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Flies from meat and wasps from trees: Reevaluating Francesco Redi's spontaneous generation experiments

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ABSTRACT

Francesco Redi's seventeenth-century experiments on insect generation are regarded as a key contribution to the downfall of belief in spontaneous generation. Scholars praise Redi for his experiments demonstrating that meat does not generate insects, but condemn him for his claim elsewhere that trees can generate wasps and gallflies. He has been charged with rejecting spontaneous generation only to change his mind and accept it, and in the process, with failing (at least in some sense) as a rigorous experimental philosopher. In this paper I defend Redi from both of these charges. In doing so, I draw some broader lessons for our understanding of spontaneous generation. 'Spontaneous generation' does not refer to a single theory, but rather a landscape of possible views. I analyze Redi's theoretical commitments and situate them within this landscape, and argue that his error in the case of insects from plants is not as problematic as previous commentators have said it is. In his research on gall insects Redi was addressing a different question from that of his experiments on insect generation—the question was not "Can insects come from nonliving matter?," but rather, "Can insects come from living organisms which are not their parents (namely, trees)?" In the latter case, he gave an answer which we now know to be false, but this was not due to any failure in his rigor as an experimental philosopher.

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1. Introduction

Until the seventeenth century it was generally believed that organisms could come to be through spontaneous generation. This view was held at least since Aristotle, who described in his *History of Animals* the generation of insects from animal dung and flesh, mud, dew on leaves, and other organic and inorganic substances (551ª1), and of some species of fish and eels from riverbeds and sand (569ª10-25; 570ª4-12). Belief in spontaneous generation persisted over the centuries, with support from experiments ostensibly reinforcing claims that, e.g., mice can be generated from piles of grain and sweaty clothing (such as van Helmont's experiments in the seventeenth century; see Fry, 2000 for further discussion).

Historical narratives of the theory's downfall generally give a three-stage account which begins in the seventeenth century with Francesco Redi and ends in the nineteenth with Louis Pasteur. This is a classic textbook story presenting the view of science as progress, with truth triumphing over false theories via controlled laboratory experiments. Redi (1626–1697) is famous for his experiments demonstrating that insects appear on rotting meat not because they are generated from the meat itself, but because their parents laid eggs there. He is regarded as the key contributor to the initial stage of the theory's demise; supporting actors in the seventeenth century were Marcello Malpighi and Jan Swammerdam, who extensively researched and documented insects' reproduction and generation cycles. In the eighteenth century, Lazzaro Spallanzani did experiments demonstrating that infusoria[1] do not grow in sterilized flasks. In the nineteenth century Pasteur continued along these lines, showing that microscopic life forms are not spontaneously generated in vessels of sterilized liquid, but rather get

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[1] 'Infusoria' is an obsolete term for a class of aquatic microorganisms, including primarily the organisms which we now classify as protists.

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there by contamination through exposure to microbes in the surrounding air (Pasteur, 1864). Thus, the organisms people took to be generated in this way became smaller and smaller over the course of three centuries, until belief in spontaneous generation was eventually completely undermined by Pasteur's work (see Farley, 1977 for an excellent historical overview).

Historical accounts often present the following picture of Francesco Redi: His research on insect generation was a crucial contribution to the beginning of the end of belief in spontaneous generation. Through repeated controlled experiments, he showed that insects are not generated by rotting organic matter. However, there was a black mark in his record. He also believed that insects born from abnormal growths of plant tissue, called galls, are generated by the plant itself. We now know that this is false; larvae appear in galls because their parents, gall-forming insects, laid eggs there. So, the story goes, while Redi got the overall picture of spontaneous generation right, in the gall case he got it terribly wrong. Walter Bernardi, the most prominent contemporary commentator on Redi, calls Redi's explanation of gall insect generation an "unforgivable epistemological sin on behalf of a scientist who proudly called himself an 'experimental philosopher'" (1997a).[2]

Commentators have interpreted Redi's conclusions about gall insects as an explicit concession to spontaneous generation, a serious crime for someone heralded as an early champion of the theory's undoing. Bardell (1985), for example, praises Redi's experimental contributions to refuting spontaneous generation, but writes:

> However, although Redi unequivocally demonstrated that putrefying flesh did not give rise to flies, he reported that gall flies were spontaneously generated by plant tissue. Redi's description of the spontaneous generation of gall flies was published in the same book as his work that is now frequently presented to show the incorrectness of the long-held belief in spontaneous generation...(237)

Others, to varying degrees, have similarly interpreted Redi's work on gall insects as contradicting the conclusions he drew elsewhere with respect to spontaneous generation; further instances of this interpretation are discussed in Section 2.3 below (see also Bernardi, 1997a, 1997b).

Historical scholars have tended to agree that the gall case is a major problem for Redi because his conclusions there indicate acceptance of spontaneous generation, undermining the work he did to reject the theory with extensive evidence from his insect experiments. Implicit in some versions of this criticism, and explicit in Bernardi's statement of it, is a two-part critique of both Redi's conclusions and his methodology. He is charged with both reneging on his claims about spontaneous generation, and with failing (at least in some sense) as an experimental philosopher.

In this paper I defend Redi from both of those charges. In doing so, I draw some broader lessons for our understanding of the theory of spontaneous generation. I argue two main points. First, while there is some inconsistency in Redi's conclusions, the problem is not as severe as previous interpreters have made it out to be. Second, to the extent that we couch Redi's error in the gall case in terms of his aptitude as an experimentalist, we should do so in terms of what good experimental methodology and epistemology were *for him*, rather than importing beliefs about what they are today. Following Findlen (1993), I look more closely at Redi's own view of what constitutes praiseworthy experimental philosophy; I argue that Redi did not depart in the gall case from the rigorous standards which he set for himself.

Before moving on to discuss Redi's work, a brief note about terminology is in order. In this introduction and in Section 2 of the paper, I use the term 'spontaneous generation' loosely to refer to the view that Redi is taken to have rejected. As I will argue in Section 3, this term covers a range of conceptual ground, and using it, without further specification, to assess theoretical stances like Redi's leads to ambiguity and misunderstanding. Distinguishing among a number of ideas at play in different formulations of the theory helps clarify what Redi was and was not rejecting. For the sake of simplicity and consistency with the historical tradition mentioned above, I will stick with the term 'spontaneous generation' until I get to the point of making these distinctions.

2. Redi's theory and experimental methodology

Redi's famous experiments on insect generation were motivated by a prior stance against spontaneous generation. In this section I describe his theoretical claims and experimental work aimed at proving that maggots on rotting organic matter come from eggs laid by their parents, not from that matter itself. I then give an overview of his writings on gall insects, and discuss why his conclusions there are traditionally regarded as problematic in light of his other theoretical commitments and empirical findings.

2.1. Views on generation

Redi's most famous work, *Esperienze intorno alla generazione degl'insetti* ("Experiments on the Generation of Insects", 1668; henceforth "*Generazione degl'insetti*"), begins with his rejection of the notion that living things—"from elephants to the most minute, almost invisible creatures" (7)—are generated from nonliving matter. Redi discusses his skepticism of the following view, held by Epicurus and his followers, that living things come from the "wombs of the earth:"

> ...lacking the force to generate men and other large perfect animals, [the Earth] retained the force to produce (in addition to plants, which are presumed to arise spontaneously without seed) certain other little animals; that is, flies, wasps, cicadas, spiders, ants, scorpions, and all the other grubs of the land and air...[both ancient and modern philosophers] claim that not only does the earth possesses this hidden power, but so do all animals and living things and dead things and all the things produced by the earth, and finally all things that are putrefying on the verge of being reconverted into earth...From my many repeated observations I am inclined to believe that the earth, ever since the first plants and animals that she produced in the first days on command of the supreme and omnipotent Maker, has never again produced from herself grass, trees, or animals perfect or imperfect. (Redi, 1668, pp. 8–10)

The last sentence of this passage is Redi's most commonly referenced negative claim against spontaneous generation. The view Redi puts forth here and in the surrounding text can be summarized as follows: Living things, be they animals or microorganisms or plants, are never generated from nonliving matter.

He offers the following sketch of a positive claim about generation more broadly:

> ...everything that we see today born in the earth or from the earth comes from the real and true seeds of plants and animals themselves, who conserve their species through means of their own. And even though we observe every day that infinite numbers of maggots are born from animal cadavers and all sorts of decaying plants and flowers and fruits, I am inclined to believe that all of those maggots come from their parental seed, and that meat and grass and all other putrefied or putrefiable things

[2] All English translations from the original Italian writings of Walter Bernardi and Francesco Redi are mine.

> play no role in insect generation other than supplying a suitable place or nest to which animals are drawn at their time of giving birth to maggots or eggs or seeds of eggs, which, as soon as they are born, find in this nest adequate materials on which to nourish themselves; and if the above-mentioned seed is not brought to the nest by their parents, nothing—absolutely nothing—is generated or born therein. (Redi, 1668, p. 10)

If we read Redi's claim here as a general claim about generation, the strongest interpretation of it is that the cause of all newly-generated life is (only) the seed of parents of the same species.[3] More specifically, Redi is saying that insects are never generated by putrefying organic matter. He contrasts the apparent occurrence of such generation, which people observe on a daily basis, with the reality he attempts to uncover from the subsequent detailed account of his experiments and their results.

References to Redi's views on spontaneous generation in the English literature focus primarily on *Generazione degl'insetti*. Further discussion and clarification of his theoretical stance on generation is found in his less-examined 1684 treatise on parasitic worms, *Osservazioni intorno agli animali viventi che si trovano negli animali viventi* ("Observations Regarding Living Animals Found Inside of Living Animals"). Here, Redi further clarifies his theoretical commitments regarding not only the status of the doctrine of spontaneous generation, but also proper methodology for natural philosophy more generally. Redi criticizes his contemporary Filippo Buonanni for writing falsehoods about insects, and in particular for having the wrong approach as an experimental philosopher. He accuses Buonanni of working "from the desk" and thus of engaging with only the opinions of others, and writes that "he did not claim, nor even think to try to be a true experimental philosopher, one who never affirms anything with certainty except what he observes, after many rounds of repeated evidence, with his own eyes" (Redi, 1684, p. 22).

Redi goes on to criticize Buonanni's own experiments on insect generation in detail:

> ...it seems that I am obligated to respond to some experimental challenges which [Buonanni], defender of generation *ex putri*, has undertaken in honor of my *Esperienze intorno alla generazione degl'insetti*. These are his words in the first part of chapter five: "I do not know how Redi could dispute the experiment I carried out, in which I took numerous hyacinth flowers, ground them up and put them in a glass jar covered by a clay lid, expecting some spontaneous generation from that rotting mass; and after having kept it in a closet for several weeks, I found that many transparent and mucoid maggots had been generated..." I wish to raise no dispute with this experiment of Father Filippo Buonanni's: I would simply courteously entreat him to try it again, and to try this time to seal the jar with diligence...(*ibid.*)

In his research, Buonanni purported to show that maggots are spontaneously generated from rotting flowers, and that there is a mapping relationship between maggots and flowers such that certain kinds of rotting flowers always generate certain kinds of maggots. By challenging him to repeat his experiments "with diligence," Redi emphasizes his belief that maggots can be found on rotting organic matter only when the latter has been exposed to the air, allowing insects to come lay their eggs in it.

2.2. Experiments on insect generation

Following his theoretical introduction, in the remainder of *Generazione degl'insetti* Redi outlines his meticulous laboratory research aimed at validating his claims about generation. He describes thousands of repetitions of his experimental protocol over the course of many years. While there were minor variations in setup and materials, his core methodology was essentially as follows: He placed samples of organic matter in jars, left some uncovered and sealed others with paper and twine, and reported that by preventing insects from gaining access to the latter jars' contents, no larvae would appear therein. His subjects were primarily flies and their maggots, and he used hundreds of different kinds of plant and animal matter to demonstrate his point, including flowers, grasses, and an impressive array of animal and fish corpses ranging from dog and eel to lion and water buffalo.[4]

In Redi's detailed descriptions of his experiments he continually emphasizes the necessity of many iterated rounds of gathering evidence to confirm his beliefs. In addition, he emphasizes the careful use of what we now call controls: experimental setups which isolate single independent variables. The following passage illustrates this nicely:

> I began to suspect that the maggots on the meat came from the seed of flies and not from the putrefying meat itself, and this suspicion was further confirmed by the fact that in every case of generation I observed, before the meat became covered in maggots, I saw a fly landing on the meat of the same species as the maggot which was then born; but belief in this point would be groundless without the confirmation of experiment. Hence, in the middle of July I placed in four wide-mouthed flasks a snake, some freshwater fish, four eels from the Arno and a piece of milk-fed veal; then, having closed the openings with paper and twine and sealed them well, I put the same materials in four other flasks and left their mouths open: before long the fish and the meat in the latter flasks became maggoty; I saw flies coming and going from these flasks as they pleased, but in the sealed flasks I never saw a single maggot born, even though many months passed from the day in which the cadavers were sealed inside...(Redi, 1668, p. 13)

Redi concludes from these experiments that rotting organic matter does not generate insects; it serves only as a potential nest for the development of eggs into eventual flies.

2.3. Gall insects

In the middle of *Generazione degl'insetti*, Redi gives a painstakingly detailed natural history of spiders, discussing the appearance of their eggs, where they can be found in houses, what Aristotle said about them, and so forth. This brings him to the topic of plant galls (illustrated in Fig. 1).[5] Before discussing Redi's account of galls, it will be useful to briefly overview what we know about them today.

Galls are abnormal growths on plants which result from parasitism by gall-forming insects. They form when adult gall insects lay their eggs in the plant's tissue, forming a growth which hosts the developing eggs and eventual larvae. Different species of gall insect form different types of gall, varying in their size and appearance. Galls come in many different shapes, sizes and positions on

[3] The notion of parentage of the same species is not unproblematic. Redi relied on an intuitive morphological concept of what a parent is: a living thing that generates another living thing of the same kind. Here I am taking the concept of parentage in this intuitive sense. This involves a pre-theoretical notion of species; a comprehensive account of species concepts, modern or seventeenth-century, is beyond the scope of this paper (but for relevant discussion see Ereshefsky, 2010).

[4] As a member of the Tuscan court, Redi had access to a vast collection of rare specimens from voyages abroad; see Bernardi (1997b) and Findlen (1993) for more in-depth historical background.

[5] Redi had a lifelong curiosity about gall insects, and wrote a number of unpublished manuscripts on the topic including *Memorie intorno agli animali che nascon dalle piante* ("Memoirs on Animals Born from Plants") and *Storie de' diversi frutti ed animali che dalle querce e da altri alberi son generati* ("Accounts of Various Fruits and Animals Generated by Oaks and Other Trees") (Bernardi et al., 1997a, p. 8).

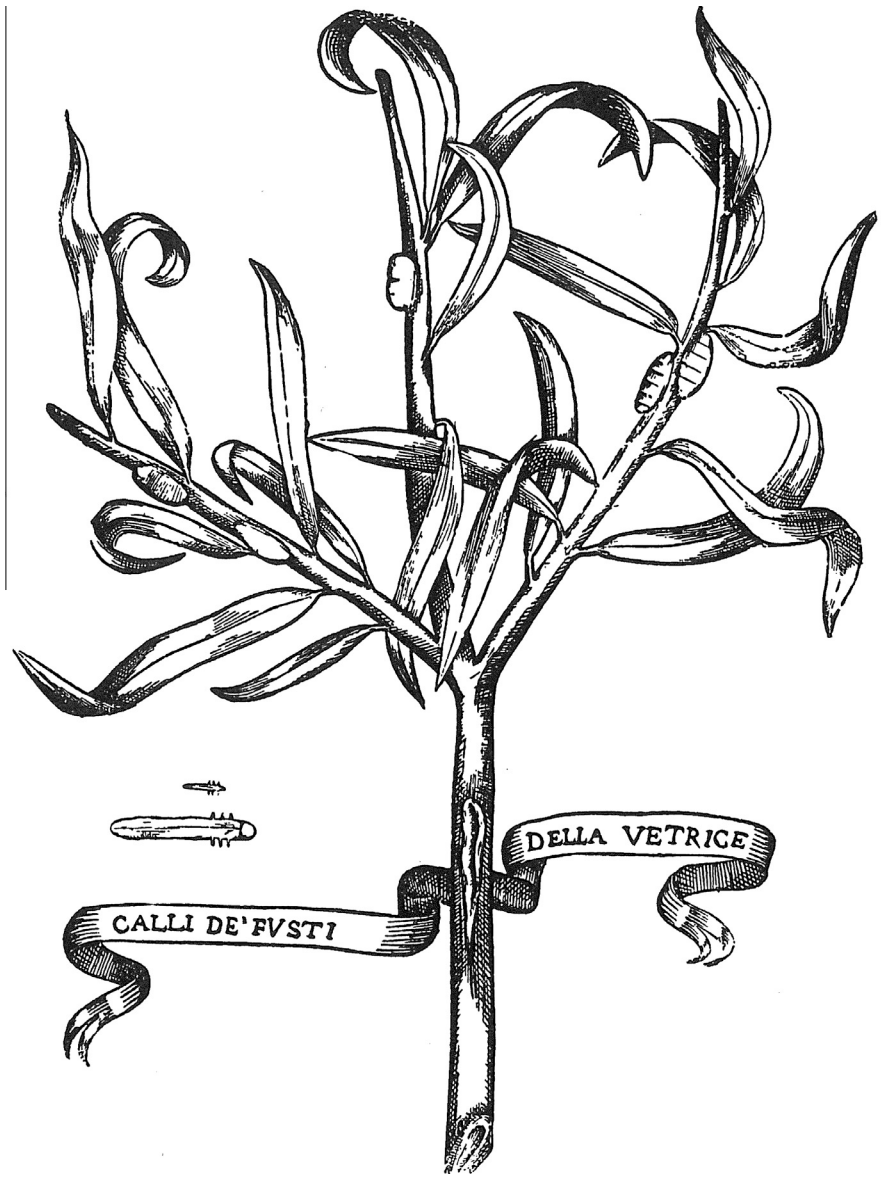

Fig. 1. One of Redi's drawings of plant galls (from *Generazione degl'insetti*, 1668).

the plant, but generally they look something like tumors or irregular growths on the plant's stem or leaves. While the gall itself is formed of plant tissue, its formation is influenced by both the parasitic insect's intervention and the plant's morphological response (Weis & Abrahamson, 1986). We know quite a lot about galls now, though there is ongoing debate about the adaptive significance of the many different forms they come in (Stone & Cook, 1998).

In the seventeenth century, plant galls were a noted phenomenon whose origin and function were a mystery. As insects were commonly observed emerging from galls, it was commonly believed that the agent responsible for their generation was the gall itself (Arber, 1942). As discussed above, Redi is clear about his commitment to the idea that all insects come from eggs laid by parents of the same species, based on what he observed through his many repetitions of experiments to that effect. One would expect Redi to apply the same standard to claims about insects allegedly generated from abnormal growths on plants. However, he turns out to have a quite different view. Considering the possibilities for how insects come from galls, he writes:

I would say that fruits, vegetables, trees and leaves can become maggoty in two ways. One, because maggots come from outside seeking food, and eat their way into the core of the fruit or wood. The other way, which I esteem to be worthy of credence, is that *the same soul or power in living plants which generates their flowers and fruits also generates their maggots*. Who knows? Perhaps many tree fruits are produced not as primary ends in themselves, but rather for the secondary, subordinate end of generating maggots, serving as a womb in which they reside for a fixed amount of time, after which they emerge to enjoy the sun.

This idea of mine will not seem a complete paradox, if you reflect on the many sorts of galls, burrs, and other such growths produced by oaks, corks and other nut-bearing trees; for in galls . . . it is very evident that the first and foremost intention of nature is to form therein a flying animal; one sees in the center of the gall an egg which, along with the growth and maturation of said gall, itself grows and matures, and in turn gives birth to a maggot . . .

> I confess to you naively that, before I did these experiments on the generation of insects[6] I believed, or better I suspected, that galls came to be because flies arrived in the spring and made small slits in the tenderest branches of oaks, in which they hid one of their seeds, which then caused galls to bloom, and that one would never see galls or burrs or other such growths except in those branches where flies had deposited their seed. (Redi, 1668, p. 48; emphasis added)

Redi says that his change of opinion came after carefully considering his observation that galls of a given kind always appear in the same particular manner and location: always on younger branches of an oak, always on the part of the leaf facing the ground as opposed to the sky, always on the veiny part of the leaf as opposed to the smooth part. (We now know that these universal generalizations are in fact false, but Redi took them to be the case, generalizing from his own observations. He claims to have examined more than 20,000 galls.) He says that having observed these regularities in the position of galls on trees, he modified his belief:

> It seems more believable to me that the generation of animals born in trees is not a random generation event, nor does it result from seeds deposited by pregnant flies; especially since every gall has a maggot inside, and every particular kind of gall always has its own particular kind of maggot, fly, or gnat, which never varies. (Redi, 1668, p. 49)

He goes on to discuss the "mastery" displayed by nature in forming the egg, and preparing a space for it inside the gall, as the insect grows inside, nourished by "a certain necessary vital fomentation from the entire oak" (*ibid.*). Redi does not give much more support to his change of mind and ensuing conclusion about the origin of gall insects, which ends up sounding hasty and unsubstantiated, especially in comparison to the rigor he displayed in drawing conclusions from his experiments on insect generation. His logic in the gall case seems to involve reasoning from a regularity he took to hold in nature to an assumption of lawfulness—as he did in the experiments on insect generation—though in this case the conclusion it led him to was based on a regularity that was only apparent. (I return to the logic of this reasoning at the end of Section 3.1, below.)

So Redi was wrong about where galls come from. As mentioned in Section 1, commentators have argued that these claims are problematic for a deeper reason, i.e., that he is conceding the very theory he set out to refute in the beginning of *Generazione degl'insetti*. Hall (1951) exemplifies this interpretation of Redi when he begins the section of his book entitled "Early opposition to spontaneous generation" with the following: "Most Greek scientists believed in the generation of living beings from nonliving matter. Redi (1628–1698) disproved this for maggots but accepted it for parasitic worms and gallflies" (382).

Others similarly imply that Redi, while he made important progress, ultimately should not be praised too highly for refuting spontaneous generation because of his ideas on gall insects, compared to others of his time who did not similarly slip up. Farley (1972), for example, writes:

> Redi maintained that animal parasites, plant worms, and galls were produced by the same potency which generated flowers and fruits. The discovery of [Redi's contemporaries] Malpighi, Reaumur, Swammerdam and Vallisneri, that plant galls and myiasis-producing worms were derived from insects, quickly limited the spontaneous generation controversy to the production of infusorians and intestinal worms. (p. 96, n. 5)

Weis and Abramson have a similar take: "Redi, whose disproof of the spontaneous generation of flies on putrefying flesh established his reputation as an anti-vitalist, thought the insect developed *de novo* in the gall…He believed that the plant gave rise to the gall and the insect egg, which then hatched and developed into an adult" (1986, p. 691).

Redi's claims about gall insect generation are problematic for him, but the charge of inconsistency is neither as straightforward nor as condemning as previous commentators say it is. His claims about gall insects are problematic because he is relaxing the specific claim he made following his experiments on insect generation: All insects come only from eggs laid by parents of the same species. The following section explains why this is not so serious a charge as others have made it out to be.

3. A closer look at spontaneous generation

To fully understand Redi's theoretical commitments, we must first get clearer on what exactly the theory of spontaneous generation is, and the manner in which he can be said to have rejected or endorsed it. It turns out that people have used this term in a number of different ways over the centuries, and continue to do so. It is misleading to portray spontaneous generation as a single theory, as Redi's commentators (among many others) tend to do. 'Spontaneous generation' is in fact a blanket term covering a landscape of views about the potential origins of newly-generated life. By situating Redi's views within that landscape, we can better understand how the gall case fits in with the rest of Redi's work, what he took himself to be committed to, and what he took himself to be rejecting. I will argue that, while Redi did suffer from some inconsistency within the overall framework of his views, this inconsistency is not fairly represented by saying he rejected spontaneous generation in one case and accepted it in another.

3.1. Origins of living things

Farley opens his 1977 book *The Spontaneous Generation Controversy from Descartes to Oparin* with the following statement of that controversy: "Must living beings necessarily arise from parents?" (ix). A few pages later, he summarizes the core view held by proponents of spontaneous generation as follows: "some living entities may arise suddenly by chance from matter independently of any parent." Bardell (1985) offers a different formulation of the theory, as held from the time of Aristotle until the seventeenth century: "It was commonly believed that some kinds of organisms could arise from matter and without the need for parent organisms of kindred stock" (237). According to Strick (1999), advocates of spontaneous generation "claimed that organisms could sometimes arise by the right combination of nonliving materials under appropriate conditions" (55).

Note that none of these three formulations are supposed to be special statements of particular people's ideas; they are intended as general statements of the view discussed in the opening of this paper, which we talk about being held since antiquity and undercut over three centuries of research. In those three definitions of 'spontaneous generation', there are a number of different ideas at

[6] It is not clear from the Italian text here whether Redi is referring to his studies surrounding the generation of gall insects in particular, or to his experiments on insect generation in general. While the wording would seem to indicate the latter, the surrounding discussion bears only on his discoveries regarding gall insects, and he does not connect those discoveries to the findings in his separate experiments on insect generation discussed in Section 2.2 above. Given this context, it makes more sense to read this as a self-contained discussion of his work on, and beliefs about, gall insects. Reading it this way highlights the separation of his beliefs here from the rest of his theoretical and experimental work, which is, of course, problematic.

play. Farley's and Bardell's stipulate only that new life need not be generated from parents (of the same species), while Strick's formulation specifies that nonliving matter can generate life. Farley explicitly states that the generation in question happens by chance, while Strick's formulation suggests the opposite, i.e., that the generation in question is nonrandom and perhaps even predictable. Bardell's formulation leaves out the issues of spontaneity or chance entirely. Scholars talking about spontaneous generation are in fact talking about a family of theoretical commitments. By using the term without further specification, discussions of early modern views on spontaneous generation end up misleadingly including a range of different theoretical positions under the same umbrella.[7]

Unifying the set of possible views called spontaneous generation is the idea that new life forms can be generated by matter or entities which we would not normally consider to be their parents. There is a three-tiered hierarchy of possibilities regarding which kinds of matter can generate new life.[8] The first two tiers are the distinctions between organic/inorganic and living/nonliving. Life could conceivably be generated from either *inorganic* or *organic* matter. Inorganic matter, such as rocks, dirt, and dinnerware, is by nature inert and nonliving. The category of organic matter can include *living* things and their parts, like flies, humans, and fruit growing on a tree. It can also include *nonliving* matter—the byproducts or remains of living things—like hay, steak, dung, and fruit picked from a tree. A third, more fine-grained distinction can be made within the category of organic, living entities as candidate generators of life: Living things could come from either parents of their same kind, or from organic, living entities which are not parents of their same kind. A maggot born from an egg laid by a fly would be an example of the former; a tapeworm generated from a living human's internal tissue or a wasp generated from a living tree would be examples of the latter. Today, we accept only members of the former category as potential life-generating entities, and reject the latter. In the seventeenth century, both were possibilities. For the sake of simplicity, I will call this distinction within the category of organic living matter a distinction between *parents* and *non-parents*. Here I am using 'parent' in a narrow sense: By an organism's parent(s) I intend an entity or entities of the same species causally responsible for that organism coming to be. 'Parent' could also be used more loosely to refer to any living thing that gives rise to another one, abstracting away the question of species membership; following Redi, this is not how I am using it (cf. footnote 3).

The following scheme summarizes the above distinctions and represents the landscape of possible kinds of matter from which newly-generated life forms might originate:

1a. *Organic, Living, Parents*
1b. *Organic, Living, Non-parents*
2. *Organic, Nonliving*
3. *Inorganic, Nonliving*

Options (1b)–(3) are all candidates for including under the heading of spontaneous generation. Option (1a) is not, because organisms born from living parents of the same species are clear contrast cases to spontaneous generation, on any of its various formulations.

The category distinctions represented in (1)–(3) above overlap with the distinction between *abiogenesis*, the generation of living organisms from inorganic matter, and *heterogenesis*, the generation of living organisms from organic matter.[9] These terms originated in the nineteenth century and thus were not part of Redi's vocabulary, but they are useful in relating my discussion of the conceptual landscape of spontaneous generation with previous discussion. Both of these terms have been used synonymously with 'spontaneous generation'; as Strick notes:

> Heterogenesis is the process of living things allegedly appearing from degenerating material, which itself was derived from previously living things (e.g., meat or vegetable infusions). [Abiogenesis] is the process of living things allegedly appearing from inorganic starting materials. While participants argued for one or the other position, many [nineteenth-century] journals, especially those aimed at a non-scientific public, continued to describe any supporter of either doctrine as an advocate of "spontaneous generation," thus often lumping together individuals with significant disagreements. (1999, pp. 55–56)

The distinctions proposed above are more fine-grained than this. While my third category, inorganic nonliving matter, coincides with abiogenesis, there is an important distinction between living and nonliving organic things, which is not captured by heterogenesis alone.

The ideas on the table so far—the framework for categorizing specific theoretical commitments about potential life-generating entities, and the notions of abiogenesis and heterogenesis—make no commitments about any chanciness associated with generation. The issue of chance deserves a brief mention, because the theory of spontaneous generation has sometimes been thought of as a theory of generation "by chance." But the element of chance in some definitions of spontaneous generation, as in Farley's, is a red herring. There are two reasons for this. First, at least until the nineteenth century, 'spontaneous' referred exclusively to something happening due to internal principles or influences, rather than from any external influence (cf. OED, 2013). This meaning of 'spontaneous' does not have to do with chance, and this is the meaning Redi had in mind.[10] Second, the sense in which spontaneous generation, so understood, could be chancy (or regular and predictable) is exactly the same sense in which generation from any kind of matter—including nonliving matter, living non-parents, and parental seed—could be chancy (or regular and predictable). Thus, while some discussions of spontaneous generation associate spontaneity with chance, this is an anachronistic reading of 'spontaneous' and paints a misleading picture of views categorized as subscribing to the theory.[11]

Redi's view on generation is emphatically not that it happens "by chance." His one notable reference to chanciness in *Generazione degl'insetti* regards the lack of it he saw in the generation of gall insects, in a passage quoted earlier: He says that "the generation of animals born in trees is *not* a random generation event" (emphasis added). He gives a lengthy account of the predictable regularities he sees in the relation between galls and the insects that come

[7] One of the main claims I will make about Redi—that interpreters have mischaracterized his views by associating them with the complex notion of spontaneous generation and associated baggage—could be illuminating as a more general point about interpreting early modern views on generation. The framework I present below is intended both to help make sense of Redi's views, and more generally as a standard for tracking changes in the meanings of terms like 'spontaneous generation' or 'heterogenesis'. I am grateful to an anonymous reviewer for highlighting this point.

[8] Of course, more fine-grained distinctions could be made here; the framework I propose is not supposed to represent every possible view on origins of newly-generated life. The goal here is just to set enough of a framework in place to give a more detailed analysis of Redi's theoretical commitments on generation than has been done to date.

[9] Farley (1977, p. 1) defines both of these as forms of spontaneous generation: *abiogenesis* is spontaneous generation from inorganic matter and *heterogensis* is spontaneous generation from "organic matter which was itself alive or derived from a living organism." Farley says that the distinction "became crucial at times when organic matter was thought to be produced only from living organisms. At such times vitalists, who would necessarily deny any possibility of abiogenesis, could readily accept heterogenesis."

[10] See the first quote in Section 2.1, and discussion in Bernardi (1997a).

[11] I am grateful to Mark Bedau and Carlos Santana for highlighting these issues about chance.

from them: "every particular gall always has its own particular kind of maggot." From this he concludes that, contrary to his prior belief that all insects come from their parents' eggs, it is more believable that gall insect generation, while not random, is not from parents' eggs but rather from the same (regular) power within plants that generates their own fruit.

Redi says that he used to think gall insects came from eggs laid by parents in the gall, but when he observed these regularities in the correspondence between the appearances of the gall and the insect that came from it, he changed his mind. His explanation of this switch seems hasty and confusing. But perhaps it is less confusing if we let go of our current knowledge that galls are formed via the plant's morphological response to intervention on behalf of an insect; that is, the parent insect "makes" the gall, or at least causes its formation. To Redi, it appears, the gall was unquestionably something made by the plant; galls are, after all, constituted of plant tissue, so this assumption was not unreasonable. His conclusion that plants make galls to house eggs was based on what he took to be evidence in the form of observed regularities. Recall the second quotation regarding gall insects from Section 2.3 above: Redi said that his change of opinion about the origin of gall insects was justified "especially since every gall has a maggot inside." He claims to have opened more than 20,000 galls and never found a single one which did not contain an egg or larvae. Had he observed empty galls, this observation—combined with his assumption that plants make galls themselves—might have supported his original view that eggs are found inside galls because an insect came and laid them there. But he took the lack of such cases as support for his belief that the gall is formed by the plant with the specific goal of housing eggs generated therein. Thus he had reasons for his conclusion; however shaky those reasons may appear to us now, his change of opinion was not unquestioned.

3.2. Getting precise about Redi's views

The preceding section's conceptual distinctions regarding views on generation help us better understand Redi's theoretical commitments. At the end of Section 2.3 I cited commentators who charge Redi with inconsistency in his overall contribution to the spontaneous generation controversy. The most extreme version of this was Hall's claim that "Redi . . . disproved [the generation of living beings from nonliving matter] for maggots but accepted it for parasitic worms and gallflies." 'Spontaneous generation', at least as it has been used to refer to Redi's views and the larger controversy to which he contributed, should be understood as referring not to a single theory but to a family of theories. By getting more precise about specific commitments regarding which kind(s) of matter can generate life, we can see that Hall's charge is straightforwardly false, and others' charges of inconsistency are misleading to varying degrees.

I posit that in his theoretical discussion and empirical methodology surrounding the question of insect generation in general, Redi set out to remove options (2) and (3) from the scheme laid out in Section 3.1. That is, his goal was to deny that living organisms can be generated from nonliving entities of any kind. In the theoretical preamble to *Generazione degl'insetti*, he stakes out his position to that effect, using examples of both organic nonliving matter (e.g., putrefying meat) and inorganic nonliving matter (e.g., mud). Redi's positive evidence to back up this theoretical stance can be understood on two different levels, a narrow one and a broad one. Distinguishing between these two levels is crucial for understanding (i) the nature of his theoretical inconsistency, and (ii) the sense in which this inconsistency is not as severe as commentators have said it is.

First, his theoretical inconsistency is as follows: Redi concluded from his experiments on insect generation that insects are generated only from eggs laid by their parents. In his study of gall insects, he concluded that insects born from galls are generated from some vital force in the gall-bearing plant, following a certain regularity such that galls of a particular type predictably give rise to insects of a particular type. His conclusions about the origins of newly-generated life forms can thus be summarized as follows, with accepted categories of life-generating entities represented in bold, and rejected categories in italics:

Experiments on insect generation:	Study of gall insects:
1a. Organic, **Living**, **Parents**	**1a. Organic, Living, Parents**
1b. Organic, *Living*, *Non-parents*	**1b. Organic**, **Living**, **Non-parents**
2. Organic, *Nonliving*	*2. Organic*, *Nonliving*
3. Inorganic, *Nonliving*	*3. Inorganic*, *Nonliving*

In other words, following his rejection of options (2) and (3) as candidate types of entities to generate life in the preamble to *Generazione degl'insetti*, Redi is left with the broad theoretical commitment that only organic living things can generate new living things. His conclusion about gall insects is consistent with this broad claim. The inconsistency comes in the finer-grained distinctions he goes on to articulate within that category. From his experiments on insect generation, he concludes that all insects come from organic living parents, and from his studies on gall insects he concludes that some insects can come from organic living non-parents, namely, plants. This latter claim does not nullify the claim drawn from his experiments on insect generation, which is what commentators have charged him with doing. In other words, by accepting (1b) as an entity type capable of generation in his study of gall insects, Redi does not deny (1a) possession of that status. His only contradiction is with respect to his earlier claim that only entities of type (1a) can give rise to living things ("all maggots come from their parental seed"): He changes the picture to say that all life comes from parents, except in the case of insects born from trees. Thus, his inconsistency lies in backing away from the claim that entities of type (1a) have universal special status as generating agents, within the category of organic living entities.

At the broader level, however, Redi's experiments on insect generation serve to solidify his broad negative claim that living things are never generated from nonliving matter. And in this point he remains consistent in his discussion of gall insects. To the extent that spontaneous generation is ever taken to involve the ideas that living things can (i) come from all sorts of different matter, including nonliving matter like mud or meat, and (ii) arise by chance without clear underlying agency and regularity, it is a view that Redi absolutely rejects.

Further evidence for this reading can be found in a passage toward the end of *Generazione degl'insetti*, when Redi briefly raises his view on the origin of parasitic worms. Referring back to his earlier claims, Redi writes that when we see insects or little larvae arise in a particular location, it is because parent insects laid eggs in that location:

> . . . and if that seed was not really brought there [by the parent], nothing, as I said before, will ever be born from grasses, or from rotting meat, *or from any other thing that is not at that time alive. On the other hand, if a thing is living,* it can produce within itself a little maggot, as in the case of cherry, pear, and plum trees . . . In this same manner it could perhaps be true, and I am inclined to believe, that in the intestines and other parts of human bodies worms are born . . . (1668, p. 63, emphasis added)

Here, Redi indicates his inclination to believe points we now know to be false: that trees can generate gall insects and human intestines can generate tapeworms. But more importantly, in support of the

reading offered here, he underlines his belief in the general principle that a thing can generate new life if, and only if, it itself is living.

Clarity about his precise views on the origin of new life forms, and his focus on finding regularities to explain them, captures Redi's views more accurately than representing them as positive or negative claims about spontaneous generation. While Redi's position on the origin of gall insects remains problematic for him, it is not problematic for the reason, or to the extent, that historical accounts of the spontaneous generation controversy have implied. Hall's interpretation of Redi, in particular, completely misrepresents his views.

I have shown why there is no inconsistency in Redi's broad theoretical stance that nonliving matter never generates life. The problem remains, however, that he got the picture of gall generation remarkably wrong. While I have argued that it is misleading to describe this as conceding to the very theory (spontaneous generation) that he elsewhere rejected, it is still a problem worth examining more closely, especially because contemporaries of Redi's like Marcello Malpighi, working at the same time in the same country on the same questions, got the story about gall insects right. Redi's experiments on insect generation are now a classic textbook example of truth-via-experiment winning out over false theories. It is tempting to explain the "success" of this part of his work in terms of its remarkable similarity to the modern experimental paradigm, in important respects: for example, his meticulous use of controls, repetition of treatments, documentation of data, modification of individual variables, and so on. However, this kind of analysis goes too far in imposing our modern idea of experimental science on Redi. It is more useful to compare his methodology not to today's experimental methodology, but to the standards he set for himself and his contemporaries as experimentalists.

4. An unforgivable epistemological sin?

Bernardi says that Redi's conclusions about gall insects are taken as "an unforgivable epistemological sin on behalf of a scientist who proudly called himself an 'experimental philosopher' and who always claimed to affirm 'with certainty' only what he had observed 'with his own eyes, after many repeated trials'" (1997a, p. 49). Bernardi gives a detailed account of Redi's work on gall insects, placing it within the larger context of his position as a researcher in the Tuscan court. He discusses a number of other accounts of how and why Redi went wrong in the gall case, which tend to explain the error in terms of Redi giving more weight to speculation than to experiment, in spite of having elsewhere "adopted as his personal epistemological currency to believe only in what he saw with his own eyes" (17). Bernardi offers an alternative, more charitable account of Redi's error: Redi's mistaken conclusion about gall insects was a product of his courtier research position, which let him amass information and collect specimens in his laboratory without ever going into the field himself. This privileged position led him to look at his specimens out of their element, on his bench within the court, removed from nature. By missing out on observing nature running its course, he missed out on properly understanding the true relationship between insects, trees, and galls. As Bernardi poetically states where Redi went wrong, "he did not go (as Malpighi did) to watch the pumpkins growing" (28). Thus Redi, who was blessed with facilities unimaginable to his contemporary natural philosophers, was not in a position to see what others like Malpighi saw when looking for answers from nature. He gained extensive knowledge of the larvae inside galls and their reproductive cycles, but because he looked at them only isolated in his laboratory, he did not see the key to where they came from, that is, insects buzzing around plants and depositing their eggs in the places where galls successively formed.

There are two issues at play in this analysis, which deserve separation. First, what led to Redi's error? Second, can he be faulted in any way for deviating from good experimental practice? In my answer to the first question I essentially agree with Bernardi, but argue that Redi's error was more than just a matter of being in the wrong place at the wrong time. My answer to the second question is emphatically no.

I agree with the core point of Bernardi's view, that Redi's study of galls at the lab bench was the source of his error in the gall case—but not because of any general point about field research having an advantage over laboratory research. Redi's error was in the appropriateness of his particular choice of experimental object for answering the particular question at hand. To see this, we can once again employ the framework for thinking about what kind of entities generate life, laid out in Section 3.1. In his experiments on insect generation, Redi set out to answer the following question: Are insects generated from nonliving matter, rather than parental seed? His experimental object was a controlled set of samples of his target of inquiry: nonliving matter (meat and dead plants), the flies that did or did not land on it, and the maggots that subsequently did or did not grow on it. That the experiments were conducted in the lab as opposed to in nature is irrelevant to this point. The relevant question was about what can come from certain substances and what cannot, and the setting in which those substances are found was already abstracted away from the theoretical question itself.

In his work on gall insects, however, Redi set out to answer a different question: Are insects generated from certain organic living non-parents, i.e., trees? His conclusion, after extensively examining galls and the eggs and larvae inside them, was that insects are generated in the galls directly from some life-giving force in the tree. But to arrive at this conclusion he looked at galls only in his laboratory. Unlike with his other experiments, the context of his object of study mattered here: The proper target of inquiry in this case should have been not just any galls, but galls on living trees. Redi was looking primarily at galls removed from trees. By studying something that was not a direct sample of his proper target of inquiry, in an important sense, he missed out on a crucial piece of causal information: flies injecting their eggs into the living plant tissue, where a gall would then form.

So Redi went wrong about galls because his objects of study, unlike in the case of his experiments on insect generation, turned out not to be in quite the right form for answering the question at hand. But this point alone does not speak to his success or failure at employing good experimental methodology. If my or Bernardi's assessment of how Redi went wrong in the gall case is correct, then it is puzzling why Redi's conclusion should be interpreted as an epistemological sin, or a blow to his status as a good experimental philosopher—especially if we understand what it is to be a good experimental philosopher in Redi's own terms.[12]

To see why, recall Redi's own criticism of his contemporary Buonanni, discussed in Section 2.1 above, in which Redi lays out what he takes to be crucial to good experimental practice. Redi said that Buonanni failed to be "a true experimental philosopher, one who never affirms anything with certainty except what he observes, after many rounds of repeated evidence, with his own eyes." What makes a good experimental philosopher, for Redi, is seeing patterns and regularities through many repeated acts of

[12] My point here adds further support to a point emphasized by Findlen (1993) and Strick (2000), namely, that we should judge Redi's experimental philosophy not in terms of twentieth-century ideas of experimental science, but rather in terms of what experimental natural philosophy was in the seventeenth century, in Redi's particular context.

observation, and seeing them in a firsthand and hands-on manner.[13] He accused Buonanni of not doing this well enough, and also of failing to conduct adequately careful experimental manipulation: Redi faults Buonanni for failing to seal his jars "with diligence." In these terms, Redi himself actually *did* apply this method to his work on gall insects. It just turns out that, unfortunately, he based his conclusions on ostensible regularities which we now know (and which even his contemporaries figured out) do not hold. Thus, his methodological error was at worst one of hasty generalization.

So I disagree with the charges of epistemological sin and lapse in praiseworthy experimental philosophy. Redi was, in fact, sticking to his guns in the main features of being a good experimental philosopher that mattered for him—relying only on first hand knowledge, and accumulating such knowledge over many repeated trials. There is nothing about accumulating such knowledge in a laboratory, rather than in the field, that makes it less epistemically valuable or commendable. This should be clear from everyone's praise of his experiments on insect generation. He went wrong in the gall case by generalizing from results collected by looking at his object of study removed from its relevant context. He did not perform a controlled manipulation analogous to that in his experiments on insect generation—but arguably such a setup would have been out of the question for him.[14] It appears that Redi applied rigorous manipulation and control where he could, but these are not always possible. It is not surprising that he got the wrong answer in the gall case by looking at galls in his laboratory removed from trees; but this mistake is not due to any lapse in what he took to be the core methodology of a good experimental philosopher.

5. Conclusion

I have shown that thinking about Redi's overall theoretical commitments regarding insect generation purely in terms of positive or negative claims about spontaneous generation is misleading, and gives rise to overly harsh accusations of inconsistency. The term 'spontaneous generation' has been used to describe what are in fact a number of different kinds of views on the origins of living things. Focusing on the details of what Redi actually said about the origins of living things shows that his theoretical claims suffered from far less inconsistency than his commentators have charged him with. Redi was not wholeheartedly rejecting spontaneous generation in his work on insect generation, and wholeheartedly accepting it in his work on gall insects. Rather, he *always* rejected the view that living things are generated from nonliving things, and he made the positive claim that all insects come from eggs, and all eggs come from other living things. The inconsistency in his theory comes in with the details of this latter claim. Redi said that *all* insects come from parents, in one case, and then said that *some* insects can come from non-parents (plants) in the other case.

In addition to this broad point about the need for clarity in what we mean by spontaneous generation, I have pointed to another broad issue, namely, the danger in relying on contemporary ideals of experimental practice to assess the methodology of someone working well before our modern conception of the scientific method existed. This is a broader conclusion about the role of intervention and controls in experiment. We look at Redi's experiments on insect generation and see features which we now consider paradigmatic of good experimental method; this is why we often learn about his experiments in science textbooks. But in Redi's terms, the crucial aspect of his experimental methodology was what he emphasized in his own critique of Buonanni: Believing only what he saw with his own eyes over the course of many repeated trials, with meticulous attention to the details of careful manipulation. Not only did Redi not take back his broad theoretical commitments in the gall case, he did not relax his standards for proper experimental methodology, as others have implied. It just turns out that, unlike in his experiments on insect generation, he applied this methodology to an object of study which ultimately failed to lead him to the right conclusion.

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References

Arber, A. (1942). Nehemiah Grew (1641–1712) and Marcello Malpighi (1628–1694): An essay in comparison. *Isis, 34*(1), 7–16.
Bardell, D. (1985). Francesco Redi's description of the spontaneous generation of gall flies. *The American Biology Teacher, 47*(4), 237–238.
Bernardi, W. (1997a). Il problema della generazione degl insetti delle galle nei manoscritti e nei protocolli di laboratorio di Francesco Redi. In W. Bernardi et al. (Eds.), *Natura e immagine: Il manoscritto di Francesco Redi sugli insetti delle galle* (pp. 49–67). Pisa: Edizioni ETS.
Bernardi, W. (1997b). Teoria e pratica della sperimentazione biologica nei protocolli sperimentali Rediani. In W. Bernardi & L. Guerrini (Eds.), *Francesco Redi: Un protagonista della scienza moderna* (pp. 13–30). Firenze: Leo S. Olschki.
Ereshefsky, M., Species. In E. N. Zalta (Ed.), *The Stanford encyclopedia of philosophy* (Spring 2010 Edition), URL = <http://plato.stanford.edu/archives/spr2010/entries/species/> Accessed April 2013.
Farley, J. (1972). The spontaneous generation controversy (1700–1860): The origin of parasitic worms. *Journal of the History of Biology, 5*(1), 95–125.
Farley, J. (1977). *The spontaneous generation controversy from Descartes to Oparin*. Johns Hopkins University Press.
Findlen, P. (1993). Controlling the experiment: Rhetoric, court patronage and the experimental method of Francesco Redi. *History of Science, 31*, 35–64.
Fry, I. (2000). *The emergence of life on Earth: A historical and scientific overview*. Rutgers University Press.
Hall, T. S. (1951). *A source book in animal biology*. New York: McGraw-Hill Book Company.
OED Online. (2013). *Spontaneous, adj. June 2013*. Oxford University Press. 4 August 2013 <http://proxy.library.upenn.edu:2266/view/Entry/187385?redirectedFrom=spontaneous>.
Pasteur, L. (1864). On spontaneous generation. *Revue de Cours Scientifics*, I, 257–264. English translation commissioned 1993 by Bruno Latour, © Alex Levine. 7 December 2013 <http://www.rc.usf.edu/~levineat/pasteur.pdf>.
Redi, F. (1668). *Esperienze intorno alla generazione degl'insetti*. Firenze. Original text at <http://www.liberliber.it> Accessed February 2011.
Redi, F. (1684). *Osservazioni intorno agli animali viventi che si trovano negli animali viventi*. Firenze. Original text at <http://www.liberliber.it> Accessed February 2011).
Stone, G. N., & Cook, J. M. (1998). The structure of cynipid oak galls: Patterns in the evolution of an extended phenotype. *Proceedings of the Royal Society B, 265*(1400), 979–988.
Strick, J. (1999). Darwinism and the origin of life: The role of H. C. Bastian in the British spontaneous generation debates, 1868–1873. *Journal of the History of Biology, 32*(1), 51–92.
Strick, J. (2000). Spontaneous generation. In J. Lederberg (Ed.), *Encyclopedia of microbiology*. Academic Press.
Weis, A. E., & Abrahamson, W. G. (1986). Evolution of host-plant manipulation by gall makers: Ecological and genetic factors in the Solidago-Eurosta system. *The American Naturalist, 127*(5), 681–695.

[13] Findlen (1993) also stresses this point in her excellent paper on Redi's experimental philosophy, looking more closely in particular at the social context and nature of the courtier culture.

[14] The analogous experimental setup, of course, would have been to somehow seal off entire trees to prevent insects from accessing them, and see whether and how larvae emerged from galls in those trees compared with unsealed ones. I will not speculate here about the actual feasibility of such an undertaking, given Redi's resources, but it seems fair to say that it would have been prohibitively difficult. Other possible avenues for a controlled experimental setup to test Redi's question exist, but the relevant point here is that he did not apply them.