Evolution of Communication

Simulation of Adaptive Behavior – Project Report

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Abstract

Traditional definitions of communication involving adaptive systems suffer from being based, either explicitly or implicitly, on an information theory, behaviorist, observer-centric perspective. This *Square Paradigm* (SP), using terminology such as sender, receiver, encoder, decoder, channel, and information, makes it difficult to theorize about, model and simulate the evolution of communication. A second approach is based on an autopoietic perspective in which an appearance of communication comes about through an ongoing adaptive coordination of the activities of "sender" and "receiver". Versions of this *Circle Paradigm* (CP), using terminology such as coordination, correlation, perturbation, and inference, have been presented by researchers in animal, human, visual, and chemical communication, in the evolution of communication in adaptive robots, and in the field of pragmatics. This paper introduces the two paradigms, which are seen to be the extreme poles on a continuum, works through a sequence of configurations to explore the evolution of communication, and concludes that traditional SP approaches are based on an ill-formed approach to communication.

Introduction and Motivation

The starting point for this paper are the several things that bothered me during the class *Evolution of Communication* seminar. I didn't find any of the definitions of *communication* that we discussed to be very satisfying, including those presented in Philips & Austad (1996) and in Hauser (1996, p.7).

The Quinn (2001) and the Werner & Dyer (1991) models of the evolution of communication bothered me in a different way. I felt that communication between organisms must have been something that evolved quite early, and yet both authors were evolving communication in what seem to be fairly sophisticated artificial organisms. But perhaps what originated early in evolution is just some form of interaction. It's hard to know without good definitions.

I have a lot of professional experience with telecommunications, data communication and distributed computer systems (Webb & Lafreniere, 1991), in which interactions are intentionally as deterministic as possible. Perhaps my own preconceptions are part of the reason why I was bothered by the seminar material.

My initial feeling is that some sort of communication or communication-like interaction must have been present as soon as the earliest life appeared on the Earth, and that it perhaps evolved out of something that already existed in pre-life. As organisms evolved over the eons, they would gradually have evolved this original capability in a variety of more and more sophisticated directions. Quinn does state that "explaining the *origins* of communicative behavior typically involves explaining how it could have evolved from originally non-communicative behaviors" (Quinn, 2001, p.1), but his non-communicative organisms already possess sophisticated IR sensors and wheels.

In this paper I will discuss communication, and the origin and evolution of communication. I will present two contrasting paradigms, the *Square Paradigm* and the *Circle Paradigm*, and will use these throughout the paper as a framework to grapple with the issues that were bothering me.

Definitions of Communication

Many definitions of communication have been proposed (Philips & Austad, 1996; Hauser, 1996; Burghardt, 1970; Shannon & Weaver, 1949). These can be seen as falling into two paradigms, some of the features of which are listed below.

The Square Paradigm (SP) :

- focuses on the transferal of information,
- is deterministic,
- is from an observer's perspective,
- is about encoding and decoding,
- is inspired by Shannon information theory, and stimulus-response behaviorism.

The Circle Paradigm (CP) :

- focuses on the ongoing processes within two or more living systems,
- is non-deterministic,
- is from the perspective of the living systems themselves,
- is about correlations and coordinated activity,
- is inspired by Maturana and Varela's autopoiesis theory.

These two paradigms lie at opposite ends along a continuum. Most of the models discussed in this paper will lie somewhere between these two extremes. To a large extent SP and CP are arbitrary designations. These names imply little about what the paradigm is. This is useful when exploring an area as difficult to define as communication. At this early stage in exploration, SP and CP just designate some set of useful properties that are not yet fully understood.

The Square Paradigm

The essence of the square paradigm (SP) is captured within Shannon's information theory (Shannon, 1949). Figure 1 is a typical portrayal of the components of this theory. A transmitter sends a message through a noisy channel to a receiver. A source is trying to send a message to a target, by means of an encoder, the channel, and a decoder. The transmission of information can also work in both directions at the same time, in which case the components temporarily reverse their roles.

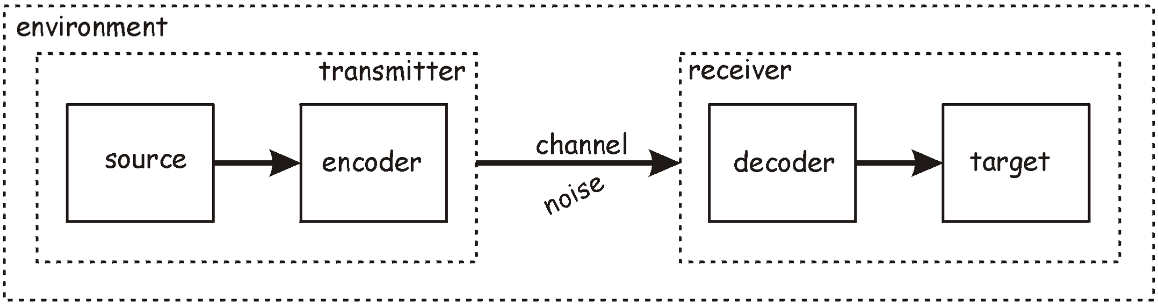

Figure 1: The Square Paradigm (SP). The main components of Shannon information theory (Webb & Lafreniere, 1991, p.178).

This is the standard paradigm used in telecommunication and data communication systems (Webb & Lafreniere, 1991). A source process on computerA needs some data that a target process on computerB could supply. It formulates an information request with a meaning such as "What is 17 + 25?" and passes this to the encoder which might encode it as "4131372B3235" before passing this on to the channel. The decoder turns it back into "What is 17 + 25?". The target does the computation, and sends "The answer is 42" in response. This is encoded as "423432", passed to the channel, decoded, and returned to the source.

This whole process is very deterministic. A given request message will always return the same response. Shannon information theory was developed for quite different purposes than to describe communications in biological systems, and yet many definitions of animal and other biological communications take this as the basic, at least implicit, paradigm. Shannon's focus was on the quantity of information (bits) that could be transmitted over a channel, and had little if any concern with the nature of the source, target, and meaning.

Sperber (1995), coming at it from a linguistic pragmatics perspective, calls this paradigm the *coding theory* of human linguistic communication.

> So, if Jill wants to communicate some meaning to Jack, she looks up in her mental grammar of English the sound associated to that particular meaning, and produces that sound for Jack to hear. Jack then looks up in *his* mental

> grammar the meaning associated with that particular sound. In that manner, Jack finds out what Jill had in mind. Of course, all this "looking-up" is automatic and unconscious … . Thanks to this double conversion – the encoding of meaning into sound, and the decoding of sound into meaning – Jill and Jack are now sharing a thought". (Sperber, 1995, p.1).

What Sperber describes here is exactly what is going on in Figure 1. Sperber also refers to the coding theory as "the old 'we-communicate-thanks-to-a-common-language' story". SP, Shannon information theory, and the coding theory are all pretty much the same thing.

Philips and Austad (1996) provide a lengthy definition of communication, with a particular emphasis on the role of animal communication (toads, birds, mammals) in the evolution of social organization. Their main focus is more on the information that is being transferred, than on the animals engaging in this behavior. They present various aspects of animal communication, three of which are summarized in Figure 2.

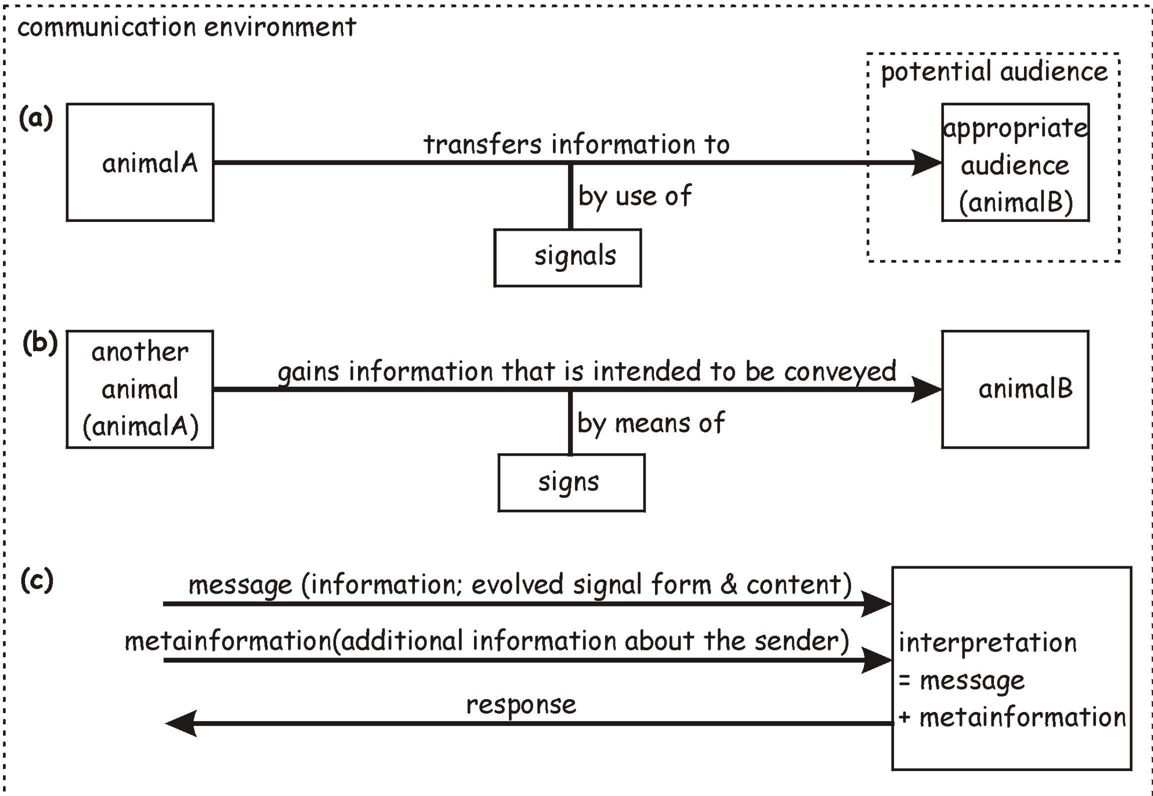

Figure 2: Elements of Philip & Austad (1996) definition of communication.

Emphasizing the role of sender of information, in (a) they state that animalA "transfers information to an appropriate audience by use of signals". The appropriate audience is another animal, animalB, "to which the signal evolved to convey information". This animalB is implicitly a subset of a much larger potential audience, those other animals, such as predators, that may also be able to make use of the transferred information. With emphasis now on the receiver of information, in (b) animalB "gains information that another animal [animalA] intends to convey by means of signs". Note the role of intention. animalA must intend, either consciously or unconsciously, for the information to go to animalB, and only to that individual. In (c) they distinguish between message, interpretation, and response. The *message* is the specific signal evolved through natural selection that provides some adaptive advantage. *Metainformation* is any additional information about the sender that is also included in the signal. An *interpretation*, embodied within an appropriate receiver, decodes the message and metainformation to derive the total information contained in the signal. The *response* is "overt behavior resulting from interpretation + context".

This definition is incomplete and ambiguous. For example, they don't elaborate on the difference between *signal form* and *signal content*. In fact signals seem to contain message form and content, as well as metainformation. It would help to have precise examples of how these three aspects combine to form a signal.

In many ways, the Philips and Austad account, is a square (SP) definition. It depends critically on terminology from information theory (information, communication, decoding, encoding, message, sender, receiver), and implies the sense-think(analyze-plan)-act process found in traditional artificial intelligence (AI) research (Pfeifer, 1999, p.54). But there are hints of some roundness. The response is not pre-determined by the receiver's interpretation of the signal. It also depends on various contexts such as the physical state of the receiving animal, and the environmental and social context.

The Circle Paradigm

The essence of the circle paradigm (CP) is captured within Maturana and Varela's autopoiesis theory (Di Paolo, 1998; Maturana & Varela, 1980). Figure 3 portrays the general idea of this theory, and of how it connects with "communication". Two autopoietic systems, cellA and cellB (based on biological cells), go about their normal metabolic and other activities of maintaining their essential organization, shown as a set of circular processes. Each also maintains the boundary around itself that separates it from the environment. Cells have channels through which they continuously exchange matter and energy with the environment. Some of this matter can have a signaling role. Some of the activity in the environment can perturb the exchange of matter and energy, and ultimately influence the internal processes of the two cells. It may happen that the cyclical exchange of chemicals may result in a coordination of activities between the two cells, something that can be measured as a statistical correlation by an external observer. This correlation can be interpreted by the observer as an indication that "communication" is taking place.

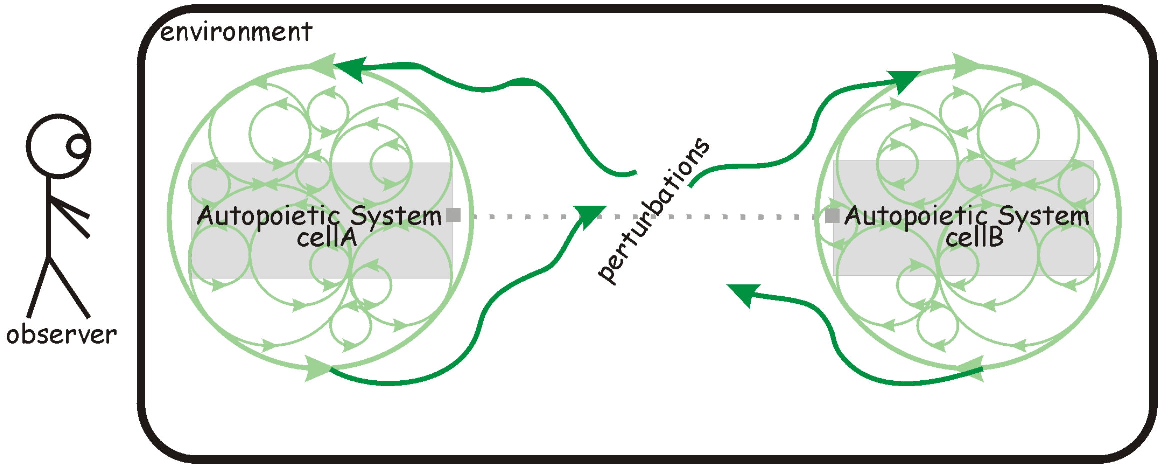

Figure 3: The Circle Paradigm. Two autopoietic systems perturbing each other.

The observer's view of things is shown in the background of Figure 3 as two rectangles and a connecting dotted line. Thus, the diagram shows CP in the foreground, and SP in the background. It should now be obvious why the names Square Paradigm and Circle Paradigm were chosen.

Di Paolo (1997) criticizes "the metaphor of communication as information exchange", and then presents an alternative characterization based on autopoiesis theory. He sees communication as ongoing coordinated activity rather than as "merely a set of descriptive interactions used by the organisms to pass on information in order to handle a particular situation" (p.294). The focus should not be on inputs and outputs, but rather on the behavior of the organisms, and on their histories (prior states) and the history of the environment that they share.

Sperber (1995) calls this paradigm the *inference model* of human linguistic communication. The problem with the coding theory is that "we manage to communicate much more than we encode and decode, and not just occasionally, but all the time". We do indeed encode and decode at the linguistic level, but then we infer the speaker's meaning. We use the decoded linguistic utterance as a complex index into the vast store of contextual knowledge that we share, an adaptive capacity brought about through evolutionary means. With the inference model the focus is on a *cognitive environment* (Sperber & Wilson, 1987) that is shared between the minds of two people and not so much on the specific words that were spoken.

Cherry (1978) and Burghardt (1970) have suggested that instances of communication can be distinguished from instances of non-communication by determining whether the potential signal supplies sufficient energy to perform the task directly, or whether something additional is required that can amplify the signal.

> It is important to keep in mind Cherry's notion (1957) [Cherry, 1978, 3rd ed., p.221-222] that to tell a man to jump off a bridge involves communication. To push him off the bridge is not communication. Therefore, a stimulus from A which has a direct effect on the responses of B, by dint of the physical or chemical force of the stimuli involved, is not communicating. This is a crucial distinction for the present argument. Obviously all signals, communicatory or not, are received through chemical or physical energy of some kind. However, a stimulus that is not intense enough to elicit the response directly, and yet does so, is qualitatively different from one that elicits the response passively as far as the receiver is concerned (such as a push), or, perhaps even reflexively (such as a startle response to a loud sound). (Burghardt, 1970, p.14).

> To what extent is the communicative act (the signal) effective in itself, via direct energetic consequences, and to what extent only via triggering? (Hockett & Altmann, 1968, p.68).

This is a CP concept. A signal does not do any work directly beyond triggering some subsequent cascade of events. The "energy" involved in this can be thought of as including all the ongoing processes in the receiver and in the environment that set a context for how the signal is actually processed. Again, the focus is more on what is going on inside the receiver than on the content of the signal.

This distinction between direct and indirect action is a key concept in defining what constitutes communication and what doesn't. If a candidate signal does *not* provide the necessary energy to carry out the action it's signaling then it is communication, otherwise it is something else. At the level of early primitive life, which is what any model of the origin of communication has to deal with, the distinction is between metabolism (matter-energy interactions) and signal transduction (information interactions). A chemical signal that binds to a protein receptor does not have enough force on its own to perform the cascade of transformations that will subsequently occur. It is merely the trigger, and is therefore part of a communicative process. The energy and matter needed to carry out the function must be provided by means other than directly from the small binding molecule (ligand).

A Sequence of Configurations

This section presents a sequence of diagrams, each intended to portray a possible step during the origin and subsequent evolution of communication. In the initial configuration there is no possibility of communication as conventionally understood, while in the final configuration there is full bidirectional communication between two entities (cells). Which paradigm is being portrayed, SP or CP, is intentionally left unspecified. The boxes have rounded corners to suggest that they exist somewhere on the continuum between SP and CP. Much of the terminology used applies more to the SP, largely because this terminology is more convenient when discussing things from an observer's perspective.

The diagrams are based loosely on the conventions of the Real-time Object Oriented Modeling (ROOM) visual formalism (Selic *et al*., 1994). In ROOM, objects (capsules) are shown as rectangles, potential points of connection with other objects (ports) are shown as small black squares, and channels between points of connection (connectors) are shown as lines. Multiple instances of the same type of object can be shown using a number in the upper right corner of an object. Importantly, the connectors also connect to an object's behavior, which is what determines the degree of roundness. I am using the ROOM conventions partly to constrain the range of possible configurations that can be discussed, presenting only configurations that can be naturally demonstrated using ROOM. These are discrete points in an otherwise vast continuous landscape. ROOM models can be implemented and executed by using the Rational Rose Real-Time (RRT) product (Rational, 2004). All configurations discussed in this paper could be implemented using RRT.

I will use a simple scenario, a kind of thought experiment, throughout this discussion. Imagine a watery environment containing a rich variety of chemicals, including two that are capable of glowing by means of radioactivity, fluorescence, or through some other physical process. They only glow under certain specifiable conditions. One chemical glows green, and the other red. Let's call these *greenGlow* and *redGlow*. Our goal is to imagine ways of evolving the appearance of cyclical yellow flashing within this environment. Initially the environment is strictly chemical, but it gradually evolves more and more sophisticated life forms that at some point can start to "communicate".

Figure 4 shows an initial configuration before the origin of life. There is no communication because there is only one single undifferentiated entity, the environment. Chemicals within the environment can cause it to have a green appearance, represented by the green circle in the figure. In nature changes in the green appearance would be caused by some continuous process operating over time within the environment. In a ROOM model, changes could occur at discrete points of time as the result of timeout messages.

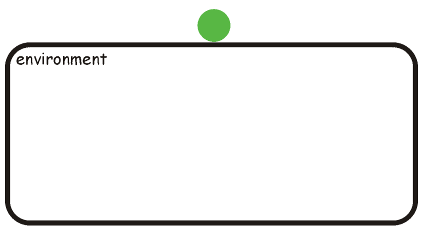

Figure 4: Simplest configuration in which communication (as conventionally understood) has not yet originated.

Perhaps this figure could represent communication after all, in this case across points of time. It seems that as soon as dynamics is allowed to play a part, the "uniform" environment is no longer so undifferentiated. Especially when discussing the evolution of communication, it may be useful to include this possibility of communication across time.

Figure 5 shows other pre-existing entities. A simple life form, such as a single-celled organism, in the process of evolving communication, will certainly be surrounded by various chemicals, and may also have to contend with other organisms of different types.

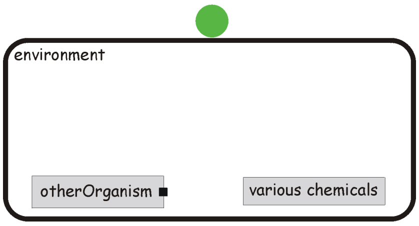

Figure 5: Environment with other possibly pre-existing entities.

In our simple scenario, some purely chemical process is causing the green appearance. Possibly there is some self-organization of clumps of chemicals allowing them not only to glow, but also to flash. Could this be done without communication? This would seem to be an example of coordination. Would a human observing green flashes in a strictly chemical environment be able to infer that some type of communication must be going on? What if it is just random motion and weak chemical bonds that are bringing the chemicals together, and if they reach a certain density they start to synchronously flash on and off? I don't think that a purely physical process like this could be considered communication.

In Figure 6 a simple cell has evolved. It consumes various chemicals in the environment including greenGlow. When the right conditions exist, parts of the environment glow and so may the cell. There is as yet no communication between the cell and its environment, although there might be an observable coordination in glowing rates between the two if the contents of the primitive cell closely mirror the content in the environment. There is only the flow of matter (including food) between the two.

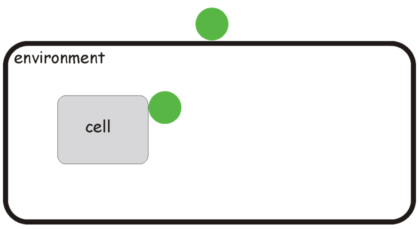

Figure 6: A simple cell has evolved in the environment.

In Figure 7 it is not just the passive flow of time that causes changes to the green appearance. Some active regulating process is at work in either the cell, or the environment, or both. This is represented by internal connections that allow processes in the objects to actively direct what will happen during the next interval of time, and to specify the length and frequency of this time interval. This may involve the use of enzymes to drastically speed up the process.

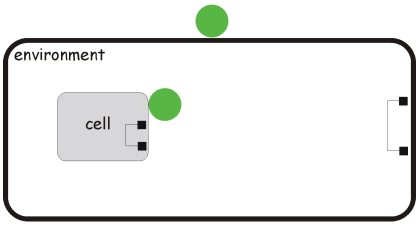

Figure 7: Cell and/or environment has internal active processes.

Figure 8 adds a new aspect. There are now multiple instances of cell up to some maximum number n, where n could be a very large number. There is now only a hint of greenGlow activity caused by the environment. Cells have consumed almost all of it, and have taken over the glow functionality from the environment. There is still no explicit "communication", but there are specific discrete locations (the cells) that are capable of glowing green.

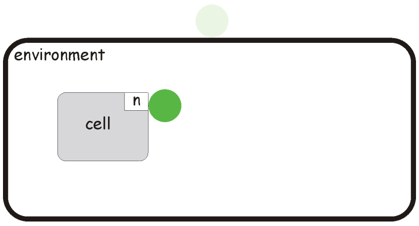

Figure 8: Multiple cells in the environment, where n, the number of cells, may be arbitrarily large.

Figure 9 adds another new aspect, multiple types of cells. cellA and cellB each belong to a different species, both evolved from the single type of cell shown up to this point. In Quinn's model, the leader and follower are of two different species, or at least they have different behavior.

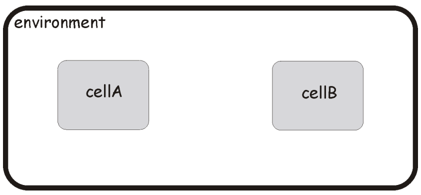

Figure 9: Multiple cell types or species.

Figure 10 is like Figure 8, but the multiple cells can potentially communicate (finally) because they now have a connection to the outside world.

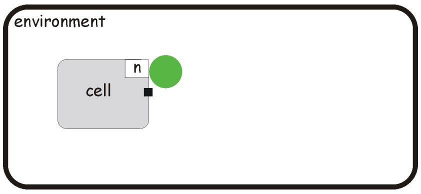

Figure 10: Multiple cells with a potential to communicate.

In Figure 11 each cell can communicate with itself using a connection that passes through some unspecified pathway in the environment.

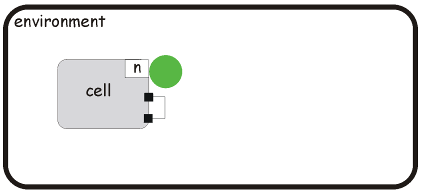

Figure 11: Multiple instances of a cell communicating with itself through the environment.

Figure 12 is similar to Figure 7 and Figure 11. In all three cases the cells can send a signal, and may subsequently receive another signal at the same or another port. The signal travels either entirely within the cell (Figure 7), in some fairly deterministic way through the environment (Figure 11), or in some more open-ended way through the environment (Figure 12). In this latter case, the environment may immediately return some sort of response, or there might be any amount of intervening processing before a response comes back, or perhaps there is no response at least none identifiable as such.

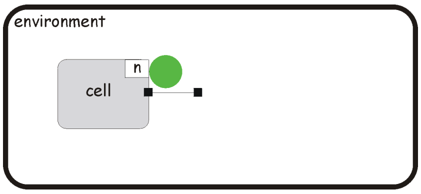

Figure 12: Cells communicating bidirectionally with the environment.

In Figure 13 a mutation has produced a second type of cell. cellG continues to appear or flash green (greenGlow), while cellR does the same in red (redGlow).

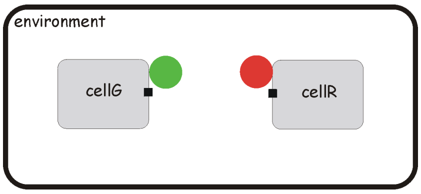

Figure 13: Two different types flash green or red.

In Figure 14 both types of cell communicate with the environment, and possibly indirectly with each other through the environment. This is how stigmergy works, how ants communicate chemically. This type of configuration could allow coordination of the two flashing patterns. This begins to look like the autopoiesis formulation of CP as in Figure 3, although it could also easily be a representation of SP. It depends on the details of what is actually going on here, and we are leaving that unspecified.

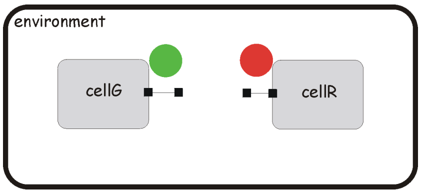

Figure 14: Communication with and through the environment.

Figure 15 shows how some object or aspect of the environment could mediate between the two cells, rather than involving the environment as a whole. This sort of functional modularization allows the environment to do many different things in parallel.

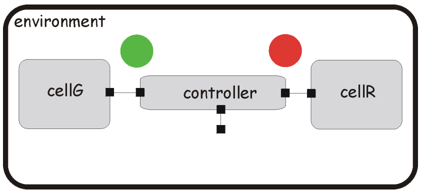

Figure 15: Functional modularization within the environment.

In Figure 16, the goal state of our investigation has been reached. The cellG variant regulates the glow activity of the greenGlow chemical, while the cellR variant does the same for the redGlow chemical. There is the appearance of direct communication (shown as the connecting line between the two), but it is in fact indirectly through the environment as in Figure 14. The flows of chemicals become coupled to each other, and the flashing rates become synchronized. The result of green and red flashing at the same time is a cyclic yellow flashing pattern.

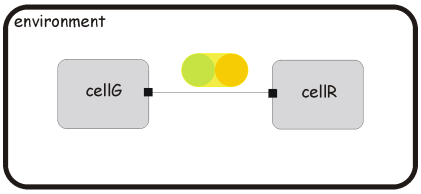

Figure 16: The goal state in which the two cells coordinate their behaviors and produce a cyclical yellow flashing pattern.

After working through the many configurations of this thought experiment, an obvious conclusion is that the term "communication" simply does not designate any particular set of features with enough precision and consistency to define it. It is unclear exactly when "communication" may have originated within this time-ordered sequence. It may be best not to think in terms of the evolution of "communication" at all, but rather of correlated or coordinated behaviors, as proposed by Di Paolo (1998), Burghardt (1970), Cherry (1978), Sperber (1995), and others.

State Machines

A state machine, in the form of a state diagram, is commonly used in ROOM, RRT, and in the industry and international standard Unified Modeling Language (UML), to model behavior of objects. In telecommunications and in many other systems, state machines fill the role taken on by CTRNN's and other neural networks in adaptive systems. Just as with neural networks, state machines can be configured using genetic algorithms and other evolutionary approaches (Koza, 1992, p.55-59). The hierarchically nested state machine in Figure 17 and Figure 18 shows conceptually the difference in behavior between SP and CP. States are rounded boxes, transitions are arrows, while events that cause transitions (signals) are shown as words attached to the transitions.

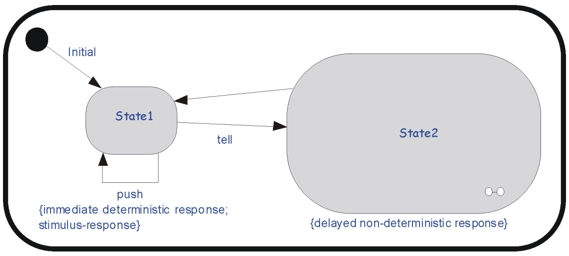

Figure 17: Top level of "push" or "tell" state machine.

In SP, one man pushes another off the bridge. The "push" event is fully deterministic, and is shown in the figure as a simple transition (attached to State1). The "tell" event triggers a non-deterministic cascade of processing, that may involve a large number of other states, and both internal and external events (signals).

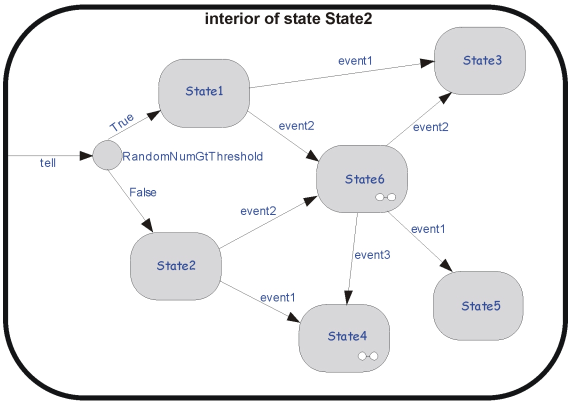

Figure 18: Part of a hierarchical state diagram, with one level of an arbitrarily deeply nested set of states and events.

This second part of the state diagram shows states that might be hierarchically nested within State2 in the main diagram. An arbitrary number of hierarchical levels are possible, resulting in an unbounded degree of complexity to the processing triggered by one signaling event, in this case to "tell someone to jump off a bridge".

Definitions of Communication: Again

Chambers Dictionary of Science and Technology (Walker, 1999) begins its definition of *communication* by stating "No generally accepted definition". This statement summarizes the state of confusion highlighted in the present paper.

I would like to propose a linguistic investigation to get at the heart of what we mean by the *evolution of communication*. How can we talk about something evolving when we don't really know what it is? Cognitive science, in which I have my undergraduate degree, has benefited by simultaneously applying insights from various fields, including linguistics, to the study of the *mind*. *Communication* seems to be just as slippery a concept.

English has a dual vocabulary. It distinguishes "between referential and emotive language" (Hughes, 2000, p.34). The emotive vocabulary consists largely of the core anglo-saxon stock of the language. These "native terms are, generally speaking, semantically *transparent*" (p.35), more intuitively meaningful. Hughes presents the following text consisting only of anglo-saxon terms:

> (1) Warm, rich and full of golden-goodness, Fido dog food will give your furry friend health, strength and get-up-and-go. (Hughes, 2000, p.34)

and then this contrasting passage with 36% of words originating from French and Latin:

> (2) Nutritionists estimate that the body needs 30 grams of fibre each day to assist the normal working of the intestine by speeding up the passage of waste so that harmful materials are eliminated quickly. Fibre plays a definite role in

> the prevention of obesity. Fibre can also be instrumental in the prevention of heart disease. (Hughes, 2000, p.34)

The argument is that (1) speaks to us at a more fundamental (more biological?) level than does (2).

Using Hughes' distinction, *communication* is a referential term. Roget's 21st Century Thesaurus (Kipfer, 1992) lists 38 terms under communication, only six of which are of anglo-saxon origin – making known, read, talk, talking, telling, writing. The Encarta Thesaurus (Jellis, 2001) lists six terms – contact, interactions, consultation, transfer, exchange, transmission – none of which have an anglo-saxon origin.

One proposal for future work is to find a more *emotive* replacement for *communication*, and try to originate and evolve that instead. It should be a term that has more evolutionarily significant meaning, something that would have been used by uneducated anglo-saxon peasants in the 13th century (arguably much closer to nature) rather than by their French-speaking Norman lords.

I suggest that *communication* just doesn't have the sort of essential meaning required of an attribute that nature (evolution with natural selection) would bother evolving let alone originating in the first place. One way of phrasing the question being asked here is: What *biological entity X* is to *communication*, in the same sort of way that *brain* is to *mind*?

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communication              mind
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biological entity X ?      brain
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To sum this up, to explore *communication* and its evolution without considering its *biological correlates*, is equivalent to exploring the *mind* without considering the *brain*.

Conclusion

This paper has looked at *communication* and its evolution from several novel perspectives, using the continuum from a Square Paradigm (SP) to a Circle Paradigm (CP) as a framework. Communication is not just about transferring information from one individual to another, but is also about coordinated activities within some context. Using a time-ordered sequence of configurations, it was shown that finding some point at which communication definitively originates, a point from which it can start to evolve, is probably an impossible task. *Communication* remains a slippery term that, when discussing it in the context of evolution and adaptation, would best be replaced by something with more evolutionary significance.

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