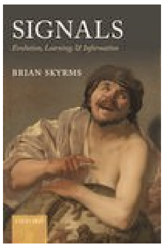

Signals: Evolution, Learning, and Information

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CHAPTER

11 11 Networks I: Logic and Information Processing

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Abstract

This chapter discusses the combination of simple signals to form complex signals. When multiple senders convey different information to a receiver (or to multiple receivers) the receiver is confronted with a problem of information processing. How does one take all these inputs and fix on what to output — what to do? Logical inference is only part of this bigger problem of information processing. It is a problem routinely solved every second by our nervous system as floods of sensory information are filtered, integrated, and used to control conscious and unconscious actions.

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Logic

David Lewis wrote *Convention* in order to use game theory to answer the skeptical doubts about the conventionality of meaning raised by the great American philosopher Willard van Orman Quine. Quine's skepticism was directed at the logical positivists' conventional theory of meaning in the service of a conventional theory of logic. According to the logical positivists, logical truths were true and logical arguments valid by virtue of the meanings of the terms involved.

Quine argued that positivist accounts of convention (by explicit or implicit definition) required the pre-existence of logic. Lewis replied that the existence of a convention can be thought of in a different way, as a strong kind of equilibrium or near-equilibrium in a signaling game played by a population. Lewis did not himself supply an account of how a population might get to signaling-system equilibrium, but we have seen how to do so.

This leaves the question of whether the account thus established in any way supports the doctrine of the conventionality of logic, whose refutation was Quine's ultimate goal. In so far as one's view of logic is expansive

—some positivists viewed all of m:mathematics as logic—the project may seem Quixotic. We begin with the more modest goal of seeing whether we can get *some* logic out of information transfer in sender-receiver games.

p. 137 I advanced some tentative suggestions in previous work.[1] These involve modifications to the basic Lewis signaling setup. First, the sender may not observe the state of the world exactly. Her observation may rule out some possibilities while leaving a class of others viable. For example, a vervet monkey may detect the presence of a ground predator—leopard or snake—without being able to see which it is. If this happens often enough and if, as is quite possible, the receiver's optimal action given this information is different from both the optimal action for a leopard or for a snake, it is plausible that a special signal could evolve for this sender's information state in exactly the same way as in the original signaling games. I call such a signal *proto truth-functional* because one way of giving its meaning is by the truth function "leopard or snake"—even though the signal itself is just a one-word sentence. Let us postulate a rich signaling environment in which lots of proto-truth functional signals have evolved.

The second modification is to consider multiple senders, each in possession of a different piece of relevant information. For example, suppose one sender on the ground—seeing a movement of grass—sends the proto-truth function "leopard or snake," and another sender, from the vantage point of a tree, sends the proto-truth function "no leopard." (Negative signals that cancel part of an alarm call are not unknown in animal signaling, as we saw in Chapter 2.) Selection favors the receiver who takes the evasive action appropriate for a snake. Such a receiver has performed—or acts as if she has performed—logical inference.

This story was put forward in a tentative and preliminary spirit, and it leaves several important questions hanging. The proto-truth functions were assumed to have already evolved. Could they co-evolve with logical inference, or are they required to exist already? Where are the precise models? Where is their analysis in terms of evolutionary or learning dynamics? We are now in a position to address these questions, and to generalize the account.

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Information processing

It is best to think of our two-sender, one-receiver model as an especially simple case of a problem of *information processing*. Multiple senders send signals that convey different pieces of information and the receiver can benefit from integrating this information. Let us consider some simple examples.

1. Inventing the Code:

Suppose that there are four equiprobable states of nature, and that two individuals are situated to make incomplete observations of the state. The first sees whether it is in {S1, S2} or in {S3, S4} and the second sees whether it is in {S1, S3} or in {S2, S4}. Together they have enough information to pin down the state of nature, but separately they do not. Each sends one of two signals to a receiver who must choose one of four acts. The payoffs favor cooperation. Exactly one act is "right" for each of the states in that each of the individuals is reinforced just in case the "right" act for the state is chosen.

I will not assume here, as I did in the story at the beginning of this chapter, that a convention has already been established for the signals used by the senders. We will make things a little harder and *require that the content of the signals evolve together with the inference*. You could think of sender 1 as waving either a red or a green flag and sender 2 as waving either a yellow or a blue one.[2]

A *signaling system* in this extended Lewis signaling game is a combination of strategies of the three players, two senders and one receiver, such that the receiver always does the right thing for the state. If we run simulations of reinforcement learning, starting with everyone out acting at random, the three individuals typically fall rapidly into one of the possible signaling systems.

p. 139 Consider the flow of information in these signaling systems. Each sender's signal conveys perfect information about her observation—about the partition of states of the world that she can see. The combination of signals has perfect information about the states of the world. Exactly one state corresponds to each combination of signals. And the receiver puts the signals together. The receiver's acts contain perfect information about the state of the world.

2. Inventing the Categories and the Code:

In the foregoing example, we postulated the categories that the senders can observe and thus those that could be embodied in their signals. For example, sender 1 can at best convey the information that the world is in one of the first two states or that it is not. That is all that she can see. In a remarkable analysis, Jeffrey Barrett considers a model where the two senders and one receiver need to interact to spontaneously invent both the categories and the code in order to achieve a signaling system.[3]

In Barrett's game there are four states and four acts, just as before, but each sender can observe exactly the true state of the world. Although each sender now has perfect information, each has only two signals available. There are two information bottlenecks. To achieve a signaling system our three individuals face a daunting task. Senders need to attach their signals to categories in such a way that these categories complement each other and jointly determine the state of the world. The receiver needs to extract the information from these signals. Receivers need to learn at the same time that senders are learning how to categorize, and senders need to learn their complementary categorizations while receivers are learning to extract information from the combination of signals received.

In a signaling system, sender 1 might send her first signal in states 1 and 2 and her second signal otherwise, and sender 2 might send her first signal in states 1 and 3 and her second otherwise. (These are just the p. 140 categories imposed by observational restrictions in ↳ example 1.) But alternatively sender 1 might lump states 1 and 4 together for one signal and states 2 and 3 for another which, together with the same receiver's strategy, would let the combination of signals peg the state of the world.

To my considerable surprise, Barrett found that Roth–Erev reinforcement learners reliably learned to optimally categorize and signal. The categories formed depended on the vicissitudes of chance—sometimes one set, sometimes another—but they always complemented one another in a way that allowed the receiver to do the right thing. Consider the flow of information in the signaling-system equilibria in Barrett's game. Sender's signals do not convey perfect information about their observations, but only partial information. Nevertheless, the combination of signals has perfect information about the states of the world. Exactly one state corresponds to each combination of signals. And the receiver puts the signals together. The receiver's acts contain perfect information about the state of the world.

Senders have learned to cooperate so as to jointly send the maximal information. The receiver has learned to interpret the signals. She has also, in a way, learned to perform a most basic logical inference: from premises *p*, *q* to infer the conjunction *p & q*.

3. Extracting Relevant Information

Appropriate information processing depends on the character of the payoffs. Let us revisit example 1. The two senders again have their categories fixed by observation. Sender 1 can see whether the world is in one of the first two states or not; sender 2 can see whether the state is odd numbered or even numbered. We modify the example so that there are only two relevant acts with the following payoffs:

	Act 1	Act 2
State 1	0	1
State 2	1	0
State 3	1	0
State 4	0	1

p. 141 Optimal signaling requires the receiver to do act 1 in states 2 and 3 and act 2 otherwise. Although there are only two acts now, the receiver cannot rely on only one sender, since neither has sufficient information. The senders have information about their own categories—their own partitions of the states of the world—but the receiver needs information about a different partition. Reinforcement learners, starting with random exploration, learn optimal signaling here just as well and just as quickly as in the previous examples.

Given optimal signaling, where players are always reinforced, each sender′s signal here carries perfect information about her observation and the combination of signals singles out the state of the world. But the receiver′s *act* contains only partial information about the state. It is "only as informative as is required" by the pragmatic considerations embodied in the reinforcement structure. The receiver has learned to extract the information that is relevant and to ignore that which is irrelevant.

This operation of filtering out the irrelevant and keeping the relevant is one of the fundamental operations of information processing. Our sensory systems receive an enormous amount of information, only a small fraction of which is passed on to the brain. Our olfactory system, for instance, contains receptors exquisitely tuned to respond to individual molecules. This information is filtered and integrated so that only relevant information makes it to the central processing unit.

We can also see our little example from different perspectives. From the viewpoint of truth-functional logic, the receiver has had to learn how to compute the truth-value of the exclusive disjunction, "*xor*", from the truth values of its constituents. Sender 1 observes whether *p* is true; sender 2 observes whether *q* is true. The act that pays off is act 1 if *p xor q*, act 2 if not.

We can look at our example in terms of logical inference. The receiver has—in a way—learned to infer *p xor q* from the premises *p, not-q*, its denial from the premises *p*, *q*, and so forth. The inferences are not just valid inferences, but also the *relevant* valid p. 142 ↳ inferences for the task at hand. Receivers can learn to compute other truth functions and to perform other inferences in just the same way.

4. Error: Taking a Vote

So far, our senders have been infallible observers of the state of the world. They may not have seen everything, but what they think they have seen they have indeed seen. Senders′ strategies so far have been based on the truth, if not always the whole truth. In the real world there is observational error.[4]

If there is imperfect observation, it may make sense to ask for a second or third opinion. Consider the most basic Lewis signaling game, with two equiprobable states, two signals and two acts, but with three senders. Each sender observes the state, but with some error—errors independent—and sends a signal to the receiver. Then the receiver chooses an act.

It is not possible for signals to carry perfect information about the state. Error is endemic to the model. It is not possible for a signaling system to assure that the receiver always gets it right. But it is possible for an equilibrium to minimize the effects of error. The senders can convey perfect information about their fallible observations, and the receiver can pool this information to make the best choice. The optimal receiver's strategy is then to take a vote. If the majority of senders "say" it is state one, then the receiver should do act one; if a majority of senders "say" it is state 2 then the receiver should do act 2. We could call this sort of equilibrium a "Condorcet signaling system." Taking a vote allows a significant improvement over the payoffs attainable with only one sender.

For example, with an error rate for observations of 10%, our receiver will have an error rate of less than 3%. p. 143 Simulations of Roth–Erev learning for this example show individuals always ↳ converging to a Condorcet equilibrium.[5] With a few more senders the error rate can be driven very low, as the Marquis de Condorcet pointed out in 1785.[6]

Logic and information processing

When multiple senders convey different information to a receiver (or to multiple receivers) the receiver is confronted with a problem of information processing. How does one take all these inputs and fix on what to output—what to do? Logical inference is only part of this bigger problem of information processing. It is a problem routinely solved every second by our nervous system as floods of sensory information are filtered, integrated, and used to control conscious and unconscious actions. We have seen how a few rudiments of this process can emerge from simple adaptive dynamics.

Logic redux: Chrysippus' hunting dog

If we consider basic logic as information processing rather than as something living in Plato's ideal realm, the emergence of logic appears much less mysterious. Logic may be conscious or unconscious. There is no reason to think of it as the sole possession of humans. This way of looking at logic is not new. It has been debated since Hellenistic times. Consider Chrysippus' hunting dog.

According to Sextus Empiricus, Chrysippus tells the story of a dog that, not unlike my hypothetical vervets at p. 144 the beginning of this chapter, performs a disjunctive syllogism: ↳

> And according to Chrysippus, who shows special interest in irrational animals, the dog even shares in the far-famed "Dialectic." This person, at any rate, declares that the dog makes use of the fifth complex indemonstrable syllogism when, arriving at a spot where three ways meet, after smelling at the two roads by which the quarry did not pass, he rushes off at once by the third without stopping to smell. For, says the old writer, the dog implicitly reasons thus: The creature went either by this road, or by that, or by the other: but it did not go by this road or by that: therefore it went by the other.[7]

You could think of the dog's brain getting signals from his eyes and from his nose, and having to integrate the resulting pieces of information.

Chrysippus himself did not think that the dog reasoned, holding to the Stoic position that animals, unlike humans, do not have reason (*logos*). He held instead that the dog acts *as if* he could reason. He thus opposes the view of Sextus. This frames a debate that has come down through the history of philosophy[8]—Descartes on the side of the Stoics, Hume on the side of the skeptics.[9] Luciano Floridi recounts a report of a debate on the subject organized for King James I at Cambridge in 1614. The question of the debate was whether dogs could make syllogisms. John Preston took the skeptic position and Matthew Wreb the stoic side. King James concluded “that Wreb had to think better of his dogs or not so well of himself.”[10] You will have your own opinion. I am with David Hume and King James.

Notes

1 Skyrms 2000, 2004.

2 The receiver will have to be able to differentiate information from the two senders, since they are placed to make different observations.

3 Barrett 2007a, 2007b.

4 Nowak and Krakauer 1999 consider a different kind of error, receiver's error in perceiving the signal. They suggest that minimizing this kind of error played an important role in the evolution of syntax.

5 Simulations by Rory Smead, reported in supporting matter for Skyrms 2009.

6 In his *Essay on the Application of Analysis to the Probability of Majority Decisions*, Condorcet assumes a jury decides a matter of fact by majority vote, probability that jurors are correct is greater than .5, and jurors' errors are independent. Then the probability of a correct decision approaches certainty as the size of the jury goes to infinity.

7 Sextus Empiricus, *Outlines of Pyrrhonism* ch. XIV.

8 See Floridi 1997 for the detailed story.

9 Hume 1793, Bk I Pt III Sec XVI.

10 Mayor 1898, quoted in Floridi 1997.