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Using superheroes such as Hawkeye, Wonder Woman and the Invisible Woman in the physics classroom

Barry W Fitzgerald

Department of Process & Energy, Delft University of Technology, Delft, Netherlands

E-mail: barry.w.fitzgerald@gmail.com and b.fitzgerald@tudelft.nl

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Abstract

Communication of difficult concepts in the physics classroom can be negatively affected by the absence of a strong link between physics content and the experiences or interests of students. One possible method towards addressing this issue is to motivate physics content with reference to popular culture figures such as superheroes. We find ourselves in an age where superhero films are immensely popular with numerous superhero films scheduled for release over the coming years. With many students familiar with many of these characters and their superpowers, superheroes can facilitate a unique platform to aid in the dissemination of physics materials in the classroom. In this paper, we present three examples where superheroes can be used to motivate learning objectives in physics and, if desired, promote critical thinking on behalf of the student. We also reflect on how using the superhero genre in the classroom can be used to address underrepresentation of women, stereotyping, and diversity issues in physics.

1. Introduction

The popularity of superhero films is evident from their gross box office receipts at the cinema. For example, the 2012 film *The Avengers* [1] grossed more than $1.5 billion while the 2016 film *Captain America: Civil War* [2] made more than $1.1 billion at cinemas around the world. Although superheroes originate from comic book publications, most superheroes are best known for their film appearances. The majority of students will at the very least be familiar with the names of the superheroes if they have not already seen the films.

Superheroes are inherently associated with superpowers as they are capable of amazing feats that we do not see on a daily basis [3]. While many people may dream about having superpowers, most are quick to dispel their hopes citing that such powers are fundamentally fictional. Nevertheless, current scientific research could be used in the future to develop technologies that mimic or even match the powers of characters such as the Invisible Woman, Wonder Woman and Spider-Man [3]. Undoubtedly, the field of physics will play a key role in the development of these potential technologies.

From an educational point of view the superhero genre can be used as a valuable cultural link for teachers and demonstrators [3–8]. As many students are familiar with the superhero characters and their associated films, the use of such popular science references in the classroom can act as a source of helpful examples for the explanation of physics concepts. In addition, superheroes can promote the societal importance of specific physics concepts in both the fictional world of the superhero and also in the real world of the student. The superhero genre can also serve to inspire teachers in the formulation of assignments or test problems and inspire students in developing ideas for potential in-class or extracurricular activities [4, 5].

In this paper, we outline three different approaches towards including superheroes in the physics classroom. These examples apply to three different aspects of a physics syllabus; namely vectors and linear motion, energy and energy conservation and, optics and refraction. For each example a brief description of the superhero's powers is presented. Thereafter, a method for including the superhero and their superpowers within a physics topic is proposed. We outline sample problems or experiments for the classroom based on the topic of superheroes. We then reflect on issues with regards to underrepresentation in terms of gender and diversity and how the use of superheroes in the classroom could alleviate these effects. In the conclusions, we reflect on the societal impact of physics using the context of superheroes.

2. Superheroes and physics

In this section we will present three examples of the use of superheroes to complement existing educational materials in the physics classroom. These examples apply to linear motion, energy principles, and optics.

2.1. Hawkeye and linear motion

Hawkeye or Clint Barton is a member of the superhero team The Avengers. Portrayed by Jeremy Renner, the character has appeared in a number of superhero films in the Marvel Cinematic Universe (MCU) including *The Avengers* [1], *Captain America: Civil War* [2] and *Avengers: Infinity War* [9]. As a master archer, Hawkeye is incredibly accurate with his bow-and-arrow, an ability that is facilitated by his advanced eyesight. His eyesight can be attributed to his physiological similarities with birds of prey such as advanced accommodative mechanisms, a larger density of photoreceptor cells in comparison to the average human and two foveae located in his retinae. Further details on the advanced physiology of Hawkeye and his eyesight can be found in a previous publication [4].

While it is possible to use Hawkeye and his advanced eyesight to discuss the optics of the eye, we will instead focus on using the character to aid in the presentation of concepts related to linear motion. Prior to studying forces and Newton's laws of motion, it is imperative for a student to understand and apply the fundamental principles of linear motion. Implicit to linear motion are both scalar and vector measures. Traditional examples used to cover concepts in linear motion utilise transport vehicles such as cars [10], ships, trucks or aeroplanes, which are robust and of particular relevance for the subject of linear motion. While these cases are representative of the real world, they do not always present the content in a stimulating manner for the student.

To use Hawkeye in an explanation of the concepts of linear motion, we consider a scene from the 2012 film *The Avengers* [1]. The scene is illustrated in figure 1. Hawkeye, indicated as the purple bow-and-arrow icon, is perched on a building on Park Avenue, which is close to Grand Central Terminal, in New York City. In the scene, Black Widow (the black icon), another member of the Avengers, is chased by Loki (the green icon), the main antagonist of the film, on East 42nd Street. Both Black Widow and Loki are flying alien gliders. In need of urgent assistance, Black Widow contacts Hawkeye indicating that she is in trouble. At the instant Hawkeye sees the two gliders for the first time, the camera zooms in on the gliders giving the audience an impression of the functionality of Hawkeye's advanced vision. As the gliders fly towards Hawkeye's position on Park Avenue, he assures Black Widow that he has successfully tracked and targeted Loki's glider by exclaiming 'I got him'. Once Loki's glider gets close enough to Hawkeye's position, Hawkeye fires an arrow. As an Asgardian god, Loki has advanced reflexes and catches the arrow. However, the arrow is a trick arrow and

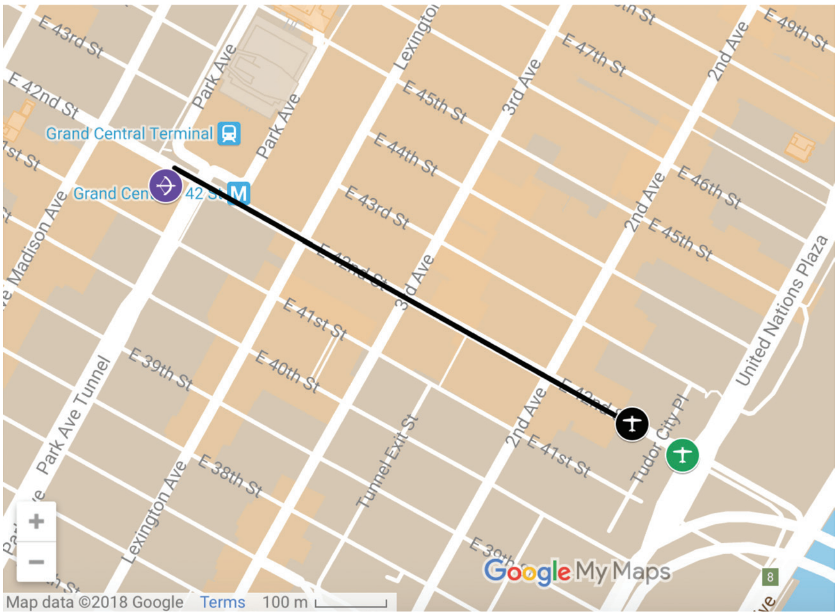

Figure 1. Illustration of the scene in New York City from the 2012 film *The Avengers*. Hawkeye is the purple bow-and-arrow icon on the building near the Grand Central Terminal. Black Widow and Loki, who are both flying alien gliders on East 42nd Street, are represented as the black and green icons, respectively. The straight black line along 42nd Street from Hawkeye to Black Widow is a measure of the distance from Hawkeye to Black Widow at the instance that Hawkeye initially sees Black Widow. This distance is approximately 700 m. Map data © 2018 Google.

subsequently explodes, destroying Loki's glider and facilitating Black Widow's escape.

This memorable scene from *The Avengers* [1] can provide the educator with an interesting platform for the discussion of concepts related to vectors and linear motion. We will first consider how this scene can be used to distinguish between *scalar* and *vector* quantities. From the film, we have estimated the approximate positions of Black Widow and Loki relative to Hawkeye at the start of the scene. Figure 1 includes a black line joining Hawkeye to Black Widow at approximately the instance that Hawkeye first sees her glider. For this particular snapshot, the black line represents the scalar distance between Hawkeye and Black Widow as measured using the Google MyMaps distance ruler. In reality, the distance between the characters would not be along a straight line parallel to East 42nd Street. Nonetheless, this assumption is more than appropriate for this example. The black line between Hawkeye and Black Widow represents a *scalar* measure of approximately 700 m, which is the magnitude of the distance between the characters, expressed in units of metres and has no associated direction.

As Black Widow and Loki fly towards Grand Central Terminal and Hawkeye's position on Park Avenue, Hawkeye remains stationary. Thus, he has zero velocity and no vector associated with his motion. On the other hand, both Black Widow and Loki have non-zero velocities as they fly towards Hawkeye's position on Park Avenue. The motion of Black Widow and Loki have associated directions along East 42nd Street. In other words, Black Widow's *vector*, indicating her direction of motion, is pointed along the black line towards Hawkeye's position. This scene provides a unique example where the difference between vector and scalar quantities can be explored in the classroom environment and motivate further discussion among students.

On the subject of kinematics, this scene from *The Avengers* can provide a wealth of options for numerical problems in the classroom. We now outline two possible numerical problems. First, we consider Black Widow's motion as she moves towards Hawkeye. At the instance Hawkeye sees Black Widow for the first time, she is 700 m away from Hawkeye. We denote this distance as $d_{\mathrm{wh}} = 700$ m and assume that Black Widow is travelling at a constant velocity $v_{\mathrm{w}} = 200$ km h^{-1}. Using these measures the student can calculate the time that it takes for Black Widow to reach Hawkeye's position on Park Avenue. While the velocity of Black Widow's glider might seem a little excessive, it is important to remember that it is an alien technology and thus can be capable of all manner of velocities. This problem allows the teacher or demonstrator to check the student's ability to convert measures to SI units and their understanding of the relationship between velocity, distance and time.

A second problem is related to a later part of the same scene in *The Avengers* [1] where Hawkeye fires an explosive trick arrow at Loki. Although Loki catches the arrow it subsequently explodes, thus destroying his glider. This situation from the film is illustrated in figure 2. Hawkeye, indicated as the purple icon, stands on a building ready to fire an arrow at Loki, indicated as the green icon. Loki follows a straight line path as indicated by the directional arrow. Given that Loki is a moving target, Hawkeye must account for Loki's motion when firing the arrow. Hence, Hawkeye must fire the arrow before Loki reaches a certain point to successfully hit Loki with the arrow. The red diamond indicates the point of intersection (POI) or the point where Loki catches the arrow. We will simplify the problem by assuming that the arrow moves in a straight line upon release from the bow and does not follow a curved path due to gravity. In addition, we assume that the arrow rapidly accelerates to a maximum velocity $v_{\mathrm{arrow}} = 100$ m s^{-1} upon release and there is negligible hydrodynamic drag on the arrow.

For the first part of the calculation we calculate d_{arrow}, the distance the arrow travels from Hawkeye's position to the POI. We have studied the film *The Avengers* [1] in detail and estimate the time of flight for the arrow to travel from Hawkeye's bow to the POI as $t_{\mathrm{arrow}} = 2$ s. Therefore $d_{\mathrm{arrow}} = v_{\mathrm{arrow}} t_{\mathrm{arrow}} = 200$ m. Having calculated the distance travelled by the arrow, the student can then explore further the motion of Loki relative to Hawkeye's stationary position. At the moment that Hawkeye fires the arrow, we assume that Loki has an initial velocity $u_{\mathrm{Loki}} = 200$ km h^{-1}. Additionally we assume that Loki is accelerating such that his final velocity at the POI is $v_{\mathrm{Loki}} = 250$ km h^{-1}. Using this information, the student is required to calculate Loki's constant acceleration and the distance Loki is from the POI, denoted as d_{Loki}, at the moment Hawkeye fires the arrow. Loki's acceleration a_{Loki} can be calculated using

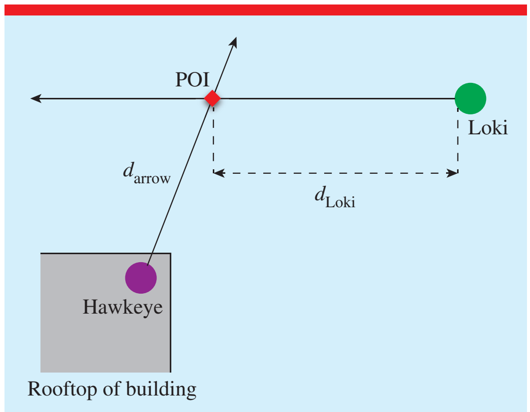

Figure 2. Sketch of Hawkeye's arrow shot at Loki from *The Avengers* [1]. Hawkeye (represented as the purple icon) is perched at rest on the rooftop of the building while Loki (represented as the green icon) travels along a straight line path towards Hawkeye, but not directly at Hawkeye's position. When Hawkeye fires the arrow Loki catches it at the point of intersection (POI), which is marked as the red diamond. At the moment Hawkeye fires the arrow, the arrow must travel a distance d_{arrow} to the POI while Loki is a distance d_{Loki} from the POI.

$$a_{\mathrm{Loki}} = \frac{v_{\mathrm{Loki}} - u_{\mathrm{Loki}}}{t_{\mathrm{arrow}}}. \quad (1)$$

To calculate d_{Loki} the student can use two different approaches. The simplest approach is to use the expression

$$d_{\mathrm{Loki}} = u_{\mathrm{Loki}} t_{\mathrm{arrow}} + \frac{1}{2} a_{\mathrm{Loki}} t_{\mathrm{arrow}}^2. \quad (2)$$

Alternatively the student can rearrange the expression

$$v_{\mathrm{Loki}}^2 = u_{\mathrm{Loki}}^2 + 2 a_{\mathrm{Loki}} d_{\mathrm{Loki}}, \quad (3)$$

leading to

$$d_{\mathrm{Loki}} = \frac{v_{\mathrm{Loki}}^2 - u_{\mathrm{Loki}}^2}{2 a_{\mathrm{Loki}}}. \quad (4)$$

Before proceeding with the question the student will be expected to convert Loki's initial and final velocities into SI units, with a decimal accuracy stipulated by the instructor. This example using characters from *The Avengers* [1] provides an interesting and stimulating approach for both teachers and students to apply the kinematic equations to the motion of superhero characters.

2.2. Wonder Woman and bulletproof materials

The 2017 film *Wonder Woman* [11], which is the fourth film in the DC Extended Universe, was a tremendous success at the box office grossing more than $820 million worldwide. Set near the conclusion of World War I, the film is based on Diana Prince, or Wonder Woman, an Amazonian warrior from the hidden island of Themyscira. When not fighting villains, Diana works as a curator at the famous Louvre museum in Paris. She possesses many abilities such as superhuman strength, accelerated healing factor and superhuman agility. She also uses a sword and shield, and wears bulletproof or indestructible bracelets. In the film, she uses these bracelets on more than one occasion to protect herself and her allies, most notably Captain Steven Trevor.

The concept of energy can be met in numerous aspects of physics from mechanics to thermodynamics, and from electrical devices to atomic and nuclear physics. In Newtonian mechanics, the principle of energy conservation in an idealised system, where potential energy is converted into kinetic energy and vice-versa without any energy loss, is usually depicted using an object falling from a height such as a ball travelling in the air or a car moving from the top of a hill. For this idealised system, any energy that could be lost in the form of heat, sound or vibration is not considered. Given the numerous energy forms, it would be desirable to use examples that illustrate as many of these energy forms as possible as well as discussing energy conservation issues in non-idealised systems. One such example would be to consider a bullet hitting one of Wonder Woman's bulletproof bracelets.

In a pivotial scene from the film, Wonder Woman uses one of her bracelets to deflect a bullet away from Steven Trevor, thus saving his life. Having studied the footage from the film, it is quite likely that the bullet was fired from a Colt New Service double action revolver, a weapon that was issued by the British War Department during World War I. Such a gun would normally fire a .45 Colt cartridge that would contain the bullet or slug, with a number of different cartridges available. We will assume that the mass of the bullet $m_{\text{bullet}} = 0.16$ kg and the velocity of the bullet upon leaving the muzzle of the gun is $v_{\text{bullet}} = 330$ m s^{-1}. Thus the kinetic energy of the bullet E_k upon leaving the muzzle of the gun is

$$E_k = \frac{1}{2} m_{\text{bullet}} v_{\text{bullet}}^2 = 8.712 \text{ kJ}. \quad (5)$$

For this idealised bullet we will assume that no kinetic energy is lost during the motion of the bullet from the gun to the point of impact with Wonder Woman's bracelet. When the bullet hits the bracelet it immediately comes to rest with the energy converted into a number of different forms of energy.

First, when the bullet hits the bracelet there is an audible sound. The sound waves result from the conversion of some of the bullet's kinetic energy into vibrational energy that is transported via the molecules in the air. Second, a portion of the energy is converted to heat as demonstrated by Stephen Trevor's reaction when he catches the hot bullet after it hits the bracelet. Third, some of the energy is directly absorbed by the bracelet. The atoms in the bracelet are more than likely arranged in a regular crystalline structure. When the bullet hits the bracelet the absorbed energy causes the atoms to vibrate about their positions, and effectively transmits thermal energy through the material. If the bracelet is made of a material that is a good conductor of heat (which is highly likely), then Wonder Woman might also have felt slightly uncomfortable by the increase in temperature of the bracelet. You might also expect that Wonder Woman would have a small bruise on her arm after the impact of the bullet. However given her accelerated healing factor, this would quickly vanish.

While this example can clearly be used to demonstrate forms of energy and energy conversion in the classroom, it can also be used to illustrate the principle of the conservation of momentum. For this numerical problem we will change some details of the scene from the film. Here we assume that the bullet actually becomes embedded in the bracelet upon impact. Once again the mass of the bullet is $m_{\text{bullet}} = 0.16$ kg and $v_{\text{bullet}} = 330$ m s^{-1}. For the problem, Wonder Woman has a mass $m_{\text{ww}} = 60$ kg and she is at rest before the bullet hits her bracelet or $v_{\text{ww}}^{b} = 0$ m s^{-1}. After the bullet becomes embedded in the bracelet, according to the conservation of momentum, Wonder Woman should start to move backwards. We can write two expressions to aid in the calculation of Wonder Woman's velocity after the impact of the bullet. First, the momentum of the bullet and Wonder Woman before the impact of the bullet is given by

$$p_b = m_{\text{bullet}} v_{\text{bullet}} + m_{\text{ww}} v_{\text{ww}}^b \quad (6)$$

$$= m_{\text{bullet}} v_{\text{bullet}}. \quad (7)$$

Second, the momentum after impact is given as

$$p_a = (m_{\text{bullet}} + m_{\text{ww}}) v_{\text{ww}}^a. \quad (8)$$

We combine Wonder Woman's mass with the mass of the bullet since both will then move backwards with the velocity v_{ww}^a. To calculate v_{ww}^a, we apply the conservation of momentum where $p_a = p_b$ and rearrange to give

$$v_{\text{ww}}^a = \frac{m_{\text{bullet}} v_{\text{bullet}}}{m_{\text{bullet}} + m_{\text{ww}}}. \quad (9)$$

Filling in the values leads to $v_{\text{ww}}^a = 0.878$ m s^{-1}, which is not very fast considering Usain Bolt's average speed of 10.43 m s^{-1} when he broke the world record in the 100 m sprint at the IAAF World Championships in Athletics in 2009.

This Wonder Woman scene can also be combined with the Hawkeye scene presented in the previous section. For example, the student could calculate the kinetic energy of an arrow fired from the bow and compare it with the kinetic energy of the bullet fired in the Wonder Woman example. The student can carry out research to estimate the likely mass of Hawkeye's arrow for the comparison. In addition, the student can compute the kinetic energy of protons accelerated in the large hadron collider (LHC) [12] and compare these with the kinetic energy of the bullet and arrow respectively. This exercise also facilitates practice with scientific notation and conversion of energy values from joules to electron-volts (eV).

2.3. Invisible Woman, invisibility cloaks and optics

The prospect of becoming invisible with a mere thought or by using a piece of advanced technology is one that is very attractive to many people. Sue Storm of the Fantastic Four, otherwise known as the Invisible Woman, is one superhero who possesses this incredible ability. In the comic books and films, Sue Storm is a prominent scientist working on research projects related to genetics and advanced materials. In *The Fantastic Four* #1 [13], which was published by Marvel Comics in November 1961, Sue along with the other members of the Fantastic Four were accidentally exposed to a high-energy cosmic ray storm in outer space. The exposure led to some permanent genetic modifications to Sue's DNA, one of which enables her power of invisibility. The secret to Sue's power is related to how the atoms and molecules in her body interact with light. When visible, light interacts with her as it would for any other person. However, when she activates her power of invisibility, the light-atom interactions drastically change with light seemingly able to pass through the atoms of her body. Hence, Sue and her power can act as a powerful stimulus for the topics of reflection and refraction of light in the classroom.

Sue Storm's ability, along with H.G. Wells' 1897 classic science fiction novel *The Invisible Man* [14] and Harry Potter's invisibility cloak have all acted to directly or indirectly inspire many scientific researchers in the pursuit of invisibility through the development of advanced materials. One approach involves a new class of materials known as optical metamaterials, which can change the path of electromagnetic (EM) waves, such as visible light, as the waves pass through the materials. A number of optical metamaterials have been proposed since the first dedicated papers on the subject were published in 2006 [15–17]. The key characteristic of these entirely artificial and man-made materials is their ability to deflect or bend EM waves around objects. Structurally a metamaterial is a regular square grid where the size of the grid cells are smaller than the EM wavelength they are intended to control. For visible light this means that each grid cell is less than 300 nm. Unlike traditional materials that the student meets in the physics classroom such as glass, water or air, metamaterials have a negative index of refraction, which helps the materials bend light in unnatural ways. This effect is illustrated in figure 3. The image on the left shows an illustration of a straw in a glass of water as it would appear in the laboratory or at home. As can be seen from the image, the straw appears to be bent when moving from the medium of air to water, where the refractive index of water $n_{\text{water}} = 1.33$. On the other hand, the image on the right shows how the straw would be bent if water had a negative index of refraction. This image is a

Figure 3. The left image shows a straw in water as it would appear in the laboratory, where the index of refraction $n_{\text{water}} = 1.33$. The right image shows the same straw in water if $n_{\text{water}} < 0$, which illustrates how the path of EM waves can be affected by metamaterials. Reproduced with permission from BW Science [3].

representation of how EM waves can be bent in a metamaterial with a negative index of refraction.

While metamaterials offers a viable approach towards creating invisibility cloaks, the metamaterial structures can be expensive and difficult to fabricate, particularly when the structures require an accuracy at the nanometre scale [3]. However, there is a cheaper and quicker way of building an invisibility cloak. Researchers at the University of Rochester, New York state have developed an invisibility cloak that uses off-the-shelf optics and there are no specialised materials in the cloak [18]. The cloak has been used to make coins and fingers appear to be invisible. Detailed instructions for the construction of the cloak can be found in the original research paper [18] and a basic outline for building the cloak is provided on a Wikipedia page under the title 'Rochester Cloak'.

Here we present the essential details for construction of the 'Rochester Cloak'. An example of the cloak is shown in figure 4. The cloak consists of an optical bench, four lens holders and four achromatic doublet lenses. An achromatic doublet lens consists of two lenses combined into a single lens to account for chromatic issues and any spherical aberrations that would affect the quality of the image. The type of lenses used in this cloak are the same as those in the original 'Rochester Cloak' [18]. Lens 1 and Lens 4 have a focal length $f_1 = f_4 = 200$ mm, a diameter of 50.8 mm and are composed of BK7 and SF2 glasses. Lens 2 and Lens 3 have a focal length $f_2 = f_3 = 75$ mm, a diameter of 50.8 mm and are composed of SF11 and BAF11 glasses. All lenses have an anti-reflection (AR) coating, are optimised for use in the visible spectrum of wavelengths from 400 nm to 700 nm and are available from the off-the-shelf catalogue of Thorlabs. It is not essential to use achromatic doublet lenses for the cloak. Ordinary lenses will also suffice. However, the quality of the images is directly influenced by the quality of the lenses. If you do not have access to an optical bench, a series of carefully placed lens holders or retort stands could also be used for the arrangement.

Construction of the cloak is crucially dependent on the distance between the lenses. A full derivation of distance expressions for the cloak is available in the original research paper [18]. We present the relevant expressions for construction of the cloak. The total length of the cloak from Lens 1 to Lens 4 is $L = d_{12} + d_{23} + d_{34}$, where d_{ij} is the distance between the ith lens and jth lens. The distance between Lens 1 and Lens 2 (d_{12}) is the same as the distance between Lens 3 and Lens 4 (d_{34}) and given by

$$d_{12} = d_{34} = f_1 + f_2. \tag{10}$$

Recall that $f_1 = f_4$ and $f_2 = f_3$. Next, the distance between Lens 2 and Lens 3 is given as

$$d_{23} = \frac{2f_2(f_1 + f_2)}{f_1 - f_2}. \tag{11}$$

From equations (10) and (11) the total length of the cloak can also be expressed as

$$L = 2d_{12} + d_{23} = \frac{2f_1(f_1 + f_2)}{(f_1 - f_2)}. \tag{12}$$

This expression can act as a check for the student or teacher during the construction of the cloak. In figure 4 a Lego bridge is placed in the region of maximum cloaking and an Ant-Man/Giant-Man Funko figure is positioned beyond Lens 1 (Giant-Man appears in the film *Captain America: Civil War* [2]). If the cloak has been built correctly, when a person looks through Lens 4 towards the Giant-Man figure the green block at the top of the Lego bridge should be invisible as this block is in the region of maximum cloaking created by the arrangement of lenses. This is demonstrated in figure 5. When looking through the configuration, it is important to stand at least one metre from Lens 4. This will help to ensure clarity of the image for the observer.

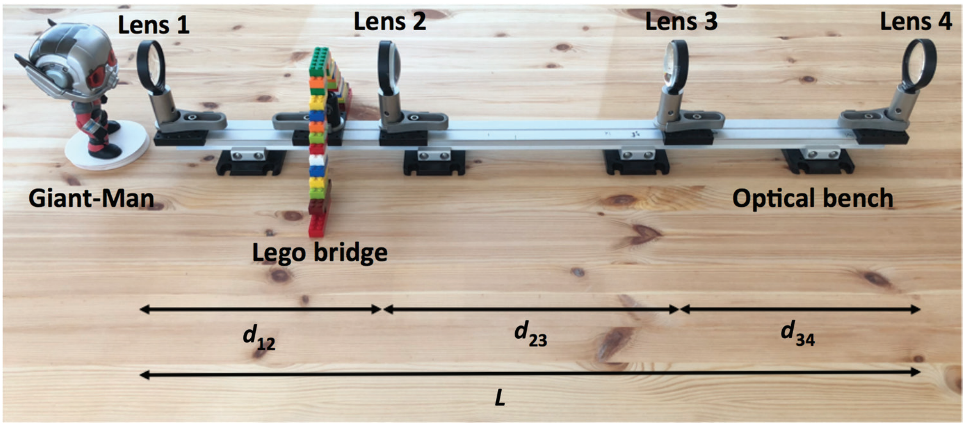

Figure 4. Setup for the 'Rochester Cloak'. Lens 1 and Lens 4 are equivalent. Lens 2 and Lens 3 are equivalent. The location of maximum cloaking is between Lens 1 and Lens 2, which is at the location of the Lego bridge. For this setup the Lego bridge will be partially cloaked. An observer should stand at least one metre away from Lens 4 and look straight through the arrangement of lenses. For this setup, the observer is able to see the head of Giant-Man without obstruction from the Lego bridge (See figure 5).

The invisibility cloak can be used for a number of activities in the classroom. First, it demonstrates an advanced application of lenses and the laws of refraction. Second, the set-up can be used to motivate numerical problems in the classroom. Students can formulate the lens equations for the individual lenses and calculate the power of the lenses. Third, this type of experiment could be used to motivate in-class experiments or extracurricular projects. Finally, the cloak can be used to instigate discussions about future developments in optics and debates as to whether a wearable invisibility cloak is a feasible or safe innovation. For example, the optics in the cloak could be used to inspire innovations in future healthcare and biosensors [19]. Currently, Sue Storm's power of invisibility is confined to the pages of Marvel Comics publications and to the adventures of the Fantastic Four in Hollywood films. However, thanks to developments such as the 'Rochester Cloak', scientists are making credible progress in the pursuit of the extraordinary power of invisibility.

3. Addressing underrepresentation in gender and diversity

These examples show that superheroes can act as an innovative platform to support the delivery of learning objectives in the physics classroom. While providing examples and experiments for physics learning objectives, the superhero genre could also be used to instigate discussion on the underrepresentation of women in physics and issues with race diversity. According to recent figures from the USA, only 21% of bachelor degrees in physics are attained by women [20], a statistic that is of great concern. A number of factors have been identified that may impact on the decisions of female students to follow careers in the physical sciences such as having a single-sex physics class, having a female physics teacher, having female scientist guest speakers, discussing the work of female scientists in class and discussing underrepresentation of women in physics [21]. A study on these factors has revealed that discussions on underrepresentation of women in physics have a marked positive effect on the interest of female students in physics while the other factors have no significant effect [21]. The authors of the study contend that 'engaging in discussions around underrepresentation affords more opportunities for female students' self-realisation about physics because the act of discussing may incorporate their perspectives'. In addition, the authors note that personal discussions might help female students identify 'feelings of inadequacy or discomfort they might have stem from external norms and pressures rather than from their capabilities, interests or values'. While these studies [20, 21] have presented evidence that female role models do not significantly affect the interest of

Figure 5. Front view through Lens 4 of the invisibility cloak in figure 4. Notice that the green Lego block joining the two sides of the bridge can not been seen and Giant-Man's head and eye are visible. For this image other blocks are obscured by the lens holders.

female students, it has also been argued that the current gender imbalance in numerical subjects such as physics and mathematics could benefit from more female physics role models [22, 23].

Superheroes, such as Sue Storm, can be used by teachers to instigate discussions on underrepresentation of women in physics. For example, the teacher and students could discuss together the issues that Sue may have encountered during her superhero and scientific careers, given that her work environments are male-dominated [13]. The superhero genre can also be used to encourage students to express their opinions or perspectives on physics. Aguilar *et al* have outlined a series of constructive psychological interventions that can encourage all students to think about their position in the classroom and give teachers the opportunity to gain a better understanding of their students' perspectives [31]. The authors note that no group should be singled out from an activity and that all students should participate. For instance, to address social belonging, students are asked to write a letter that is addressed to future physics students describing their concerns and worries during their first days in a new course. This task, which can be completed at home or in class, has been shown to have a positive impact on minority students in an introductory physics course at university [32]. Another intervention, the values-affirmation intervention, can be used to address the negative effects of stereotypes and has been shown to reduce racial [33] and gender gaps [34]. To aid these exercises, students could be asked to reflect on similar biases that may have been experienced by female scientists and engineers in the superhero genre. These reflections could then be compared to the perspective of the student, thus providing the teachers with valued insight on their students' perspective.

There are a number of examples of female scientists and engineers in the films of the Marvel Cinematic Universe (MCU) that can be used as points of reference when discussing underrepresentation of women in physics and also provide role models for female students. For example, in the 2011 film *Thor* [24], Dr. Jane Foster is an one of the world's most renowned astrophysicists while Dr. Helen Cho from South Korea is an expert on biophysics and nanomaterials in the 2015 film *Avengers: Age of Ultron* [25]. Most recently, Shuri, the 16-year-old sister of T'Challa or Black Panther, is the lead scientist in the 2018 film *Black Panther* [26], which is set in the fictional African country of Wakanda. In the modern comic books, Riri Williams is a 15-year old engineering student who reverse-engineered the Iron Man suit to create the Ironheart suit [27]. These examples do not represent 'diversity for the sake of diversity' but, rather, a more representative portrayal of women in science and technology in science fiction. In particular, Dr. Helen Cho, Black Panther, Shuri and Riri Williams can be used to address racial equity in the physics classroom [28] and present a diverse set of role models that can be of benefit to all students [29]. In a recent study, demographic diversity has been shown to strengthen science such that scientific papers with a greater diversity of authorship can boost the quality of the paper and the coverage of the paper in the scientific community [30].

Using superheroes and scientists from the superhero films for contemplation of underrepresentation, discussion of student perspectives and as a diverse set of role models could all have positive effects in the physics classroom. Nevertheless, science fiction, particularly fiction focusing on technological innovations such as the superhero genre, may have an inherent gender bias [35, 36]. Hard science fiction, which focuses on technological developments such as time machines or superpowers, can act as a source of inspiration for many students. Hard science appears 'to be the genre most directly entangled with visions in physics' [35]. This hard science fiction content may appeal more to male students in the physics classroom, while female students express greater interest in the soft science fiction, where the emphasis is on the development of technologies for healthcare or to address climate issues for example [35]. In a recent paper, we discussed the physiology of Hawkeye's advanced eyesight [4] where we address both hard and soft science aspects. Genetic engineering and technological methods proposed for the development of advanced eyesight superpowers or devices can be viewed as hard science. However, in the paper, we highlight that the same methods can be used in modern healthcare, and thus present a soft science viewpoint. For example, genetic engineering can be used to combat diseases such as cancer, while technologies such as electronic foveae can be used to reverse the effects of blindness caused by retinal diseases. For Sue Storm, creating invisibility cloaks appeals to those attracted by hard science [18] while the application of advanced optics in healthcare addresses focuses on soft science [19]. Therefore, the teacher should exercise caution when using superhero analogies in the classroom. The materials should be introduced in a manner such that the teacher attempts to address both the hard and soft science groups in a physics classroom, examine underrepresentation and avoid stereotyping.

4. Conclusions

In this paper, we have outlined using three superheroes, a number of approaches for the constructive integration of superhero popular culture into the physics classroom. These examples are intended to complement existing educational materials and resources related to specific learning objectives in a physics syllabus. Linking physics concepts to superheroes and their exploits in the films and comic books offers the possibility of fostering an engaging and accessible learning environment, given the relevance of popular culture in the life of the student. Although some students may never have seen a superhero film, many students are more than likely familiar with characters such as Iron Man, Wonder Woman, Spider-Man and the Invisible Woman (Sue Storm). The current and past successes of superhero films means that these films will be a significant component of future popular culture. Other aspects of popular culture can also be included in the physics classroom such as the computer game *Angry Birds* [37] in relation to kinematics and projectile motion and Santa Claus in relation to the weather and advanced materials [38].

Besides connecting with physics learning objectives and addressing representation issues, the superhero genre can be used to reflect on the possible societal impact of physics, thus prompting critical reflection on the part of the student. For example, having explored the development and operation of an invisibility cloak (section 2.3), the teacher can use the experiment to prompt discussions on responsible development in physics and technology. Questions of relevance include

(i) Is the development of invisibility cloaks truly desired by society?
(ii) Should physicists invest their time on potentially more beneficial research fields such as bioenergy or medical treatments rather than developing invisibility cloaks?
(iii) How can physicists dictate or control the development and release of new technologies such as an invisibility cloak?
(iv) What are the other possible applications of the optics in an invisibility cloak such as the 'Rochester Cloak'?

Additionally, the Hawkeye/Loki example on linear motion (section 2.1) can be used in conjunction with mathematics and the manipulation of algebraic formulae while the Wonder Woman example on energy conservation (section 2.2) can provoke discussions on progress in renewable energy and responsible innovation in bulletproof technologies. Hence, these superhero examples can encourage critical thinking on the part of the student in relation to not only fundamental physics but also on the impact of physics and innovation in physics on society.

This paper also reflects on how the superhero genre can be used to address underrepresentation in the classroom. Female scientists in the superhero films can be used to initiate discussions on underrepresentation in the physical sciences, a process that has shown a positive impact on the career paths of female students [21]. These scientists can also act as positive female role models in the classroom. Modern superhero films include superheroes and scientists with diverse backgrounds. In terms of superheroes, Black Panther comes from the fictional country of Wakanda Africa, Wong who appears in Doctor Strange is Asian [39], and Black Widow is Russian. In terms of scientists, Dr Helen Cho is from South Korea while Shuri comes from Wakanda. The superhero genre can also appeal to groups interested in hard or soft science [35]. Teachers should implement superhero examples in a careful manner in the classroom. The examples presented here can be used to support educational materials for learning objectives. However, they can also be used to aid constructive interventions that enable students to critically reflect on their place in the classroom [31].

The approaches presented here are predominantly aimed at secondary school level. Optical metamaterials and the concept of a material with a negative index of refraction are more relevant for a third level optics syllabus. Nevertheless, this content can act as a source of inspiration for student projects or extracurricular reading. We have integrated the superheroes paradigm in the teaching of physics, computer programming and fluid dynamics at third level institutions in the Netherlands. In addition, we have used superheroes as a powerful platform for scientific communication and outreach [3, 40]. The response from audiences to the material has been overwhelmingly positive as demonstrated by the energy and enthusiasm of an audience during and after a workshop or presentation. We encourage teachers and educators alike to consider merging the above superhero examples with their existing educational resources, while also taking into account representation issues. While superheroes and superpowers are *currently* confined to Hollywood films and the pages of comic books, these characters and their associated abilities can act as compelling points of reference for students on key learning objectives in physics.

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Barry W. Fitzgerald is a research associate in the Department of Process & Energy at the Delft University of Technology. His research interests include the numerical modelling of polymeric systems, fluid dynamics and particle processing related to bioenergy production. He also focuses on scientific communication, education and outreach, using elements of popular culture such as the superhero genre as a platform for the dissemination of scientific content. He has self-published books on the science behind superheroes and Santa Claus, and spoken at numerous science events in Ireland and the Netherlands on these subjects.