Chemistry in the comics: molecular marvels of Iron Man

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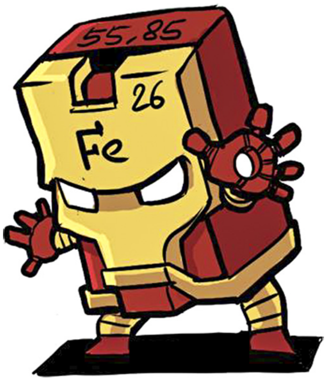
Abstract Chemical evidence is provided to illuminate the innovative armour and marvellous prowess of Iron Man as described in the Marvel comic-book and cinematic universe. Taking a critical-but-fun look at the 'Crimson Dynamo', rational explanations as well as tangential facts are provided to describe the lifestyle, aesthetic choices and teammate collaborations documented in movies and graphic novels about this superhero. In the hope of inspiring students to examine the properties of superheroes through a chemical perspective, the chemistry of iron behind his astonishing tales is distilled to discern fiction from fact and inspire the comic-book fan with chemistry enthusiasm. Ultimately, with a pedagogic intent, a teaching assignment is described in which students employ chemistry concepts to characterise their own superhero creations.

Comic-book superheroes are reaching a wide audience of potential science enthusiasts; their films are grossing billions of dollars worldwide and TV show adaptations of their stories proliferate. Science inspired by fictional icons offers an intriguing means to relate chemical concepts to the comic-book aficionado.[a–h] Amazing chemistry has been a traditional source of inspiration for the creation of superheroes and supervillains in comics. Silver Surfer, Silver Sable, Silver Samurai, Silvermane, Silver Fox, Cobalt Man, Titanium Man and Magneto's Magnetic Men including Cobalt, Antimony, Iron, Bismuth and Nickel… all one needs to do is look at their names to know that chemistry is fundamental to the life of Marvel Comics' superheroes and supervillains. Let's not forget DC Comics share of elemental characters: Silver Banshee, Silver Blade, Booster Gold, Doctor Phosphorus, and the Metal Men including Gold, Iron, Lead, Mercury, Platinum, Tin and their numerous foes and allies.

Focusing on the most popular superhero based on an element of the periodic table, this article presents a critical and amusing overview of the chemistry behind Iron Man. Among the superheroes created out of the elements on the periodic table, including the Man of Steel, Iron Man is undisputedly the most popular chemically sound comic-book idol. There are in-depth reports on the physics (Kakalios, 2009), engineering (Zehr, 2011) and philosophy (White, 2010) of Iron Man. Mixed with, or in the absence of the Avengers, Iron Man has consistently scored blockbuster hits on the big screen, but with all due respect to the acting talents of Robert Downey Jr, comic-book fans who enjoy science know it's the chemistry of iron that gives this superhero his punching power.

The UK has had the largest grossing opening weekend box office outside of North America for all three Iron Man movies.[i] British fandom has even manifested a real-life Iron Man of Wiltshire, where inventor Richard Browning created a personal flight suit that piqued military interest (Knapton, 2017). Furthermore, Colin Furze, the popular inventor, YouTuber and Guinness World Record holder recreated a homemade Iron Man 'Hulkbuster' suit, documented on video seen by over three million viewers worldwide in less than a month.[j]



Although some may argue that the use of standardised testing remains the tried-and-true way to provide a chemical education, innovative methods are becoming more vital to spark interest in scientific subjects (Vreken, McChlery and Visser, 2006). The largest meta-analysis of undergraduate STEM education published to date supports active learning as the preferred, empirically validated teaching practice to increase student performance on examinations and concept inventories (Freeman *et al.*, 2014). In the light of a British education renaissance awakening interest in teaching beyond exam-oriented material (Elias, 2009; Scott, 2013), opportunities exist for Iron Man to fly higher. Analysis of science in comics can supplement and support learning, because popular box-office heroes, such as Iron Man, offer relatable icons for introducing chemistry concepts.

In Canadian classrooms, science and non-science students aged 17 to 19 have been successfully introduced to chemistry concepts through the analysis of superheroes. Considering the popularity of superheroes among British youth, similar teaching techniques may adapt well to UK institutions. The intent of this article is to provide a motivational exercise to engage students to study the fundamental properties of the elements. To provide food for thought for students, teachers and the general-public readership to explore an alternative pedagogic approach to relate science, we strive now to iron out some of the chemistry behind the heavy-metal hero.

Lifestyle

In the live-action movie *The Avengers* (2012), Captain America provokingly asks Iron Man what he is when we take away his armour and Tony Stark proudly describes himself as a '*genius billionaire playboy philanthropist*'. Grossing the biggest solo film of the franchise,[k] Iron Man is naturally magnetic, captivating our interest, probably because the chemistry of iron is richer than Tony Stark. A virtual desire to soak up Iron Man comics parallels our essential nutritional need for iron, the key component of haemoglobin, the substance in red blood cells that carries oxygen from our lungs throughout our body (Figure 1). Although we cannot condone Stark's blatant misogyny,[l] the fact[m] that women need typically 10 mg more iron daily than men raises the question whether Stark's appeal to the ladies stems from their greater need for this essential element. Similarly, in addition to his clueless sexism,[n] Stark's inability to sustain a lasting relationship may be in part due to the toxicity of excess iron. Iron overload increases the risk of heart attack and heart failure,[o] a feeling Tony's heart-broken love-interests may experience when they've had too much of the Iron Man. Imagine if Stark could use Iron Man filters to clean up quips of harassment before they leave his mouth, in the same way that iron chloride, iron sulfate and iron hydroxide have been widely used in sewage system treatment plants (Slater, 1888). Iron Man could make amends to the women who have helped to make him a superhero, such as Bethany Cabe, who helped him surmount his drinking problem in the nine-comic-book story 'Demon in a Bottle' from *Iron Man* volume 1, issues 120–128 in 1979. Stark's affinity for alcohol may however be innately linked to ethanol's ability to increase the body's iron stores, albeit when taken in low quantities (Whitfield *et al.*, 2001).

Armour

If clothes make the man, body armour makes the Iron Man. Since his first appearance in a pure grey suit of bulletproof iron in *Tales of Suspense* issue 39 (1963) (Figure 2), Stark demonstrated mastery of inorganic chemistry by continually improving the performance and aesthetics of his body armour. For example, on his date's suggestion that gold armour would make Iron Man look more like a 'knight in shining armour', Stark probably employed yellow iron oxide $Fe(OH)_3$ pigment (Figure 3) to paint the Mark-2 model suit, described in 'Iron Man versus Gargantus!', *Tales of Suspense* issue 40 (1963). Yellow is, however, a contentious colour for the costume of a superhero. Iron Man's trademark red and gold armour was notably born soon after yellow Iron Man suffered a defeat at the hands of the villain Mister Doll. Stark probably added red iron oxide Fe_2O_3 pigment, commonly known as haematite (Lambourne and Strivens, 1999) to give his suit its classic colours in *Tales of Suspense* issue 48 (1963).

Were there ever to be a fight between Iron Man and Superman (The Man of Steel) in a Marvel/DC cross-over, the latter would be likely to be the victor, because steel is tougher than iron. Although steel is mostly iron, the alloy gains strength from the addition of impurities, such as carbon (for carbon steel), chromium and nickel (for stainless steel), as well as tungsten, chromium, vanadium and molybdenum (for tool steel). Aware of the

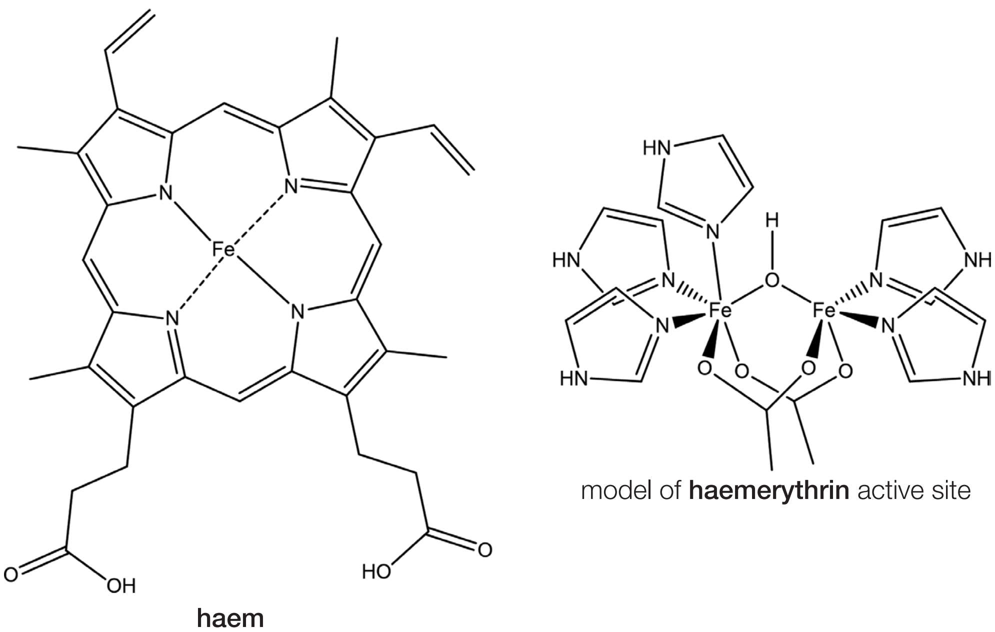


Figure 1 Structures of iron-containing sites of oxygen transporters: haem (left) is found in the protein haemoglobin which circulates in the blood of all vertebrates; haemerythrin showing an active site model (right), which is used to transport oxygen in the blood of certain marine invertebrates. In haemerythrin, the iron is bound within the protein through the carboxylate side chains of the amino acids glutamate and aspartate, as well as through the imidazole side chains of five histidine residues.

Figure 2 First appearances (left to right): Iron Man and his pure grey, iron armour in *Tales of Suspense* issue 39 (1963); gold (yellow) armour in *Tales of Suspense* issue 40 (1963); gold and red armour in *Tales of Suspense* issue 48 (1963)

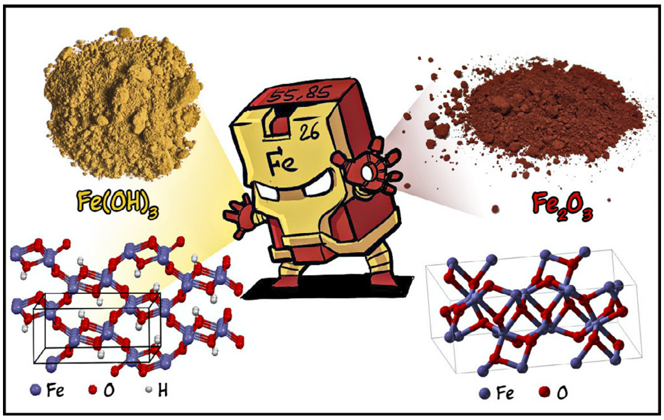


Figure 3 Yellow iron oxide $Fe(OH)_3$ and red iron oxide Fe_2O_3 pigments for a trademark Iron Man armour

chemistry of alloys and materials science, Tony Stark has often modified the composition of the Iron Man suit (Biever and Hooper, 2008). For example, when duelling against Magneto, the master of magnetism (*AVX: VS* issue 1, June 2012), Stark needed to overcome the ferromagnetic properties of iron. To avoid being tossed about like an iron filing in the presence of a magnet, which causes the unpaired electrons in iron atoms to align with those of neighbouring atoms such that the bulk metal becomes magnetised, carbon nanoparticle fibres proved effective. Carbon nanofibres are effective because they have been shown to have twice the stiffness and strength, and 20 times the toughness, of the same weight and length of steel wire (Schwartz, 2005). Moreover, although carbon nanotubes, graphite and related forms of carbon can conduct electricity, they are not ferromagnetic in pure form and thus could give Stark the shielding he desired to fight against this magnetic villain (Céspedes *et al.*, 2004).[p] Retaining an iron constituent, today's suit contains carbon nanoparticle fibres, which among other modern materials make Iron Man's armour stronger and lighter.

Chest power source

Although his past loves may say shrapnel is closest to Tony's heart, Pepper Potts may argue for powerful chemistry. In Tony's chest, a mini fusionreactor keeps him alive and fuels the energy needed to perform extraordinary feats. Although Pepper complained that puss oozed from his chest when they upgraded his reactor to the Mark-III model, Tony corrected her saying: '*It's an inorganic plasmic discharge.*' The tokamak fusion reactor does create large amounts of energy by using magnetic fields to keep in place a torus (doughnut) shaped mass of plasma (ionised gas) (Dini *et al.*, 2010). Tokamak prototypes have been made that fit on a large 3.3 m radius tabletop (Sorbon *et al.*, 2015), but at present only Tony's genius has enabled the arc reactor to be scaled down to fit on his chest.

Teamwork

The team-up between Iron Man and Spider-Man seen in the 2017 blockbuster movie *Spider-Man: Homecoming* ignored the insecticide properties of iron-containing salts such as ferrous arsenate (or iron(II) arsenate), ferric fluoride (or iron(III) fluoride) and ferric fluorosilicates (or iron(III) fluorosilicates) (Frear, 1948), yet offered a chance to compare the strengths of spider silk and steel (Oyen, 2013). When it comes to being torn apart, the tensile strength of spider silk is on par with high-quality steel (respectively about 1.3 and 1.6 GPa); however, silk is almost six times less dense than steel, and thus stronger on a per-weight basis. On the other hand, silk is elastic and lacks the stiffness of steel, which is why Tony Stark offered Peter Parker an iron spider armour in *Amazing Spider-Man* volume 1, issue 529 (2006). Considering the high density and heaviness of steel,[q] Tony Stark probably made the spider armour from ultra-strong, high-aluminium, low-density steel that has a strength-to-weight ratio that matches that of titanium alloys (Kim, Kim and Kim, 2015), which could account for the arachnid hero's ability to smash through Titanium Man's helmet sensors in *Amazing Spider-Man* volume 1, issue 531 (2006).

Surrounding himself with ground-breaking science may have protected Iron Man from harm; moreover, collaboration with other scientists has provided the innovative knowledge to guarantee superiority. Although Tony Stark may have egotistically summed up his role in the team in the live-action movie *Avengers: Age of Ultron* (2015) as '*Actually* [Captain America] *is the boss. I just pay for everything, and design everything, and make everyone look cooler*', Iron Man exhibits a collaborative spirit as natural and life sustaining as iron coordination chemistry (Raymond, Allred and Sia, 2015). To the Avengers' scientific team, Tony Stark and Bruce Banner have recruited other world-renowned scientists, including biologist Elizabeth 'Betty' Ross, astrophysicist Dr Jane Foster as well as entomologist and physicist Dr Henry 'Hank' Pym (also known as Ant-Man). Their collective expertise has been the critical mass for creating chemistry having multiple medicinal, environmental and industrial applications.

Conclusion

Evidently, Iron Man has an undercover mission to arouse public curiosity about chemistry. Fighting the most treacherous villain of all, ignorance, by his superhero combination of molecular forces, our comic-book superhero has unlimited powers. The atomic and molecular forces behind such qualities merit further investigation. To uncover the chemistry behind such brilliance, like all good comic books, our story remains, to be continued…

Leading discussion questions

Noting that the chemistry of iron may be beyond the learning objectives for students at this stage in their education, the text above is oriented to enhance reading and comprehension skills, for which the following questions are provided for individual or group analysis and discussion.

1. What other chemical compounds could be used to obtain the red and yellow colours of Iron Man's suit?
2. By improving his suit, Iron Man mixed other elements with iron to truly become a man of steel. What variations in the chemical composition of steel would you suggest to obtain metal alloys with different properties? How would you make *Game of Thrones*' Valyrian steel?
3. Which symptoms will result from a low storage of iron in your body? In which ways is iron lost by the body? Can our bodies produce iron itself?
4. Explain why some animals, such as the horseshoe crab, do not have red-coloured blood.

Elemental Superhero class project

The above text on the chemistry of Iron Man is designed to reach out to students by stirring scientific interest and triggering discussion as a preamble to the following active learning 'Elemental Superhero' class project. In accordance with the progression of Bloom's taxonomy for learning,[r] students are invited to use information learned, in and outside of class, and draw connections among science and fiction. Furthermore, they are introduced to the peer reviewing of classmates' work to ultimately create an original chemically anchored product.

The Elemental Superhero class project has been performed with three groups, each of 42 students, aged 17–20 years, registered in a science complementary course offered to non-science learners. Prior discussion using a popular known superhero, such as Iron Man, was found to effectively engage students to create a chemistry-based character. The steps of this class project presented below are aimed at motivating students to document the potential and limits of different elements of the periodic table.

The class is divided into two groups; each student chooses an element from the periodic table to create a fictional character that personifies the chosen atom, either as a superhero or a supervillain. Three descriptive properties of the elemental character must be given to highlight appearance (including costume, armour or weapons), behaviour and superpower that link with the properties of the chosen element. In the case of Iron Man, the appearance of his armour is influenced by iron oxide pigments to colour the armour red and yellow. The drinking habits of Tony Stark may be attributed to ethanol's ability to increase body iron stores. Among many iron-based powers, Iron Man exhibits great tensile strength. Examples of characters created by students included the following.

- **Sulfa-Woman** has yellow curly hair due to the colour of solid yellow sulfur and the S–S cross-links in the hair protein keratin. A loner, probably because of her pungent breath that exhales SO_2, Sulfa-Woman has elastic powers due to the plasticising effects of liquid S_8 sulfur.[s]

- **Henry-Helium** is well dressed, in keeping with his noble character, in a suit that looks bright yellow from afar (as do planets with an atmosphere of concentrated helium), but on a closer look appears soft peach and orange coloured (characteristic of heated helium in a tube). A squeaky voice and inert face are only two reasons why Henry-Helium does not interact well with others. Able to levitate like an air blimp, Henry-Helium derives his superpower from the low density of helium gas.
- **The Carbonator** is a muscular warrior, who wears diamond armour, but is always dirty, because soot (charcoal ash) often forms from oxidation of his body. Among the super powers, The Carbonator has the ability to slide using graphite lubricant under his boots and to smash his opponents with diamond toughness.

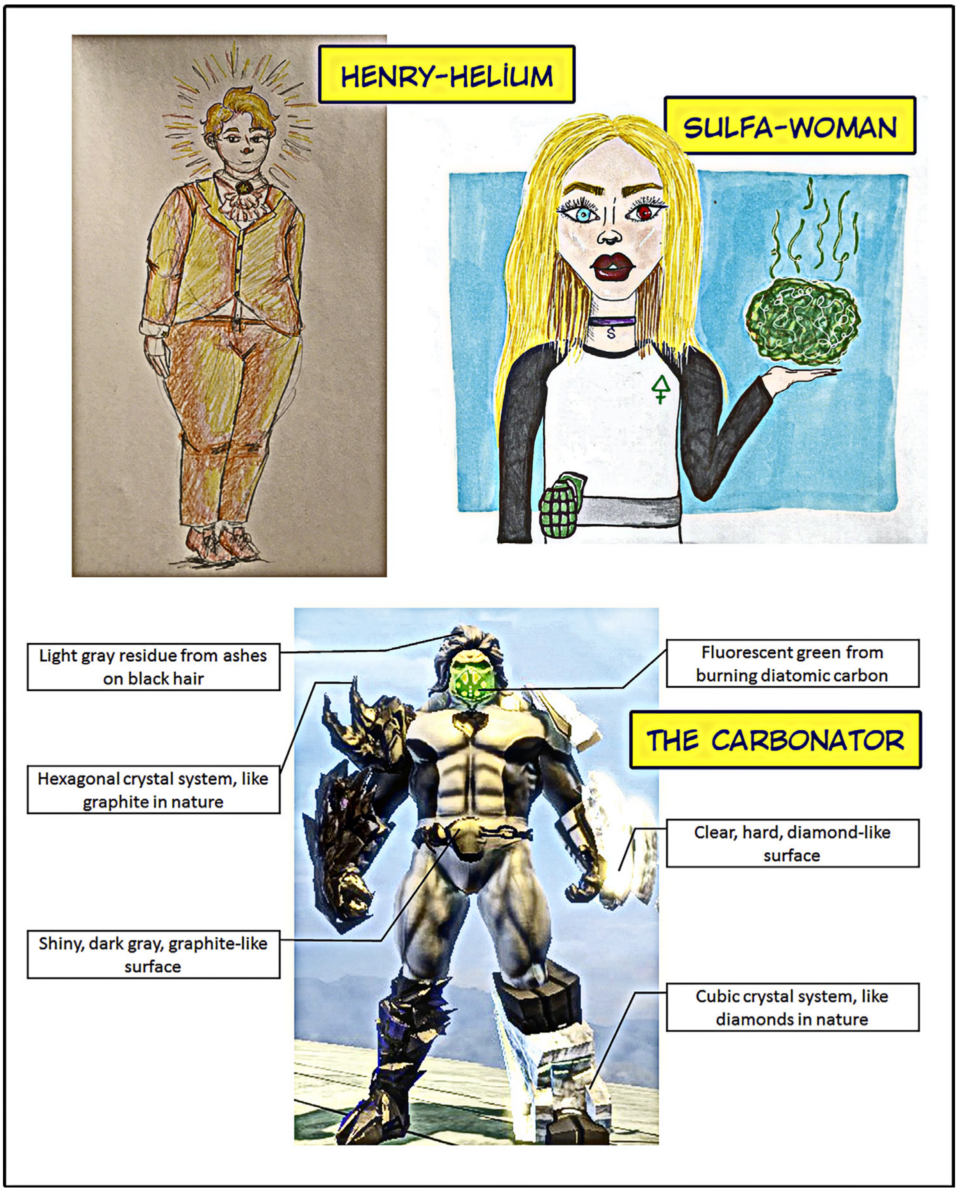


Figure 4 Elemental Superhero class project illustrations by students: Henry-Helium, Sulfa-Woman and The Carbonator

With the spirit of constructive criticism, every student is asked to add two properties to another student's elemental character. The peer-review process can be carried out using simple Bristol boards (https://en.wikipedia.org/wiki/Bristol_board) and markers, but can also be taken outside the classroom by using an online interactive collaboration platform, such as *Visual Classrooms*,[t] on which students have directly posted their comments below the description of their peers' character to facilitate the organisation and exchange. Analysis of their colleagues' notes has improved character design through feedback. To facilitate their independent research, the teacher may suggest references: for example, Theodore Gray's *Photographic Periodic Table of the Elements*[u] or the *Periodic Table of Videos*.[v]

Each student is required to draw their character (Figure 4). Noting that student skills vary, the web-based character creation software of the *DC Universe Online*[w] video game has been allowed as a digital option for producing drawings of the elemental character (Figure 4, The Carbonator).

Students are next required to pair-up to find their character's nemesis and form a superhero vs supervillain team. Each team is required to describe a 'reactive encounter' between their two characters. Examples of reactive encounters involving characters illustrated in Figure 4 include the following.

Sulfa-Woman produces hydrogen sulfide to disable the hydrogen bomb preparation of Dr Hydrogen. Without bonding, Henry-Helium and Neve-Neon mingle to form a HeNe laser that is used to excite the bullying Xenon-Man until he floats into space. The Carbonator is set aflame by the evil Combustionatrix Oxy-Jean, but uses the resulting carbon dioxide to suffocate his adversary.

Finally, students are asked to produce a 1000 word essay depicting the adventures of the two characters, using the chemistry of their respective elements. A maximum word count is suggested, noting some students may write sagas that lose track of the chemical aspect originally intended. For example, students have often described tangentially the origins of their character's powers from the chosen element, and needed to be reminded that such justification may be superfluous, because the focus of the project is to extrapolate on chemical properties and reactivity of the chosen atom.

Without any prior comic-book knowledge, chemistry students have been engaged successfully by this pedagogic project that brings down boundaries between the arts and sciences to liven up discussion about elements and their reactivity.

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