

Bacterial Communication

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Abstract

Recent research on bacteria and other microorganisms has provided interesting insights into the nature of life, cooperation, evolution, individuality or species. In this paper, I focus on the capacity of bacteria to produce molecules that are usually classified as 'signals' and I defend two claims. First, I argue that certain interactions between bacteria should actually qualify as genuine forms of communication. Second, I use this case study to revise our general theories of signaling. Among other things, I argue that a plausible requirement for a state to qualify as a signal is that it is a minimal cause.

1 Introduction

In the last two decades there has been a growing interest in bacteria and other microorganisms. Various reasons justify this fact. Most biodiversity on Earth is and has always been microbial. The global chemistry of life (the carbon cycle, the nitrogen cycle, ...) depends on microbes. Microorganisms are the oldest and much more numerous than macroorganisms and some of them are also important pathogens that have caused dramatic plagues. Philosophy, however, only recently started to pay close attention to the microbial world. Recent work has investigated what bacteria can tell us about life (Parke, 2013), cooperation (Lyon, 2007), individuality (Clarke, 2016), species (Franklin, 2007) or general questions in philosophy of science (O'Malley, 2014, O'Malley and Parke, 2020). Some surprising claims

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have also been put forward, such as the idea that some bacteria aggregates (biofilms) are superorganisms (Shapiro, 1988) or that there is such a thing as bacterial cognition (Shapiro, 2007). In this essay I would like to focus on a different aspect of microbes that has been receiving an increasing amount of attention by scientists: the capacity of certain bacteria to produce signals. More precisely, I will focus on the phenomenon called 'quorum sensing' (QS).

Biologists routinely claim that bacteria communicate by producing and sensing chemical messengers that enable them to coordinate behaviors. However, is this a metaphorical use of 'communication' and 'signal', or should we take these expressions at face value? Do bacteria really transmit semantic information in the same sense in which vervet monkeys or humans do? If this is true, what are the consequences for our understanding of bacteria and communication? This is an important question that has generated some debate in microbiology (Diggle et al., 2007a; Redfield, 2002; Keller and Surette, 2006; Stacy et al., 2012; Whiteley et al., 2017). From a philosophical perspective, microbial communication has often been mentioned, but rarely discussed in detail (Ereshefsky and Pedroso, 2013; O'Malley, 2014; Bich and Frick, 2018). Generally, the notions of communication and signal have mostly been studied in the context of animals (indeed, mostly in mammals). A remarkable exception is the work on formal models of signaling, which sometimes have taken bacterial communication as their target (Skyrms, 2010; Pacheco et al., 2015). These models have been extremely useful in understanding different properties of signals, yet they also have important limitations, three of which are specially important for us: they do not usually engage with microbiological research, omit most empirical detail and assume a very liberal notion of 'signal'. A primary goal of this essay is precisely to address these issues.

There are various reasons that make bacterial communication a fascinating topic. Research on bacteria have already provided very interesting results in understanding some key evolutionary concepts like altruism, kin discrimination or enforcement of cooperation (West et al., 2007). Furthermore, since theoretical approaches to communication have mostly been developed with animals in mind, bacteria provide an excellent opportunity to test these ideas in a different domain. Bacteria also provide exceptional conditions for experimental studies due to short generation times and a context in which mechanistic details are relatively well-known and can easily be manipulated (Popat et al. 2015). Additionally, from a scientific point of view, pressing questions concern the real function of QS molecules and whether they always work as signals, and addressing them requires some conceptual theorizing. As a re-

cent review suggests, "the current literature sometimes conflates signalling, cueing and coercion, and whether bacteria are interacting via a signal, a cue or coercion can lead to different biological outcomes" (Whiteley et al., 2017: 315). Understanding this phenomenon is also crucial from a practical point of view, since an intervention on QS can be used to control the production of virulence factors or biofilms, among other things (Foster, 2005). Last but not least, it illustrates how different fields can collaborate to understand better a given phenomenon; microbiology, ethology and philosophy have addressed the question of signals and communication from different angles, and I would like to explore how these different perspectives can engage in fruitful collaboration. All in all, this case study is interesting not only because it helps us understand better a captivating phenomenon, but also because we will gain key insights into the nature of signaling and communication from a collaborative perspective. Quorum sensing (QS) provides an excellent opportunity for this kind of research.

More precisely, in this paper I will argue that certain aspects of QS (e.g. its functions, sender-receiver structure, etc.) fit relatively well into extant definitions of communication, whereas other features are more problematic (e.g. excessive liberalism, arbitrariness). As a result, I will defend that bacteria probably engage in genuine communication, although we might need to refine standard definitions of 'signal'. I will also argue that a promising modification appeals to the idea that signals are 'minimal causes'.

Accordingly, the paper is structured in three main sections. In section 2 I will explain the phenomenon called 'quorum sensing'. Section 3 describes the standard approach to communication and presents the good news, i.e. those features of QS that fit this model. Section 4 focuses on the bad news: it presents some difficulties with using the standard model in the context of QS and suggests a strategy for dealing with these worries. I will end with some conclusions and directions for future research.

2 Bacterial signaling

Although it used to be believed that bacteria live as monads, we now know that this is a very rare exception (Shapiro, 1988; Dunn and Handelsman, 2002). To coordinate their intense social activity, research carried out in the last twenty years strongly suggests that bacteria typically engage in cell-to-cell communication (Kolter and Greenberg, 2006; Mukherjee and Bassler,

2019). Increasing evidence points at the existence of intra-species, inter-species (Ley et al., 2008) and inter-kingdom communication (Hughes and Sperandio, 2008; Ismail et al., 2016), as well as different kinds of signaling systems – including a form of electrical signals (Prindle et al. 2015; Beagle and Lockless, 2015).

The most important and better understood exchange classified as a form of communication is called 'quorum sensing'. 'Quorum sensing' (QS) refers to a set of sign-mediated interactions in which certain molecules are produced, released and uptaken by other bacteria to coordinate action (Miller and Bassler, 2001; Witzany, 2011a, 2). QS is a process used by Gram-negative as well as Gram-positive bacteria, although the mechanisms might differ (Papenfort and Bassler, 2016).

One of the first and most famous cases involves the symbiotic relationship between *Vibrio fischeri* and the squid *Euprymnia scolopes*. In the nights in which the moon and the stars penetrate the sea waters, organisms cast a shadow when seen from beneath. In these circumstances, any opaque organism can easily be detected by predators. To avoid this effect, the squid *E. scolopes* recruits bacteria *V. fischeri* within its light organ. Once some of the bacteria get into the organ, they start to multiply, which they do at an astonishing rate (Ruby, 1996). After about 12 hours, when the night comes and millions of bacteria inhabit the organ, these bacteria generate bioluminescence, which helps the squid to avoid casting a shadow and hence being detected (Waters and Bassler, 2005; Haddock, 2010). Of course, light production is a costly process for bacteria in metabolic terms. Nonetheless, both the squid and the bacteria seem to benefit from the interaction: bacteria gain a nutrient-rich environment and protection, and their light helps the squid deter predators (Dessaux et al. 2011).

Yet note that this costly behavior can only benefit the squid if many bacteria are involved in it. When bacteria are scattered in the open sea or when there are too few of them in the light organ, generating light is irrelevant and energetically wasteful (Miyashiro and Ruby, 2012). This is why they need some way of detecting that there is a sufficient number of cells at the right place, and the way they do that is by means of QS. In *V. fischeri* the protein LuxI synthesizes the autoinducer 3OC6-homoserine lactone, which is subsequently released into the environment. As the number of individuals in the light organ increases this molecule rapidly accumulates in the milieu and, once a certain threshold is reached, the autoinducer initiates a signaling cascade within bacteria (which includes binding the transcription factor

LuxR and the induction of the *lux* operon) that concludes in the emission of light (Waters and Bassler, 2005; Mukherjee and Bassler, 2019). Thus, a high autoinducer concentration is usually described as signaling that the light organ contains a large number of bacteria. Interestingly, other organisms use the light emitted by *V. fischeri* for other purposes: for instance, the fish *Monocentris japonicus* employs this light to attract mates (Miller and Bassler, 2001). Other uses, such as luring prey and warding off predators have also been identified (Haddock, 2010)

Another bacterial species that uses an homologue of LuxI-LuxR QS system is *Agrobacterium tumefaciens*. *A. tumefaciens* is well-known for inserting a Ti plasmid into plants, which integrates a segment of its DNA into the chromosomal DNA of its host plant. This DNA induces the production of plant growth hormones that cause crown gall (tumours) and the synthesis of opines, which *A. tumefaciens* uses for growth. Interestingly, opines released by the plant also induce in agrobacteria the transcription of the *tra* QS system that leads to the production of the autoinducer acylhomoserine lactone (AHL); a threshold concentration of AHL in the environment (together with other features) leads to the transfer of the Ti plasmid to other *Agrobacterium* strains via conjugation (Lang and Faure, 2014; Dessaux and Faure, 2018). As a result, the QS system facilitates the spread of the tumour-inducing Ti plasmid into nearby agrobacteria, thereby increasing the pathogenic potential of the population (Frederix and Downie, 2011).

QS is also involved in remarkable collective behaviors, such as the complex developmental cycle of *Myxococcus xanthus*. *M. xanthus* is a rod-shaped myxobacteria that exhibits various forms of coordinated organization as a response to environmental cues. When food is abundant, they form an aggressive swarm that glides onto solid surfaces and feeds on any microorganism they find in their way, such as yeasts, fungi, protozoans or other bacteria (Spormann, 1999). However, when nutrients are sparse, they aggregate into a fruiting body that resembles a mushroom. In forming this structure between 65-90 % of cells lyse (their cell membrane disintegrates) and they serve as nutrients for the other bacteria, that form myxospores. The fruiting body can survive for fifteen years, but when myxospores detect the presence of enough nutrients in the environment, they germinate and initiate a new growing cycle. Producing a fruiting body is a complex process that requires the coordination of a large amount of bacteria (Muñoz-Dorado et al., 2016). And, again, this developmental process is mediated by at least two signaling pathways: the first ('A-signaling') leads to the aggregation of cells (Dworkin

and Kaiser, 1985). The second form of communication ('C-signaling') leads to the formation of the fruiting body (Kaiser, 2004; Keller and Surette, 2006).

Many more examples could be added. The opportunistic pathogen *Pseudomonas aeruginosa*, for instance, uses four main pathways of QS signaling to regulate motility, virulence factor production and biofilm formation, among others (Pesci et al., 1997; Schuster and Greenberg 2006, Lee and Zhang, 2015). Similarly, oral bacteria employ it to coordinate the actions of a polymicrobial community (Kolenbrande et al., 2002, Miller and Lamont, 2019). Each of these examples suggest interesting issues, but rather than focusing on any of them, in what follows I will address a general question, namely what is involved in classifying QS as an instance of signaling.

3 Quorum sensing and the Standard Approach to Signaling

Do QS autoinducers qualify as genuine signals? Do bacteria really communicate? When scientists assert that bacteria engage in cell-to-cell signaling, should we interpret these claims at face value or should we take them as metaphorical expressions that simply point at some superficial analogies between this pattern of interaction and genuine communication? Addressing these questions will allow us to understand better certain aspects of bacteria and, at the same time, assess extant theories of communication.

Scientists working on QS typically adopt Maynard-Smith and Harper's definition of signal, which is also standard in the study of animal communication (see, for instance, Keller and Surette, 2006; Diggle et al., 2007a; Stacy et al., 2012; Witzany, 2011a). According to them, a signal can be defined as follows:

Any act or structure that alters the behavior of other organisms, which evolved owing to that effect, and which is effective because the receiver's response has also evolved (Maynard-Smith and Harper, 2003: 3).

In philosophical jargon, this analysis can be considered as a version of *teleological* or *teleosemantic* theories, since it defines 'signal' (or 'representation') by appealing to the the notion of function (Millikan, 1984; Papineau,

1984; Neander, 1995). In this context, function is usually understood etiologically: the function of a trait is the effect of past items of the same type that account for its selection. The heart’s function, for instance, is to pump blood (and not to make thump-thump noises) because pumping blood is the effect that explains why hearts were selected for by natural selection. Teleosemantic approaches typically hold that representations are states produced and consumed by mechanisms endowed with certain biological functions. The key idea is that a signaling system consists of a mechanism (‘sender’) that has been selected for generating certain signals (‘act or structure’) when certain states of affairs obtain (the referent) and a second mechanism (‘receiver’) that has been selected for behaving in certain ways in response to the signal. Usually it is also assumed that a certain amount of cooperation among participants is required for genuine communication to exist. Although all these features have been disputed in the literature (see Stegmann, 2009; Cao, 2012; Schulte, 2015; Neander, 2017), I will assume this analysis broadly defines the standard approach to signaling.

In what follows, I will assess if these properties (functions, sender-receiver mechanisms, cooperation, etc.) are indeed present in the case of bacterial communication and whether they play any important theoretical role. At the same time, if we discover some notion that plays a key role in QS but is not included in the general analysis, that will provide an compelling motivation for modifying the standard approach to communication.

3.1 Sender-receiver

Does QS typically involve a sender and a receiver? This question can be addressed at different levels. If senders and receivers are conceived as organisms, then QS obviously involves some cells sending these molecules and others receiving them. If the question is whether some sub-organismic components are responsible for releasing and detecting them, an answer requires paying close attention to the molecular mechanisms underlying this phenomenon.

In many species, the molecular basis of QS is well-understood. In *V. fischeri*, it requires the action of five structural genes (*luxCDABE*) and two regulatory genes (*luxR* and *luxI*). The LuxI protein is responsible for the production of the 3OC6-homoserine lactone (HSL) autoinducer. As cell density increases, HSL molecules accumulate outside and inside the cell. When a certain threshold is reached, the LuxR protein binds the autoinducer. Afterwards, the structure composed of the LuxR and the autoinducer binds the

promoter at the *luxCDABE* and activates the transcription of this operon. This action results in an exponential increase in the transcription of *luxI* (and, accordingly, the production of the autoinducer) and an exponential increase in the transcription of *luxCDABE* that generates light (Waters and Bassler, 2005). Other bacteria possess more complex mechanisms. *P. aeruginosa*, for instance, has four pathways: the LasR-LasI system, the RhlR-RhlI system, the PqsR-controlled quinolone system and the IQS system (Papenfort and Bassler, 2016). In this case, the regulatory systems are organized hierarchically, rather than in parallel. In general, bacteria that engage in some form of communication typically possess a signal producer and a cognate transcriptional regulator that responds to the concentration of the signal (Miller and Bassler, 2001, Witzany, 2011b). As a result, the sender-receiver structure of QS seems to fit the standard approach to signaling.

Nonetheless, despite this general agreement, some important questions remain open. For example, although cellular components producing and detecting signal molecules can be identified, in many cases these roles seem to be distributed over different components. Consider, for example, how an accumulation of signal molecule affects *Vibrio cholerae*: the autoinducer binds receptors CqsS and LuxPQ, which dephosphorylate protein LuxO, via LuxU; since dephosphorylated Lux is inactive, *qrr1-4* is not transcribed, which causes AphA not to be translated; finally, given that AphA is a repressor of the master regulator HapR, in the absence of AphA HapR promotes cell aggregation (Jemielita et al., 2018). An interesting question is whether we should pick out one of these steps as playing the role of receiver or whether an interpretation in terms of a single distributed receiver is preferable.

3.2 Functions

It should be obvious that microbiologists are not simply attributing signals to any molecule produced by bacteria that affects other organisms. Cyanobacteria, for instance, perform photosynthesis that results in the release of oxygen, which most organisms employ, but this is obviously not a case of signaling. To distinguish signals from these other products, microbiologists typically assume that the sender's signals and the receiver's behaviors need to have evolved to fit each other. In other words, a central aspect that distinguishes signals from other molecules that lack a representational status is that signaling mechanisms have been selected for this task. Furthermore, this aspect is explanatorily central: when we classify an interaction as a form of commu-

nication, we expect it to evolve in certain ways (Stacy et al., 2012). Oxygen emitted by cyanobacteria does not qualify as a signal partly because the benefit other organisms obtain does not explain why bacteria produce it.

Indeed, not only those who support the representational status of QS appeal to evolutionary functions. For instance, when Redfield (2002) argues that autoinducer release does not signal the presence of a quorum, but it is used instead to detect certain features of the cell’s microenvironment, her main argument relies on an alternative evolutionary hypothesis. Similarly, the widespread suggestion that AI-2 molecule works as a form of ‘bacterial Esperanto’ by allowing communication between different genera has been questioned because the candidate for AI-2 receptor probably has a function unrelated to communication (Rezzonico and Duffi, 2008; Whiteley et al., 2017). Thus, a shared assumption seems to be that evolutionary function is a key element distinguishing signals from other interaction patterns.¹

3.3 Cooperation

Research on QS also vindicates the idea that cooperation is an essential requirement for communication (Diggle et al. 2007a; Maynard-Smith and Harper, 2003; Stacy et al., 2012). In particular, whether a state should qualify as a signal partly depends on whether the agents involved are both benefiting from the interaction or whether they are not. Two examples can be used to illustrate this point.

First, many bacteria have the capacity to release antibiotic molecules against other bacteria, which in turn have developed defensive strategies against them. Now, if the only requirement for signaling were that state and response must have co-evolved, then antibiotics would count as signals. That outcome would be highly problematic; for one thing, the evolutionary dynamics of antibiotic resistance and signaling significantly differ: whereas in the former, receiver success pushes the sender in the direction of changing the strategy, this is not so in paradigm cases of communication. Thus, it is sensible to assume that sender and receiver must have (at least) partial common interest.

A second case illustrating this idea is the phenomenon called ‘chemical manipulation’ (Keller and Surette, 2006). *Veilonella atypica* is an oral bac-

¹For a defense of a non-etiological understanding of function in the context of bacterial communication, see Bich and Frick (2018).

terium that requires the presence of another bacterium *Streptococcus gordonii* to colonize the oral cavity because *S. gordonii* ferments sugars and releases lactic acid, which is the preferred carbon source for *V. atypica*. *V. atypica* produces a soluble chemical that induces amylase expression in *S. gordonii*, which increases the degradation of complex carbohydrates and lactic-acid production, but it is not described as an instance of signaling, but of manipulation, and the reason seems to be that cooperation is missing. Again, classifying the case as a instance of genuine communication would suggest the wrong kind of evolutionary dynamics.

The cooperation requirement implies that no communication can exist between individuals that have no common interest. One might suggest the existence of QS in the context of fruiting body formation in *M. xanthus* challenges this idea, since a large proportion of cells lyse in the process.² Yet, despite appearances, standard explanations of this phenomenon support the idea of shared interest between cells. First, standard evolutionary explanations of this process appeal to kin selection (Claessen et al., 2014) and closely related individuals tend to have their interests aligned. Certainly, in natural populations cheaters also exist (although they are kept under control by different mechanisms such as spatial structure, allorecognition, social policing, metabolic constraints or 'metabolic prudence' – see Velicer et al., 2000; Xavier et al., 2011; Whiteley et al., 2017). However, note that cooperative individuals and cheaters might still have partial common interest; for instance, all of them are interested in the public good being produced and also prefer the situation in which all of them produce it to a scenario in which none does.³ Consequently, I think fruiting body formation fails to challenge the cooperation requirement.

3.4 Explanatory role

So far, I argued that QS possesses some of the central properties that are usually thought to define signals (sender-receiver, function, cooperation) and I distinguished QS from other phenomena. Yet signals also play certain explanatory roles. For instance, the signal's content should explain behaviour: we explain why a vervet monkey ran up a tree by mentioning that another

²I would like to thank an anonymous reviewer for raising this question.

³It is worth stressing that the cooperation requirement is compatible with different evolutionary dynamics of QS populations in the face of defectors. It has been argued, for instance, that QS acts as a cheater restraint (Bruger et al. 2021).

group member produced a signal that means *leopard approaching*. Furthermore, the claim that bacteria engage in cell-to-cell communication should be a theoretically fruitful assumption. Are these conditions met by QS?

I think they probably are. Suppose that we see a strain of bacteria producing a certain molecule that has no effect in low concentrations, but when a certain density is reached, all bacteria start releasing a virulence factor. Why are bacteria behaving this way? Why is there a threshold (and why this threshold, rather than another one)? Why is this behavior dependent on this molecule rather than any other? Talk of signaling provides a straightforward answer: the autoinducer signals that a critical amount of individuals of a certain kind is around (and, perhaps, that in these circumstances performing a specific behavior pays off).

Moreover, note that autoinducers possess one of the essential properties of signals: the capacity to misrepresent. Diggle et al. (2007b: 12–43) suggest that overproduction of QS molecules provides a mechanism for some bacteria to force their neighbors to increase their production of public goods. Now, if a bacterium releases a high amount of autoinducer, which in normal conditions are produced by n bacteria, this high concentration signals that there are n bacteria, which in this occasion might be false. This is a clear instance of misrepresentation.

Additionally, classifying these states as signals probably has some heuristic value. Think about the following fact: all states involved in quorum sensing have something important in common. Nonetheless, many different kinds of molecules can play this role (oligopeptides, proteins, acyl homoserine lactones,...) and they also initiate various kinds of behaviors (aggregation, sporulation, antibiotic production, etc...). Thus, what all these interaction patterns share can not be adequately described in molecular or behavioral terms. This is precisely what can be captured from a representational point of view: all these states have in common that they mean or represent that sufficient number of bacteria have assembled.

Other theoretical virtues can be pointed out. For instance, this assumption suggests some other useful concepts, such as the notion of ‘eavesdropping’, that describe a situation in which a signal between A and B is used as a cue by C (Smith et al. 2011). Relatedly, it establishes fruitful connections between models and theories from other disciplines, such as microbiology, ethology and evolutionary biology (Keller and Surette, 2006, 257; Popat et al. 2015) and might boost research on shared mechanisms with other living organisms, which might even include eukaryotic signaling systems (Gallio et

al., 2002; Hughes and Sperandio, 2008). It also suggests certain research questions, such as what prevents individuals from defecting from social behavior by failing to produce the costly signal and reaping the benefits that result from cooperation (Velicer, 2003; Bruger, 2016), as well as certain hypotheses about how such a system will behave; for example, if a molecule is a signal, then all things being equal there would be a tendency for senders and receivers to improve the efficiency of the interaction. This is not true of many other interactions, such as coercion (Stacy et al., 2012). Consequently, supposing that autoinducers are signals has a remarkable heuristic value and suggests important questions for future research.

In conclusion, I think QS meets all conditions that the standard model requires for an organism to engage in genuine communication.

4 Some challenges

In the last section I argued QS fits pretty well with the standard model of communication. Furthermore, I showed that scientific research on QS as well as philosophical theories on signaling are largely in agreement (which is a remarkable result given the little contact between them). So this is the good news. In what follows, however, I will show that microbial signaling also poses a challenge to the standard model. In particular, I will argue that the most common analysis of signaling is probably too liberal, in the sense that it wrongly classifies some structures as signals. To address this difficulty, I will suggest a slight modification of the standard model. Finally, I will also discuss the related question of the relationship between signals and arbitrariness.

4.1 Liberalism

An especially interesting interaction pattern between bacteria that is not classified as an instance of communication is horizontal gene transfer (HGT). HGT is the lateral exchange of genetic material between bacteria, which can take place through transformation, transduction or conjugation (Soucy et al., 2015). It has been an important factor in the evolution of bacteria, and it is a primary process by means of which antibiotic resistance is spread through a population (Barlow, 2009, Gyles and Boerlin, 2014; Husnik and McCutcheon, 2017). Indeed, in many cases HGT is induced by QS signaling

(McAnulla et al., 2007; Sanchez-contreras et al., 2007). Moreover, genetic material is often beneficial to the recipient, as it might acquire antibiotic resistance or the ability to produce virulence factors or use new metabolites. This idea is coherent with the suggestion that there is a positive correlation between higher relatedness and more exchange of genetic material (Soucy et al., 2015).

Now, HGT seems to meet all standard conditions for qualifying as a signal: there is a sender and a receiver (bacteria), the sender has a mechanism whose function is to release integrative or conjugative elements (ssDNA, plasmids, etc.) in certain circumstances (e.g. when certain antibiotic is around) and the receiver has a mechanism whose function is to act in certain ways when this element is received (e.g. produce antibiotic resistance, etc.). In addition, as we saw above, there is a positive correlation between HGT and relatedness, so the cooperation requirement is also satisfied. As a result, the standard approach to signaling seems to predict that sending genetic material should actually qualify as genuine form of communication. Something has gone wrong somewhere.

This problem is an instance of a classical objection against teleological approaches, according to which these theories are too liberal: they tend to overattribute representations (Sterelny, 1995; Ramsey, 2007; Burge, 2010). The worry is not just that some counterexamples challenge the idea that the standard approach provides sufficient conditions; I think the most important point is that there might be an important feature of signals that has escaped our attention. Different proposals have been put forward to solve this problem within the framework of a teleological theory (Schulte, 2015, Butlin, forthcoming). Although there might be different ways to deal with this difficulty, here I will argue that one of the solutions that have been offered can be applied to this case: Minimalism (see Artiga, noo3001forthcoming).

According to this suggestion, signals are minimal causes. Although signals are certainly causes of behavior, they are 'minimal causes' in the sense that (roughly) the function of paradigm cases of signals is to trigger the appropriate behavior at the right circumstances, rather than providing the means for action. In a nutshell, the intuition is that signals are useful to the extent that they carry useful information about the world, not because of any property of the signal itself. To the extent that the intrinsic properties of the vehicle explain why the receiver behaves as it does, this vehicle is not a paradigm case of a signal.

I think the idea of 'minimal cause' captures a central property of signals,

yet defining this concept precisely is tricky, partly because it cannot be easily analysed by appealing to standard distinctions between causes (necessary, sufficient, specific, robust, etc.). For our purposes, it is enough to provide two necessary conditions for minimal causation: S is a minimal cause of effect A only if (1) S is a cause of A (2) S is not an enabling cause of A. Let me elaborate.

On the one hand, signals are causes. They are certainly difference-makers; assuming certain background conditions, if an intervention is made on the signal, a change in behaviour ensues. For example, whether a vervet monkey produces an alarm call or not makes a difference with respect to the behaviour of other members of group (Seyfarth et al., 1980). Likewise, altering the number of waggles performed by a bee dancing at the nest makes a difference concerning the distance at which other bees will search for nectar (von Frisch, 1927). This, I think, should be largely uncontroversial.

The idea of an enabling cause is harder to specify. As a first approximation, an enabling cause is a state that enables a receiver to perform some behaviour i.e. that makes the receiver able to behave in a certain way. I use ‘ability’ in the same sense in which we say that chameleons are able to change their skin color or that cheetahs are able to run at 100km/h. Of course, since our goal is to employ these notions in the context of bacteria, a working definition would be very much appreciated. Unfortunately, standard definitions of ‘ability’ are probably of no avail here, since they either appeal to beliefs and desires (and it is unclear such propositional attitudes can be ascribed to microorganisms at all) or to modal claims involving restricted possibilities that do not seem to correspond to the kind of analysis we need (Maier, 2020).

As an alternative, Artiga (noop3001forthcoming) suggests to understand this notion in mechanistic terms. Roughly, M is able to F iff M contains a (complete or nearly complete) mechanism for F-ing. Here ‘mechanism’ should be understood in the sense employed in the recent mechanistic literature, as involving ‘entities (or parts) whose activities and interactions are organized in such a way that they are responsible for the phenomenon’ (Glenan, 2017: 13; see also Machamer et al., 2000).⁴ For example, a chameleon is able to change its skin color because it possesses a complete mechanism (the

⁴Indeed, we are probably relying on a ‘functional sense of mechanism’ (Garson, 2013), since the relevant parts and interactions must have been selected (or stabilized) for this effect and, according to a popular theory of function, this suffices for an entity to acquire a function.

pigment-rearranging device) for changing color and a cheetah is able to run at 100km/h because it has a bodily mechanism for reaching this velocity.

Accordingly, an enabling cause provides some of the components that are required for an organism to possess a complete or nearly complete mechanism for performing certain behavior. Thus, enabling a receiver to perform a behavior A is to make it able to A, in the sense of providing some of the parts and processes that are required for this behavior. Now, paradigmatic signals are not enabling causes: they do not provide the means for action, but only trigger the right behaviour at the right time. Thus, the Minimalist suggestion is that if a state or structure provides significant components (parts and processes) that are required for the receiver to have the ability to act, then it is not a minimal cause and, as a result, is not a clear case of signal.

Let me provide an example. When plants are exposed to stress factors such as disease or herbivory, some of them release volatile organic compounds (VOC), which are molecules transported by wind that activate a range of physiological adjustments in other plants to prepare for those situations (Baluska and Ninkovic, 2010). A growing body of scientists consider these molecules as an instance of genuine communication. Compare it now to anemophily, which is a form of pollination whereby pollen is distributed by wind. Why are VOCs considered signals whereas pollen isn't, given that both processes involve organisms sending certain entities that are transported by wind and which are received by other plants, whose response have been designed by evolution, and where cooperation is involved? According to Minimalism, this is partly because pollen provides the means for the receiver to produce the right output (e.g. producing a viable seed and, eventually, a new plant). Without the DNA supplied by pollen, the receiving plant would be unable to produce the right kind of response. In other words, pollen itself provides essential parts of the mechanism that enables receivers to behave in the right way. In contrast, VOCs just trigger the correct behavior in appropriate circumstances. Hence, pollen does not play a signaling role because it is not a minimal cause (since it is an enabling cause), whereas VOCs, which are minimal causes, can be rightly categorized as signals.

I think this idea can be applied to bacterial communication. HGT is not an instance of signaling due to the fact that the integrative or conjugative elements provide the means for action. Note the receivers are not able to produce antibiotic resistance unless these pieces of genetic material are delivered. Thus, these elements provide a significant part of the mechanism

that makes the receiver able to act. Indeed, the idea that HGT is an enabling cause seems to fit some of the claims one can easily find in the literature: "[HGT] has *enabled* the red agla to survive hot-metal rich and acidic environments." (Husnik and McCutcheon, 2017: 8), "[HGT] has *enabled* leaf and stick insects to diversify" (Husnik and McCutcheon, 2017, 2017: 8) or "the elements can include virulence factors that *enable* colonization of eukariotic cells" (Norman et al. 2009) [emphasis added].

In contrast, QS autoinducers are not enabling causes. QS is used for bacteria to ascertain when a certain number of individuals have assembled but, crucially, bacteria are able to perform the behavior before sensing the QS molecule. For instance, the internal mechanism that enables *V. fischeri* to produce bioluminescence is largely in place before it detects the autoinducer HSL, and the same can be said of *P.aeruginosa* and the other examples I discussed. Consequently, an appeal to the notion of 'minimal cause' can contribute to distinguishing cases of genuine signaling from non-communicative interactions.

Let us consider a different example to show that this idea can be extended to other cases. Nitrogen fixation is the process by means of which nitrogen existing in the air (N_2) is transformed into ammonia (NH_3). Whereas ammonia is metabolized by most organisms, atmospheric nitrogen is a relatively nonreactive molecule useless for most organisms, except for some microorganisms. Some bacteria living in the soil that belong to the genus '*Rhizobium*' are able to fix nitrogen and have established a symbiotic relationship with some plants, specially legumes. Symbiosis is triggered by nitrogen starvation of the plant: the plant secretes flavonoid signal molecules that attract the right sort of bacteria and also induce the expression of a range of genes in bacteria (Maróti and Kandorosi, 2014). In turn, some of these genes in bacteria are required for the production of certain compounds called 'Nod factors', which trigger the development of nodules in the host plant that provide a comfortable environment for bacterial infection (Murray, 2011, Oldroyd, 2013). Within the plant nodules, bacteria convert nitrogen to ammonia, which the host plant uses to produce amino acids, nucleotids and other cellular components.

Note that Nod factors sent by bacteria to the host plant are classified as signals, whereas ammonia does not qualify as such (Straight and Kolter, 2009; Stacy et al., 2012). Why? After all, in both cases there are evolutionary functions, the same senders (*Rhizobia*), receivers (legume) and a similar amount of cooperation. One way to answer this question is that ammonia

(nitrogen fixation) fails to qualify as a signal because it is not a minimal cause: the vehicle itself provides the resources (ammonia) that the receivers need to perform their functions (e.g. amino acid production). In contrast, Nod factors trigger certain genes in the host plant, but fail to enable the bacteria to behave, in the sense of providing or completing the mechanism that is required for performing its functions; they just "*instruct* the plant to prepare for a controlled invasion." (Straight and Kolter, 2009: 102; emphasis added). Thus, the idea of 'minimal cause' can also be used in this case to distinguish signals from other kinds of interactions.

A similar analysis can be provided for the bacterium *A. tumefaciens*, described in section 2: in contrast to the *tra* QS system that triggers conjugation, the transfer of the Ti plasmid between bacteria fails to play a signaling role because plasmid transference provides the means for the receiver to act. Examples could be easily multiplied.

Interestingly, the idea of 'minimal causation' connects with some of the general explanatory roles associated with signals reviewed in section 3.4.⁵ On the one hand, a general property of signals is that their content contributes to explaining receiver behavior, and Minimalism complements this suggestion by noting that the vehicle's intrinsic properties fail to explain it. In other words, a distinctive feature of signals is the contrast between the little explanatory role of vehicle features and the central explanatory role of content in making sense of the behavior. It also accounts for some of the heuristic value of classifying an interaction pattern as an instance of signaling: as I mentioned earlier, even though many different kinds of molecules are used in QS, all of them have something important in common that cannot be captured in molecular terms. Minimalism vindicates the idea that, from the point of view of communication, the intrinsic properties of the vehicle (such as its molecular basis) have a minor explanatory relevance.

Consequently, to avoid an excessive liberalism and exclude some processes such as HGT as a form of communication, one option is to supplement the standard model of communication with the idea that signals are minimal causes. Of course, other options might be available. In any case, this discussion reinforces the idea that paying close attention to microorganisms can help us improve our understanding of signals and communication. At the same time, this refined model supports the hypothesis that QS constitutes a genuine form of signaling.

⁵I would like to thank an anonymous referee for pressing me on this issue.

4.2 Arbitrariness

Finally, I would like to focus on a property that has traditionally been associated with signals: arbitrariness. In which sense does QS involve arbitrary signals? Can this feature be used to identify signals? What explains this property?

I already mentioned that various molecules can play a signaling role in different bacteria: just to name a few, oligopeptides, proteins, amino acids, liposaccharides, fatty acids or acyl homoserine lactones have been identified (Shapiro, 2007; Witzany; 2011a). Likewise, the same molecules are used in a variety of situations (Witzany, 2011a) and can play different functions (Vendeville et al., 2005). Acyl homoserine lactones (AHLs) and linear oligopeptides, for instance, are used as signs of diverse processes (Henke and Bassler, 2004). AHL is used in quorum sensing and also in 'quorum quenching' (the enzymatic degradation of an autoinducer component to prevent communication between other bacteria). AI-2 is employed in a variety of processes and in bioluminescence (Sun et al., 2004) and it is involved in many different forms of interspecies communication (Winans, 2002). The A-signal, which as we saw is involved in *M. xanthus* aggregation, also plays a role in early developmental processes (Witzany, 2011a: 3).

The fact that many different molecules are used for the same task and the same molecules perform different functions suggests that quorum sensing molecules are arbitrary, in the sense that many other molecules could be used to perform the same job. This idea connects with the classical suggestion that a defining property of representations is their arbitrariness, although this notion has been understood in various ways (Stegmann, 2004). Here I will simply assume that (roughly) the arbitrariness of structure S for content C is proportional to the number of alternative structures that could have played the same role (see Planer and Kalkman, forthcoming).

Yet, even though QS molecules tend to be relatively arbitrary, I think they also illustrate the difficulties of defining signals by appealing to this feature. On the one hand, no signal is completely arbitrary, since there are always some constraints in place. The fact that, within a single bacterium, the very same molecules often play different functions places some constraints on them. The 30-C12-HLS produced by the opportunistic pathogen *P. aeruginosa*, for instance, not only works as a signal, but also has immunomodulatory effects on the host, which is a form of coercion. In many cases metabolic constraints have also been suggested, since some of the same pro-

cesses involved in quorum sensing also produce 'private goods' (Dandekar et al., 2012). Additionally, the avoidance of signal degradation and interference partly accounts for the variety of mechanisms and further constrains the type of molecules that can efficiently work as signals; for example, some protobacteria living in warm regions such as *Ralstonia* and *Xanthomonas* produce 3 OH-PAME and DSF molecules instead of AHLs because the former is more heat-stable than the later. Thus, although it is certainly true that autoinducers tend to be relatively arbitrary, the set of alternative molecules that could have played the same role is always constrained by different factors (cost, multiple functions, noise, degradation,...)

On the other hand, although the available evidence suggests that signals can adopt different forms, the same is probably true of many non-signaling interactions such as cues, coercive states or virulence factors. For example, different molecules and strategies can be used to coerce or attack another species (consider, for instance, the long list of virulence factors *P. aeruginosa* can produce – see . Moradali et al., 2017.) Therefore, despite the fact that signals tend to be arbitrary, it is unclear that some interpretation of this notion captures a distinctive aspect of QS that distinguishes it from cues, coercive states and other phenomena. After all, QS molecules are only partly arbitrary, as are some non-communicative interactions. In any case, bacteria illustrate some of the difficulties with this claim.⁶

Finally, note an interesting connection between Minimalism and arbitrariness: if signals are minimal causes, this fact can partly explain why they tend to be arbitrary. Since the vehicle's intrinsic properties fail to play an important role in explaining receiver behavior, it is to be expected that vehicles of different types would be able to play the same communicative role. Thus, while it is unlikely that signals can be defined by their exhibiting a certain degree of arbitrariness, their special causal role can explain why they are likely to be relatively arbitrary.

5 Conclusions

The goal of this essay was to examine the fit between the evidence for bacterial communication and theoretical approaches to signaling. The first prelim-

⁶Obviously, a lot depends here on how 'arbitrary' is defined. In any event, my purpose is not to present a knock-down argument, but only to highlight some difficulties related to a popular way of understanding this notion.

inary conclusion is that quorum sensing probably is an instance of full-blown communication. We saw that this interaction pattern between bacteria meets all standard requirements for a process to qualify as genuinely representational. Furthermore, this assumption contributes to an explanation of behavior, has some heuristic value and allows for misrepresentation. Consequently, the idea that bacteria engage in genuine communication by means of signals is not just a metaphor, but it is grounded in an independent theory of the nature of signals and our current understanding of these organisms.

Similarly, there are also important lessons to be learned for a general theory of signs. Microbial signaling fits pretty well with a teleological theory of signals. I argued that this case study supports the idea that cooperative sender-receiver systems are required and that they need to possess certain functions, although we discussed some potential difficulties. I also showed one way of avoiding an excessive liberalism supplements the standard approach with the idea that signals are minimal causes. Furthermore, I argued that even though signals tend to be arbitrary, it is not obvious that there is any sense of 'arbitrariness' that distinguishes signals from other phenomena.

Finally, let me point out that in this paper I mainly focused on one kind of interaction between bacteria, quorum sensing, but there are at least three other close interesting areas to explore. First, bacteria also seem to employ quorum sensing to communicate with plants and animals (Lowery et al., 2008). This idea might have potential implications for other philosophical claims, such as the suggestion that microbiota 'extend our minds' (Boem et al. 2021). Secondly, it has been suggested that bacteria like *B. subtilis* communicate using electrical signals, which might have close analogies with neuronal communication by means of action potentials (Prindle et al. 2015; Beagle and Lockless, 2015). Thirdly, it has recently been shown that other organisms such as fungi also communicate via quorum sensing (Padder et al., 2018; Mehmood et al, 2019). Examining these interesting cases remains as work for future research.

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