller spaces to be the last person standing. The game has cartoon graphics and does not present graphic violence such as bloodshed. Fortnite Battle Royale became a resounding success, drawing in more than 125 million players in less than a year and earning hundreds of millions of dollars per month. In early 2018, students of Tippecanoe High School in Ohio, USA, used a social media platform to challenge their professor to have a *Fortnite*-based final exam in chemistry. Although there is no report on how this story ended, it motivated the authors of this article to develop a new *Fortnite*-based protocol for chemistry classes that could be used by teachers facing a similar situation.

The videogame *Fornite* is more oriented toward physics than chemistry (*e.g.* bullet and rocket trajectories, amount of force per impact of projectiles, etc.). Nevertheless, in the game, once players have landed on the map, they must scavenge for weapons, resources and other items. The objective of this activity is to reproduce in the lab several items present in the Fortnite video game to illustrate simple chemical reactions. One of these items is the "*slurp juice*", a consumable that adds shield and health points to the character. This item is represented by a two-colored viscous fluid with beads in a jar, which could be prepared in the chemistry lab with a teacher. The fluids can be made as slime paste using common material (hot water, a spoonful of borax, and glue) or chemical products (water, polyvinyl alcohol, and boric acid) in order to illustrate the mechanism of polymerization of polyvinyl alcohol[110]. This activity is recommended for middle school students', high school students' or even for beginners in chemistry at University level. Materials and methods for this activity are detailed in the supplementary information. Some glass beads and dyes (green for the bottom fluid and blue for the top fluid) can be added after the polymerization in order to improve the resemblance to the "real" *slurp juice* as depicted in Figure 1.a. The polymer unique properties (of both a solid and a liquid) can first be discussed in the classroom. Then experiments can be planned to answer the following questions:

i) How can you make the polymer stretch the farthest?

ii) Does the amount of borax added change the slime structure?

iii) What method of storage will make the polymer last the longest?

iv) What brand of glue makes the stretchiest polymer?

v) Does the amount of water added to the glue affect the gooeyness of the potion?

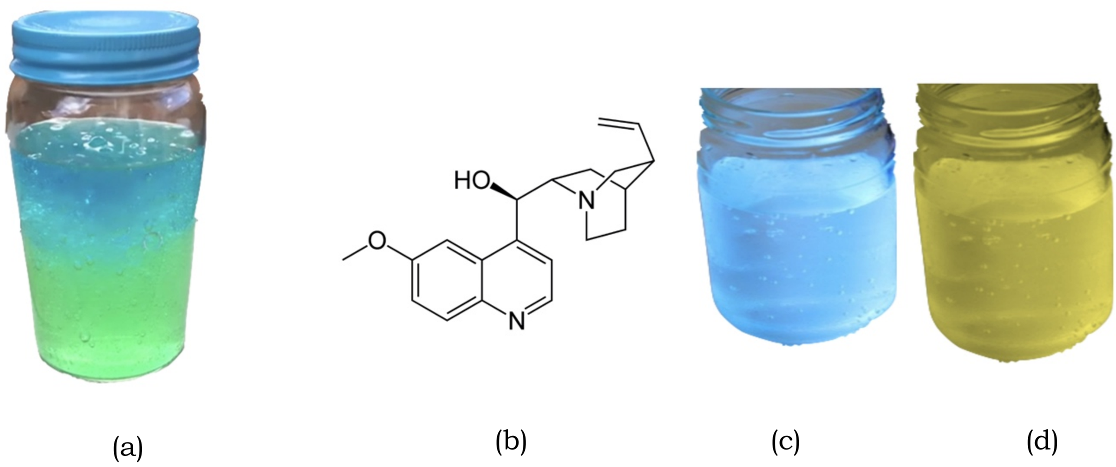


Figure 1. Example of *Fortnite* items that can be made in the chemistry lab: (a) "*slurp juice*" (b) the quinine molecule (c) "*shield potion*" (d) "*stink bomb*".

A second famous item in the game is the "*shield potion*", a glowing blue liquid in a jar with gems floating inside. This item can be easily made using tonic water and a black light. The quinine (Figure 1.b) in tonic water will glow blue[111–113], and the carbonic bubbles can perfectly mimic the gems (Figure 1.c). This experiment highlights the phosphorescence properties of quinine but fluorescein could also be used to show fluorescence effects [114]. Other products, such as energy drinks with B vitamins, milk, vanilla ice cream, caramel, and honey (to give a yellow color) could be used to produce a "*stink bomb*" (Figure 1.d) by adding few spoonfuls of table vinegar and hydrogen peroxide or directly with luminol to illustrate chemiluminescence[115–117]. The "*stink bomb*" can also illustrate chemical reaction and gas-liquid equilibrium as it is composed of ammonium hydrosulfide (NH_4SH), an unstable compound that decomposes into ammonia and hydrogen sulfide. As soon as the container is broken (open), the dissolved ammonium sulfide rapidly decomposes and liberates copious amounts of the pungent gas.

GAME OF THRONES

Game of Thrones is an American fantasy drama television series created by David Benioff and D. B. Weiss for HBO in 2011[118]. It is an adaptation of *A Song of Ice and Fire*, George R. R. Martin's series of fantasy novels, the first of which is A Game of Thrones, first published on August 1, 1996[119]. "Blackwater" is the ninth and penultimate episode of the second season of HBO's medieval fantasy television series. The entire episode is dedicated to the climactic Battle of the Blackwater, in which the Lannister army, commanded by acting Hand of the King, Tyrion Lannister, defends the city of King's Landing. This episode is famous for its epic wildfire explosion during the Battle of Blackwater Bay. In the series, wildfire is a flammable liquid that is created and controlled by an Alchemist's Guild. When ignited, it can explode with tremendous force and the resulting fire cannot be extinguished with water. Wildfire is identifiable by the distinctive green hue of its flames and a bright green color in its liquid state.

The objective of this activity is to reproduce the flame. This activity is recommended as a demonstration only for high school or university students' but the wildfire must be made in the lab only by the educator with screen protection and a safety disclaimer[48,120] (see hazard section).

When mixing boric acid with methanol; the reaction occurring is the synthesis of trimethyl borate, $B(OCH_3)_3$ depicted in Figure 2.a, and is as follows:

$$H_3BO_3 + 3\ CH_3OH \rightarrow B(OCH_3)_3 + 3\ H_2O \quad (1)$$

Trimethyl borate burns distinctively green, as represented in Figure 3.a, due to the presence of boron:

$$4\ B(OCH_3)_3 + 21\ O_2 \rightarrow 4\ BO_3 + 12\ CO_2 + 18\ H_2O \quad (2)$$

The experiment can be carried out with common products such as gas line antifreeze (methanol) and laundry booster/cleaning agent (borax - sodium borate) although this gives a mixture of orange and green flames due to the presence of sodium with the borate. This experimentation could be completed with the flame test to discuss the effect of ion on the flame color[121], as done for the older pop culture reference *Harry Potter*[32]. More information about the experiment is given in the supplementary section.

BREAKING BAD

Breaking Bad, a crime drama television series created by Vince Gilligan in 2008[122] for AMC, also offers numerous opportunities for use in classroom. The chemist protagonist, Walter White, chooses to stop using his chemistry skills to teach for an immoral world of drugs, death, destruction and destabilization[123]. In order to promote the positive value of chemistry, we hereby propose having students work on a similar but useful molecule, dextroamphetamine. Unlike the methamphetamine in *Breaking Bad*, dextroamphetamine is a central nervous system stimulant that is prescribed for the treatment of attention deficit hyperactivity disorder and narcolepsy[124]. The synthesis of this molecule is depicted in Figure 2.b. The proposed activity for organic or chemical engineering students is, like the main character of the series, to build the chemical process on paper from the raw data (solubility in water, boiling point, fusion point, reaction enthalpy, etc.) as depicted in the supplementary section. This activity is recommended as a project support for university students' in chemistry or chemical engineering.

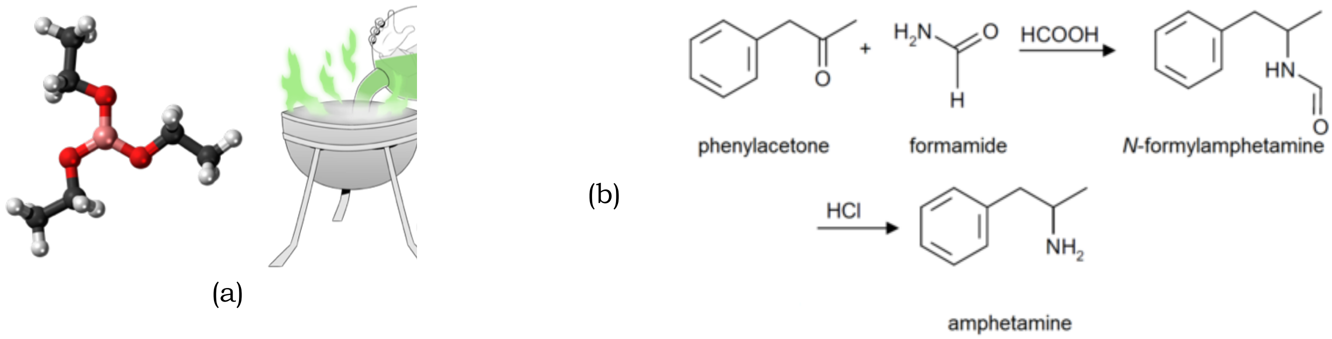


Figure 2. (a) The triethyl borate molecule and an illustration of the "green fire" reaction from Game of Thrones (b) Synthesis of the dextroamphetamine

Many other references from this series can be used for illustration, such as the reaction of hydrofluoric acid with silicon material (bath tube), the chemical composition of the human body (63 % hydrogen, 26 % oxygen, 9 % carbon, 1.25 % nitrogen, 0.04 % sodium, 0.25% of calcium, 0.00004% iron and 0.19 % phosphorus), chirality of molecules and its possible consequences (such as Thalidomide[125,126]), explosives, and ricin poisons[127]. As discussed later, an activity with such a controversial series must be well supervised by educators.

BLACK PANTHER

Movies are the pop culture medium that is most widely used to illustrate science and chemical concepts, especially science fiction and superhero movies. *Black Panther* has been used recently to encourage students to think about an imaginary element, called Vibranium[59]. In the movie, Wakanda's economy focuses on the production and use of this element, which has extraordinary chemical and physical properties. In this activity, the students were questioned on the possible place of Vibranium in the periodic table and its properties. The students' were separated in several groups and have to build a product with this element. A majority of the students developed a process to build the Vibranium steel, based on classical steel production (depicted in the supplementary section) whereas only very few groups worked on super-plastics or super-fertilizers based on vibranium. This overwhelming representation of steel production must be due to the influence of the movie, then an idea to avoid this behavior could be to impose a different product for each group, or to ask students for an alternative to the steel application. This activity is recommended as a project support or a discussion for university students' in chemistry or chemical engineering. The periodic table is a chemical concept that is easy to link with pop culture, and a large number of films include an element in their title[56]. Many fictional elements are also present in the movies[128] (Table 1). As an activity for students, they could be asked to find an occurrence in a movie of a real or a fictional element and to discuss the properties of both, and to develop their creativity by linking these elements with the Mendeleev periodic table. Having a strong knowledge of the periodic table is also fundamental to understand the basic principles of chemistry and different strategies and games have been proposed to help students memorize the position of each element in the periodic table[129,130].Recently, different periodic tables have been designed using fictional characters to be used as a mnemonic for high school students. For example, Disney characters have been organized in the periodic table relating each character to a property of the element (*i.e.* Boron (B) = Bambi, *Bambi* was Disney's fifth movie)[131] whereas Marvel, DC and Asterix characters have been periodically distributed in the periodic table by choosing characters whose names are reminiscent of the elements (*i.e.* Magnesium (Mg) = Magneto)[132,133]. This can be also an activity to be carried out in class where each student could choose other pop culture characters (*i.e.* The Simpsons, Star Wars) or popular public figures (i.e. soccer players, rock stars) they like best in order to organize them in the periodic table according to their properties and/or names. Besides being a strategy to increase the attention of younger students for introducing the periodic table in classroom, relating the elements of the periodic table to pop culture characters is a very useful strategy to help memorize the groups and periods as well as to explain the properties of each element.

Table 1. List of fictional elements present in pop-culture media

Name	**Assumed Symbol**	**Reference**

Adamant	**Ad**	The Lord of the Rings (books, movie), Final Fantasy (videogame)
Adamantium	**Am**	Marvel Comics (comic book)
Bavarium	**Ba**	Just Cause 3 (videogame)
Bolognium	**Bo**	The Simpsons, Futurama (TV shows)
Dilithium	**Di**	Star Trek (movie and series)
Divinium	**Dv**	Call of Duty series (videogame)
Duranium	**Du**	Star Trek (movie and TV series)
Feminum	**Fm**	Wonder Woman (comic book)
Jerktonium	**Je**	SpongeBob SquarePants (TV animation show)
Kryptonite	**Ky**	DC Comics (comic book)
Mithril	**Mi**	Terraria/Final Fantasy (videogames)
Redstone	**Re**	Minecraft (videogame)
Saronite	**Sa**	World of Warcraft (videogame)
Transformium	**Tr**	Transformers: Age of Extinction (movie)
Valeryan	**Va**	Game of Thrones (TV series)
Vibranium	**Vb**	Marvel Comics (comic book)

■ HAZARDS

Boric acid can be irritating for the eyes, skin, nose, throat and lungs, so it is recommended to wear rubber gloves when handling cleaning products, to wash away any cleaning product with water, and to avoid contact with nose, mouth, and eyes. Boric acid is classified as toxic to reproduction and should not be handled by students. The reaction involves fire therefore it should be conducted by a trained person in a safe area with a use of a protection shield. Prepare a lid to cover the container in order to quench the fire. Do not attempt to refill the container during or after the experiment. Methanol can cause metabolic acidosis, neurologic sequelae, and even death, when ingested, so it is recommended to wear rubber gloves when handling cleaning products, to wash away any cleaning product with water, and to avoid contact with the nose, mouth, and eyes. Personal protective equipment such as dust mask, eyeshields, face shields and gloves should be used for the manipulation of the resazurin dyes.

■ STUDENT'S EVALUATION AND DISCUSSION

Students from three separate courses used these activities ("Fortnite", "Game of Throne", "Breaking Bad" and the "Black Panther") after attending a series of lectures (10 h) covering the topic of chemical engineering. The first two activities were used as a demonstration tool while the last two were done as a supplementary homework project. A total of 125 students participated to these activities and came from either a Chemical Engineering course (class 1, 53 students, in 2018; class 2, 51 students, in 2019) or a Chemical reaction master course (class 3, 21 students, 2019).

At the end of the activity, the teacher invited all students to evaluate the activities by completing a printed form containing ten questions with responses based on a Likert[134] scale (the response rate was 95%). Data are presented in Figure 3. In general, all statements showed high levels of agreement ("agree" and "strongly agree") on the benefits of pop culture, ranging from 60% to 92.8% of those surveyed.

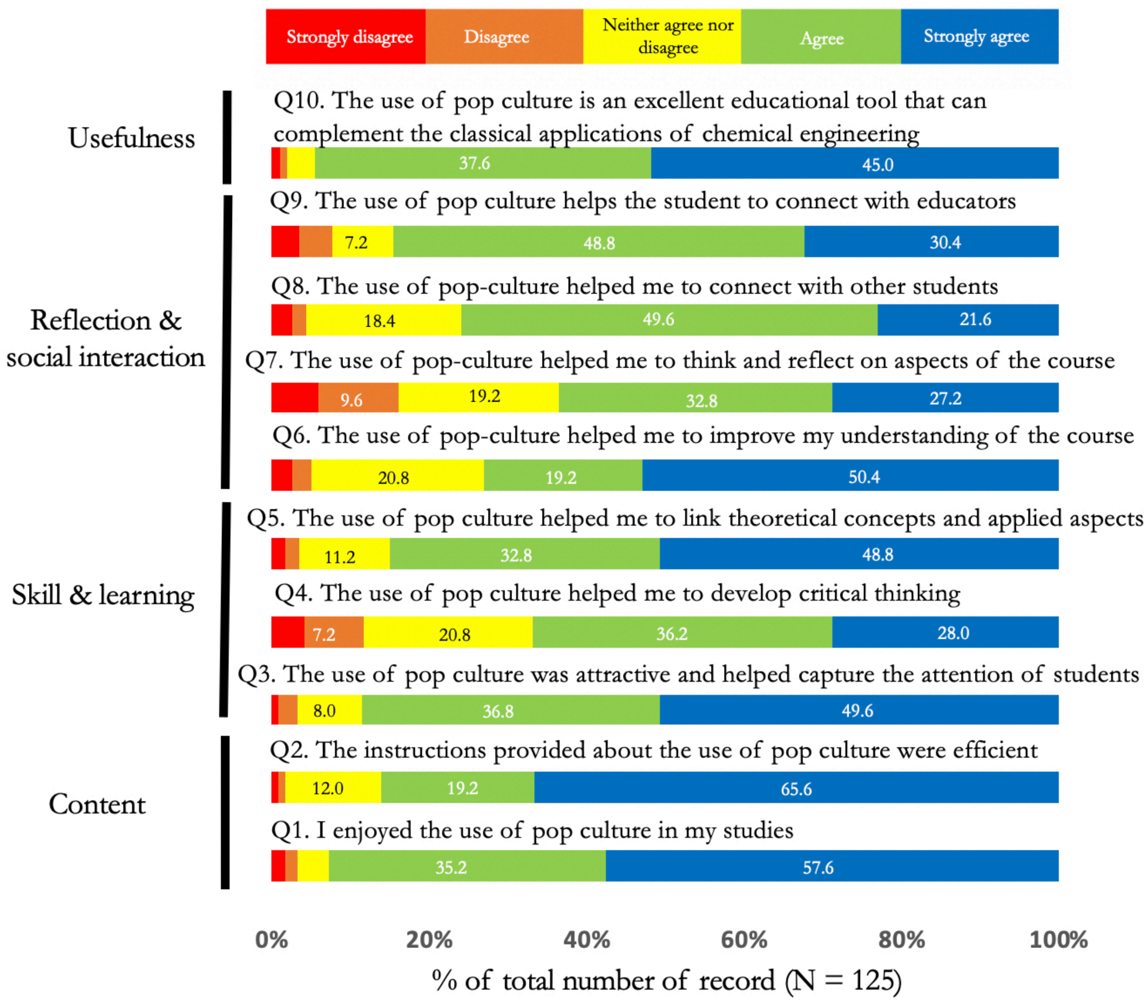


Figure 3. Student responses relating to the use of pop-culture in the courses. Total number of respondents = 125 (academic year 2018/2019).

A majority of students (92.8%) enjoyed the use of pop culture in the courses and thought it was attractive and helped capture their attention (86.4%). A majority (81.6 %) also agreed that the use of pop culture elements helped them make connections between the theoretical aspects of the course and their application and helped improve their understanding (69.6%). Fewer (64.8 %) students agreed that the pop culture helped them to develop their critical thinking or made them think about aspects of the course (60%). It is worth noting that a majority thought that pop culture helped them to connect with other students (71.2%) and even more with educators (79.2%). Finally, a large majority (83.2%) think that the use of pop culture is an excellent educational tool that can complement the classical application of chemical engineering. In a free-response section of the questionnaire, students were asked to provide comments on the activities. One of them was "I will keep this exercise in mind all my life".

■ SUGGESTIONS FOR ADDITIONAL OUTREACH ACTIVITIES

In this section, five supplementary activities based on recent pop-culture references are proposed as a support for educative purpose ("Spiderman", "Angry birds", "Stranger Things & Chernobyl", "Raving rabbids" and "Dragon Ball"). All of them were performed with students' or visitors during open days or outreach forums. A specific evaluation is proposed at the end of this section to discuss the benefits of such activities.

SPIDER-MAN

As pointed out in the movie *Into the Spider-Verse*, Peter Parker has a degree in chemical engineering and teaching materials can be developed from one of the most popular video games of 2018: Insomniac Games' *Spider-Man*. An important aspect of the game is the completion of missions that involve collecting PAH (PolyAromatic Hydrocarbons) samples, studying vehicle emissions, and determining the chemical composition of atmospheric particulate matter[135]. The video game directly simulates chemical analysis of these samples by having the player solve simplified versions of absorption spectra. Completion of the collection and analysis of these samples grant the players research tokens that can be used to upgrade their suit and gadgets. Though a limited amount of the underlying scientific content is conveyed to the player in analyzing these spectra, it is very straightforward to create a puzzle game using a similar format that could be an effective way to teach concepts in atomic spectroscopy. An example of such a puzzle game is shown in Figure 4.a.

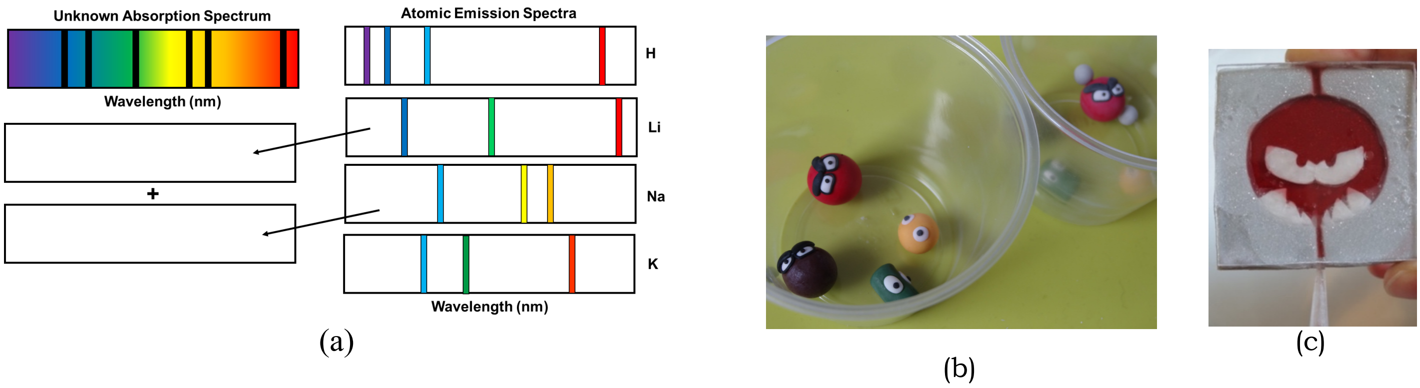


Figure 4. (a) Puzzle game to assign an unknown absorption spectrum using an inventory of atomic emission spectra. (b) Particles made from modelling clay (FIMO®) are used to mimic heterogeneous particles present in drinking water samples. Those with "angry" faces model waterborne pathogens that can be harmful to humans and should be separated and detected to prevent outbreaks. (c) Macro-fluidic device made of modelling clay, a Plexiglass layer and silicon for bonding[136].

In this puzzle, the player assigns the unknown absorption shown on the left as a simple sum of the individual atomic spectra using the emission spectra inventory on the right. Providing conceptual background about atomic absorption and emission spectroscopy and using known line positions of hydrogen atom (Balmer Series) or alkali atom spectra as shown in Figure 4.a conveys actual science to the player. In addition to assigning spectra using a spectral line inventory, an exercise could be envisaged using the Rydberg formula:

$$\frac{1}{\lambda} = RZ^2\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) \qquad (3)$$

to predict the different electronic spectra by varying the nuclear charge and principal quantum numbers of hydrogenic atoms.[137] The puzzle game could also be expanded to other kinds of absorption spectroscopy such as infrared (IR) absorption.

This activity is recommended for middle school students' and high school students' as a game or a discussion in the classroom with a video of the game. This inventory-based video game puzzle may be well-suited for an electron impact mass spectrometry-based game as well. Instead, consider that your fragment inventory shown on the right is a molecular fragment inventory, and the player determines the molecular structure of the parent ion based on the fragmentation pattern. An interactive, video game puzzle could also include variables like varying the electron impact energies to show how the mass spectrum changes as a function of hard vs. soft ionization.

ANGRY BIRDS

Another famous video game is *Angry Birds*, a casual puzzle video game developed by Rovio Entertainment in 2009[138]. The gameplay revolves around players using a slingshot to launch birds at pigs stationed in or around various structures, with the goal of destroying all the pigs on the playing field. The *Angry Birds* series had a combined tally of over 2 billion downloads across all platforms and has been adapted in movies and television shows. In previous work, the franchise has been used as an introduction to the separation of waterborne pathogens using microfluidics[136], channels in the micrometer range allowing for a precise control of fluid and particles at the micrometer scale[139]. In this activity, the analogy with pop culture icons was used to rapidly identify harmful pathogens in water samples. The wide range of particles that would normally be present in water but not visible to the naked eye due to their microscopic size are represented magnified using modelling clay. This activity is recommended for middle school students' and high school students' as hands-on activity. Some particles, representing pathogens that can cause a potential threat to human health, have facial expressions mimicking those from the video game *Angry Birds* for rapid identification (Figure 4.b). The overarching aim of the activity was then to engineer a suite of devices that replicate ongoing research in the field to isolate those "angry" pathogens and understand the chemistry associated with 1) the detection of those pathogens (fluorescence), the manufacturing process (e.g. bonding) of microfluidic devices (Figure 4.c) and how viscous liquids can be used to mimic at a macroscale a microfluidic environment[136,140].

STRANGER THINGS & CHERNOBYL

Another TV shows that can be used for illustrating chemical reaction is *Stranger Things*, an American science fiction horror web television series created by the Duffer Brothers and released on Netflix in 2016. In the show a large tentacled monster named the Mind Flayer terrorizes the citizens of Hawkins, and in season 3, it expresses a huge desire to consume chemicals, most often poisonous (*e.g.* fertilizer and cleaning products). The reason is that the monster wants to create caustic reactions associated with this chemical consumption to cause violent explosive transformations into amorphous blobs of human biomass. This example is a very good tool to discuss acid-base reactions and pH. *Chernobyl* is a historical drama television miniseries created and written by Craig Mazin and directed by Johan Renck for HBO in 2019. The series centers around the Chernobyl nuclear disaster of April 1986 and the unprecedented cleanup efforts that followed. *Chernobyl* received widespread critical acclaim and became the highest rated TV show in history on some review platforms. The series is a very good example to discuss the operating principle of a nuclear power station, nuclear reactions and the principle of radioactivity[141]. Other major accidents can also be mentioned (Three Mile Island and Fukushima) in order to discuss the danger of this type of energy. Beyond the chemical aspect of the nuclear power plant, it is possible to encourage students to think about the series. For example, during episode 3, the basement of the plant is successfully drained, but a nuclear meltdown has begun, threatening to contaminate the groundwater. Authorities decide that a heat exchanger is needed under the plant to cool the reactor core and, according to the scientists, all the liquid nitrogen available in the Soviet Union will be required. This can be solved from a chemical engineering point of view, with a simple heat balance between the core of the plant and the nitrogen flowing below the power station as described Equation (4):

$$Q = m_{core}.C_{p,core}.\frac{dT}{dt} = U_{heat\ exchanger}.Surface_{Heat\ Exhanger}.\Delta T_{ml} \quad (4)$$

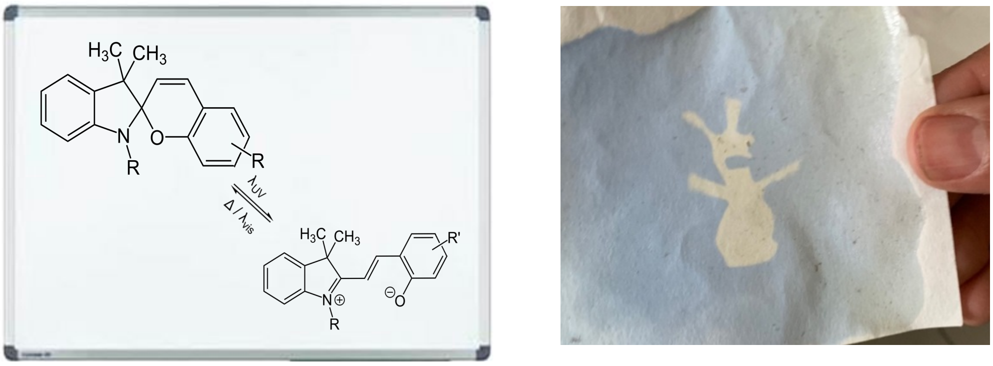
From this balance, the students can estimate, with some hypotheses on the parameters of the reactor core given in the supplementary material, the amount of nitrogen necessary to cool the power station down, from Equation 5:

$$Q = W_{N_2}.C_{p,N_2}.\left(T_{N_2,outlet} - T_{N_2,inlet}\right) \quad (5)$$

This show is thus a good example of the links between chemistry, chemical engineering, reactor design and a recent pop-culture hit that could be used as project or a discussion in the classroom for middle school students' and high school students'.

RABBIDS INVASION

Rabbids Invasions is an animated television series that premiered in 2013[142]. The show is based on the *Raving Rabbids* video game series produced by Ubisoft and created in 2006[143]. Among the hundreds of episodes of *Rabbids invasions,* developed by *TeamTO* for *Ubisoft Motion Pictures*, some, e.g. episode 17 of season 1 ("Rabbid Dreams" by Fabien Ouvrard & Mélanie Duval, 2014), involve scientific observations of those strange creatures. Part of the action takes place in a lab comprising an experiment room separated from a glass-walled observation office, where the scientists Gina and John try to decipher the reaction of a sample rabbit. To make it more realistic, a library of images has been compiled in which the cartoonist has selected the lab's etiquette. Thus, along with the mandatory white lab coats, there is a board covered with scientific formulas, some from physics and some from chemistry. The surprise is that the chemistry ones are complex and related to a specific field of organic chemistry called "photochromism" (reproduced in Figure 5a) and a chemical reaction describing the light-induced coloration of a dye belonging to the spiropyran family is clearly visible[144]. Photochromic dyes are commonly used in sunglasses, to adapt the optical density of the lenses to the surrounding luminosity. However, spiropyran dyes are rather unstable and fade away readily when used intensively. Thus, these dyes are now used for pedagogical or research purposes. A famous example is the commercially available "NitroBIPS", the photochemistry of which can be tested in the teaching lab[145,146]. The one on display in the *Rabbid Invasion* is the "1′,3′-dihydro-8-methoxy-1′,3′,3′-trimethyl-6-nitrospiro[2H-1-benzopyran-2,2′-(2H)-indole", which differs from NitroBIPS by the presence of an extra methoxy group CH_3O on the ring carrying a nitro group NO_2, and is thus more expensive. As *TeamTO* is a French company, it is probably inspired from work of the CEA-Paris that was working on such dyes[147]. The experiments could be done with students, using a polystyrene film and a UV light as depicted in Figure 5.b. This activity is recommended for middle school students', high school students' or even for open days as the reaction is fast and visual. Materials and methods for this activity are detailed in the supplementary information.



(a) (b)

Figure 5. (a) Reproduction of the molecule presented in the Raving Rabbids (b) experiment to illustrate the photochromism of the NitroBIPS molecule with a Raving Rabbid as a blank marker.

DRAGON BALL

Dragon Ball is a Japanese manga franchise written and illustrated by Akira Toriyama originally serialized in Weekly Shōnen Jump magazine from 1984 to 1995[148]. Since its release, Dragon Ball has become one of the most successful manga and anime series of all time, having generated more than $20 billion in total franchise revenue as of 2018. Genki dama (元気玉) is one of the most powerful attacks of Son Goku, the famous hero of the anime (illustrated in Figure 6). It consists of a giant sphere of vital energy provided by all the living cells surrounding Goku. Although similarities seem to exist with the well-known Kamé Hamé Ha (かめかめ波), no real description of its energy nature can be found. While this energy is indeed able to vaporize in some of the anime episodes, this energy also appears as mostly mechanical in others (buildings destruction, etc). One reasonable hypothesis is to assume that it behaves as a blackbody, whose spectral irradiance distribution is given by the Planck distribution. This activity is recommended for middle high school or university students' (Chemical Engineering) as a project or a tutorial with professor.

Thus, let us consider that this sphere is a blackbody of temperature T_{GD}, with a radius r_{GD} = 10 m. Let also assume that the shortest distance between the sphere surface and Son Goku is p = 20 m (see Figure 6). It is also important to note that no value for the temperature T_G seems available but, regarding the visible emission (bright blue) of the Genki dama, a reasonable temperature would be around 6000 K. The radiative emission of Son Goku should also be neglected and Son Goku is assumed to be a cylinder of height $l_2 - l_1 - r_{GD}$ = 1.8 m and radius r_{SG} = 0.3 m. In order to propose an original work to the student, we propose to calculate the net radiative flux from the Genki dama to Son Goku.

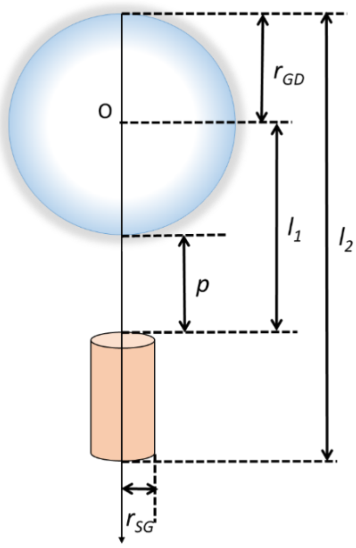


Figure 6. Scheme of the problem

The net radiative flux between two blackbodies is given by the Stefan-Boltzmann radiation law, assuming that both material emissivities are close to 1:

$$q_{GD-SG} = q_{GD\rightarrow SG} - q_{SG\rightarrow GD} \simeq A_{GD}F_{GD-SG}\sigma T_{GD}^4 \qquad (6)$$

With A_{GD} (m²) the total area of the Genki dama, F_{GD-SG} the view factor from the Genki-Dama sphere to Son Goku, assumed as the external surface of a coaxial cylinder (see Figure 6). $\sigma = 5.67 \times 10^{-8}$ W/(m² K⁴) is the Stefan-Boltzmann constant. The resolution of the problem is given in the supplementary section.

As some of these suggested additional activities were not tested in situ with students, they were presented to a panel of students' (N = 35 - Chemistry, Environment and Chemical Engineering – Academic year 2019/2020) during a scientific discussion (2 h) on the links between science and pop-culture in order to evaluate students'. The survey was conducted as an anonymous paper exercise, with students required to strongly agree, agree, neither/neutral, disagree or strongly disagree with a series of 10 statements. The majority of respondents were positive about educational benefits of pop culture with 82% of the respondents agreeing that the use of pop culture was a useful learning activity. More specifically, 75% of the students agreed (or strongly agreed) that pop culture had helped them apply chemistry/chemical engineering in a useful way. Having just discussed about these pop-culture activities, the majority of respondents agreed (78%) that they would appreciate this approach in different subject areas of their cursus. These findings support the high level of student engagement and interaction observed by instructors when pop-culture is used. The data collected show that the majority of students enjoyed discussing science with a pop culture approach, in the open section of the survey some students' recommended to use it at a recreative moment between students' or with educators.

■ DISCUSSION

Pop-culture in classrooms can be beneficial as it creates engaging links between chemical concepts and their applications, and between educators' and students' interests. The objective is not to promote movies or video games but to connect and use the interest of students for these pop culture elements towards learning science. Connection with recent pop culture elements such as those proposed in the present work could be used as support for demonstrating reactions, as side projects, analogies to communicate concepts and/or as a platform to start discussions. Educators need to be careful about inappropriate content depending on the student's age, to avoid spoiling anything for someone reading or watching a show, movie or book, to make sure the science involved is actually correct. It is also important to leave the students free to search chemistry during project in all types of media, recent or not, according to their interests to unleash their curiosity. Finally, pop-culture promotes critical thinking and cultural literacy, which are important skills for students to develop.

CONCLUSION

The present work provides creative and original activities based on pop culture (*e.g.* video games, movies and TV series) to engage chemistry and chemical engineering students. The goal has been to show that chemistry and chemical engineering phenomena are widely present and play an essential role in recent pop culture as typified in the superhero movies, action video games or fantasy drama series. Instructors can stimulate students' interest in these domains by discussing the chemical content of such works during lectures, tutorials, by generating quizzes and assignment items based on occurrences in these videogames and movies, or by creating a stock of scientific trivia collected from popular culture sources. To conclude, pop-culture offers a wide range of possibilities for involving students in classroom, from hands-on activity to critical thinking, and from basic chemistry to chemical engineering.

ASSOCIATED CONTENT

Supporting Information

Fortnite: Making "slurp juice"; Game of Thrones and Harry Potter: Making green fire; Breaking Bad: Synthesizing dexerine; The Black Panther movie: Proposing a process flow diagram for fabrication of "vibranium steel"; Raving Rabbids: Making color-changing paper; Dragon Ball: Calculating the net radiative flux from the Genki Dama to Son Goku (DOCX)

AUTHOR INFORMATION

Nicolas DIETRICH

E-mail: nicolas.dietrich@insa-toulouse.fr
Personal website: ndietrich.com
ORCID: orcid.org/0000-0001-6169-3101

Mélanie JIMENEZ

E-mail: Melanie.Jimenez@glasgow.ac.uk
Personal website: https://jimenezmelanie.weebly.com
Researcher ID: D-8469-2016/ORCID number: 0000-0002-4631-0608

Manuel SOUTO

E-mail: Manuel.Souto@ua.pt
Personal website: https://ciceco.ua.pt/manuelsouto
Researcher ID: D-1014-2017/ORCID number: 0000-0003-3491-6984

Aaron W. HARRISON

E-mail: aharrison@chapman.edu
ORCID: orcid.org/0000-0003-3102-8201

Christophe COUDRET

E-mail: coudret@chimie.ups-tlse.fr
ORCID number: 0000-0001-7334-5112

Note: The authors declare no competing financial interest.

REFERENCES

(1) Skluzacek, J. M.; Harper, J.; Herron, E.; Bortiatynski, J. M. Summer Camp To Engage Students in Nutritional Chemistry Using Popular Culture and Hands-On Activities. *J. Chem. Educ.* **2010**, *87* (5), 492–495. https://doi.org/10.1021/ed8001732.

(2) Clapson, M. L.; Gilbert, B.; Mozol, V. J.; Schechtel, S.; Tran, J.; White, S. ChemEscape: Educational Battle Box Puzzle Activities for Engaging Outreach and Active Learning in General Chemistry. *J. Chem. Educ.* **2020**, *97* (1), 125–131. https://doi.org/10.1021/acs.jchemed.9b00612.

(3) Clauss, A. W. Using Popular Culture To Teach Chemistry. *J. Chem. Educ.* **2009**, *86* (10), 1223. https://doi.org/10.1021/ed086p1223.

(4) Pye, C. C. Chemistry and Song: A Novel Way To Educate and Entertain. *J. Chem. Educ.* **2004**, *81* (4), 507. https://doi.org/10.1021/ed081p507.

(5) Last, A. M. Combining Chemistry and Music To Engage Students' Interest. Using Songs To Accompany Selected Chemical Topics. *J. Chem. Educ.* **2009**, *86* (10), 1202. https://doi.org/10.1021/ed086p1202.

(6) Behrman, E. J. Music and Chemistry. *J. Chem. Educ.* **2005**, *82* (1), 37. https://doi.org/10.1021/ed082p37.1.

(7) Ward, S. J.; Price, R. M.; Davis, K.; Crowther, G. J. Songwriting to Learn: How High School Science Fair Participants Use Music to Communicate Personally Relevant Scientific Concepts. *International Journal of Science Education, Part B* **2018**, *8* (4), 307–324. https://doi.org/10.1080/21548455.2018.1492758.

(8) Crowther, G. J.; Davis, K. Amino Acid Jazz: Amplifying Biochemistry Concepts with Content-Rich Music. *J. Chem. Educ.* **2013**, *90* (11), 1479–1483. https://doi.org/10.1021/ed400006h.

(9) André, J. P. Opera and Poison: A Secret and Enjoyable Approach To Teaching and Learning Chemistry. *J. Chem. Educ.* **2013**, *90* (3), 352–357. https://doi.org/10.1021/ed300445b.

(10) Cobb, C. The Chemistry of Lucrezia Borgia et al. In Characters in Chemistry: A Celebration of the Humanity of Chemistry; American Chemical Society: Washington, DC, **2013;** Chapter 5, pp 61–72; DOI: 10.1021/bk-2013-1136.ch005

(11) Uffelman, E. S. Teaching Science in Art: Technical Examination of 17th-Century Dutch Painting as Interdisciplinary Coursework for Science Majors and Nonmajors. *Journal of Chemical Education* **2007**, *84* (10), 1617–1624.

(12) Nivens, D. A.; Padgett, C. W.; Chase, J. M.; Verges, K. J.; Jamieson, D. S. Art, Meet Chemistry; Chemistry, Meet Art: Case Studies, Current Literature, and Instrumental Methods Combined To Create a Hands-On Experience for Nonmajors and Instrumental Analysis Students. *J. Chem. Educ.* **2010**, *87* (10), 1089–1093. https://doi.org/10.1021/ed100352f.

(13) Burke, S. N.; Farling, C. G.; Svoboda, S. A.; Wustholz, K. L. Research with Undergraduates at the Intersection of Chemistry and Art: Surface-Enhanced Raman Scattering Studies of Oil Paintings. In *Raman Spectroscopy in the Undergraduate Curriculum*; ACS Symposium Series; American Chemical Society, 2018; Vol. 1305, pp 165–180. https://doi.org/10.1021/bk-2018-1305.ch010.

(14) Tallman, K. A. Introducing Students to Fundamental Chemistry Concepts and Basic Research through a Chemistry of Fashion Course for Nonscience Majors. J. Chem. Educ. J. Chem. Educ. **2019**, 96 (9), 1906–1913; DOI: 10.1021/acs.jchemed.8b00826

(15) Samet, C.; Higgins, P. J. Napoleon's Buttons: Teaching the Role of Chemistry in

History. *J. Chem. Educ.* **2005**, *82* (10), 1496. https://doi.org/10.1021/ed082p1496.

(16) Bucholtz, K. M. Spicing Things Up by Adding Color and Relieving Pain: The Use of Napoleon's Buttons in Organic Chemistry. *J. Chem. Educ.* **2011**, *88* (2), 158–161. https://doi.org/10.1021/ed100374w.

(17) Bucholtz, K. M. Historical Examples Integrated into the Organic Chemistry Curriculum. In *Advances in Teaching Organic Chemistry*; ACS Symposium Series; American Chemical Society, 2012; Vol. 1108, pp 131–150. https://doi.org/10.1021/bk-2012-1108.ch009.

(18) Federico, E. D.; Kehlet, C.; Schahbaz, H.; Charton, B. ConfChem Conference on Case-Based Studies in Chemical Education: Chemistry of Pompeii and Herculaneum—A Case Study Course in Chemistry at the Interface of Ancient Technology and Archeological Conservation. *J. Chem. Educ.* **2013**, *90* (2), 264–265. https://doi.org/10.1021/ed200801s.

(19) Beilby, A. L. Art, Archaeology, and Analytical Chemistry: A Synthesis of the Liberal Arts. *J. Chem. Educ.* **1992**, *69* (6), 437. https://doi.org/10.1021/ed069p437.

(20) Giménez, J. Finding Hidden Chemistry in Ancient Egyptian Artifacts: Pigment Degradation Taught in a Chemical Engineering Course. *J. Chem. Educ.* **2015**, *92* (3), 456–462. https://doi.org/10.1021/ed500327j.

(21) Harper, C. S.; Macdonald, F. V.; Braun, K. L. Lipid Residue Analysis of Archaeological Pottery: An Introductory Laboratory Experiment in Archaeological Chemistry. *J. Chem. Educ.* **2017**, *94* (9), 1309–1313. https://doi.org/10.1021/acs.jchemed.7b00225.

(22) Labianca, D. A.; Reeves, W. J. An Interdisciplinary Approach to Science and Literature. *J. Chem. Educ.* **1975**, *52* (1), 66. https://doi.org/10.1021/ed052p66.

(23) Liberko, C. A. Using Science Fiction To Teach Thermodynamics: Vonnegut, Ice-Nine, and Global Warming. *J. Chem. Educ.* **2004**, *81* (4), 509. https://doi.org/10.1021/ed081p509.

(24) Schwartz, A. T. Chemistry Education, Science Literacy, and the Liberal Arts. 2007 George C. Pimentel Award. *J. Chem. Educ.* **2007**, *84* (11), 1750. https://doi.org/10.1021/ed084p1750.

(25) Spillane, N. K. What's Copenhagen Got To Do With Chemistry Class? Using a Play to Teach the History and Practice of Science. *J. Chem. Educ.* **2013**, *90* (2), 219–223. https://doi.org/10.1021/ed2007058.

(26) Herrick, R. S.; Cording, R. K. Using a Poetry Reading on Hemoglobin To Enhance Subject Matter. *J. Chem. Educ.* **2013**, *90* (2), 215–218. https://doi.org/10.1021/ed300129q.

(27) Afonso, A. S.; Gilbert, J. K. The Role of 'Popular' Books in Informal Chemical Education. *International Journal of Science Education, Part B* **2013**, *3* (1), 77–99. https://doi.org/10.1080/21548455.2012.733439.

(28) Kloepper, K. D. Bringing in the Bard: Shakespearean Plays as Context for Instrumental Analysis Projects. *J. Chem. Educ.* **2015**, *92* (1), 79–85. https://doi.org/10.1021/ed500504r.

(29) Harper-Leatherman, A. S.; Miecznikowski, J. R. O True Apothecary: How Forensic Science Helps Solve a Classic Crime. *J. Chem. Educ.* **2012**, *89* (5), 629–635. https://doi.org/10.1021/ed200289t.

(30) Last, A. M. Chemistry in Victorian Detective Fiction: "A Race with the Sun." *J. Chem. Educ.* **2012**, *89* (5), 636–639. https://doi.org/10.1021/ed200110z.

(31) Last, A. M. Chemistry and Popular Culture: The 007 Bond. *J. Chem. Educ.* **1992**, *69* (3), 206. https://doi.org/10.1021/ed069p206.

(32) Copes, J. S. The Chemical Wizardry of J. K. Rowling. *J. Chem. Educ.* **2006**, *83* (10), 1479. https://doi.org/10.1021/ed083p1479.

(33) Waddell, T. G.; Rybolt, T. R. The Chemical Adventures of Sherlock Holmes: The Case of the Screaming Stepfather. *J. Chem. Educ.* **1992**, *69* (12), 999.

https://doi.org/10.1021/ed069p999.

(34) Waddell, T. G.; Rybolt, T. R. The Chemical Adventures of Sherlock Holmes: The Blackwater Escape. *J. Chem. Educ.* **2003**, *80* (4), 401. https://doi.org/10.1021/ed080p401.

(35) Shaw, K. The Chemical Adventures of Sherlock Holmes: The Serpentine Remains. *J. Chem. Educ.* **2008**, *85* (4), 507. https://doi.org/10.1021/ed085p507.

(36) Southward, R. E.; Hollis, W. G.; Thompson, D. W. Precipitation of a Murder: A Creative Use of Strychnine Chemistry in Agatha Christie's The Mysterious Affair at Styles. *J. Chem. Educ.* **1992**, *69* (7), 536. https://doi.org/10.1021/ed069p536.

(37) Hollis, W. G. Jurassic Park as a Teaching Tool in the Chemistry Classroom. *J. Chem. Educ.* **1996**, *73* (1), 61. https://doi.org/10.1021/ed073p61.

(38) Kennepohl, D.; Roesky, H. W. Drawing Attention with Chemistry Cartoons. *J. Chem. Educ.* **2008**, *85* (10), 1355. https://doi.org/10.1021/ed085p1355.

(39) Giese, R. W. Connecting Current Literature, Cartoons, and Creativity: Incorporating Student-Created Cartoons in a Biochemistry Course to Enhance Learning. J. Chem. Educ. **2020**, 97 (2), 462–465; DOI: 10.1021/acs.jchemed.9b00876.

(40) Kakalios, J. The Materials Science of Marvel's The Avengers—Some Assembly Required. In *Hollywood Chemistry*; ACS Symposium Series; American Chemical Society, 2013; Vol. 1139, pp 215–227. https://doi.org/10.1021/bk-2013-1139.ch018.

(41) Szafran, Z.; Pike, R. M.; Singh, M. M. Microscale Chemistry in the Comics. *J. Chem. Educ.* **1994**, *71* (6), A151. https://doi.org/10.1021/ed071pA151.

(42) Carter, H. A. Chemistry in the Comics: Part 1. A Survey of the Comic Book Literature. *J. Chem. Educ.* **1988**, *65* (12), 1029. https://doi.org/10.1021/ed065p1029.

(43) Carter, H. A. Chemistry in the Comics: Part 2. Classic Chemistry. *J. Chem. Educ.* **1989**, *66* (2), 118. https://doi.org/10.1021/ed066p118.

(44) Carter, H. A. Chemistry in the Comics: Part 3. The Acidity of Paper. *J. Chem. Educ.* **1989**, *66* (11), 883. https://doi.org/10.1021/ed066p883.

(45) Carter, H. A. Chemistry in the Comics: Part 4. The Preservation and Deacidification of Comic Books. *J. Chem. Educ.* **1990**, *67* (1), 3. https://doi.org/10.1021/ed067p3.

(46) Ruekberg, B. A Chemistry Tidbit for Batman Fans. *J. Chem. Educ.* **2010**, *87* (10), 1017–1018. https://doi.org/10.1021/ed1003228.

(47) Di Raddo, P. Teaching Chemistry Lab Safety through Comics. *J. Chem. Educ.* **2006**, *83* (4), 571. https://doi.org/10.1021/ed083p571.

(48) Kumasaki, M.; Shoji, T.; Wu, T.-C.; Soontarapa, K.; Arai, M.; Mizutani, T.; Okada, K.; Shimizu, Y.; Sugano, Y. Presenting Safety Topics Using a Graphic Novel, Manga, To Effectively Teach Chemical Safety to Students in Japan, Taiwan, and Thailand. *J. Chem. Educ.* **2018**, *95* (4), 584–592. https://doi.org/10.1021/acs.jchemed.7b00451.

(49) Frey, C. A.; Mikasen, M. L.; Griep, M. A. Put Some Movie Wow! In Your Chemistry Teaching. *J. Chem. Educ.* **2012**, *89* (9), 1138–1143. https://doi.org/10.1021/ed300092t.

(50) Baños i Díez, J. E.; Bosch Llonch, F. Using Feature Films as a Teaching Tool in Medical Schools. Educación Médica. **2015**, 6(4), 206-11. http://dx.doi.org/10.1016/j.edumed.2015.09.001.

(51) Goll, J. G.; Woods, B. J. Teaching Chemistry Using the Movie Apollo 13. *J. Chem. Educ.* **1999**, *76* (4), 506. https://doi.org/10.1021/ed076p506.

(52) Goll, J. G.; Wilkinson, L. J.; Snell, D. M. Teaching Chemistry Using October Sky. *J. Chem. Educ.* **2009**, *86* (2), 177. https://doi.org/10.1021/ed086p177.

(53) Bormanis, A. Science Fictions and Fictional Science: A Brief Tour of Science in the Star Trek Universe. In *Hollywood Chemistry*; ACS Symposium Series; American Chemical Society, 2013; Vol. 1139, pp 17–24. https://doi.org/10.1021/bk-2013-1139.ch002.

(54) Wink, D. J. "Almost Like Weighing Someone's Soul": Chemistry in Contemporary Film. *J. Chem. Educ.* **2001**, *78* (4), 481. https://doi.org/10.1021/ed078p481.

(55) Griep, M. A.; Mikasen, M. L. Based on a True Story: Using Movies as Source

Material for General Chemistry Reports. *J. Chem. Educ.* **2005**, *82* (10), 1501. https://doi.org/10.1021/ed082p1501.

(56) Taarea, D.; Thomas, N. C. The Elements Go to the Movies. *J. Chem. Educ.* **2010**, *87* (10), 1056–1059. https://doi.org/10.1021/ed1002543.

(57) Stengler, E. Beyond Teaching and Learning: Bringing Together Science and Society with and through Movies. In *Hollywood Chemistry*; ACS Symposium Series; American Chemical Society, 2013; Vol. 1139, pp 289–297. https://doi.org/10.1021/bk-2013-1139.ch024.

(58) Nelson, D. J., Grazier, K. R., Paglia, J., Perkowitz,. *Hollywood Chemistry: When Science Met Entertainment*; 2013.

(59) Collins, S. N.; Appleby, L. Black Panther, Vibranium, and the Periodic Table. *J. Chem. Educ.* **2018**, *95* (7), 1243–1244. https://doi.org/10.1021/acs.jchemed.8b00206.

(60) King, D. The Science (and the Scientists) Behind 'Ant-Man' - The New York Times. 2018.

(61) Allain, R. The Physics of Spider-Man's Webs. *Wired*. April 29, 2014.

(62) Slabaugh, W. H. Trends in Instruction of Chemistry by Films and Television. *J. Chem. Educ.* **1959**, *36* (12), 588. https://doi.org/10.1021/ed036p588.

(63) Clark, T. M.; Cervenec, J.; Mamais, J. "The Price Is Right" for Your Classroom. *J. Chem. Educ.* **2011**, *88* (4), 428–431. https://doi.org/10.1021/ed100224w.

(64) Li, R.; Orthia, L. A. Communicating the Nature of Science Through The Big Bang Theory: Evidence from a Focus Group Study. *International Journal of Science Education, Part B* **2016**, *6* (2), 115–136. https://doi.org/10.1080/21548455.2015.1020906.

(65) Cass, S.; Grazier, K. R.; Thompson, B.; Marrinan, C. Constructing Crimes: How the CSI Effect Is Created. In *Hollywood Chemistry*; ACS Symposium Series; American Chemical Society, 2013; Vol. 1139, pp 145–151. https://doi.org/10.1021/bk-2013-1139.ch012.

(66) Orthia, L. A.; Dobos, A. R.; Guy, T.; Kan, S. Z.; Keys, S. E.; Nekvapil, S.; Ngu, D. H. Y. How Do People Think About the Science They Encounter in Fiction? Undergraduates Investigate Responses to Science in The Simpsons. *International Journal of Science Education, Part B* **2012**, *2* (2), 149–174. https://doi.org/10.1080/21548455.2011.610134.

(67) Milanick, M. A.; Prewitt, R. L. Fact or Fiction? General Chemistry Helps Students Determine the Legitimacy of Television Program Situations. *J. Chem. Educ.* **2013**, *90* (7), 904–906. https://doi.org/10.1021/ed300155p.

(68) Millard, J. T. Television Medical Dramas as Case Studies in Biochemistry. *J. Chem. Educ.* **2009**, *86* (10), 1216. https://doi.org/10.1021/ed086p1216.

(69) Costa, M. J. CARBOHYDECK: A Card Game To Teach the Stereochemistry of Carbohydrates. *J. Chem. Educ.* **2007**, *84* (6), 977. https://doi.org/10.1021/ed084p977.

(70) Nowosielski, D. A. Use of a Concentration Game for Environmental Chemistry Class Review. *J. Chem. Educ.* **2007**, *84* (2), 239. https://doi.org/10.1021/ed084p239.

(71) Roštejnská, M.; Klímová, H. Biochemistry Games: AZ-Quiz and Jeopardy! *J. Chem. Educ.* **2011**, *88* (4), 432–433. https://doi.org/10.1021/ed100231r.

(72) Domínguez, A.; Saenz-de-Navarrete, J.; de-Marcos, L.; Fernández-Sanz, L.; Pagés, C.; Martínez-Herráiz, J.-J. Gamifying Learning Experiences: Practical Implications and Outcomes. *Computers & Education* **2013**, *63*, 380–392. https://doi.org/10.1016/j.compedu.2012.12.020.

(73) Silva, D. de M.; Ribeiro, C. M. R. Analogue Three-Dimensional Memory Game for Teaching Reflection, Symmetry, and Chirality to High School Students. *J. Chem. Educ.* **2017**. https://doi.org/10.1021/acs.jchemed.7b00219.

(74) Triboni, E.; Weber, G. MOL: Developing a European-Style Board Game To Teach Organic Chemistry. *J. Chem. Educ.* **2018**, *95* (5), 791–803. https://doi.org/10.1021/acs.jchemed.7b00408.

(75) Adair, B. M.; McAfee, L. V. Chemical Pursuit: A Modified Trivia Board Game. *J.*

Chem. Educ. **2018**, *95* (3), 416–418. https://doi.org/10.1021/acs.jchemed.6b00946.

(76) da Silva Júnior, J. N.; Santos de Lima, P. R.; Sousa Lima, M. A.; Monteiro, Á. C.; Silva de Sousa, U.; Melo Leite Júnior, A. J.; Vega, K. B.; Alexandre, F. S. O.; Monteiro, A. J. Time Bomb Game: Design, Implementation, and Evaluation of a Fun and Challenging Game Reviewing the Structural Theory of Organic Compounds. J. Chem. Educ. 2020, 97 (2), 565–570; DOI: 10.1021/acs.jchemed.9b00571

(77) Iribe, J.; Hamada, T.; Kim, H.; Voegtle, M.; Bauer, C. A. Rolling the Dice: Modeling First- and Second-Order Reactions via Collision Theory Simulations in an Undergraduate Laboratory. *J. Chem. Educ.* **2020,** 97 (3), 764–771. https://doi.org/10.1021/acs.jchemed.9b00657.

(78) Yayon, M.; Rap, S.; Adler, V.; Haimovich, I.; Levy, H.; Blonder, R. Do-It-Yourself: Creating and Implementing a Periodic Table of the Elements Chemical Escape Room. *J. Chem. Educ.* **2020**, *97* (1), 132–136. https://doi.org/10.1021/acs.jchemed.9b00660.

(79) da Silva Júnior, J. N.; Sousa Lima, M. A.; Silva de Sousa, U.; do Nascimento, D. M.; Melo Leite Junior, A. J.; Vega, K. B.; Roy, B.; Winum, J.-Y. Reactions: An Innovative and Fun Hybrid Game to Engage the Students Reviewing Organic Reactions in the Classroom. *J. Chem. Educ.* **2020**, 97, 3, 749–753. https://doi.org/10.1021/acs.jchemed.9b01020.

(80) da Silva Júnior, J. N.; Uchoa, D. E. de A.; Sousa Lima, M. A.; Monteiro, A. J. Stereochemistry Game: Creating and Playing a Fun Board Game To Engage Students in Reviewing Stereochemistry Concepts. *J. Chem. Educ.* **2019**, *96* (8), 1680–1685. https://doi.org/10.1021/acs.jchemed.8b00897.

(81) Sousa Lima, M. A.; Monteiro, Á. C.; Melo Leite Junior, A. J.; de Andrade Matos, I. S.; Alexandre, F. S. O.; Nobre, D. J.; Monteiro, A. J.; da Silva Júnior, J. N. Game-Based Application for Helping Students Review Chemical Nomenclature in a Fun Way. *J. Chem. Educ.* **2019**, *96* (4), 801–805. https://doi.org/10.1021/acs.jchemed.8b00540.

(82) da Silva Júnior, J. N.; Sousa Lima, M. A.; Nunes Miranda, F.; Melo Leite Junior, A. J.; Alexandre, F. S. O.; de Oliveira Assis, D. C.; Nobre, D. J. Nomenclature Bets: An Innovative Computer-Based Game To Aid Students in the Study of Nomenclature of Organic Compounds. *J. Chem. Educ.* **2018**, *95* (11), 2055–2058. https://doi.org/10.1021/acs.jchemed.8b00298.

(83) Dietrich, N. Chem and Roll: A Roll and Write Game To Illustrate Chemical Engineering and the Contact Process. *J. Chem. Educ.* **2019**, 96 (6), 1194–1198. https://doi.org/10.1021/acs.jchemed.8b00742.

(84) Battersby, G. L.; Beeley, C.; Baguley, D. A.; Barker, H. D.; Broad, H. D.; Carey, N. C.; Chambers, E. S.; Chodaczek, D.; Blackburn, R. A. R.; Williams, D. P. Go Fischer: An Introductory Organic Chemistry Card Game. *J. Chem. Educ.* **2020**, 97 (8), 2226–2230. https://doi.org/10.1021/acs.jchemed.0c00504.

(85) Estudante, A.; Dietrich, N. Using Augmented Reality to Stimulate Students and Diffuse Escape Game Activities to Larger Audiences. *J. Chem. Educ.* **2020**, 97 (5), 1368–1374. https://doi.org/10.1021/acs.jchemed.9b00933.

(86) Monnot, M.; Laborie, S.; Hébrard, G.; Dietrich, N. New Approaches to Adapt Escape Game Activities to Large Audience in Chemical Engineering: Numeric Supports and Students' Participation. *Education for Chemical Engineers* **2020**, 32, 50–58. https://doi.org/10.1016/j.ece.2020.05.007.

(87) Brassinne, K.; Reynders, M.; Coninx, K.; Guedens, W. Developing and Implementing GAPc, a Gamification Project in Chemistry, toward a Remote Active Student-Centered Chemistry Course Bridging the Gap between Precollege and Undergraduate Education. *J. Chem. Educ.* **2020**, 97(8), 2147–2152. https://doi.org/10.1021/acs.jchemed.9b00986.

(88) Vergne, M. J.; Simmons, J. D.; Bowen, R. S. Escape the Lab: An Interactive Escape-Room Game as a Laboratory Experiment. *J. Chem. Educ.* **2019**, 96 (5), 985–991. https://doi.org/10.1021/acs.jchemed.8b01023.

(89) Vergne, M. J.; Smith, J. D.; Bowen, R. S. Escape the (Remote) Classroom: An Online Escape Room for Remote Learning. *J. Chem. Educ.* **2020**, 97 (9), 2845–2848. https://doi.org/10.1021/acs.jchemed.0c00449.

(90) Dietrich, N.; Wongwailikhit, K.; Mei, M.; Xu, F.; Felis, F.; Kherbeche, A.; Hébrard, G.; Loubière, K. Using the “Red Bottle” Experiment for the Visualization and the Fast Characterization of Gas–Liquid Mass Transfer. *J. Chem. Educ.* **2019**, *96* (5), 979–984. https://doi.org/10.1021/acs.jchemed.8b00898.

(91) Yang, L.; Dietrich, N.; Hébrard, G.; Loubière, K.; Gourdon, C. Optical Methods to Investigate the Enhancement Factor of an Oxygen-Sensitive Colorimetric Reaction Using Microreactors. *AIChE Journal* **2017**, *63* (6), 2272–2284.

(92) Yang, L.; Loubière, K.; Dietrich, N.; Le Men, C.; Gourdon, C.; Hébrard, G. Local Investigations on the Gas-Liquid Mass Transfer around Taylor Bubbles Flowing in a Meandering Millimetric Square Channel. *Chemical Engineering Science* **2017**, *165*, 192–203. https://doi.org/10.1016/j.ces.2017.03.007.

(93) Dietrich, N.; Mayoufi, N.; Poncin, S.; Midoux, N.; Li, H. Z. Bubble Formation at an Orifice: A Multiscale Investigation. *Chem. Eng. Sci.* **2013**, *92*, 118–125. https://doi.org/10.1016/j.ces.2012.12.033.

(94) Dietrich, N.; Francois, J.; Jimenez, M.; Cockx, A.; Guiraud, P.; Hébrard, G. Fast Measurements of the Gas-Liquid Diffusion Coefficient in the Gaussian Wake of a Spherical Bubble. *Chem. Eng. Technol.* **2015**, *38* (5), 941–946. https://doi.org/10.1002/ceat.201400471.

(95) Xu, F.; Hébrard, G.; Dietrich, N. Comparison of Three Different Techniques for Gas-Liquid Mass Transfer Visualization. *International Journal of Heat and Mass Transfer* **2020**, *150*, 119261. https://doi.org/10.1016/j.ijheatmasstransfer.2019.119261.

(96) Xu, F.; Midoux, N.; Li, H.-Z.; Hébrard, G.; Dietrich, N. Characterization of Bubble Shapes in Non-Newtonian Fluids by Parametric Equations. *Chemical Engineering & Technology* **2019**, 42 (11), 2321-2330. https://doi.org/10.1002/ceat.201800690.

(97) Xu, F.; Cockx, A.; Hébrard, G.; Dietrich, N. Mass Transfer and Diffusion of a Single Bubble Rising in Polymer Solutions. *Ind. Eng. Chem. Res.* **2018**, *57* (44), 15181–15194. https://doi.org/10.1021/acs.iecr.8b03617.

(98) Dietrich, N. Escape Classroom: The Leblanc Process—An Educational “Escape Game.” *J. Chem. Educ.* **2018**, *95* (6), 996–999. https://doi.org/10.1021/acs.jchemed.7b00690.

(99) Burks, R.; Deards, K. D.; DeFrain, E. Where Science Intersects Pop Culture: An Informal Science Education Outreach Program. *J. Chem. Educ.* **2017**, *94* (12), 1918–1924. https://doi.org/10.1021/acs.jchemed.7b00070.

(100) The Video Games’ Industry is Bigger Than Hollywood http://lpesports.com/e-sports-news/the-video-games-industry-is-bigger-than-hollywood (accessed Jul 28, 2019).

(101) Video game https://en.wikipedia.org/w/index.php?title=Video_game&oldid=908034167 (accessed Jul 28, 2019).

(102) Dietrich, N.; Kentheswaran, K.; Ahmadi, A.; Teychené, J.; Bessière, Y.; Alfenore, S.; Laborie, S.; Bastoul, D.; Loubière, K.; Guigui, C.; Sperandio, M.; Barna, L.; Paul, E.; Cabassud, C.; Liné, A.; Hébrard, G. Attempts, Successes, and Failures of Distance Learning in the Time of COVID-19. J. Chem. Educ. 2020, 97 (9), 2448–2457. https://doi.org/10.1021/acs.jchemed.0c00717.

(103) Rovner, S. L. Video Game Aims To Engage Students. *Chem. Eng. News Archive* **2006**, *84* (15), 76–77. https://doi.org/10.1021/cen-v084n015.p076.

(104) Franco, J. Online Gaming for Understanding Folding, Interactions, and Structure. *J. Chem. Educ.* **2012**, *89* (12), 1543–1546. https://doi.org/10.1021/ed200803e.

(105) Winter, J.; Wentzel, M.; Ahluwalia, S. Chairs!: A Mobile Game for Organic Chemistry Students To Learn the Ring Flip of Cyclohexane. *J. Chem. Educ.* **2016**, *93* (9), 1657–1659. https://doi.org/10.1021/acs.jchemed.5b00872.

(106) Cain, J.; Piascik, P. Are Serious Games a Good Strategy for Pharmacy Education? *Am J Pharm Educ* **2015**, *79* (4), 47. https://doi.org/10.5688/ajpe79447.

(107) Barr, M. Video Games Can Develop Graduate Skills in Higher Education Students: A Randomised Trial. *Computers & Education* **2017**, *113*, 86–97. https://doi.org/10.1016/j.compedu.2017.05.016.

(108) Mayer, R. E.; Parong, J.; Bainbridge, K. Young Adults Learning Executive Function Skills by Playing Focused Video Games. *Cognitive Development* **2019**, *49*, 43–50. https://doi.org/10.1016/j.cogdev.2018.11.002.

(109) Smaldone, R. A.; Thompson, C. M.; Evans, M.; Voit, W. Teaching Science through Video Games. *Nature Chemistry* **2016**, *9*, 97–102. https://doi.org/10.1038/nchem.2694.

(110) Isokawa, N.; Fueda, K.; Miyagawa, K.; Kanno, K. Demonstration of the Coagulation and Diffusion of Homemade Slime Prepared Under Acidic Conditions without Borate. *J. Chem. Educ.* **2015**, *92* (11), 1886–1888. https://doi.org/10.1021/acs.jchemed.5b00272.

(111) O'Reilly, J. E. Fluorescence Experiments with Quinine. *J. Chem. Educ.* **1975**, *52* (9), 610. https://doi.org/10.1021/ed052p610.

(112) Sacksteder, L.; Ballew, R. M.; Brown, E. A.; Demas, J. N.; Nesselrodt, D.; DeGraff, B. A. Photophysics in a Disco: Luminescence Quenching of Quinine. *J. Chem. Educ.* **1990**, *67* (12), 1065. https://doi.org/10.1021/ed067p1065.

(113) Coleman, W. F. Featured Molecules: Quinine and Urea. *J. Chem. Educ.* **2003**, *80* (10), 1219. https://doi.org/10.1021/ed080p1219.

(114) Froehlich, P. Fluorescence and Phosphoresence Spectroscopy: Physicochemical Principles and Practice (Schulman, Stephen G.). *J. Chem. Educ.* **1979**, *56* (1), A41. https://doi.org/10.1021/ed056pA41.1.

(115) White, E. H.; Zafiriou, Oliver.; Kagi, H. H.; Hill, J. H. M. Chemilunimescence of Luminol: The Chemcial Reaction. *J. Am. Chem. Soc.* **1964**, *86* (5), 940–941. https://doi.org/10.1021/ja01059a050.

(116) Chalmers, J. H.; Bradbury, M. W.; Fabricant, J. D. A Multicolored Luminol-Based Chemiluminescence Demonstration. *J. Chem. Educ.* **1987**, *64* (11), 969. https://doi.org/10.1021/ed064p969.1.

(117) Martin, T.; Fleissner, J.; Milius, W.; Breu, J. Behind Crime Scenes: The Crystal Structure of Commercial Luminol. *Crystal Growth & Design* **2016**, *16* (5), 3014–3018. https://doi.org/10.1021/acs.cgd.6b00425.

(118) *Game of Thrones* https://en.wikipedia.org/w/index.php?title=Game_of_Thrones&oldid=906921790 (accessed Jul 19, 2019).

(119) *A Game of Thrones* https://en.wikipedia.org/w/index.php?title=A_Game_of_Thrones&oldid=906455223 (accessed Jul 19, 2019).

(120) Zhu, B.; Feng, M.; Lowe, H.; Kesselman, J.; Harrison, L.; Dempski, R. E. Increasing Enthusiasm and Enhancing Learning for Biochemistry-Laboratory Safety with an Augmented-Reality Program. *J. Chem. Educ.* **2018**, *95* (10), 1747–1754. https://doi.org/10.1021/acs.jchemed.8b00116.

(121) Sanger, M. J. Flame Tests: Which Ion Causes the Color? *J. Chem. Educ.* **2004**, *81* (12), 1776A. https://doi.org/10.1021/ed081p1776A.

(122) *Breaking Bad* https://en.wikipedia.org/w/index.php?title=Breaking_Bad&oldid=907809675 (accessed Jul 29, 2019).

(123) Fahy, D. The Chemist as Anti-Hero: Walter White and Sherlock Holmes as Case Studies. In *Hollywood Chemistry*; ACS Symposium Series; American Chemical Society, 2013; Vol. 1139, pp 175–188. https://doi.org/10.1021/bk-2013-1139.ch015.

(124) Dextroamphetamine

https://en.wikipedia.org/w/index.php?title=Dextroamphetamine&oldid=907015456 (accessed Jul 29, 2019).
(125) Cornely, K.; Bennett, N. Thalidomide Makes a Comeback: A Case Discussion Exercise That Integrates Biochemistry and Organic Chemistry. *J. Chem. Educ.* **2001**, *78* (6), 759. https://doi.org/10.1021/ed078p759.
(126) Coleman, W. F. Enantiomer Specificity in Pharmaceuticals. *J. Chem. Educ.* **2004**, *81* (7), 981. https://doi.org/10.1021/ed081p981.
(127) Epstein, J. Weapons of Mass Destruction: It Is All about Chemistry. *J. Chem. Educ.* **2009**, *86* (12), 1377. https://doi.org/10.1021/ed086p1377.
(128) Ober, J.; Krebs, T. Chemical Elements in Fantasy and Science Fiction. *J. Chem. Educ.* **2009**, *86* (10), 1141. https://doi.org/10.1021/ed086p1141.
(129) Martí-Centelles, V.; Rubio-Magnieto, J. ChemMend: A Card Game To Introduce and Explore the Periodic Table While Engaging Students' Interest. *J. Chem. Educ.* **2014**, *91* (6), 868–871. https://doi.org/10.1021/ed300733w.
(130) Hoffman, A.; Hennessy, M. The People Periodic Table: A Framework for Engaging Introductory Chemistry Students. *J. Chem. Educ.* **2018**, *95* (2), 281–285. https://doi.org/10.1021/acs.jchemed.7b00226.
(131) Chapman, K. A Disney Periodic Table Https://Kitchapman.Co.Uk/a-Disney-Periodic-Table/ (accessed Jul 26, 2020).
(132) Osa, R. A. de la. Tabla Periódica DC https://rodrigoalcarazdelaosa.me/blog/2020/07/16/tabla-periodica-dc/ (accessed Jul 26, 2020).
(133) Souto, M, Marvel Periodic Table https://marvelperiodictable.blogspot.com/2020/07/1.html (accessed Jul 26, 2020).
(134) Likert, R. A Technique for the Measurement of Attitudes. *Archives of Psychology* **1932**, *22 140*, 55–55.
(135) Harrison, A. W. Lessons from "Spider-Man": How Video Games Could Change College Science Education. *The Conversation*. 2019.
(136) Jimenez, M.; L. Bridle, H. Angry Pathogens, How to Get Rid of Them: Introducing Microfluidics for Waterborne Pathogen Separation to Children. *Lab on a Chip* **2015**, *15* (4), 947–957. https://doi.org/10.1039/C4LC00944D.
(137) Bernath, P. F. *Spectra of Atoms and Molecules*; Oxford University Press, 2005.
(138) *Angry Birds* (video game) https://en.wikipedia.org/w/index.php?title=Angry_Birds_(video_game)&oldid=914589232 (accessed Sep 8, 2019).
(139) Chia, M. C.; Sweeney, C. M.; Odom, T. W. Chemistry in Microfluidic Channels. *J. Chem. Educ.* **2011**, *88* (4), 461–464. https://doi.org/10.1021/ed1008624.
(140) Vangunten, M. T.; Walker, U. J.; Do, H. G.; Knust, K. N. 3D-Printed Microfluidics for Hands-On Undergraduate Laboratory Experiments. *J. Chem. Educ.* **2020**, *97* (1), 178–183. https://doi.org/10.1021/acs.jchemed.9b00620.
(141) Teeter, C. E. An Introduction to Nuclear Power in a Freshman Chemistry Course. *J. Chem. Educ.* **1970**, *47* (3), 208. https://doi.org/10.1021/ed047p208.
(142) *Rabbids Invasion* https://en.wikipedia.org/w/index.php?title=Rabbids_Invasion&oldid=906885522 (accessed Jul 19, 2019).
(143) *Raving Rabbids* https://en.wikipedia.org/w/index.php?title=Raving_Rabbids&oldid=903130009 (accessed Jul 20, 2019).
(144) Guglielmetti, R.; Meyer, R.; Dupuy, C. Synthesis of a Photochromic Benzothiazolinic Spiropyran. *J. Chem. Educ.* **1973**, *50* (6), 413. https://doi.org/10.1021/ed050p413.
(145) Negri, R. M.; Prypsztejn, H. E. An Experiment on Photochromism and Kinetics for the Undergraduate Laboratory. *J. Chem. Educ.* **2001**, *78* (5), 645.

https://doi.org/10.1021/ed078p645.
(146) Piard, J. Influence of the Solvent on the Thermal Back Reaction of One Spiropyran. *J. Chem. Educ.* **2014**, *91* (12), 2105–2111. https://doi.org/10.1021/ed4005003.
(147) Poisson, L.; Raffael, K. D.; Soep, B.; Mestdagh, J.-M.; Buntinx, G. Gas-Phase Dynamics of Spiropyran and Spirooxazine Molecules. *J. Am. Chem. Soc.* **2006**, *128* (10), 3169–3178. https://doi.org/10.1021/ja055079s.
(148) *Dragon Ball* https://en.wikipedia.org/w/index.php?title=Dragon_Ball&oldid=914364416 (accessed Sep 8, 2019).