Perspective

Sex and gender analysis improves science and engineering

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Cara Tannenbaum[1,7], Robert P. Ellis[2,7], Friederike Eyssel[3,7], James Zou[4,5,7] & Londa Schiebinger[6]*

The goal of sex and gender analysis is to promote rigorous, reproducible and responsible science. Incorporating sex and gender analysis into experimental design has enabled advancements across many disciplines, such as improved treatment of heart disease and insights into the societal impact of algorithmic bias. Here we discuss the potential for sex and gender analysis to foster scientific discovery, improve experimental efficiency and enable social equality. We provide a roadmap for sex and gender analysis across scientific disciplines and call on researchers, funding agencies, peer-reviewed journals and universities to coordinate efforts to implement robust methods of sex and gender analysis.

Integrating sex and gender analysis into the design of research, where relevant, can lead to discovery and improved research methodology. A deeper understanding of the genetic and hormone-mediated basis for sex differences in immunity, for example, promises insights into novel cancer immunotherapies[1]. Evidence that facial recognition systems misclassify gender more often for darker-skinned women than for lighter-skinned men has led to refinements in computer vision[2]. Understanding sex-based responses to climate change allows better modelling of demographic change among marine organisms and the downstream effects for humans[3,4]. Sex or gender analysis can be critical to the interpretation, validation, reproducibility and generalizability of research findings (Box 1).

The documented importance of sex and gender analysis in research has underwritten policy change at major funding agencies. New policies have been implemented at the Canadian Institutes of Health Research (2010), European Commission (2014), US National Institutes of Health (2016), German Research Foundation (2020), among others. Concurrently, peer-review journals have implemented editorial guidelines to evaluate the rigour of sex and gender analysis as one criterion among many when selecting manuscripts for publication. The goal is to increase transparency, promote inclusion and reset the research default to carefully consider sex and gender, where appropriate.

In this Perspective, we discuss how incorporating sex and/or gender analysis into research can improve reproducibility and experimental efficiency, help to reduce bias, enable social equality in scientific outcomes and foster opportunities for discovery and innovation. From highlighted examples, we extract decision-tree roadmaps for researchers across disciplines. We consider the limits to sex and gender analysis and offer recommendations to researchers and funding agencies on how to move the field forward. Throughout this Perspective, we explore how integrating sex and gender analysis into research design has the potential to offer new perspectives, pose new questions and, importantly, enhance social equalities by ensuring that research findings are applicable across the whole of society.

Reproducibility and efficiency

Reproducibility is important for scientific excellence. One important reason for a lack of reproducibility in experimentation is inconsistency in methodological reporting, which varies widely across disciplines from biology to chemistry, human–robot interaction, medicine, physics, psychology and beyond[5,6]. Sex- and gender-specific reporting is still limited in a range of scientific disciplines. In preclinical microbiology and immunology, a review of published studies using primary cells from diverse animal species (that is, humans and nonhuman vertebrates) revealed that the majority failed to report the sex of donors from which the cells were isolated[7,8]. In marine science, a review of experimental ocean acidification studies showed that only 3.9% of studies statistically assessed sex-based differences, while only 10.5% of studies accounted for possible sex effects by assessing females and males independently[9]. Similarly, in ecotoxicology, a review of omics studies showed that although most reported sex, only 23% (5 out of 22) examined the omics response of each sex to a toxicant[10]. In social robotics, the notion of robot gender, gender-stereotypical domains and their interaction with user gender has only recently become a target of scientific inquiry[11]. A lack of transparency in reporting sex and gender-related variables makes it difficult to reproduce experiments in which these variables affect experimental results.

Disaggregating the data

Analysing experimental results by sex and/or gender is critical for improving accuracy and avoiding misinterpretation of data (Fig. 1). The common practice of pooling the response of females and males or

[1]Institute of Gender and Health, Canadian Institutes of Health Research, Université de Montréal, Montreal, Quebec, Canada. [2]College of Life and Environmental Sciences, University of Exeter, Exeter, UK. [3]Center of Excellence Cognitive Interaction Technology, Department of Psychology, Universität Bielefeld, Bielefeld, Germany. [4]Biomedical Data Science, Stanford University, Stanford, CA, USA. [5]Chan-Zuckerberg Biohub, San Francisco, CA, USA. [6]History of Science, Gendered Innovations in Science, Health & Medicine, Engineering and Environment, Stanford University, Stanford, CA, USA. [7]These authors contributed equally: Cara Tannenbaum, Robert P. Ellis, Friederike Eyssel, James Zou. *e-mail: schiebinger@stanford.edu

Box 1

Distinguishing sex and gender

Sex refers to the biological attributes that distinguish organisms as male, female, intersex (ranging from 1:100 to 1:4,500 in humans, depending on the criteria used[126,127]) and hermaphrodite (over 30% of noninsect nonhuman animals[128]). In biology, sex describes differences in sexual characteristics within plants or animals that go beyond their reproductive functions to affect appearance, physiology or neuroendocrine, behavioural and metabolic systems. In engineering, sex includes anthropometric, biomechanical and physiological characteristics that may affect the design of products, systems and processes.

Gender refers to psychological, social and cultural factors that shape attitudes, behaviours, stereotypes, technologies and knowledge. Gender includes three related dimensions. Gender norms refer to spoken and unspoken rules in the family, workplace, institution or global culture that influence individuals. Gender identity refers to how individuals and groups perceive and present themselves within specific cultures. Gender relations refer to power relations between individuals with different gender roles and identities[129].

Sex and gender interact in unexpected ways. Pain, for example, exhibits biological sex differences in the physiology of signalling. Pain also incorporates sociocultural components in how symptoms are reported by women, men and gender-diverse people, and how physicians understand and treat pain according to a patient's gender[130].

women and men can mask sex differences. For example, consider copepods, small aquatic crustaceans. Failure to disaggregate and analyse data by sex leads to the false interpretation that increased levels of p_{CO_2} have no significant biological effect on respiration (Fig. 1b). By contrast, disaggregating data by sex reveals important sex-based differences in the respiration rate of females and males in response to increased p_{CO_2} levels[12].

The same is true for human research. Pooling data yields inexact results. In a human–robot experiment, humans were asked to touch or point to anatomical regions on a 59-cm NAO robot. When asked to touch accessible regions (such as hands and feet), there was little physiological reaction; when asked to touch inaccessible regions (such as the plastic buttocks or genitals of the robot), human participants had increased heart rate and blood pressure[13]. Equal numbers of women and men were recruited for the experiment; however, the data were not disaggregated or analysed separately. We know that norms for human social touch vary according to the age, gender identity and cultural background of the participant—as well as social context and purpose of the touch[14]. If results are not stratified by these variables, opportunities will be missed to provide clearer insights into their influence on human judgments and behaviour.

Variability, sample size and interactions

Scientists have erroneously assumed that females should be excluded from experiments because of the variable nature of the data caused by the reproductive cycle[15]. In fact, research has shown that males exhibit equal or greater variability than females for specific traits owing to fluctations in testosterone levels and other factors, such as animal group caging[16]. Analysis of microarray datasets reveals similar findings that females are no more variable than males on measures of gene expression in both mice and humans[17]. Accounting for sex and gender enhances the likelihood of detecting meaningful effects, elucidating unexplained variability and potentially reducing the overall number of experiments required to determine trends or make ground-breaking discoveries. In a meta-analysis of 11 proteomics datasets from humans and mice, sex explained 13.5% of the observed variation of complex protein abundances and stoichiometry, even more than other environmental factors, such as diet[18].

On the surface, it may appear that including females and males, women and men in a study necessitates doubling the number of experimental participants. However, this is not always the case. More efficient experimental designs can incorporate both sex and gender while maintaining control over variance[19]. Factorial designs, in which two experimental factors with multiple levels are tested, and data are collected across all possible combinations of factors and levels, are one such strategy. This enables the effect of each factor to be tested, in addition to the interaction between the factor levels. For such cases, sample sizes may need to be slightly increased by 14–33% to account for the extra parameter being estimated, but they do not need to be doubled, according to sample size calculators that consider interaction effects[20,21]. Analysing data by sex or gender enhances the likelihood of detecting meaningful effects that, in turn, help to reduce confounding, increase reproducibility and reduce the cumulative number of experiments required.

Numerous interactions, such as the interaction of the sex of the research participants, may also influence outcomes. In animal research, females and males are often studied separately in the laboratory. Yet in the wild, the sexes coexist—and their interactions can influence research results. Recent studies of longevity in the nematode, *Caenorhabditis elegans*, found that the presence of males accelerated ageing in individuals of the opposite sex (in this case, hermaphrodites). In other words, hermaphrodites died at a younger age in the presence of males. Researchers traced this 'male-induced demise' to pheromones released by males and found it could occur without mating and required only that the hermaphrodites be exposed to the medium in which males were once present[22]. Ignoring such interactions potentially leads to an incomplete understanding of species viability in the wild.

Other interactions focus on the sex of the researcher and potential impacts on research participants. In social science, it has long been understood that the simple presence of an observer can alter the response of the observed, whether in the field or in laboratory experiments[23]. In quantum mechanics, the act of observation can alter the phenomenon by collapsing the wave function. Similarly, in animal research, experimenter sex can influence research outcomes. A study exploring pain showed that rats and mice did not exhibit pain when a male experimenter was present, as opposed to when a female experimenter was present in the room or when in an empty room. Both female and male mice displayed this 'male observer' effect, but female mice did so to a greater extent. Researchers determined that the mice responded to male-associated olfactory stimuli[24]. The authors suggest that not controlling for experimenter sex throws into question many of the previously published studies on pain research.

Many other examples of these types of interactions—crucial to excellence and discovery in research—could be discussed. However, here we would like to include one further interaction of note, namely of researcher gender and the type of research conducted. Two studies provide compelling evidence that in biomedical, clinical and public health research, women in leading positions (first and last author) are more likely to analyse sex and gender in published research[25,26]. However, this dynamic has not yet been replicated in other research fields, such as computer science, engineering or the physical sciences.

Opportunities for discovery

Ignoring sex and gender analysis can lead to inaccuracies, research inefficiency and difficulties generalizing results. Integrating sex and gender analysis into research can open the door to discovery and innovation.

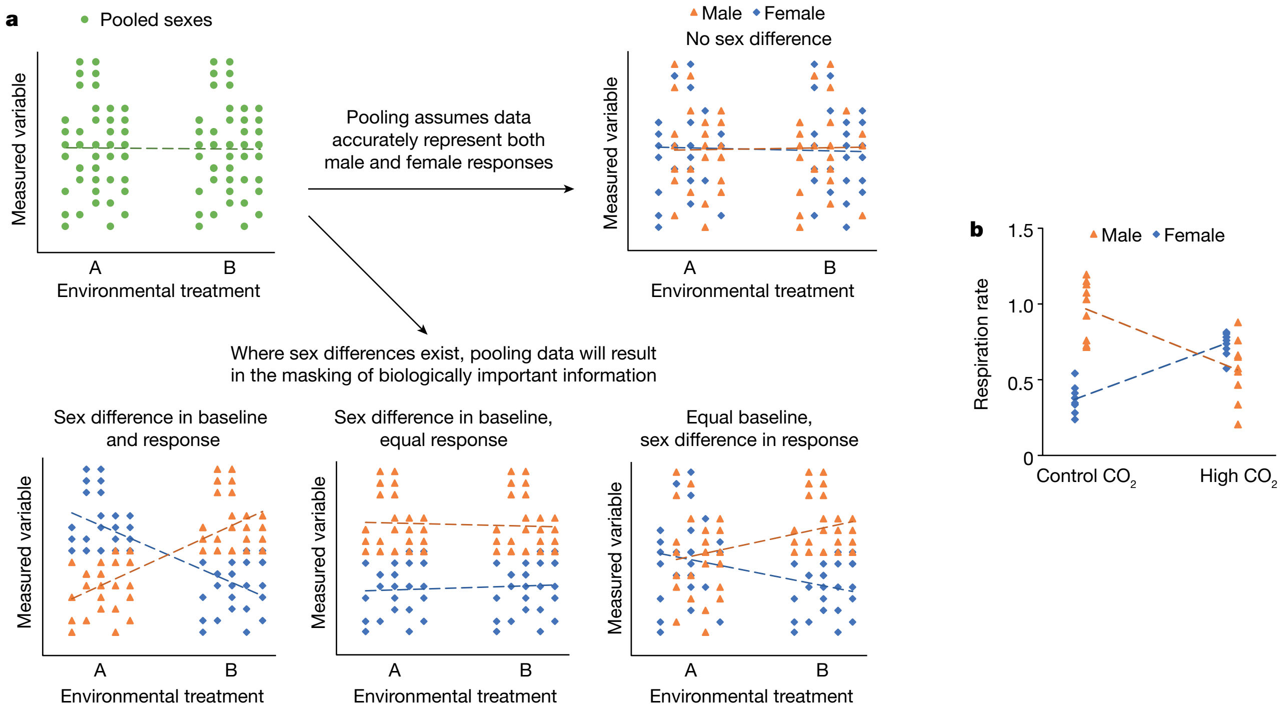

Fig. 1 | Hazards of pooling data from both sexes. Pooling data across sexes not only assumes that there is no difference between males and females, but also subsequently prevents researchers from testing for the dependency of an experimental response on the sex of a study participant. **a**, The theoretical examples reveal that pooling (green circles) masks important male (orange triangles) and female (blue squares) differences in baseline data, treatment response and sex × treatment interactions—any one of which leads to misinterpretation of the results. **b**, An example of experimental data in which pooling would have masked both the sex difference in the respiration rate of copepods, as well as the response of this variable to increased levels of p_{CO_2}. Theoretical examples were generated using hypothetical data; experimental data were taken from a previously published study[12].

A prevalent assumption is that sex is a binary trait determined genetically before birth, and that it is fixed across lifespan[27,28]. Commonly used model organisms in biology, such as mice, *Drosophila melanogaster* and *C. elegans*, reinforce these perceptions. Sex, however, can be highly plastic, and studying interactions with the environment, for example, has led to new understandings of the mechanisms of sex determination within the context of global climate change.

The sex ratio of a population influences its resilience to environmental disturbances. The mechanism that determines sex is thus a vital consideration for predicting population viability[29,30]. Enhancing the capacity of sex analysis for a growing number of species, across a wide range of settings, may increase our ability to accurately model the effects of climate change.

Climate impacts in the ocean

For species reliant on temperature for sex determination, rapid global warming poses a risk to sex ratios and demographic stability. Turtles are the most widely studied group in which sex is determined by temperature. The ability to differentiate between female and male juvenile green sea turtles using non-invasive endocrine markers has enabled the discovery that global warming negatively skews population sex ratios. Turtles originating from warmer northern Great Barrier Reef sites, for instance, exhibit a female sex ratio of 99%, whereas cooler southern sites maintain a 68% female juvenile ratio[3]. Similarly, in fish species with temperature-dependent sex determination, warming is projected to result in male-skewed populations (up to 3:1 male:female) by the end of the century[28]. Such changes in sex balance can limit mate choice, reduce reproductive capacity and undermine population viability[31,32].

Warming is not occurring in isolation, but against a backdrop of anthropogenic disturbances across marine environments, which include habitat destruction, pollution and overfishing. Primary sex differentiation has been shown to respond to a diverse range of these environmental factors in a growing number of species. Hypoxia, for example, has resulted in a higher ratio of males in zebrafish[33]. Similarly, ocean acidification results in 16% more female oysters over a single generational cycle[4], and increased aquatic pH results in more female cichlids[34]. What is increasingly apparent is that alterations in sex ratio—in either direction—will result in populations that are less resilient to further disturbance and potentially lead to demographic collapse[35,36].

Social organization can also influence population sex ratios. Numerous nonhuman species develop elaborate social organizations, and sex determination can be socially mediated. Clownfish, for example, are protandrous hermaphrodites (they mature as male; some change to female) that live in a strict social hierarchy with a single dominant and highly fecund female at the top who mates with a single large male in the social group; all remaining individuals remain immature juveniles. Removal of the alpha female results in the alpha male changing sex to female, with all subordinates moving up a rung in the social hierarchy[37]. By contrast, many grouper species, a subfamily of long-lived and high-value reef species, are protogynous hermaphrodites (they mature as female; some change to male). Large dominant males control groups of females with strong sexual selection, resulting in these males achieving the greatest reproductive success. These sequentially hermaphroditic individuals consistently produce more offspring and enjoy greater reproductive success after they have changed sex[36]. Thus, the timing and the direction of sex change are crucial species-specific factors that determine demographic resilience to disturbance in sex-changing organisms.

A mechanistic understanding of these and other ecologically important sex-based responses enables more accurate modelling of the effects of environmental variability, climate change or anthropogenic disturbance (for example, overfishing) at a population level. Sex-specific effects of climate change stressors on sex determination mechanisms, particularly in commercially important species, have potentially important implications for humans with respect to aquatic food production, ecosystem services and biodiversity. Incorporating sex analysis into marine science—and the natural sciences more widely—enhances research excellence and opportunities for discovery.

Targeted human therapeutics

Sex analysis also reveals opportunities for human drug development. In the areas of pain and depression, the discovery of sex differences in molecular pathways has signalled new directions for targeted therapies[38]. Pain research that uses experimental mouse models of chronic pain shows that male and female mice withdraw from painful stimuli in a similar fashion, except when the contribution of microglial cells is inhibited[39]. Microglia are specialized immune cells located exclusively in the spinal cord and the brain. Inhibitors of microglia reduce pain sensing in male—but not female—mice, underscoring the potential importance of sex-dependent molecular pain pathways. Mouse models of depression also show sexually divergent networks in the brain with distinct patterns of stress-induced gene regulation in males and females[40]. These findings have now been reproduced in human postmortem tissue and may provide insights into why males and females with major depressive disorder respond differently to treatment with antidepressants[40].

Although sex-specific dosages are rare, a few already exist. Such is the case for the drug desmopressin that activates vasopressin receptors in the kidney to regulate water homeostasis. Because the gene for the arginine vasopressin receptor is found on the X chromosome in a region that is likely to escape X-chromosome inactivation, women are more sensitive to the antidiuretic effects of vasopressin than men, who have only one X chromosome and therefore only one copy of the vasopressin receptor gene per cell[41]. As a result, older women who take desmopressin are more likely to experience a reduced sodium concentration in the blood than men, which corresponds to a higher incidence of side effects in women. To avoid unnecessary harm, both the European Union and Canada have recommended lower dosages for older women taking desmopressin.

Even cancer immunotherapy is benefitting from a deeper understanding of previously recognized genetic and hormone-mediated sex differences in immunity. Patients with melanoma or lung cancer, who are treated with checkpoint inhibitors, respond differently based on their sex, with a higher proportion of male than female patients achieving successful remission[1]. Designed to outsmart the defence tactics of the cancer cells, checkpoint inhibitors stimulate natural killer cells to attack tumour cells. Natural killer cells are sensitive to oestrogen and testosterone, which may explain these observed sex differences. Understanding the underlying mechanisms will enable us to fine-tune future therapies[42].

We expect to see an exponential rise in biomedical discoveries now that new computational biology and statistical genetics software facilitates the exploration of X-chromosome-related expression in complex diseases[43]. Until recently, sex chromosomes were excluded from most genome-wide association studies because of the difficulty in distinguishing the active from the inactive X chromosome in females, and because of a mismatch in chromosomal size[44,45]—the X chromosome has 1,669 known genes and the smaller Y chromosome contains only 426. Including sex chromosomes in genome-wide association studies, as well as including and analysing adequate numbers of female and male cells, tissues, animals and humans in research, will broaden our understanding of why women and men are affected differently by certain diseases and how we can adapt life-saving therapies to their specific needs.

Engineering for equality

An often neglected but crucial component of engineering is to understand the broader social impacts of the technology being developed and to ensure that the technology enhances social equality by benefitting diverse populations. Human bias and stereotypes can be perpetuated, and even amplified, when researchers fail to consider how human preferences and assumptions may consciously or unconsciously be built into science or technology. Gender norms, ethnicity and other biological and social factors shape and are shaped by science and technology in a robust cultural feedback loop[46]. This section discusses examples from product design, artificial intelligence (AI) and social robotics to illustrate how sex and gender analysis can enhance excellence in engineering.

Designing safer products

When products are designed based on the male norm, there is a risk that women and people of smaller stature will be harmed. Motor vehicle safety systems provide one such example. Because male drivers have historically been overrepresented in traffic data, seatbelts and airbags have been designed and evaluated with a focus on the typical male occupant with respect to anthropometric size, injury tolerance and mechanical response of the affected body region. When national automotive crash data from the United States were analysed by sex between 1998 and 2008, data revealed that the odds for a belt-restrained female driver to sustain severe injuries were 47% higher than those for a belt-restrained male driver involved in a comparable crash, after controlling for weight and body mass[47]. The subsequent introduction of a virtual female car crash dummy allowed mathematical simulations to account for the effect of acceleration on sex-specific biomechanics, highlighting the need to add a medium-sized female dummy model to regulatory safety testing[48,49]. Beyond automotive safety systems, the importance of anthropometric characteristics, such as the carrying angle of the elbow or the shape and size of the human knee, can be used to guide sex-specific design for artificial joints, limb prostheses and occupational protective gear[50,51].

Reducing gender bias in AI

Alarming examples of algorithmic bias are well documented[52]. When translating gender-neutral language related to science, technology, engineering and mathematics (STEM) fields, Google Translate defaults to male pronouns[53]. When photographs depict a man in the kitchen, automated image captioning algorithms systematically misidentify the individual as a woman[54]. As AI becomes increasingly ubiquitous in everyday lives, such bias, if uncorrected, can amplify social inequities. Understanding how gender operates within the context of the algorithm helps researchers to make conscious decisions about how their work functions in society.

Since the Second World War, medical research has been submitted to stringent review processes aimed at protecting participants from harm. AI, which has the potential to influence human life at scale, has yet to be so carefully examined. Numerous groups have articulated 'principles' for human-centred AI. These include, most importantly, the UN Human Rights Framework that consists of internationally agreed upon human rights laws and standards, as well as the 'Asilomar AI Principles', 'AI at Google: Our Principles', 'Partnership on AI', and so on. What we lack are mechanisms for technologists to put these principles into practice. Here we delve into a few of such rapidly developing mechanisms for AI.

A first challenge in algorithmic bias is to identify when it is appropriate for an algorithm to use gender information. In some settings, such as the assignment of job ads, it might be desirable for the algorithm to explicitly ignore the gender of an individual as well as features such as weight, which may correlate with gender but are not directly related to job performance. In other applications, such as image/voice recognition, it might be desirable to leverage gender characteristics to achieve the best accuracy possible across all subpopulations. To date, there is no unified definition of algorithmic fairness[55–57], and the best approach is to understand the nuances of each application domain, make transparent how algorithmic decision-making is deployed and appreciate how bias can arise[58].

Training data are a source of potential bias in algorithms. Certain subpopulations, such as darker-skinned women, are often underrepresented in the data used to train machine-learning algorithms, and efforts are underway to collect more data from such groups[2]. To highlight the issue of underrepresented subpopulations in machine-learning data, researchers have designed 'nutrition labels' to capture metadata about how the dataset was collected and annotated[59–61]. Useful metadata should summarize statistics on, for example, the sex, gender, ethnicity and geographical location of the participants in the dataset. In many machine-learning studies, the training labels are collected through crowdsourcing, and it is also useful to provide metadata about the demographics of crowd labellers.

Another approach to evaluate gender bias in algorithms is counterfactual analysis[62]. Consider Google Search, in which men are five times more likely than women to be offered ads for high-paying executive jobs[63]. The algorithm that decides which ad to show inputs features about the individual making the query and outputs a set of ads predicted to be relevant. The counterfactual would test the algorithm in silico by changing the gender of each individual in the data and then studying how predictions change. If simply changing an individual from 'woman' to 'man' systematically leads to higher paying job ads, then the predictor is—indeed—biased.

Work to debias word embeddings is another example of counterfactual analysis[64]. Word embeddings associate each English word with a vector of features so that the geometry between the feature vector captures semantic relations between the words. It is widely used in practice for applications such as sentiment analysis[65], language translation[66] and analysis of electronic health records[67]. It has previously been shown that gender stereotypes—for example, men are more likely to be computer scientists—are manifested in the feature vectors of the corresponding words[64]. Whether this association between man and computer is problematic depends on the application of the features. To test for gender effects, gender-neutral word features were created. For each downstream application, counterfactual analysis can then be performed by running the application twice, once using the original word features, and once using the gender-neutral features. If the outcome changes, the algorithm is sensitive to gender. In some applications, such as job searches, it might be preferable to use gender-neutral features.

An alternative approach to quantify and reduce gender bias in algorithms is called multi-accuracy auditing[68,69]. In standard machine learning, the objective is to maximize the overall accuracy for the entire population, as represented by the training data. In multi-accuracy, the goal is to ensure that the algorithm achieves good performance not only in the aggregate but also for specific subpopulations—for example, 'elderly Asian man' or 'Native American woman'. The multi-accuracy auditor takes a complex machine-learning algorithm and systematically identifies whether the current algorithm makes more mistakes for any subpopulation. In a recent paper, the neural network used for facial recognition was audited and specific combinations of artificial neurons that responded to the images of darker-skinned women were identified that are responsible for the misclassifications[70].

The auditor also suggests improvements when it identifies such biases[71]. Although achieving equal accuracy across all demographic groups may not always be feasible, these auditing techniques improve the transparency of the AI systems by quantifying how its performance varies across race, age, sex and intersections of these attributes.

These are only a few of the specific techniques computer scientists are developing to promote gender fairness in algorithms. Some, such as data checks, are relevant across all disciplines that amass and analyse big data. Others are specific to machine learning, which is now widely deployed across broad swathes of intellectual endeavours from the humanities to the social sciences, biomedicine and judicial systems. In all instances, it is important to be completely transparent where and for what purpose AI systems are used, and to characterize the behaviour of the system with respect to sex and gender[72].

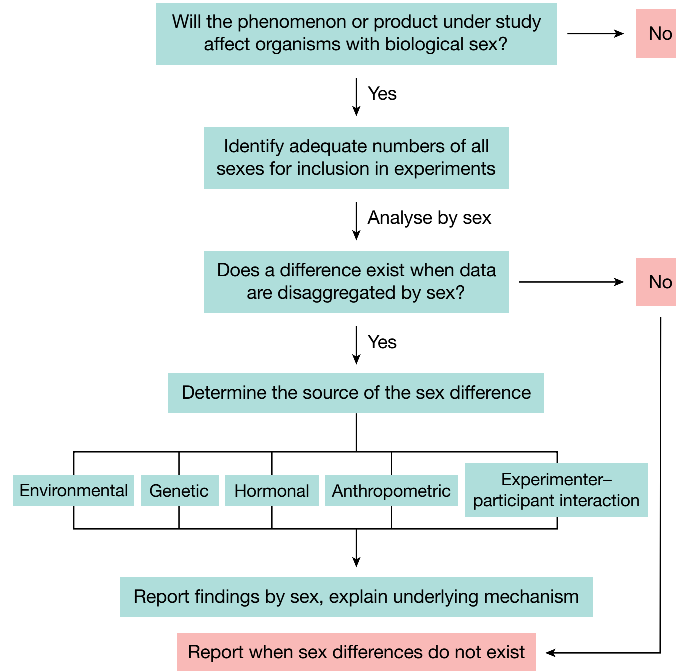

Fig. 2 | Sex analysis and reporting in science and engineering. This decision tree represents a cognitive process for analysing sex. A 'no' indicates no further analysis is necessary. A 'yes' suggests the next step that should be considered.

Combatting stereotypes

Analysing gender in software systems is one issue; configuring gender in hardware—such as social robots—is another, and the focus of this section. Until recently, robots were largely confined to factories. Most people never see or interact with these robots; they do not look, sound or behave like humans. But engineers are increasingly designing robots to assist humans as service robots in hospitals, elder care facilities, classrooms, homes, airports and hotels. The field of social human–robot interaction examines, among other things, when and how 'gendering' robots, virtual agents or chatbots might enhance usability while, at the same time, considering when and how to avoid oversimplifications that may reinforce potentially harmful gender stereotypes[73].

Machines are, in principle, genderless. Gender, however, is a core social category in human impression formation that is readily applied to nonhuman entities[74]. Thus, users may consciously or unconsciously gender machines as a function of anthropomorphizing them, even when designers intend to create gender-neutral devices[75–78].

Anthropomorphizing technologies may help users to engage more effectively with them, which poses the question as to whether there are benefits to tapping into the power of social stereotypes by building gender into virtual agents[79–83], chatbots[84] or social robots[11,85,86]. For example, if roboticists deploy female carebots in female-typical roles, such as nursing, would users better comply with the robot's requests to take daily medication or to exercise? Does gendering robots or virtual agents facilitate interaction or boost objective outcomes such as performance[11,80–91]? Will personalizing robots or chatbots by gender increase consumer acceptance and, even, sales figures? Systematic empirical research is needed to address these open research issues.

What features lead humans to gender a robot? So far, experimental research designed to analyse robot gender has manipulated gender in a number of ways, including (1) by choosing a male or female name to label the robot[87–92]; (2) by colour-coding the robot[93,94]; (3) by manipulating visual indicators of gender (for example, face, hairstyle or lip colour[94,95]); (4) by adding a male or female voice, or low or high pitch to simulate this, respectively[87–92,94,96,97]; (5) by designing a gendered personality[87,98];

and (6) by deploying robots in gender-stereotypical domains, such as a male-voiced robot for security and a female-voiced robot in a healthcare role[95]. Other aspects, such as movements or gestures, that may potentially gender a robot still require empirical research[85,86].

But there are dangers here. As soon as designers or users assign a gender to a machine, stereotypes follow. Designers of robots and AI do not simply create products that reflect our world, they also (perhaps unintentionally) reinforce and validate certain gender norms that are considered to be appropriate for men, women or gender nonconforming individuals[11,73].

Eliciting gendered perceptions of technologies implies actively designing human gender biases, including binary constructions of gender as male or female, into machines. From a social psychological viewpoint, this can contribute to stereotypical gender norms in society[95]. Even though this might not seem relevant from an engineering point of view, social psychological research would suggest that a robot with a female appearance, for example, may perpetuate ideas of women as nurturing and communal, traits stereotypically associated with women[95]. Thus, a female robot may be deemed socially warm and particularly suitable for stereotypically female tasks, such as elderly care, or it might be openly sexualized and objectified as revealed in abusive commentary on video clips of female robots in recent qualitative research[99]. Similarly, virtual personal assistants with female names, voices and stereotypical, submissive behaviours, such as Siri or Alexa, represent heteronormative ideas about females and thereby indirectly contribute to the discrimination of women in society[100,101]. An interesting development in this regard is the genderless voice, Q, which has recently been developed in Denmark to overcome such bias[102].

There are many questions regarding these features. How, for example, do user attributes, such as age or gender, interact with different robot design features? How do robots enhance or harm real-world attitudes and behaviours related to social equality? How does robot gender elicit different responses across cultures? More experimental, laboratory and longitudinal field research is needed to test whether, and how, a machine's gendered, gender-diverse or gender-neutral appearance or behaviour influences human affect, cognition and behaviour. It is likely that even social robots designed to be genderless or gender neutral elicit gender attributions owing to the relatively automatic nature of anthropomorphizing humanoid robots. It is also likely that when potential end users are offered the option to select a digital assistant's gender, their choice will be driven by their own gender identity and gender-related attitudes and stereotypes. Addressing these research questions and issues remains important to shed light on the psychological, social and ethical implications of implicit or explicit design choices for novel technologies.

Developing technologies that enhance, or at least do not harm, social equality will require novel configurations of researchers. Much attention has been paid to the need for interdisciplinary research, consisting of humanists, legal experts, technologists and social scientists, especially in the fields of human-centred AI. The historical development of universities, however, has artificially separated human knowledge into disciplines over the course of the nineteenth and twentieth centuries that may not support current research needs. Research institutions now need to develop robust mechanisms to bring together social analysis and engineering in a way that rigorously addresses the emerging needs of society[103].

Pathways to improving study design

To reach the full potential of sex and gender analysis for discovery and innovation, it is important to integrate sex and gender analysis, where relevant, into the design of research from the very beginning. Much of science and engineering research is path-dependent: once research has been designed, it becomes difficult to change. It is also important to understand that sex and gender are categories of analysis or variables (or controls) that need to be incorporated into the research process, but do not need be the main focus of the research. Nor will sex and gender analysis be relevant to all types of research. As the decision trees for analysing sex (Fig. 2) and gender (Fig. 3) indicate, in cases in which researchers have considered sex and/or gender but judge that this analysis is not relevant for a specific hypothesis, they may rule it out. Moreover, if researchers expect sex or gender to be important but find no significant differences, this may represent a result worthy of publication. Reporting cases in which sex or gender sameness, overlap or no difference is found may represent an important finding.

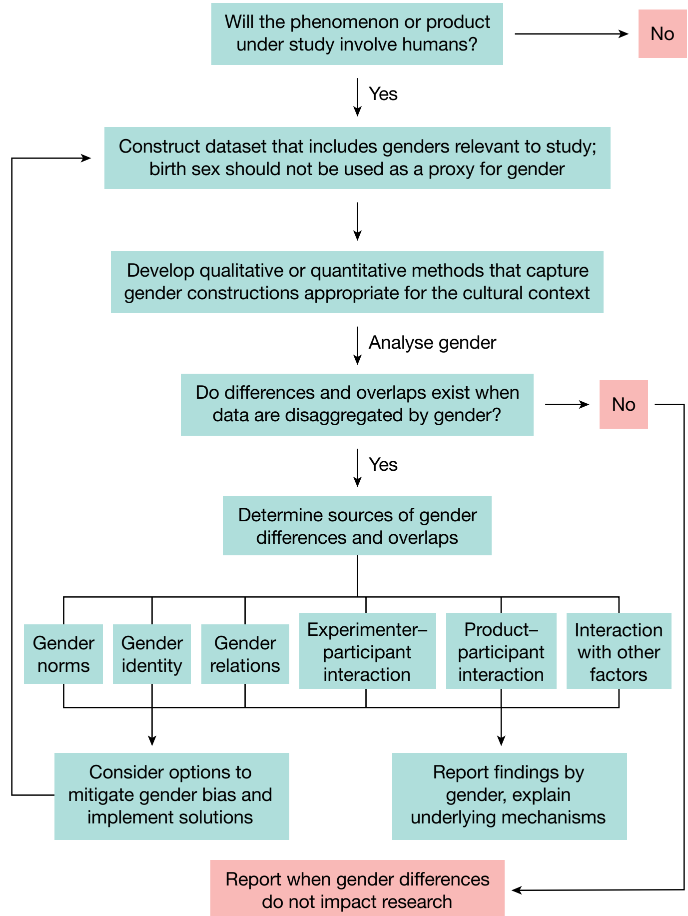

Fig. 3 | Gender analysis and reporting in science and engineering. This decision tree represents a cognitive process for analysing gender. A 'no' indicates no further analysis is necessary. A 'yes' suggests the next step that should be considered.

In this Perspective, we highlight the need and promise for designing sex and gender analysis into research through specific case studies and examples. From these, we extracted key considerations for analysing sex (Fig. 2) and gender (Fig. 3). These are generic recommendations that work across disciplines. However, more related studies are needed in the next five years. First, through interdisciplinary work, researchers need to sharpen and standardize generic approaches to sex and gender analysis that generalize across fields. Second, through discipline-specific work, researchers need to craft state-of-the-art analytics for study design and data analysis in their own subfields. The European Commission is currently funding an expert group that seeks to tailor sex and gender methods of analysis to field-specific protocols[104].

Future challenges

We do not yet have results for sex and gender analysis in the physical sciences, such as basic chemistry, pure physics, geology or astronomy. Much work has analysed gender gaps in participation and gender bias

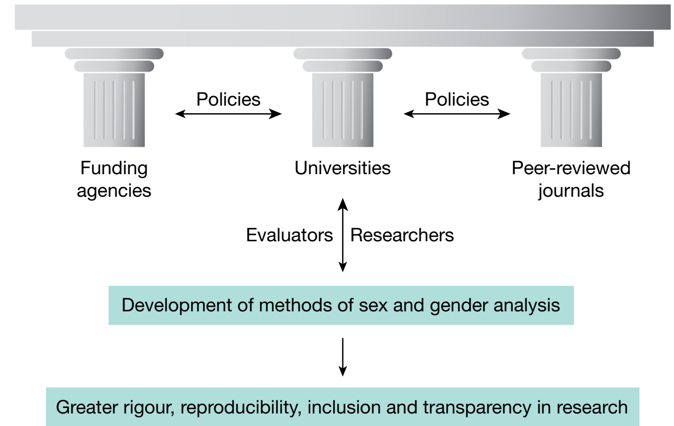

Fig. 4 | Three pillars of science and engineering infrastructure. To reap the benefits of sex and gender analysis, the pillars of science infrastructure must develop and implement coordinated policies.

in the culture of these fields, but attention has yet to turn to how the research itself may respond to gender analysis. As research in the physical sciences becomes more applied, sex and gender analysis become more relevant—for example, in the chemistry of aerosols, sex differences govern rates of inhalation and gender differences influence rates of exposure[105].

Several methodological challenges remain for the field of sex and gender analysis itself. Although advances have been made in methods for analysing sex[106], we lack non-invasive methods of sex determination in numerous non-model organisms, in which sexual morphological dimorphism is not easily detected. Technological advances through the development of genetic[107], metabolomic[108] and endocrine[3] markers of organism sex are needed for non-model species at all stages of development, an endeavour that will be aided by the innovation and increased affordability of omics approaches. Attention will also need to be paid to the translation of evidence from animal species to humans as—in many cases—molecular sex differences observed in humans may not be mirrored in nonhuman mammals[109].

Although sex as a biological variable in science and engineering is increasingly well understood[110], the same cannot be said for gender as a cultural variable. Gender is complex and multidimensional (Facebook introduced 58 gender categories in 2014[111]) and applications in technical fields often require collaboration with social scientists to understand the relevant aspects of gender for specific projects. Even in health research, we lack systematic measures for assessing how gender relates to health because gender does not reduce easily to variables that can be manipulated statistically. Two recent studies have attempted to remedy this. The first used a binary gender index (masculinity versus femininity) constructed from seven variables and found that the incidence of recurrence and death 12 months after diagnosis of acute coronary syndrome in young adults was associated with gender and specifically not with biological sex[112]. A second study under development at Stanford University seeks to capture the multidimensionality of gender better by identifying theoretically robust gender-related variables relevant for health research. This study is based on US data, and new variables tailored to specific cultural settings need to be identified. Developing measures of gender is clearly an area for which more research is needed.

Other methodological challenges include going beyond the binary—female and male, women and men—in both sex and gender analysis. Take, for instance, the Gender API algorithm that allows social scientists to understand gender differences in research patterns. The algorithm identifies only binaries: female/male; woman/man. In the United States, 0.6% of the population—nearly 2 million people—identify as transgender[113], and more than 15 countries offer a third sex category on legal documents, birth certificates and passports. Research needs to keep pace with social change. Similarly, consider the lack of research that addresses how hermaphroditic animals respond to environmental change. In simultaneous hermaphrodites in which reproductively mature individuals have both male and female gametes, there is a need to consider the role of male or female tissues in determining the response of the whole organism. By contrast, in sequential hermaphrodites that change sex, there is a need to consider whether an organism responds as a female or a male to environmental stress during the sex change process, given that this process is dynamic, with behavioural, endocrine and genetic systems switching sex on markedly different timescales[114].

Additional challenges include accounting for other social variables, such as age, race and geographical location, and how these intersect with sex and/or gender. Sex or gender cannot be isolated from other characteristics, and we need model systems and intersectional methods to understand these interrelationships[115]. An intersectional approach in human research underscores the importance of unmasking and rectifying overlapping and interdependent systems of discrimination that are often built into knowledge, programs and policies. Benefits for global health, for example, will only be achieved when unbiased decision-making about resources takes into account the lived experiences of women and men with multiple identity characteristics who simultaneously suffer from race, class, education, economic and cultural power imbalance in accessing food and water, digital technology and healthcare services[116].

Science policy

Policy is one driver of discovery and innovation that can enable sex and gender analysis in science and technology. To push forward rigorous sex and gender analysis, interlocking policies need to be implemented by three pillars of academic research: funding agencies, peer-reviewed journals and universities (Fig. 4).

Government-led funding agencies have taken the lead by asking applicants to explain how sex and gender analysis is relevant to their proposed research, or to explain that it is not (for a list of agencies and policies, see Supplementary Information section 1). The Canadian Institutes of Health Research showed robust uptake after mandating applicants to declare whether sex and/or gender were accounted for in proposals and to justify exclusion in 2010. Their evaluation revealed that from 2010–2011 the proportion of funded proposals incorporating sex and/or gender analysis nearly doubled[117,118].

The second pillar, peer-reviewed journals, have developed editorial policies advocating for sex or gender analysis to ensure excellence in papers selected for publication (for a list of journals and policies, see Supplementary Information section 2). Uptake has been swift in health and medicine. *The Lancet*, for example, adopted such guidelines in 2016, followed quickly by the International Committee of Medical Journal Editors[119]. The Structured, Transparent, Accessible Reporting (STAR) methods of Cell Press have required transparent reporting of the sex distribution of donor cells, also since 2016. Importantly, the widely adopted Sex and Gender Equity in Reporting (SAGER) guidelines recommend that data be disaggregated by both sex and gender[120]. Although biomedical journals have moved rapidly, we are not aware of any engineering or computer science conferences or journals with such guidelines.

Pillars one and two need the support of a third pillar: universities. Both funding agencies and journals may have policies in place, but researchers and evaluators by and large lack expertise in sex and gender analysis. The European Commission, which has had policies in place since 2014, found that fewer than expected funded research proposals incorporated sex and gender analysis and has correlated this low proportion to an 'absence of training on gender issues'[121]. Similarly, an analysis of animal research in the neurosciences showed that in 2014 only about 14% of peer-reviewed articles considered sex as a biological variable[122].

Universities need to step up and incorporate sex and gender analysis as a conceptual tool into science and engineering curricula. Numerous universities offer gender analysis in the humanities and social sciences, but not in core natural science and engineering courses. Efforts have been made in medicine—the Charité in Berlin, Germany, for instance, has successfully integrated sex and gender analysis throughout all six years of medical training from early basic science to later clinical modules[123]. However, this is a rare example, and universities must do more to prepare the scientific workforce for the future.

Several initiatives have endeavoured to fill this gap. Gendered Innovations—a global, collaborative project initiated from Stanford University in 2009 and supported by the European Commission and the US National Science Foundation—has developed practical methods of sex and gender analysis for natural scientists and engineers, and provides case studies as concrete illustrations of how sex and gender analysis lead to discovery and innovation (https://genderedinnovations.stanford.edu/). The WHO (World Health Organization) has developed a gender-responsive assessment tool[124]. The Organization for the Study of Sex Differences (https://www.ossdweb.org/) has advanced sex and gender analysis methods for the life and health sciences. The Canadian Institutes of Health Research have developed online training modules for integrating sex and gender analysis into biomedical research[125]. These initiatives should now be mainstreamed into university education.

Much work remains to be done to systematically integrate sex and gender analysis into relevant domains of science and technology—from strategic considerations for establishing research priorities to guidelines for establishing best practices in formulating research questions, designing methodologies and interpreting data. To make real progress in the next decade, researchers, funding agencies, peer-reviewed journals and universities need to coordinate efforts to develop and standardize methods of sex and gender analysis.

But eyes have been opened, and by integrating sex and gender analysis into their work, researchers can enhance excellence and social responsibility in science and engineering.

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Correspondence and requests for materials should be addressed to L.S.
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