Why we should strive for gender equality in Physics: looking beyond the moral imperative

Abstract

This report argues a case for gender equality in Physics. In doing so, it looks beyond the moral imperative that is most frequently cited as the key reason for greater representation of women in this scientific field. Instead, drawing on the findings of a wide range of research, it highlights a number of other benefits. Gender equality in physics would help address a shortage of skilled physics researchers; enhance the quality of innovation in the field, and significantly increase the impact of science outreach. The paper goes on to highlight potential challenges to achieving gender equality, most notably unconscious bias and opposition to gender quotas. These findings imply that realising gender equality in physics, though challenging, is not just a moral imperative, but also an imperative for the future development and progression of physics.

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Introduction

Picture a famous physicist. Was that physicist female? Probably not. I suspect there is a higher probability you pictured Albert Einstein than a female physicist.

I pictured Einstein, the man who developed the theory of relativity and received a Nobel Prize in Physics for his discovery of the law of the photoelectric effect.

But why did I picture Einstein and not Marie Curie, the woman who conducted pioneering research on radioactivity (a term she coined), discovered two elements and received two Nobel Prizes? Or Maria Goeppert Mayer who was awarded a Nobel Prize in physics for proposing the nuclear shell model of the atomic nucleus?

Is it because women are inherently worse at physics? Definitely not. Curie and Mayer were both world-class physicists, and nobody has ever proven there are any meaningful innate differences in physics ability between the genders (Saini, 2017).

Is it because women face significant hurdles and are therefore underrepresented at all levels in physics? If so, it raises the question of what impact this under-representation has had on the field of physics and by implication - society as a whole. In turn, the answer to this question would inform the case, beyond the moral imperative, in favour of gender equality in physics (Ivie & Tesfaye, 2012).

In physics, gender equality is still some way off. The under-representation of women in science, and in particular in physics, is still profound enough that we do not need detailed statistics to see its existence. However, the statistics do paint a sombre picture. In the United States of America, 21 per cent of bachelor's degrees and 17 per cent of PhDs in physics go to women (Ivie & Tesfaye, 2012). In the United Kingdom, 17 per cent of physics lecturers and seven per cent of physics professors are female (Jamieson, 2018). Among the Institute of Physics members, only 28 per cent are female (Institute of Physics, 2016).

These figures are dismal, though they are not particularly surprising. But they should be. Article 27 of The Universal Declaration of Human Rights states that "Everyone has the right freely to participate in the cultural life of the community, to enjoy the arts and to share in scientific advancement and its benefits" (United Nations General Assembly, 1948). The moral argument for gender equality in physics, but also universally, is therefore overwhelming, and the acceptance of this argument is almost entirely uncontested in the 21^{st} century. Despite this, physics still fails to achieve gender equality, so we are not delivering on this human right.

Typically, arguments for gender equality in physics, as in any field, focus on this evident moral imperative. In contrast, this report looks beyond the moral imperative to other crucial benefits that striving for gender equality would bring. It does this not because it regards the moral imperative as in any way unimportant - on the contrary, it takes it for granted - but because relatively little emphasis has been given to other relevant issues.

These issues include, but are certainly not limited too, gender equality in physics helping to address a shortage of skilled physics researchers, enhance the quality of innovation in the field, and significantly increase the impact of science outreach.

This report aims to objectively analyse recent literature on the advantages and potential challenges of achieving gender equality. Some of this evidence will come from research addressing physics in particular, but much will look to other fields. Such research does not make a direct case for gender equality in physics; however, it offers useful pointers and raises vital questions. The research in this report will draw on an extensive array of sources to ensure a holistic and comprehensive study.

It is worth noting that throughout this report, I will look at the arguments for achieving gender equality, “the state in which access to rights or opportunities is unaffected by gender” (Oxford English Dictionary), in physics. However, quantifying the holistic term, gender equality is practically challenging, and thus, the report is often forced to regard the easily quantifiable gender diversity as interchangeable with gender equality. This is not an entirely valid leap as gender diversity, the “equitable or fair representation of people of different gender” (Oxford English Dictionary), does not necessarily imply that gender equality has been fully achieved. However, it does serve as an essential step on the way to achieving it. Because of this critical distinction, conclusions made in this report based solely on evidence of, or arising from, gender diversity, will often be qualified with further evidence explaining the significance of the evidence for gender equality in physics.

The report concludes that the benefits of achieving gender equality in physics far outweigh the challenges of doing so and that by developing both gender diversity and gender equality, all physicists can better realise the potential of the subject. The leading advantages of gender equality are the significant impacts of increased productivity and enhanced research. Improving the quality and quantity of outreach and promoting physics scholarship are also identified as impacts that a more equal and diverse field of physicists could accomplish. However, potential challenges identified include unconscious bias and opposition to gender quotas. These findings imply that realising gender equality in physics, though challenging, is not just a moral imperative, but also an imperative for the future development and progression of physics.

Discussion

Arguments for Achieving Gender Equality in Physics

Productivity in Physics and the Broader Economy

When considering the case for gender equality's ability to improve productivity[1] in physics, it is essential to begin by considering gender equality in the corporate environment. This is a crucial first step because, in the corporate world, women are massively under-represented in leadership and senior management roles, in a similar way to physics. However, a widely held consensus already exists, and much research has already focused on the matter.

A 2018 McKinsey & Company study of 1,000 companies covering 12 countries found that companies in the top-quartile for gender diversity on executive teams were 21 per cent more likely to outperform the competition on profitability. They were also 27 per cent more likely to have superior value creation[2] (Hunt, et al., 2018). Another study that surveyed the gender composition of management teams in Standard & Poor 1,500 companies[3] found that women in senior management positions were associated with "an increase of US$42 million in firm value". Furthermore, the study found that companies which prioritised innovation saw more significant financial gains when they had female managerial representation (Dezso & Ross, 2011).

It is possible to argue that the causation may work in reverse; higher-performing firms attract a more extensive range of talent. To investigate this, the authors tracked performance changes after an organisation employed more women to diversify their team. In doing this, they were able to disentangle cause and effect between diverse groups and economic output. Their results concluded that better performance followed hiring, not the other way around. This conclusion supports the consensus that gender diversity leads to better financial returns, thereby economically benefiting more diverse companies.

However, it is also crucial to note that current literature suggests the benefits of gender equality extend beyond financial returns solely for the diverse corporation. Instead, increased gender diversity will also result in broader benefits for the economy. Normative societal acceptance of working women and belief in the importance of gender equality for economic output (Turban, et al., 2019) is predicted to add 1.2 trillion Euros per annum to the Gross Domestic Product of EU member states by 2050 (European Institute for Gender Equality, 2015).

Estimates suggest that increasing female participation in the United Kingdom's labour market could be worth between £15 billion and £23 billion (1.3 - 2.0 per cent of national GDP), with STEM accounting for at least two billion of this (Royal Society of Biology, 2012). In Scotland, a doubling of women's high-level skill contribution to the economy could be worth as much as 170 million Pounds per annum to national income (Royal Society of Edinburgh, 2012).

Successive British Governments have also recognised the economic case for diversity in science. In July 2012, Vince Cable stated that "women make up less than a fifth of all employees in the science sector" and that "there is no way we can generate the number of scientists and engineers the economy requires without addressing this situation" (Rt Hon Sir Vince Cable MP, Secretary of State for Business, Innovation and Skills, 2012). Furthermore, in a 2016 interview, the Institute of Physics

[1] Productivity in physics refers to the amount and quality of research being carried out
[2] Measured as economic profit margin
[3] A stock market index tracking 90% of the market capitalization of U.S. stocks (S&P Global, 2020)

president, Professor Roy Sambles, detailed how the economy of the United Kingdom was dependent on physics departments producing enough well-qualified graduates (Sambles, 2016).

Increased gender diversity in physics will therefore lead to economic growth in the UK and the EU due to the interdependence between gender diversity and physics productivity.

However, the consequence of gender equality on productivity in physics is far more significant than merely the impact of diverse teams on fiscal returns (Lauring & Villeseche, 2019). Achieving gender equality in physics is also vital for encouraging the uptake of physics in education and the workforce, hence increasing the available talent pool.

A report published by the House of Commons concluded that "the UK economy needs more skilled scientists and engineers and this need will not be met unless more significant efforts are made to recruit and retain women in STEM careers" (House of Commons: Science and Technology Committee, 2014). The British government also lists physical scientists and engineers in their shortage occupation list (Her Majesty's Civil Service, 2019). This implies that there is no shortage of demand for physicists; instead, there is a shortage of supply.

This severe shortage of physicists is partly due to the gender imbalance in the uptake of physics at school. At A-level, physics was the third most popular subject for 16-year-old boys. However, it was only the 18th most popular subject for girls, despite their marginally higher attainment (Institute of Physics, 2018). This disparity increases through a physicist's career and, in the UK, just 17 per cent of physics lecturers and seven per cent of physics professors are women (Jamieson, 2018).

> "Half the workforce is missing … economically having more of the workforce with physics qualifications would be an advantage to us. Half of the potential ideas and solutions to solve the world's problems are also missing." - Dr Jessica Hamer, Institute of Physics

This points towards the conclusion that there is certainly no shortage of demand for physicists. Instead, there is a shortage of supply. A deficit that could be filled most efficiently by tapping into the female workforce of potential physicists. Though this is an incredibly simple deduction, it is also profound. A significant proportion of the potential physics workforce is missing. It then inevitably follows that not unlocking this potential reduces the overall productivity of the sector and its research.

Quality of Ideas and their Societal Impact

Scientific narratives all too often focus on a singular, usually male[4], scientist who makes extensive contributions through their innate brilliance - for example, Albert Einstein or Isaac Newton[5]. However, this narrative is fundamentally flawed. Instead of 'genius' being innate, scientists develop it during many hours of learning and experience. Moreover, teams, not individuals, typically conduct scientific research meaning, the narrative of the brilliant, individual scientist fails us, especially in the modern research environment (Wuchty, et al., 2007).

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[4] The Matilda effect is a bias against acknowledging the achievements of female scientists whose work is instead attributed to their male colleagues (Wikipedia, 2020)

[5] While both of Einstein's and Newton's contribution to science is unparalleled, scientific research today no longer fits the narrative of their time

From the perspective that research is analogous to group problem-solving, instead of the realisation of individual brilliance, gender diversity becomes key to academic excellence. Professor Scott Page supports this paradigm in his book, The Difference, where he offers a mathematical analysis of the argument for diversity. He concludes that, when trying to solve challenging problems, progress often results from diverse perspectives (Page, 2007). That is, the diversity of a group of intelligent individuals is of more considerable significance than their ability as individuals (Hong & Page, 2004). Hence, gender diversity is integral to realising overall ability.

It is, however, essential to note that two people from similar backgrounds can have profoundly different perspectives, just as two people can be from distinct backgrounds and yet approach problem-solving almost identically. Nevertheless, while it is vital to avoid essentialising[6] people, individuals with different backgrounds tend to approach work and problem solving differently. Gender, as explored in a report from the University of Cambridge, does have a marked impact on an individual's background and identity, especially when considered in academia where women will likely have had to creatively overcome significant barriers to progression (Bostock, 2014).

These differences in background, brought about by gender, can therefore bring the new perspectives needed to promote the formation of quality ideas (Gibbs, 2014) consequently benefiting idea creation in physics as a whole.

It has also been suggested that gender diversity could increase the number of ideas that physicists have. Though no quantitative literature for that particular hypothesis currently exists, a study into the effect of increased ethnic diversity in STEM yielded suggestive results. The study, of 2.5 million research papers, whose authors all had US addresses, found that authors with English surnames were significantly more likely to have co-authors also with English surnames. This trend held for eight other groups, including Russian, Chinese and Korean populations between 1985 and 2008 in 11 scientific fields, including physics. This homophily[7] was associated with a 5-10 per cent fall in the mean number of citations of a given publication, compared to publications with four or five authors of multiple ethnicities (Freeman & Huang, 2014).

While this study focused solely on ethnic diversity, it is not too big of a leap to suggest that a similar effect might well hold for gender equality and diversity (Elsevier, 2017). At the very least, it is a hypothesis well worth testing. This paper does not attempt to conclude why the mean number of citations increases. Despite this, some potential theories are that diverse research groups are more likely to develop innovative ideas, or that diverse research is often of higher impact. The study does, however, rule out the hypothesis that physicists with lacklustre or fewer papers may intuitively have a narrower pool of potential collaborators. While it is true that homophily is more significant for authors with weaker publication records, the authors controlled for this variable and still demonstrated that ethnic diversity among collaborators does result in a higher number of citations.

In other fields, significant research has shown that more diverse teams can develop more innovative ideas (Chamorro-Premuzic, 2017). When people with different life experiences (for example, being of different genders) work together, their unique perspectives often lead to greater creativity. Further investigation has shown that leaders with diverse backgrounds and experience helped companies innovate more (Hewlett, et al., 2013). Hence, diverse leaders were more likely to foster

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[6] "Characterise a quality or trait as fundamental or intrinsic to a particular type of person or thing" (Oxford English Dictionary)

[7] "The tendency for people to seek out or be attracted to those who are similar to themselves" (Oxford English Dictionary)

an environment where their teams considered new and creative ideas, an invaluable skill in both theoretical and practical physics.

However, this advantage of diversity does not work without the psychological security that, in part, comes with gender equality. An article in the Annual Review of Psychology found that people only contribute unique ideas to groups when they feel comfortable enough to speak up and present a contrarian view (van Knippenberg & Schippers, 2007). Experimental studies further support this, showing that psychological safety is key to idea generation (Department for business, Innovation and Skills, 2013).

Fully realising the potential of equality for science and innovation also requires attention to the methods employed and questions raised in scientific knowledge-making (Nielsen, et al., 2018). When practical physicists, especially engineers, design projects, all too often they overlook the real-life applications of their work for women. This lack of gender analysis leads to adverse societal outcomes.

Engineering car safety features is one particularly noteworthy example of this lack of representation. When a woman is in a traffic collision, she is 47 per cent more likely to be seriously injured, and 71 per cent more likely to be moderately injured than a man (Bose, et al., 2011). This finding holds when researchers control factors such as height, weight, seatbelt usage, and crash intensity. She is also 17 per cent more likely to die (Kahane, 2013). The predominant cause of this disparity is that engineers base most crash-test dummies on a fiftieth percentile male. Doing this means the dummy is 1.77 metres tall and has a mass of 76 kilograms, and is thereby taller and more massive than an average woman. The dummy will also have male muscle-mass proportions and a male spinal column. This example of insufficient gender analysis demonstrates that not achieving gender equality in the research process can be extremely harmful. A more gender diverse research team would likely better consider and implement this gender analysis, thereby benefiting society (Criado-Perez, 2019).

Overall, it is evident that the equality of women in research practices and the gender equality of teams positively impacts the generation of ideas. Furthermore, gender diversity and equality have a similarly positive influence on the results and impact of research, directly benefiting society.

Outreach and the Accessibility of Physics

Most scientists and members of the public, consider scientific outreach[8] to be a worthwhile endeavour. However, scientists' amount and quality of outreach can be lacking, limiting the value that society places on physics (Varner, 2014). For physicists, having a public more engaged with science is highly beneficial, leading to increased funding and uptake of the subject (da Rocha-Azevedo, 2015).

A study on outreach done for the Science Communication Journal in 2014 interviewed 133 physicists and biologists. It analysed their perception of, and participation in, public outreach. The paper concludes that women are more likely than men to participate in outreach and that this commitment often results in their peers forming negative associations of them (Johnson, et al., 2014). A second study also found that women were significantly more likely to be involved in outreach work. It concluded that 76 per cent of female physicists were engaged in science outreach work, compared to only 58 per cent of male physicists (Ecklund, et al., 2012).

[8] An umbrella term for a variety of activities by research institutes, universities, and institutions such as science museums, aimed at promoting public awareness (and understanding) of science and making informal contributions to science education (Wikipedia, 2020)

This research shows that increasing gender diversity in physics will positively impact the quantity of outreach undertaken. In turn, this has many benefits for both the physicist and their audience (Shropshire, 2014). The most vital of these is contributing to making physics more accessible to a broader number of people. However, the physicist's laboratory and their research will also get positive visibility. They will benefit from the valuable possibilities of networking with different people resulting in increased exposure to fresh external ideas and funding (Quaglia, 2015). Therefore, the more outreach physicists can do the better, for both the subject as a whole and the physicist's individual scientific development.

Despite female participation in outreach on average being higher than male participation, the lack of gender diversity in physics means men still do most of the outreach. A rise in gender equality would result in an increased number of female physicists participating in outreach. The effect of increased female representation in outreach is relatively unknown, and little clear research currently exists on what the consequences of this may be. However, if we look to broader society, the effect of an increased number of female role models is relatively evident. An increase in female role models resulted in increased participation in further education and politics (Wolbrecht & Campbell, 2007) (Porter & Serra, 2020).

There is also some evidence that female scientists that participate in outreach are more likely to reach out to the often-overlooked so-called 'non-traditional' publics. Such groups include urban or at-risk youth (Pandya, 2012), religious or cultural organisations (Hitzhusen & Tucker, 2013), incarcerated men and women (Nadkarni, 2004), and legislators and public officials (Meyer, et al., 2010). It is critical that physicists engage with these non-traditional publics as widespread societal support for the subject brings benefits for both physics and society more widely.

Furthermore, the overwhelming majority of scientists (who are mostly men) described that they thought they had a duty to educate the public, whom they perceive as inadequately informed about science (The Royal Society, 2006) (Davies, 2008) (Jensen, et al., 2008). The underlying assumption[9] is that the answer is to provide information or educational materials that will reverse negative attitudes and catalyse science uptake. Although this belief is instinctively appealing and enormously widespread, it has little experimental support. In fact, a significant amount of evidence demonstrates that gaining knowledge does not change attitudes or behaviour (Kahan, et al., 2012) (Ho, et al., 2008). Instead, scientists should address factors, including social context, self-confidence, and emotional intelligence (Heimlich & Ardoin, 2008). A more diverse outreach team would be able to address these factors better[10].

The evidence is, therefore, reasonably clear that increased gender equality and diversity in physics would lead to further outreach; with the outreach likely to be more effective at making physics more accessible to the general public. The consequence of the increased accessibility would be widespread and could include increased funding and the increased uptake of physics.

The Number of Highly Skilled Workers

A survey of chemistry doctoral students by the Royal Society of Chemistry found that women are more likely than men to re-evaluate their decision to enter a research career throughout PhD study, and therefore look for alternatives. Amongst first-year students, 72 per cent of women reported planning a research career, but this proportion dropped to 37 per cent amongst those in their third

[9] This is an example of deficit-model thinking
[10] Research has shown that women, on average, have higher emotional intelligence than men (Sanchez-Nunez, et al., 2008) (Toussaint & Webb, 2005)

year. Men's intentions regarding a research career varied far less throughout the PhD with 61 per cent in their first year and 59 per cent in their third-year planning to remain in research (The Royal Society of Chemistry, 2008). Though this report focuses on chemistry students, the findings also hold for physics students, as the subjects are broadly similar[11]. This substantial finding exemplifies the so-called 'leaky pipeline'[12] in physics, which is damaging to the subject as a whole by reducing the size of the highly skilled workforce.

In order to combat the leaky pipeline, it is necessary to address women's negative beliefs about physics. Examining science majors enrolled in chemistry and engineering courses, a study in the Psychology of Women Quarterly investigated how contact with female role models impacts women's beliefs about STEM. The study used the Implicit Association Test to measure attitudes toward science, identification with science, and gendered stereotypes about science. The research also compared students with female and male professors. The paper concludes that when the students saw female professors as encouraging role models, the female students identified more with science and perceived science as more 'feminine'[13] than usual (Young, et al., 2013). Notably, the study also demonstrated both direct and indirect paths between beliefs and a women's career aspirations in STEM; implying that physics would benefit from increased gender equality amongst professors.

Global education standards also stand to benefit from increased equity and diversity amongst highly skilled physicists, though perhaps the significance of the benefit is less than those already explored.

A literature review of fifty studies found a positive association existed between parental involvement in their child's education and their child's educational achievement (Hill & Tyson, 2009). Previous research has also indicated an association between mothers' beliefs about education and their children's self-perception and then the realisation of their ability, especially concerning maths and science. Furthermore, the review found that a mother's aspiration for their child's success in maths and science resulted in the increased uptake of highly skilled quaternary occupations, including physics (Bleeker & Jacobs, 2004). This means that if there were more highly skilled female physicists, we would likely see an increased uptake of the subject.

Increasing gender equality and diversity amongst physics educators would be an effective measure to block up the 'leaks' in the physics career pipeline, thereby increasing the number of physicists at the highest levels of the profession. Having more female physicists is also likely to lead to an increase in children realising their maths and science ability and hence foster a positive feedback loop, ultimately resulting in more physicists.

[11] See "Source Evaluation" for more analysis as to whether it is fair to make such comparisons between Chemistry and Physics students

[12] The phenomenon of a progressive "evaporation" or disappearance of women as they advance in physics (Dubois-Shaik & Bernard, 2015)

[13] "Having qualities or an appearance traditionally associated with women" (Oxford English Dictionary)

Practical Challenges to Achieving Gender Equality

So far, this report has focused on the numerous and significant benefits of achieving gender equality in physics. However, to achieve the desired results of gender equality, we must first overcome the substantial difficulties that the current social environment presents. There are numerous difficulties in achieving gender equality in physics, and most of them manifest as challenges, entrenched into society by historical male overrepresentation.

Overcoming Unconscious Bias

One of the most pressing challenges to achieving gender equality in physics is an unconscious bias against women and, therefore, ignorance of the disadvantages they face in academic physics.

In a randomised, double-blind study, science faculty from research-intensive universities, deliberately chosen to mirror the academic community's demographics, evaluated a student's application for a position as a laboratory manager. The student's identical application was randomly assigned either a typical male or female name. On average, participants rated the male applicant as significantly more competent and hireable than the identical female applicant. The faculty also offered a higher starting salary and more career mentoring to the male applicant. The only category in which the female applicant outperformed their identical male counterpart was for likeability. Interestingly, the gender of the faculty participants did not affect their responses. Female and male faculty were equally likely to exhibit unconscious bias against the female student (Moss-Racusin, et al., 2012).

Another impact of unconscious bias exists in the amount of grant funding offered to male and female physicists. In one frequently cited study, Christine Wennerås and Agnes Wold at the University of Gothenburg, Sweden, found that for female applicants to be perceived as equal to their male counterparts for postdoctoral fellowships they needed to score an average of 2.5 times higher on an index of publication impact (Wennerås & Wold, 1997). A more recent replication of this study again found similar "persistent nepotism" (Sandström & Hällsten, 2008).

This ingrained unconscious bias is intrinsically challenging to tackle, and some more costly techniques, such as unconscious bias training are perhaps less successful than required (Noon, 2018). However, lower-level, more nuanced approaches may offer more success. For example, creating an environment where it is acceptable to point out bias in others (as detecting others' bias is often more straightforward) is likely to be more effective (The Royal Society, 2015).

The Unclear Advantages of Gender Quotas

In their 2020 Global Gender Gap Report, the World Economic Forum estimated that it would take 257 years to close the economic[14] gender gap (World Economic Forum, 2020). Though this index is for the workforce more generally, physics is only performing marginally better. An analysis of 36 million authors of academic papers over the last two decades suggested that at current rates it would be more than two centuries until there are equal numbers of senior male and female researchers in physics (Holman, et al., 2018).

While it is recognised that voluntary targets can stimulate the hiring of women, this approach fails to reach all corners of physics (GENERA Network, European Commission, 2016). In order to speed up

[14] The 'Economic Participation and Opportunity' index is based on male to female ratios for 'labour force participation rate, wage equality for similar work, estimated earned income (PPP), male-female percentage of legislators, senior officials and managers, and male-female ratio of professional and technical workers' (World Economic Forum, 2020)

the rate of progression, multiple countries have implemented mandated quotas for gender equality in universities and research.

France, for example, enacted a law in 2015 that requires all public-university hiring committees to have a gender balance of at least 60 per cent to 40 per cent. This means that neither men nor women can account for more than 60 per cent of the committee members (Helsinki Group on Gender in Research and Innovation, European Commission, 2018). In fields where men are generally over-represented, such as physics and engineering, the law effectively required organisations to add female members to hiring committees.

However, a report into the French quotas' short-term impact observed an estimated 38 per cent decrease in the number of women hired to committees. The data also suggested that the downward trend in female recruitment was particularly significant in committees that had male presidents. This implies the quota may have changed the voting behaviours of men. The report concludes that “it could be a backlash” and that “some men may be angry because they feel like the government did not trust them”. An alternative conclusion also offered by the report is that the quotas might have reduced committees’ impetus to hire more women by creating an illusion of gender diversity (Deschamps, 2018).

Furthermore, the author posits that the quota could have had other unintended consequences. Women in male-dominated departments could find themselves assigned to more committees to meet the quotas, resulting in a substantial drain on their time and productivity (Woolston, 2019).

Another issue arising from quotas is their perception as unjust. An analysis of the free verbal associations to the stimuli ‘women quotas’ and ‘men quotas’ of 327 medical students revealed that they perceived female quotas as counterproductive, derogatory and unfair. The investigation found no statistically significant correlation between a student’s gender and their responses. In line with the conclusion from the above report on French quotas, several respondents reported that they perceived female quotas as misandrist[15] (Zehnter & Kirchler, 2020).

This backlash against change is certainly not exclusive to gender diversity in physics; similar effects often occur whenever societal change happens (Stephan, et al., 2005) (Prasad, 2020). Though acceptance of the change usually happens eventually, ensuring that physicists engage with those that feel threatened is vital to preventing individuals from feeling ostracised (Higgs & Rowland, 2011).

A final drawback of quotas is their potential to undermine women's self-esteem because they perceive themselves, or are perceived by others, as “simply being a quota filler” (Boast, 2020). This is not a valid conclusion for a woman to come to since physics is not properly meritocratic, and they have had to overcome more significant challenges than their male counterparts. However, the belief is still relatively prevalent and can lead to imposter syndrome.

Overall, the research as to the effectiveness of gender quotas is mixed. Though there is some evidence of them being effective, there are also potential pitfalls of this method for achieving gender diversity, including the potential backlash and the likelihood of unintended negative consequences.

[15] “A person who dislikes, despises, or is strongly prejudiced against men” (Oxford English Dictionary)

The Need to Restructure Physics to Allow for Female Participation

Physics academia is currently not adequately set up for women. The usual steps for earning tenure, winning a mid-career grant or completing a middle-step degree coincide with the time of starting families or raising young children (Criado-Perez, 2019) (O'Laughlin & Bischoff, 2005).

A survey of 15,000 physicists worldwide, deployed by the American Institute of Physics, shed light on female physicists' home-life burdens. Although many respondents reported that chores are shared equally, women were more likely than men to report that they do more housework than their partner. Households in which both partners are physicists also see the same result (Ivie & Tesfaye, 2012).

When family responsibilities do affect physicists' careers, they are more likely to affect women than men. This effect occurs as "when push comes to shove, and somebody needs to care for a sick child or family member, it makes economic sense for the partner who makes less money to take on that responsibility. For most men, that partner is someone else" (Ivie & Tesfaye, 2012). These findings have been confirmed and expanded upon in various other studies of women in science (Ecklund & Lincoln, 2012) (Whittington, et al., 2011) (Xie & Shauman, 2003).

A large-scale international project on women in science observed that STEM researchers view family as an obstacle to research success. The perception was that family undermines productivity and commitment, as the full availability required by "good" researchers was unattainable for mothers. This potentially arises from additional pressures such as unaligned work school-hours (GENERA Network, European Commission, 2016) (Boast, 2020).

A study from the University of California, Berkeley, found that male and female postdocs without children are equally likely to decide against research careers; each leaving physics at a rate of around 20 per cent. However, female postdocs who became parents, or planned to have children, left research careers up to twice as often as men in similar circumstances (Goulden, et al., 2009). "The plan to have children in the future, or already having them, is responsible for an enormous drop-off in the women who apply for tenure-track jobs" (Shen, 2013). Furthermore, women who did become faculty members in astronomy, physics and biology tended to have fewer children than their male counterparts (1.2 compared to an average of 1.5) and had fewer children than they desired (Ecklund & Lincoln, 2011).

Moreover, parents who decide to take time out of physics for childbirth face increased career destabilisation (higher risk of a downward move and a lower chance of an upward move). This effect, albeit to a lesser extent, was even observed in countries perceived as progressive such as Sweden and Germany (Aisenbrey, et al., 2009).

To improve gender equality, physicists must address this issue. The challenge of physics not currently being compatible with the average women's work-life balance is hard to resolve. However, potential solutions include the industry ensuring it offers flexible working patterns, paid maternity and paternity leave, childcare facilities and technical training for those returning to work (Cartlidge, 2002). Political gender equality would also likely lead to more inclusive national policies concerning parental leave (Haas & Rostgaard, 2011).

Conclusion

This literature review has looked at the evidence for why we should achieve gender equality in physics, beyond the established moral imperative. This review has also investigated some of the practical challenges to realising gender equality.

The primary quantitative reason identified for achieving gender equality in physics is the boost to productivity in physics that can be achieved. There is currently a shortage of physicists, and to tackle this issue most efficiently, we can begin by employing more women into the sector. However, in order for this to happen, physics as a whole must become a more attractive environment for female physicists, and we must overcome the unconscious bias that currently exists in the subject. The broader economy will also see a meaningful boost if we increase gender equality in physics; and achieving this goal in STEM could add as much as two billion Pounds to the United Kingdom's annual Gross Domestic Product (Royal Society of Biology, 2012).

Within academic physics, increasing gender equality will improve the quality of ideas produced and their potential societal impact. This effect is due to diverse teams often being better at idea creation, an essential skill in practical and theoretical physics. Furthermore, gender equality has a similarly positive influence on the results and impact of research. A female engineer is more likely to consider the effect of their design on women. A car seat belt, for example, that has been tested on female crash dummies can potentially save thousands of lives (Criado-Perez, 2019).

Another reason identified for achieving gender equality is the increased amounts of outreach that female physicists usually do and, in consequence, the improved accessibility of physics. For the public, more outreach means more opportunities to engage with the subject. For the physicist, this increased visibility will likely lead to higher funding and greater uptake of physics.

Finally, increased gender equality amongst physics educators would be a useful measure to sure up the 'leaks' in the physics career pipeline, thereby increasing the number of physicists at the highest levels of the profession. Additionally, having more female physicists is also likely to lead to an increase in children realising their ability in maths and science and hence foster a positive feedback loop, ultimately resulting in more physicists.

This literature review has, however, also examined some of the practical challenges to achieving gender equality in physics. These challenges include overcoming an unconscious bias against women in the subject, the difficulties of gender quotas and the incompatibility of the average women's work-life balance with physics. Though this certainly is not an exhaustive list, these challenges were all identified as surmountable, especially given the weighty benefits of achieving gender equality.

We already know that gender equality is a moral imperative. Nevertheless, the argument for achieving gender equality is made twice over when we weigh the arguments for achieving gender equality in physics against the challenges of doing so. We find that the scale overwhelmingly justifies the need to overcome the challenges and achieve gender equality in physics once and for all.

Source Evaluation

The following tables offer an analysis of a few of the central sources that this project utilised. For a full list of the sources used, please refer to the bibliography.

Evaluation criteria	Criado Perez, C., 2019. In: P. Hampson & J. Stoltz, eds. Invisible Women: Exposing Data Bias in a World Designed for Men. London: Chatto & Windus, pp. 186-191.
Source type	Book
Author credentials	Caroline Criado Perez is an award-winning and bestselling writer, campaigner and consultant. Her most notable campaigns have included co-founding The Women's Room, getting a woman on Bank of England banknotes, getting Twitter to revise its procedures for dealing with abuse and successfully campaigning for a statue of suffragist Millicent Fawcett to be erected in Parliament Square. She won the Liberty Human Rights Campaigner of the Year Award 2013, and in 2015 she was named an OBE in the Queen's Birthday Honours.
Date published	March 2019
Position of the author	The author is a campaigner for gender equality in society.
Reliability of data	The book's data has undergone legal fact-checking, and the source of any data used has been provided.
Critical response	The book was a number one Sunday Times bestseller and has spent twenty weeks (and counting) in the Sunday Times bestseller lists. Invisible Women is the winner of the 2019 Royal Society Science Book Prize, the 2019 Books Are My Bag Readers Choice Award, and the 2019 Financial Times Business Book of the Year Award. It was The Times Current Affairs Book of the Year and named a book of the decade by the Sunday Times (Criado-Perez, 2020).
Assessment of usefulness for project	The book provided useful background reading on gender inequalities. The author's authority on the topic and the high level of impact this book made it both a useful and reliable source for this literature review.

Evaluation criteria	Hunt, V., Prince, S., Dixon-Fyle, S. & Yee, L., 2018. *Delivering through Diversity,* s.l.: McKinsey & Company.
Source type	Report
Author credentials	McKinsey & Company is a United States-based management consulting firm, founded in 1926 by University of Chicago professor James O. McKinsey, that advises on strategic management to corporations, governments, and other organizations (Wikipedia, 2020). The lead author, Dame Vivian, is a senior partner of the firm. She served as managing partner of McKinsey & Company's United Kingdom and Ireland offices from 2013-2020. Dame Vivian is an alumna of Harvard College and received her MBA from Harvard Business School. She has also been awarded an Honorary Doctorate of Law from the University of Warwick, an Honorary Doctorate from the University of York and an Honorary Fellowship from University College London (UCL). In 2018, she was appointed Dame Commander of the Order of the British Empire for services to the economy and women in business (McKinsey & Company, 2020).
Date published	January 2018
Scope of the report	The report tackles the business case for gender diversity and provides a perspective on how to take action on inclusivity and diversity to impact growth and business performance. This research reaffirms the global relevance of the correlation between diversity (defined here as a greater proportion of women and ethnically/culturally diverse individuals) in large companies' leadership and financial outperformance.
Reliability of data	A full methodology for the report is set out, and this provides the primary source of the report's credibility. The failure to provide the primary data does limit the integrity of the report. However, this is not a significant issue due to the comprehensive detailing of the report's sampling strategies and a clear statement on the work's limitations.
Critical response	Not peer-reviewed; no other response is available; however, the authors and the publishing firm's credentials suggest a high level of expertise on the topic.
Assessment of usefulness for project	The report focuses on the benefits of gender diversity for business. This is entirely relevant to Physics due to the natural parallels that exist between business and research. The report also serves to make a more general point about the economic benefits of gender diversity for society.

Evaluation criteria	Freeman, R. B. & Huang, W., 2014. Collaboration: Strength in diversity. *Nature,* 513(7518), p. 305.
Source type	Journal Article
Author credentials	Richard B. Freeman is director of the Science and Engineering Workforce Project at the National Bureau of Economic Research, and professor of economics at Harvard University in Cambridge, Massachusetts, USA. Wei Huang is a PhD candidate in economics at Harvard University (Nature, 2014).
Date published	The findings have been published in multiple places, including Nature in September 2014 and The Journal of Labour Economics in July 2015.
Objectiveness	There are no obvious ways in which the authors' objectivity could be compromised; however, their affiliations are outlined above in the author credentials section.
Reliability of data	The primary data is set out clearly, and the methodology is explained in great depth.
Critical response	Peer-reviewed; the original article, published in Nature, has been cited over 120 times including in other high impact articles such as “Diversity in Clinical and Biomedical Research: A Promise Yet to Be Fulfilled”.
Assessment of usefulness for project	This article's relevance to gender diversity in physics is not direct, since the article focuses on ethnic diversity and does so across science as a whole. However, ethnic diversity and gender diversity share similar patterns, and because of this, they are often grouped in academic literature. Hence it was deemed appropriate to conclude on gender equality from data on ethnic equality as long as it was backed up with other literature more closely aligned with the topic. This article was therefore deemed to be both a reliable and useful resource for this report. This is due to the authors' impressive credentials and the articles publishing in multiple high impact academic journals.

Evaluation criteria	The Royal Society of Chemistry, 2008. *Change of Heart: Career intentions and the chemistry PhD,* London: The Royal Society of Chemistry.
Source type	Report
Author credentials	Since 1841, the RSC has been a leading society and professional body for chemical scientists. It is committed to ensuring that an enthusiastic, innovative and thriving scientific community is in place to face the future. The RSC has a global membership of over 46,000, with a further 300,000 associated chemical scientists internationally, and is actively involved in education, qualifications and professional conduct. It runs conferences and meetings for chemical scientists, industrialists and policymakers, at both national and local level. It is a major publisher of scientific books and journals, most of which are held in the RSC Library and Information Centre. The Society of Chemistry was granted its Royal Charter in 1980. The charter states that the object for which the society is constituted is "the general advancement of chemical science and its application”. The societies aim are as follows: • to foster and encourage the growth and application of such science by the dissemination of chemical knowledge • to establish, uphold and advance the standards of qualification, competence and conduct of those who practise chemistry as a profession • to serve the public interest by acting in an advisory, consultative or representative capacity in matters relating to the science and practice of chemistry • to advance the aims and objectives of members of the Society so far as they relate to the advancement of the science or practice of chemistry (Royal Society of Chemistry, 2020).
Date published	November 2008
Objectivity	“In all its work, the Royal Society of Chemistry aims to be objective and impartial and is recognised throughout the world as an authoritative voice of the chemical sciences. Funding for the report was provided by the Economic and Social Research Council as part of a CASE award. The Royal Society of Chemistry also provided financial support” (The Royal Society of Chemistry, 2008).
Assessment of usefulness for project	The report focuses on gender equality in chemistry. Though there are differences between chemistry and physics, and chemistry is substantially more gender diverse than physics, the two sciences are broadly similar, and both involve similar working patterns. The similarities between the content in the two subjects is a point further explored in ‘The Feynman Lectures on Physics’ (Feynman, 1963). The standing of the Royal Society of Chemistry and its use of expert sources and its primary data, make this both a reliable and useful source for this literature review.

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