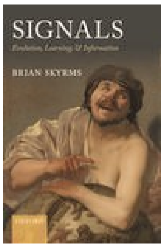

Signals: Evolution, Learning, and Information
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CHAPTER

9 9 Generalizing Signaling Games: Synonyms, Bottlenecks, Category Formation

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Abstract

This chapter presents a model of signaling with invention of new signals. It maintains the assumption that in all contingencies sender and receiver get the same payoff. But even where sender and receiver continue to have pure common interest, relaxing the strict assumptions on payoffs imposed so far may lead to new phenomena.

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Generalizing Sender-Receiver

To require that the number of states, acts and signals are equal is a drastic restriction. It may make sense to load up the model with all possible symmetries in order to demonstrate the power of spontaneous symmetry-breaking, but for a naturalistic account of signaling we need to move beyond these very special cases. Some organisms may have a quite limited repertoire of signals, while others—in particular ourselves—may seem to have an embarrassment of riches. So we have cases of too few signals and too many signals.[1] Other mismatches are possible. There may not be enough acts to respond effectively to all the states.

In our simplest model, we also imposed an extreme symmetry on payoffs. If an act was “right” for a state, both sender and receiver got a payoff of one, otherwise a payoff of zero. In general, we should consider all sorts of payoffs in including ones where sender and receiver are in full or partial conflict. We will discuss such cases in a later chapter. Here we maintain the assumption that in all contingencies sender and receiver get the same
p. 107 payoff. But even where sender and receiver continue to have pure common interest, relaxing ↳ the strict assumptions on payoffs imposed so far may lead to new phenomena.[2]

Many states

If states of the world are whatever the organism can discriminate, then for all but the most perceptually limited organisms there are very many states indeed. Even for organisms with rich signaling systems, such as ourselves, there are more states than will fit comfortably within our signaling systems. The evolution of signals must somehow deal with this fact. We can consider miniature versions by looking at signaling games with more states than signals or acts.

Suppose we have three states, but only two signals and two acts. Let us say that act 1 is the right act for state 1 and act 2 is the right act for state 2. If we ignore state 3, payoffs are just as they would be in a two-state signaling game, but what about state 3?

	Act 1	Act 2
State 1	1, 1	0, 0
State 2	0, 0	1, 1
State 3	?, ?	?, ?

There are various alternatives. It could be that one of these acts is also “right” for state 3. For example, act 1 might be right for state 3. Signaling system equilibria are not yet defined for such games, but there seems to be an obvious candidate. That is one composed of a sender's strategy that maps states 1 and 3 onto the same signal, which elicits act 1 from the receiver, and which maps state 2 onto the other signal, which the receiver's strategy maps to act 2. A realization is shown in figure 9.1:

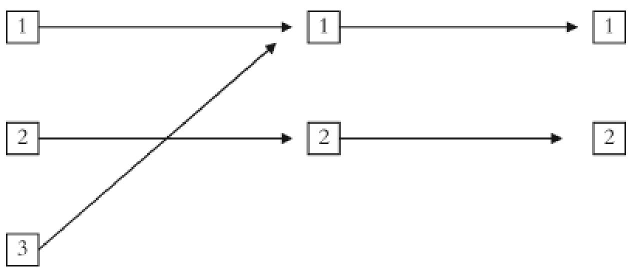

Figure 9.1: A signaling system where there are many states.

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	Act 1	Act 2
State 1	1, 1	0, 0
State 2	0, 0	1, 1
State 3	1, 1	0, 0

These signaling systems are optimal for sender and receiver, and they are evolutionarily stable strategies, just as in the original signaling games. In the equilibrium shown, we could say that signal 1 carries disjunctive information. It indicates "state 1 or state 3." Alternatively, from the point of view of the signaling system, states 1 and 3 are treated as if they were a single state. So, as David Lewis pointed out in *Convention*, we could call states 1 and 3 a single state and assimilate this case to the original 2 state, 2 signal, 2 act model.

At the other extreme, it might be that neither act is any good for state 3. Perhaps state 3 is the proximity of a predator that will get you whether you do act 1 or act 2. The payoffs might look like this:

	Act 1	**Act 2**
State 1	1, 1	0, 0
State 2	0, 0	1, 1
State 3	0, 0	0, 0

p. 109 Now there are no evolutionarily stable strategies. The reason is that it doesn't matter what signal is sent in state 3. The only acts available are ineffectual. No matter what natives do in state 3, mutants who do something different in state 3 will do as well as natives. Any equilibrium that does the right thing in states 1 and 2 is as good as it gets.

We looked at two extreme cases, but it is plausible to suppose that many cases are intermediate between the two. Consider:

	Act 1	**Act 2**
State 1	1, 1	0, 0
State 2	0, 0	1, 1
State 3	a, a	b, b

where a is greater than b. Then a signaling system that uses one signal which elicits act 1 in both states 1 and 3 is evolutionarily stable just as before. It gives the participants the best possible payoff. The intermediate cases look like figure 1. Simulations show reinforcement learners rapidly learning to use such a signaling system.

The example illustrates a general point. In general, where there are many states, a signaling system partitions the states. Evolution of a signaling system is *evolution of a system of categories* used by that system. That evolution is driven by pragmatics—by the available acts and payoffs.

Many signals

Suppose that there is an abundance of signals, relative to the available states and acts. Then if all the signals are used, an efficient system of signals will include functional *synonyms*, which are used in the same states and lead to the same acts. On the other hand, there are efficient equilibria where some signals are never used. As recently shown by Matina Donaldson, Michael Lachmann and ↳ Carl Bergstrom,[3] the concept of evolutionary
p. 110
stability here has no teeth. No equilibrium is evolutionarily stable.

There are, nevertheless, many equilibria where complete information about the state is transmitted, and players always get paid. Consider the simplest case with two states, three signals, and two acts, with one act being right for each state and the states equiprobable. Payoffs are just:

	State 1	State 2
Act 1	1,1	0,0
Act 2	0,0	1,1

Figure 9.2 shows some cases of synonyms:

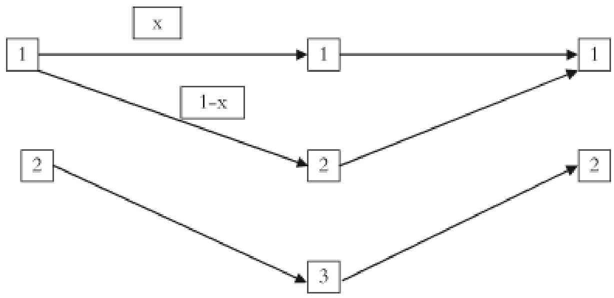

Figure 9.2: Synonyms.

Signals 1 and 2 are used with probability x and (1–x) respectively. They both indicate state 1 and lead to act 1, and so may be regarded as functional synonyms. Every value of x gives one equilibrium, so we have a whole line of equilibria here.

Figure 9.3 shows a signaling equilibrium where synonyms have died out.

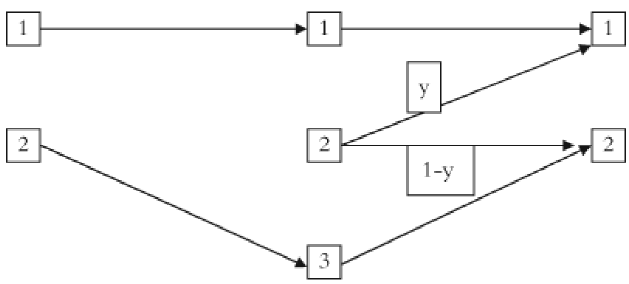

Figure 9.3: No synonyms.

p. 111 In this equilibrium the sender sends signal 1 exclusively in state 1, signal 3 exclusively in state 2, and never sends signal 2. The receiver may have propensities to respond in signal 2 in various ways, but these are never exercised. Every value of y gives an equilibrium, so we have a whole line of equilibria here.

Now notice that the line of equilibria in figure 2 and the line of equilibria in figure 3 are connected—they share a point. If x = 1 and y =1, we are in both pictures. But now it should be apparent that if y = 0 in figure 3, we have a point that is shared with another line of synonym equilibria—as shown in figure 9.4.

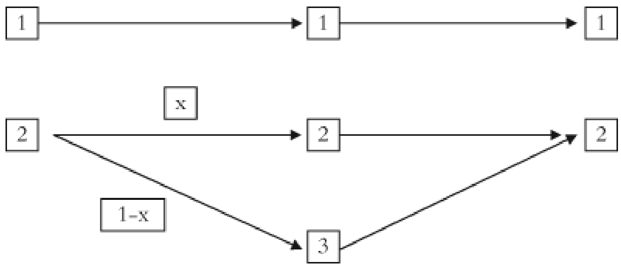

Figure 9.4: More synonyms.

All these equilibria are perfectly good for signaling, and they are all connected in one big component of signaling systems. There is one continuous path through all of them.

p. 112 With such a rich set of signaling systems, which will you get? That is a question that cannot be answered by equilibrium analysis, but must be addressed in terms of the dynamics. The answer may depend on the dynamic law, and on the starting point. One possibility would be to use reinforcement learning on acts operating on repeated encounters between a sender and receiver. We start with everything symmetrical—one ball of each color, so to speak, in each sender's and receiver's urn.

One might expect that with this dynamics and this starting point reinforcement would eliminate synonyms. One of the synonyms would be used a little more, get reinforced more, used even more, and take over—so the thought goes.[4] But this verbally plausible argument is incorrect. Synonyms are formed and they persist.

A different dynamics could give quite a different result. In replicator dynamics, our basic model of differential reproduction in a large population, this situation is structurally unstable. Adding a little uniform mutation to the large population model will tend to collapse components to points, and to stabilize synonyms. Finite population models may allow the state to drift around the component of equilibria. A full analysis remains to be done.

Few signals

Some agents may have appropriate acts for the states, but too few signals to coordinate states with acts. This is the case of an informational bottleneck. Informational bottlenecks affect humans as well as other organisms because, although we have a rich repertoire of signals, we may not have the time or means to utilize it in a specific situation.

p. 113 Signaling games with information bottlenecks present quite a different picture. Bottlenecks can create suboptimal evolutionarily stable strategies, as shown by the following example of Matina Donaldson, Michael Lachmann, and Carl Bergstrom.

	Act 1	Act 2	Act 3
State 1	7, 7	0, 0	2, 2
State 2	4, 4	6, 6	0, 0
State 3	0, 0	5, 5	10, 10

We suppose that the states are equiprobable. If there were three signals, then agents could always behave optimally, for an average payoff of 7 2/3. But there are only two signals. Then they might settle into the signaling system shown in figure 9.5.

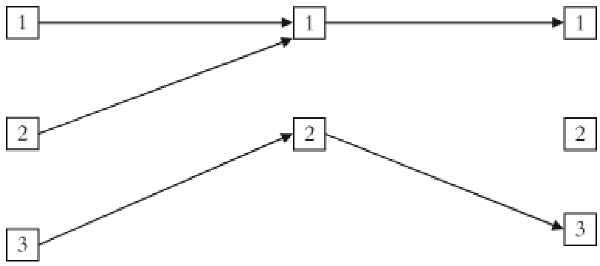

Figure 9.5: An efficient solution to a bottleneck.

This is an evolutionarily stable strategy. It is not a bad way of dealing with the informational bottleneck, with an average payoff of 7.

But this is not the only evolutionarily stable strategy. Another is shown in figure 9.6.

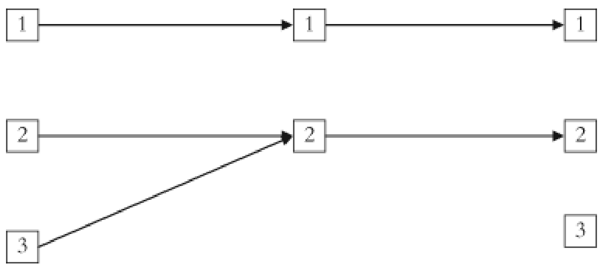

Figure 9.6: An inefficient solution to the same bottleneck.

This equilibrium is suboptimal, with an average payoff of 6. But it is still a strict equilibrium of the two-person game, and an ↳ evolutionarily stable strategy.[5] A reasonable adaptive dynamics can fall into this state.

These two equilibria represent two different ways in which a signaling system can categorize the world. But, unlike the examples of the first section of this chapter, we see that the system of categories that evolves may not be optimal.

Systems of categories

In a given signaling game, we have seen how the signals evolve so as to embody a system of categories. States that the sender maps onto the same signal belong to the same category according to the signaling system. But signals may be used in different situations. They may become “decoupled” from a particular signaling game, at least in the quite rigid sense which we have given to signaling games.[6] How should we think about this process?

We can move part of the way to an answer by broadening our model of a signaling game. Suppose the sender sometimes is in a position to observe the state exactly, but sometimes can only determine the member of some p. 115 coarser system of categories. For example, suppose that sometimes a monkey may be able to ↳ determine whether a leopard, eagle, or snake is present; sometimes only whether there is an aerial or terrestrial predator. We can incorporate this in our model by letting nature not only choose a state, but also choose an observational partition. Sometimes nature may choose the finest partition whose members are the states themselves, sometimes a coarser partition. The sender sees only the member of the partition in which the true state resides. A sender's strategy now maps members of observational partitions to signals.

There may be acts optimal for some coarse-grained information that are different from the acts optimal for any specific state. We can put them in the model as well. Then it is quite possible to evolve a signaling system where some signals represent disjunctions of states.[7] More generally, we can evolve a signaling system that incorporates a system of categories of different specificity.

Consider a game with three equiprobable states. There are three acts, one right for each state, just as in the simplest signaling game:

	Act 1	Act 2	Act 3
State 1	1,1	0,0	0,0
State 2	0,0	1,1	0,0
State 3	0,0	0,0	1,1

but there are also three other acts that are less than optimal in each state, but also less risky:

	Act 1	Act 2	Act 3	Act 4	Act 5	Act 6
State 1	1,1	0,0	0,0	.6,.6	0,0	.8,.8
State 2	0,0	1,1	0,0	.6,.6	.8,.8	0,0
State 3	0,0	0,0	1,1	0,0	.8,.8	.8,.8

p. 116 Using the fact that states are equiprobable, we get the average payoff for sets of states:

	Act 1	Act 2	Act 3	Act 4	Act 5	Act 6
State 1	1,1	0,0	0,0	.6,.6	0,0	.8,.8
State 2	0,0	1,1	0,0	.6,.6	.8,.8	0,0
State 3	0,0	0,0	1,1	0,0	.8,.8	.8,.8
1 or 2	.5,.5	.5,.5	0,0	.6,.6	.4,.4	.4,.4
2 or 3	0,0	.5,.5	.5,.5	.3,.3	.8,.8	.4,.4
1 or 3	.5,.5	0,0	.5,.5	.3,.3	.4,.4	.8,.8

A sender's strategy in this extended game maps sender's observational states to signals sent, and a signaling system equilibrium is an equilibrium that gives optimal payoffs to the players. For instance:

State 1 => Signal 1 => Act 1

State 2 => Signal 2 => Act 2

State 3 => Signal 3 => Act 3

S1 or S2 => Signal 4 => Act 4

S2 or S3 => Signal 5 => Act 5

S1 or S3 => Signal 6 => Act 6

This is evolutionarily stable in our extended signaling game.[8] Signals 4, 5, and 6 might be thought of as having a proto-truth-functional content relative to signals 1, 2, and 3.

Consider the alternative observational partitions of states implicit in this little example. There is the finest partition, where the observer sees the state exactly. There are three coarsenings of this partition, {S1-or-S2, not-(S1-or-S2)}, {S2-or-S3, not-(S2-or-S3)}, {S1-or-S3, not-(S1-or-S3)}. It should be obvious how to construct more p. 117 complex examples. We have an account of the evolution of systems of categories. It can happen without any ↳ complex rational thought, simply as a consequence of the action of adaptive dynamics.

Conclusion

Once we allow modest generalizations of signaling games, interesting new phenomena appear. We have synonyms and bottlenecks. We have the pragmatics of signaling inducing systems of categories into which states are sorted. These new phenomena raise new questions. Do synonyms persist or do they fade away? Are bottlenecks permanent or is there a plausible account of how adaptive dynamics can eliminate them? How can agents combine the information from various levels of categories? We have seen that for at least one plausible dynamics synonyms persist. We will try to shed a little light on the two remaining questions in subsequent chapters.

Notes

1 Wärneryd 1993 considers the case where there are too many signals. Donaldson, Lachmann, and Bergstrom 2007 discuss mismatches in general.

2 Lewis 1969 allows this, but does not go very far in exploring its consequences.

3 Donaldson, Lachmann, and Bergstrom 2007. This is the first systematic treatment of the equilibrium structure in these signaling games.

4 The thought is based on a misconception. Once the players have learned to treat two signals as synonyms, the relative reinforcement between them is a Pólya urn process. Then the synonyms may end up being used with any kind of relative frequency. This is what we see in the simulations.

5 In both one and two population settings.

6 Compare Sterelny 2003 on decoupled representations.

7 I first floated this idea in a discussion of the evolution of logical inference in Skyrms 2000.

8 There is no guarantee that this will always happen.