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# Misconceptions in Science

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**Abstract**
Disagreement in science exists in a variety of strengths, from doubt-raising articles and issues of non-reproducibility up to raging disputes and major controversies. An often-latent form of disagreement consists of misconceptions whereby false ideas are held that run contrary to what is commonly accepted as knowledge. Misconceptions have been the focus of much research in education science and psychology. Here we draw attention to misconceptions that may arise in the very practice of science. We highlight formal features that can be used to characterize misconceptions and distinguish them from controversies, in addition to how they relate to knowledge creation.

**Keywords**: scientific misconception; scientific controversy; scientific disagreement; scientific dispute; knowledge creation; astrobiology



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## 1. Introduction

The phenomenon of scientific misconceptions—whereby one holds ideas or beliefs about scientific matters that run contrary to what is commonly accepted as knowledge—has been the focus of much attention in psychology and education science: misconceptions have been documented to affect children and college students alike, triggering work on the conceptual characterization of misconceptions, on the classification of concrete cases of misconceptions, and on the identification of factors favoring the emergence of misconceptions (e.g., Driver et al. 1994; Offerdahl, Prather, and Slater 2002; N. G. Lederman et al. 2002; Williams 2009; J. S. Lederman et al. 2014). In science, disagreement about scientific knowledge has typically been approached through the perspective of scientific controversies, be they about facts, theories or methodology (Engelhardt and Caplan 1987; Machamer, Pera, and Baltas 2000; Dascal and Boantza 2011; Raynaud 2015). However, misconceptions in science have so far received little or no attention. Yet if scientific misconceptions affect students, why wouldn't they also affect professionals, including practicing scientists? The very practice of science—as notably experienced by authors of the present contribution—tends to indicate that scientific misconceptions are indeed very real among researchers.

We hereby propose to characterize misconceptions in science from a formal point of view, identifying some of their most salient features, notably in contrast to scientific controversies. By so doing, we also hope to draw attention to the phenomenon of misconceptions in science and highlight the need for further research, notably field work aiming at documenting and cataloguing concrete cases of such misconceptions but also experimental and theoretical approaches. In the next section (Section 2), we use the notion of scientific controversy as a foil for making sense of the notion of scientific misconception in science. We then show that misconceptions, like controversies, concern three types of objects: facts, theoretical constructs, and methodologies (Section 3). Using the set of dimensions proposed by Raynaud (2015) to characterize scientific controversies, we highlight five formal features—form of acknowledgement, extent, intensity, duration, and settlement—that characterize misconceptions in science and notably distinguish them from scientific controversies (Section 4). We further argue that another differentiating characteristic concerns contribution to knowledge (Section 5). We illustrate the phenomenon of scientific misconceptions by drawing on examples from astrobiology, which is very much multidisciplinary and particularly prone to this issue (Section 6) and investigate a set of potential factors affecting the presence of misconceptions in science (Section 7). We identify areas for further research in the concluding section.

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## 2. "Controversies" as a foil for understanding "misconceptions"

In short, scientific controversies are scientific disputes. From the Latin *controversus* or "turned in opposite direction", a controversy is a dispute in which arguments point to opposite directions and lead to disagreement. Such a dispute presupposes that a debate, or an exchange of arguments, takes place between a number of proponents over a certain period of time, a couple weeks or months up to several decades. A scientific controversy can hence be said to refer to "the persistent and public division of members of a scientific community (either individually or as coalitions), who sustain contradictory arguments in the interpretation of reality" (Raynaud 2015, 8).[1] Proponents often fall into two (or more) groups that defend incompatible or contradictory views. These groups can be quite extended and involve numerous researchers and schools of thoughts, or just concern a few isolated scholars. The debate at the heart of any controversy consists in exchanges of arguments whose overarching objectives are to win over the opposing camp, and, maybe more importantly, convince a third neutral party, usually the one also arbitrating the dispute. Because of this dialectical characteristic, rhetoric and persuasion skills are an integral part of how controversies develop and eventually come to an end (Raynaud 2015), in addition, of course, to such factors as corroboration by evidence or coherence with other accepted claims.

On the other hand, a misconception simply is a false belief or a false idea. "Misconception" comes from the Latin prefix *mis-* or "bad, wrong", and the noun *conceptio* in the sense of "act of conceiving" or "taking into the mind". Related words include fiction, distortion, inaccuracy, miscomprehension, misinterpretation, misjudgment, misperception, misunderstanding, misinformation, or misrepresentation, among others. With such a broad definition, misconceptions are quite diverse and numerous: one may say that "it is a misconception that dolphins and whales are fish; or that "many people have a misconception about how diseases such as AIDS are transmitted".

Note that controversies are not limited to science and scientific disciplines. Controversies may concern political questions, for instance about which political

[1] Definitions and nuances abound. For instance, for Engelhardt and Caplan, "a scientific controversy is defined by the existence of a community of disputants who share common rules of evidence and of reasoning with evidence" (1987, 12). For Machamer, Pera, and Baltas, "a scientific controversy refers specifically to a persistent antagonistic discussion over a disagreement concerning a substantial scientific issue that is not resolvable by standard means of the discipline involved" (2000, 126). Since our objective is not to argue about any specific definition in particular, a general understanding of 'scientific controversy' will suffice. For the sake of simplification, we also portray the dispute as taking place between *opposing* groups, though, of course, the relationships between disputants can be of a different antagonistic nature.




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system might be best to alleviate poverty, but also artistic matters, for instance whether certain forms of expression should be considered art, and many other domains: there are judiciary controversies, educational controversies, ethical controversies and so forth. Therefore, formal considerations are not sufficient to fully characterize *scientific* controversies: the very content of the controversies matters. In this respect, scientific controversies are controversies that concern claims of a scientific nature.

Misconceptions too can be just about anything: science, medicine, politics, the arts, religion, or history, among many others. Misconceptions may even concern quite mundane matters, such as the origin of fortune cookies—which, contrary to well-entrenched beliefs, appears not to be China but Japan (Lee 2008)—or the drinking habits of Vikings—who did not drink at all out of the skulls of vanquished enemies (Gordon 1962, lxix–lxx). In fact, misconceptions can be entertained just about anything. *Scientific* misconceptions then are specific misconceptions that concern scientific claims. For instance, specific scientific misconceptions have been well documented about the theory of natural selection among children, teenagers and university students (Nehm and Reilly 2007; Gregory 2009; Smith 2010a; 2010b; Gresch and Martens 2019; Kampourakis 2020), but also among biology teachers, adults such as museum visitors, and even scientists (Jungwirth 1977; MacFadden et al. 2007; Kelemen and Rosset 2009; Sickel and Friedrichsen 2013; Asghar, Wiles, and Alters 2007).

Let us point to a difficulty that arises from the definition of misconceptions as false beliefs or false ideas, namely its reliance on falsehood. Falsehood (and conversely truth) can be interpreted in two ways. First, in a broad sense, falsehood could be construed as not being in accord with facts or reality.[2] Accordingly, there would be a scientific misconception whenever a belief would not accord with reality. Yet this would be a lot to ask: after all, how do we know what reality is? A solution then is to take reality to be how science depicts it to be. With this narrower sense, a scientific misconception is a belief that does not accord with reality as depicted by science. Here, a subsequent difficulty arises as to which scientific context should be chosen to evaluate beliefs, especially as the scientific view of nature is in constant flux. One possibility is to claim that beliefs should always be evaluated with respect to the latest state of scientific knowledge. The problem of this view is to characterize as misconceptions all past scientific claims that have been held at a time and that have been refuted since. There is, of course, a sense in which one may want to say that Newton was wrong now that Einstein is right. Yet asserting that Newton had a scientific misconception is not how we would want to

[2] Truth is, of course, a very central subject in philosophy, and has received dozens of book-length analyses. For the sake of our argument here, a simple definition will suffice. But see, for instance (Glanzberg 2018) for a recent overview. The same could be said about the notion of reality. See for instance (Saatsi 2017) for a review on scientific realism.

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characterize the situation. A second possibility is therefore to require that beliefs be evaluated with respect to their being or not in accord with reality as depicted by the commonly available scientific knowledge at the time when the agents held these beliefs. These different considerations therefore lead us to propose the following definition of scientific misconceptions:

(SM) Scientific misconceptions consist in the persistent holding (and use) by agents, acting individually or collectively, of beliefs about reality that are false when compared to then available and commonly agreed-upon scientific knowledge.

With such definition, one cannot be said to having hold a misconception when one accepted as true the then available scientific claims even if these claims later turned out to be refuted. In other words, we propose to construe misconceptions not as concerning beliefs about reality simpliciter, but as concerning such beliefs in the context of the state of scientific knowledge available at the time when one entertained such beliefs. The belief that "phlogiston is contained within combustible bodies and released during combustion" was not a misconception when held in the early 18th century; yet the same belief held after diffusion of Lavoisier's findings in the late 18th century was a misconception. The definition also tends to characterize misconceptions in terms of states (the states of holding false beliefs) whereas controversies are probably best thought of as social processes (from emergence to settlement). Yet, misconceptions can also be analyzed in terms of processes, especially when conditions for their emergence and diffusion are analyzed, as well as when measures are taken to counter them as we will see below.

## 3. Characterizing the objects of disputes

One major characterization of scientific controversies concerns the types of objects that scientific controversies are about. Objects of scientific controversies can be sorted into (i) facts, (ii) theoretical constructs and (iii) methodologies (McMullin 1987; Machamer, Pera, and Baltas 2000). Controversies about (i) facts may typically concern observations and experimental results that need to be interpreted to make sense within a particular theoretical framework, or that are obtained at the limit of measurement instruments. More generally, facts may include any sorts of claims about specific states of affairs being the case. For instance, Galileo's observations of moons around Jupiter were contested as being mere artifacts of his telescope. Scientific facts can be questioned as to their existence as facts. They can also be questioned as to their inclusion into the domain of things to be explained. This is, for instance, the case with the so-called Attention Deficit Hyperactivity Disorder (ADHD) and whether it should be considered as a problem requiring medical intervention, a view largely shared in North America but not in Europe. Facts can also be called into question as to their relevance for testing a specific theory or hypothesis. Newton, for instance, argued that the "razor-edge"




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experiment was not relevant in settling his dispute with Hooke about light and colors (Mamiani 2000). When controversies have to do with (ii) theoretical constructs such as theories, models or hypotheses, debates may concern a diversity of features, for instance the reference of specific theoretical terms, the metaphysical or ontological commitment to such entities, or even the exact nature of these terms (for instance as idealizations, as intervening variables, or as hypothetical constructs). Debates also concern the very formal structure of theories, including their mathematical formalism, their simplicity or their tractability, as well as how they may or may not connect to other pre-existing and sometimes well-entrenched theories, as illustrated for instance by the debates over punctuated equilibria in biological evolution (Ruse 2000). When scientific controversies involve arguments about (iii) methodology, such arguments typically relate to observation techniques, instruments, and experimental design. But they may also concern epistemological presuppositions, such as the evidential relationship that is taken to connect empirical observations and scientific theories (e.g., the degree of support provided to a theory by a certain set of observations, or the degree of refutation of specific claims). Even more generally, scientific controversies of a methodological nature concern the very reasons for accepting a theory, for preferring it to a rival one: they may involve, for instance, debates about the relevance of symmetry principles, of formal simplicity, of comprehensiveness, of explanatory power, or of fecundity, just to name a few (Salmon 2000).

Although misconceptions are ultimately about ideas, scientific misconceptions, like controversies, and for practical reasons, can be also analyzed in terms of their primary objects. Misconceptions can be about (i) facts or statements about states of affairs, their very content, their existence, or their relevance. Frequent among students, biology-related misconceptions include the erroneous belief that bacteria and viruses are the same type of biological entities (Prout 1985), or in chemistry, the false idea that a redox reaction is a chemical reaction that must involve oxygen (Barke, Hazari, and Yitbarek 2009, 209). Misconceptions can also be about (ii) theoretical constructs, namely the very formulation of specific scientific theories and hypotheses. Among such misconceptions, many well-studied cases concern diverse aspects of Newtonian mechanics, for instance the misconception that is often formed by children according to which a force would be needed to keep a body moving at constant speed even though all resistance could be removed (in other words, this is a misconception that equates force and speed instead of force and acceleration). More generally, there is a plurality of ways in which the concept of "force" can be grasped and understood, often leading to numerous misconceptions (Savinainen and Scott 2002; Rowlands et al. 2007; Coelho 2009). In biology, probably one of the most studied sources of misconceptions is the theory of evolution by natural selection which has been shown to often be mischaracterized not only by school children and students but also by teachers, adults in general and sometimes even scientists, as mentioned above. For instance, adaptations can be interpreted in terms of purpose or teleology/design (Jungwirth 1977; Kelemen and Rosset 2009; Kampourakis 2020); evolution may be thought of as being typically Lamarckian, with organisms voluntarily adapting to their environment, gaining novel functions depending on their needs, and passing on their acquired characteristics to their offspring (Brumby 1984; MacFadden et al. 2007; Nehm and Reilly 2007); or still, species can be thought in terms of types or essences, leading to transformationist views whereby evolution would affect entire species as wholes (Bishop and Anderson 1990; Shtulman 2006; Sinatra, Brem, and Evans 2008). There are also misconceptions as to whether one has ever been able to observe evolution, or about the existence of adaptations that would be too complex to have gradually emerged through evolution by natural selection (hence misconceptions about the relevance of evolution for explaining certain traits), thereby supporting creationist views (Gregory 2009; Williams 2009). Finally, misconceptions can also concern (iii) methodologies. This is for instance the case with misconceptions about the nature of experiments, the evidential relations that are supposed to hold between the empirical base and scientific claims, or simply the limits of observation techniques, instrumentation, and experimental design. Misconceptions have been studied that concern the very activity of scientific inquiry, the process of scientific discovery and justification, and more generally the nature of science (N. G. Lederman et al. 2002; J. S. Lederman et al. 2014).

## 4. Five distinguishing characteristics of misconceptions

As we have just seen, misconceptions, like controversies, can be characterized in terms of their objects (facts, theories, or methodologies). Yet, scientific controversies have also been characterized by a variety of other formal properties that, as we intend to show, are most relevant to characterize misconceptions as well. In particular, Raynaud (2015) has proposed a framework that depicts controversies depending on a set of formal elements about the types of debates controversies produce. According to this framework, controversies may differ as to (1) their polarity, that is to say the number of parties involved in the dispute. Often, controversies oppose two groups of scientists, especially when they intensify and adopt a bipolar form, but this number could well be different, going up to three or more, in particular at start. In addition, the number of parties that acknowledge the existence of a controversy may also vary. This acknowledgement (2) can, for instance, be bilateral when the two parties involved in a controversy acknowledge the existence of the controversy, or unilateral when only one party acknowledges the controversy. Controversies may also differ when it comes to (3) their extent: on one end of the spectrum, they may involve very few isolated but extremely engaged scholars, and on the other they may concern vast groups of researchers, with varying degrees of engagement. The intensity (4) of controversies





may also vary, in the sense that exchanges of arguments between parties may be more or less virulent and violent. Controversies may vary in terms of (5) duration as well: they can be short-lived and quickly settled, or long and never-ending, sometimes owing to reformulations of the problems at stake. Controversies vary also depending on (6) the forum and the institutional resources that they mobilize: some only take place within the scientific arena and are mediated through peer-reviewed publications and communications, whereas others percolate into the general public and media. Finally, (7) the settlement of controversies may strongly vary from one case to another. This settlement can be explicit, as when a controversy leads to experimental tests, sometimes arbitrated by scholarly institutions such as an academy of sciences. But a settlement can also be implicit, for instance when the controversial arguments somehow end up appearing as too implausible.

How do scientific misconceptions compare? We have seen above that misconceptions can concern scientific facts, theories, or methodological principles, and in all scientific disciplines, varying therefore along the same types of objects as scientific controversies do. How about their formal characteristics? Characterizing misconceptions along the dimensions identified by Raynaud for controversies reveals similarities but also notable differences (Table 1). First, misconceptions may vary depending on (1) their polarity, that is to say the number of parties involved. Typical misconceptions will tend to be bipolar, like most scientific controversies, and revolve around one group characterized as holding the truth—according to best available scientific knowledge—and the other holding the misconception. Consider misconceptions about evolutionary theory: these have been observed among specific sets of students and professionals, all characterized as belonging to the target group of misconception-affected individuals, while truth is to be found in evolutionary biology and its scholars (e.g., Gregory 2009; Sickel and Friedrichsen 2013). Misconceptions can also vary depending on (2) the type of acknowledgment. However, a notable difference with controversies is that acknowledgment of misconceptions is very often unilateral: only one group recognizes the existence of the misconception, the other group often being unaware of its holding a false belief. This difference is significant because misconceptions tend to affect individuals who are not experts in a given discipline but who nonetheless often believe that they are. A key characteristic of misconceptions, therefore, is this asymmetry in awareness and acknowledgment. As we have seen with evolutionary theory, this is typically the case with school and university students who develop misconceptions about empirical facts or scientific theories without realizing the falsity of their beliefs (Nehm and Reilly 2007; Smith 2010a; 2010b). Yet, this is also the case about teachers (Asghar, Wiles, and Alters 2007; Nehm et al. 2009; Sickel and Friedrichsen 2013), adults in general (MacFadden et al. 2007; Kelemen and Rosset 2009) and even sometimes scientists themselves (Jungwirth 1977). Another dimension along which misconceptions may vary is (3) their extent: misconceptions can concern a greater or lesser number of persons. However, whereas controversies may sometimes involve just a few individuals—in some cases even a single individual—misconceptions usually concern a sizeable group, as we have seen above with examples of misconceptions in biology and physics alike that affect such a high number of students as to become objects of investigation and justify specific remediation strategies (Gregory 2009; Sickel and Friedrichsen 2013; González Galli, Peréz, and Gómez Galindo 2020). Indeed, false beliefs held by just a small set of individuals or even a single person would typically go unnoticed. In addition, whereas controversies are tightly linked to the names of the scientists that partake in them, misconceptions are usually never associated with names of specific individuals. The intensity (4) of the exchanges is also a dimension along which misconceptions may vary compared to controversies. It is true that, in some cases, the individuals holding a misconception can be aware that their views differ from those offered by science and argue, sometimes very strongly, in their favor (e.g., creationism). Yet, in much more frequent cases, misconceptions are held by individuals in a passive way, these individuals not being aware of the falsehood of their views (Shtulman 2006). Misconceptions can also be classified according to (5) their duration. This duration can be understood in two ways: either as the time-span during which one particular individual holds the misconception (for instance as is the case for young children who spontaneously develop some form of intuitive teleological view of nature (Nehm and Reilly 2007), but later abandon such views in light of their education), or as the time-span during which one particular misconception survives in society (for instance as has been the case of geo-centrism for several centuries, and as still is the case for creationism). One specificity of misconceptions is that they tend, so to speak, to have a life of their own: whereas controversies usually end-up by being settled (see below), misconceptions can be hard-lived despite numerous efforts to mitigate them (Evans 2001; Sinatra, Brem, and Evans 2008). Scientific misconceptions can also vary according to (6) their type of forum. Misconceptions usually concern the general public, with research typically focusing on how they emerge and spread within students at all ages, through perspectives often anchored in education sciences and with views geared towards remediation strategies (Sickel and Friedrichsen 2013; González Galli, Peréz, and Gómez Galindo 2020). Interestingly, misconceptions have also been shown to affect professional teachers, including biology teachers in the case of evolution-related misconceptions (Asghar, Wiles, and Alters 2007; Nehm et al. 2009), and scientists as well (Jungwirth 1977), though studies about this latter group remain scarce. Yet ultimately, as with controversies, it is the scientific community that acts as referee, and arbitrates which views are right and which are misconceptions. We saw above how (7) settlement is a key aspect of scientific controversies, whereby one of the opposing views wins and gets included into what is accepted as knowledge. In the case of misconceptions, settlement is not *per se* the inclusion of any one of the two opposing views into



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accepted knowledge, but a change of belief by the group holding the misconception—hence all the efforts towards implementing educational strategies to lower the incidence of misconceptions, for instance about evolutionary theory in biology curricula (Sickel and Friedrichsen 2013; González Galli, Peréz, and Gómez Galindo 2020). At the level of the individuals, a misconception is settled when they abandon the misconception in favor of the scientifically accepted view. Collectively, a misconception is settled when it disappears from society and is replaced by the scientifically accepted view. But whereas scientific controversies are usually settled once and for all, scientific misconceptions often emerge *de novo*. This can be the case among younger individuals, especially if such misconceptions partly result from naturally occurring cognitive biases, for instance, the way young children often equate force and speed, instead of acceleration, or tend to see the world in terms of purpose as seen above (Kelemen and DiYanni 2005; Rowlands et al. 2007). This is also likely to be the case among newcomers to any scientific discipline, be they students or mature scientists coming from other disciplines.

These different formal elements therefore make it possible to map out key features of scientific controversies and misconceptions, and highlight where they differ, in addition to specificities of content. In what follows, we argue that an even more salient element that sets apart misconceptions from controversies is epistemic and concerns the differing roles that they play in the growth of scientific knowledge.

**Table 1.** Characteristics of controversies and misconceptions (the dimensions are those identified by Raynaud (2015) as classificatory elements for controversies; shaded areas highlight dimensions where misconceptions differ from controversies).

| Dimensions | Controversies | Misconceptions |
|---|---|---|
| **Object** | Facts, theories, methodologies | Facts, theories, methodologies |
| **Polarity** | Usually two | Usually two |
| **Acknowledgment** | Bilateral or unilateral | Unilateral (asymmetry) |
| **Extent** | Individual researchers and their teams | Large number of anonymous individuals |
| **Intensity** | More or less violent exchanges | Often not intense (passive) |
| **Duration** | Short or long | Long lived (a life of their own) |
| **Forum** | Scientific arena and public sphere | Scientific arena and public sphere |
| **Settlement** | Yes, explicit or implicit | Rarely (resilience) |

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## 5. Another significant difference: contribution to knowledge

Scientific controversies are often described as events in the growth of scientific knowledge: they are taken to lead to novel knowledge. When a controversy arises—say between two opposing groups, one claiming $P$ and the other $\neg P$—the scientific community becomes the main forum of the controversy and some of its institutions act as referees. This role presupposes neutrality with regards to the two opposing groups. For this reason, the scientific community, as a whole, can be said to be agnostic or undecided with regards to $P$, accepting neither $P$ nor $\neg P$. Take the Pasteur-Pouchet controversy about spontaneous generation. Though this episode of the history of science is quite intricate (Raynaud 1999), consider for the sake of the argument the simplified statement $P$ that "microbial spontaneous generation is false", with Pouchet claiming $\neg P$ as early as 1858, and Pasteur claiming $P$. The scientific community at that time remained divided on the topic up until Pasteur's swan-neck bottle experiments in the early 1860s (though the popularity of spontaneous generation had already started to dwindle earlier). Within this community, the French *Académie des sciences* acted as referee for the controversy by organizing a prize-contest. By awarding the prize to Pasteur in 1862, the *Académie* made the denial of spontaneous generation commonly accepted knowledge. Though the historical details are more convoluted, our point is that, generally speaking, the settlement of a controversy often results in one claim being accepted and the other rejected, thereby transforming one of the two opposing claims into scientific knowledge (and the other one into a refuted hypothesis). In this sense, controversy settlement leads to novel pieces of knowledge.

Compare with misconceptions (see Fig. 1). Like controversies, misconceptions also typically involve two groups: one group believes in $\neg P$ and is said to hold the misconception by another group holding the opposite view, $P$, that latter view being scientifically accepted. But note that, contrary to controversies, the scientific community is neither divided nor agnostic with regards to $P$: the scientific community considers $P$ as valid scientific knowledge (and $\neg P$ as a refuted hypothesis). Take the case of the misconception that consists in believing that "life cannot exist without oxygen": this misconception has been shown to be held by a significant fraction of college students (Offerdahl, Prather, and Slater 2002)—and likely by a non-zero proportion of adults as well—but the scientific community agrees and acknowledges the fact that "life can exist without oxygen". The settlement of the misconception here consists in making the students realize that their beliefs are wrong, thereby encouraging them to adopt the viewpoint of the scientific community. In the case of misconceptions therefore, settlement only consists of the change of belief of the group holding the misconception, not the scientific community. Scientific knowledge is unaffected by the settlement of




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misconceptions. This is to say that, contrary to controversies, misconceptions do not contribute by their settlement to the growth of scientific knowledge. Quite to the contrary, scientific misconceptions among scientists may even negatively impact scientific knowledge through insidious misconceived claims percolating in publications and communications.

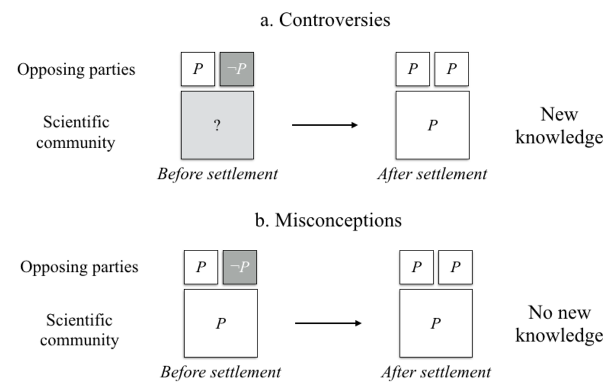


**Figure 1.** How controversies and misconceptions matter differently in terms of their contribution to scientific knowledge ($P$ is the object of the controversy or misconception). (a) In controversies, while two opposing parties hold opposite claims, the scientific community is initially undecided. Settlement makes the scientific community adopt one particular view (which is usually also accepted by the opposing party). That view becomes part of accepted knowledge. (b) With misconceptions, two opposing parties hold opposite claims, but the scientific community is unified behind an accepted body of knowledge. When it happens, settlement only affects the opposing party in conflict with accepted knowledge but does not lead to the creation of any new knowledge.

## 6. Illustrations from astrobiology research

While scientific misconceptions have been well-researched among students (and to a certain extent their teachers), systematic studies about scientific misconceptions among scientists are scarce—but see (Jungwirth 1977). Here we consider the domain of astrobiology for investigating cases of misconceptions that arise among scientists. Astrobiology is an interdisciplinary research domain that emerged a few decades ago and that encompasses "the search for potentially inhabited planets beyond our Solar System, the exploration of Mars and the outer planets, laboratory and field investigations of the origins and early evolution of life, and studies of the potential of life to adapt to future challenges, both on Earth and in space" (Marais et al. 2003). In the European Astrobiology Roadmap, astrobiology is defined as "the study of the origin, evolution, and distribution of life in the context of cosmic evolution; this includes habitability in the Solar System and beyond" (Horneck et al. 2016). Being relatively young and interdisciplinary, and targeting an extremely complex question, astrobiology provides a fertile ground for disputes and disagreement.

Controversies are no doubt present in astrobiology. To give a few examples, controversies can be about (i) facts, for instance: about the putative traces of life on Mars discovered by the *Viking* landers in 1976 (Klein et al. 1976; Biemann et al. 1977; Bianciardi et al. 2012; Levin and Straat 2016); about the biogenicity of the oldest fossilized candidate micro-traces of life (Schopf 2006; Brasier et al. 2015; Javaux 2019); or about the existence of "arsenic life" or microbes capable of incorporating arsenic instead of phosphorus into their DNA (Wolfe-Simon et al. 2011; Erb et al. 2012; Reaves et al. 2012). There are also controversies about (ii) theories or theoretical constructs, for instance about the heterotrophic or autotrophic nature of the first living entities, the temporal priority of genetic information over metabolism, and the importance of cellularization in the early stages of life (Peretó 2005). There is notably a long running controversy about the plausibility of the "RNA world" hypothesis (Rich 1962; Woese 1967; Morowitz 1992; Shapiro 2000; Orgel 2004; Robertson and Joyce 2012; Neveu, Kim, and Benner 2013). There are also controversies about (iii) methodological principles, for instance: about how to interpret biosignatures (Gargaud, Mustin, and Reisse 2009; Schwieterman et al. 2018; Green et al. 2021); about the reliability of inferring the presence of arsenic in DNA by nanoSIMS or EXAFS of whole cells (Wolfe-Simon et al. 2011) instead of by classical chemical analysis (e.g. mass spectrometry of purified DNA) (Benner 2011; Borhani 2011; Csabai and Szathmáry 2011; Oehler 2011; Redfield 2011), or about standards of proofs in cross-disciplinary science (Benner, Bains, and Seager 2013) or confounding factors in detecting life at its extreme physicochemical limits (Belilla et al. 2022).

Misconceptions about astrobiology-related topics exist among the general public. This is notably the case with creationist stances or intelligent design theories (Ruse 1982; Laudan 1982; Plutynski 2010; Reiss 2011). Yet, more subtle misconceptions have been identified among high school and undergraduate students about the range of environments in which life may exist: for instance, many students—and many non-biology scientists we would argue—believe that life cannot exist without oxygen, or that complex organisms (such as plants, animals, and humans) have a better chance of surviving in extreme environments compared to microbial organisms (Offerdahl, Prather, and Slater 2002).

To the best of our knowledge, misconceptions have not been studied per se among practicing astrobiologists, but there are strong reasons to believe that astrobiologists are not immune to false beliefs. One example is the misconception that everything "organic" must be "of biological origin". In the 18$^{th}$ century,





substances such as urea were called "organic" because it was thought they could only be produced by living organisms (Wohl 1960; Roger 1979), but that view later changed, notably when Wöhler synthesized urea from inorganic compounds in 1828 (Cerceau and Bilodeau 2009). In chemistry, organic compounds are defined as molecules that include C-H bonds, and not by their having been produced by living organisms. As a matter of fact, it has been shown that numerous complex organic compounds can form abiotically in various natural environments such as the interstellar medium, meteorites, comets, or hydrothermal systems. Yet the semantic connection between "organic" and "of biological origin" remains vivid. This is notably exemplified by the search for complex organic compounds—"molecular biosignatures" (Summons et al. 2008; Vago et al. 2017)—that would be specific enough to be deemed evidence for life, notably when found in association with morphological and other geochemical traces. More generally, the risk exists that anything defined as a "biosignature" might be considered as effective evidence for life, instead of being considered more reasonably as "potential" evidence only. This is all the more true as communication hyperbola are frequent in this domain, notably in science popularization media that may claim, for instance, that "NASA's Perseverance rover has found the strongest signs yet that life once existed on Mars" (Sutherland 2022) when the rover has actually only taken rock samples of interest, not even knowing whether potential biosignatures might be present (the author rectifies his claim later in the text by specifying that "finding organic compounds in the rock samples isn't a definitive sign of life", yet one needs to read the full text). Misconceptions may further concern the robustness of any type of extrapolation, as is for instance the case when global environmental conditions are extrapolated from a local geological record (Inglis et al. 2018). Misconceptions can also be about the robustness of inferences based on models, for instance the retrodictions of early life environmental conditions based on planetary models (Kasting 1993) which are then used as a basis for carrying out prebiotic chemical experiments (Miyakawa et al. 2002; Cleaves et al. 2008). Another example of misconception is the extrapolation of the hypothetical hyperthermophilic nature of LUCA (the Last Universal Common Ancestor) to the first life forms. A hyperthermophilic LUCA was inferred from early phylogenetic studies that placed modern hyperthermophilic prokaryotes at the most deep-branching positions in the tree of life (Stetter 1996). However, the inclusion of additional taxa placed mesophilic bacteria at even deeper branches in the tree of life, leaving the temperature adaptation of LUCA unresolved (Brochier and Philippe 2002; Boussau et al. 2008). Furthermore, it now appears clear that LUCA was an already highly evolved organism as compared to the first proto-cells (Zhaxybayeva and Peter Gogarten 2004; Krupovic, Dolja, and Koonin 2020) and, consequently, its ecological preferences and adaptations may have evolved and diverged considerably. Yet another example concerns an exaggerated optimism with regards to the status of scientific investigations about the origin of life. Related sections in some biology textbooks have been identified that give the impression that the origin of life problem is nearly solved (Mills and Bradley 1993), whereas this is definitely not the case to date (Scharf et al. 2015; Preiner et al. 2020). In the same study, Mills and Bradley also identify textbook sections with the misconception that the likelihood of life's appearance has been established to be very high, which is still an unsettled question. With these possible examples, our objective here is not to claim that they are all documented cases of misconceptions among scientists, but at least to provide reasonable grounds that such misconceptions are indeed quite likely. Field work of the sort Offerdahl and colleagues (2002) carried out with students would deserve to be launched among populations of practicing scientists. Here we limit ourselves to a more formal characterization of misconceptions (and notably in comparison to controversies).

## 7. Taking misconceptions in science seriously

Misconceptions in science matter for at least four main reasons. First, consisting in false beliefs, scientific misconceptions have the potential to lead to erroneous claims and spread falsity through chains of ill-grounded inferences. Because they are held by scientists themselves, and because scientists precisely work on formulating and justifying knowledge claims, one cannot exclude the possibility for these misconceptions to appear somewhere within premises of other scientific inferences, thereby leading to other false claims and misconceptions. As a result, internal misconceptions pose a direct threat to knowledge. Second, a somehow weaker consequence of misconceptions is the risk that they induce irrelevant research. This could be the case, for instance, if one were to devise prebiotic experiments in misconstrued environmental conditions that would be drastically different from plausible prebiotic conditions. In such a case, the experiments may lead to knowledge about new chemical reactions, but such a knowledge would be irrelevant to astrobiology objectives due to misconceptions about the conditions in which these reactions are supposed to take place. Third, misconceptions are likely to hinder communication between scientists. This is notably the case when scientists from a given discipline differently construe a concept compared to other scientists in another discipline and with whom they are supposed to collaborate in a joint research effort. An example would be a misconception by exoplanetologists of what a biosignature is when talking to a paleobiologist (and vice versa). Finally, misconceptions threaten the credibility of scientific claims. Whereas controversies are considered as a normal, though by no means necessary, feature of science, misconceptions are viewed as undesirable, both outside of science and inside. Because science is endowed with the privileged status of building knowledge about the world, the presence of misconceptions (aka false beliefs) directly undermines the very foundational purpose of science.



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Whereas sources of misconceptions among scientists remain (to the best of our knowledge) unexplored, studies targeting misconceptions within the general public, notably children and students, can provide interesting heuristics. Misconceptions are generally thought to occur as a result of ignorance or lack of understanding, but their multifaceted origins also involve a complex array of cognitive, pedagogical, social, and ideological factors. Indeed, misconceptions have been shown to often arise as a result of social influences and personality traits (Williams 2009; Mazur 2012), in addition to factual misunderstanding and misinformation. Alternative (notably religious) worldviews have also been shown to be a major source of misconceptions. For instance, creationism and intelligent design—which have been characterized as deeply-entrenched systems of beliefs aspiring to scientific status (Kitcher 1982; Ruse 1982; Dawkins 1986) and to being taught in the classroom (Plutynski 2010; Reiss 2011)—have been shown to play a strong role in the rejection of evolutionary theory in large segments of the population, thereby leading to significant misconceptions about how life evolved on Earth (Evans 2001; Kelemen and DiYanni 2005; Williams 2009). Misconceptions may also arise from cognitive biases. At least since Piaget's studies in the early 20th century (Piaget 1929), scholars have investigated how children spontaneously make sense of terms such as life, living, non-living or dead, how their perceptions evolve as they grow, differently classifying plants, animals, microorganisms, rocks, fire, water, or bones as being alive or not (Brumby 1982; Caravita and Falchetti 2005). Teleological intuitions appear to be deeply rooted in the human cognitive system. Young children in particular have been shown to be prone to attributing artifact-like teleofunctional properties to living entities, thereby endorsing some form of spontaneous intelligent design misconception (Kelemen and DiYanni 2005).

Whether any or all of these sets of general factors are at play with regards to scientific misconceptions among scientists remains an open question. Other possible sources of misconceptions in science may also arise from the nature of the scientific enterprise itself. We will mention two: multidisciplinary and complexity. Consider again astrobiology. The domain mobilizes numerous scientific disciplines—prebiotic chemistry, biochemistry, molecular biology, evolutionary biology, synthetic biology, micropaleontology, geology, planetology to name a few. Exchanges between disciplines favor erroneous interpretations. One typical case is oversimplification of knowledge claims during exchanges between experts from different fields. Furthermore, the field is characterized by complex questions, such as the origin of life, which may receive different interpretations as to what needs explaining (Malaterre, Jeancolas, and Nghe 2022), leading in turn to possible misconceptions about what might constitute appropriate explanations. Additional sources of misconceptions may therefore arise from the specificities of the scientific domain itself.

## 8. Conclusion

While scientific misconceptions have been studied among children and university students, misconceptions have eluded attention as to their potential presence in the very practice of science. Indeed, when it comes to investigating disagreement in science, philosophers and sociologists of science have tended to focus on scientific controversies. Here, we argued that scientific misconceptions in science deserve to be examined. We proposed that, like controversies, misconceptions concern three types of objects in science: facts, theoretical constructs, and methodologies. We identified five features—form of acknowledgement, extent, intensity, duration, and settlement—that can be used to characterize misconceptions from a formal perspective. We also discussed how misconceptions and controversies differ in their relations to knowledge creation. Though misconceptions in science have not been extensively documented, we used illustrations from astrobiology to argue about their relevance in the practice of science and highlight possible factors that may favor their appearance. Field studies are now needed to more extensively document and categorize misconceptions in science. Numerous questions indeed remain open, for instance whether misconceptions in the practice of science can be traced back to misconceptions among science students; whether misconceptions in science concern some very specific topics; whether some research domains are more prone to misconceptions compared to others and why; whether specific factors can be identified to explain the emergence and sustained presence of specific types of misconceptions. All these questions and more matter when it comes to envisioning strategies for countering the deleterious effects of misconceptions in science.

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**Declaration of Interest**



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