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MODELING BIOLOGICAL SYSTEMS: THE BELOUSOV–ZHABOTINSKY REACTION

ABSTRACT. In this essay I examine the ways in which the Belousov–Zhabotinsky (BZ) reaction is being used by biologists to model a variety of biological systems and processes. The BZ reaction is characterized as a *functional model* of biological phenomena. It is able to play this role because, though based on very different substrates, the model and system modeled are examples of the same type of *excitable medium*. Lessons are drawn from this case about the relationships between the sciences of chemistry and biology.

1. INTRODUCTION

Over the last one hundred and fifty years, the biological sciences have come to be ever more closely intertwined with the chemical sciences, beginning first with organic chemistry, and later, biochemistry. Leaving aside the vexing philosophical issue as to whether biological systems are *nothing but* chemical systems, chemical processes do nevertheless undergird all biological phenomena. Indeed, it is now inconceivable that the biological sciences should proceed without a detailed understanding of basic chemical processes.

But the chemical sciences do not merely provide an understanding of the molecular underpinnings of biological phenomena. In the last two decades, chemical systems (based on substrates very different from those found in typical biological systems) have come to be used as dynamical models for the study of biological systems. In this essay, I explore these developments with a view to clarifying the kinds of explanations that are involved in this new approach to biological modeling.

It will emerge that the new chemical models provide *functional* models for patterns of activity exhibited by the biological systems

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they model. In view of this, some parallels will be drawn between the roles played by the new chemical models, and the roles played by computers in the context of *artificial intelligence*, where there is considerable interest in machine-based, functional models of human cognitive phenomena.

In particular, the famous Belousov–Zhabotinsky (BZ) reaction has been the focus of much attention by theorists interested in modeling complex patterns of dynamical activity in biological systems. The biological significance of this reaction is best understood in the light of *complexity theory*, which has emerged in the last two decades (Nicolis, 1989; Kauffman, 1993, 1995; Waldrop, 1993; Casti, 1994; Cohen and Stewart, 1994; Goodwin, 1994; Depew and Weber, 1995; Shanks and Joplin, 1999). The aim of complexity theory is to provide a theoretical account of the nature of complex, interactive dynamical systems found in nature, and studied in disparate branches of scientific inquiry – e.g., chemistry, biology, or economics. It is a tenet of complexity theory that, while complex systems may be based on widely disparate substrates, they often exhibit shared *dynamical characteristics* that can be analyzed and modeled.

In their attempts to come to grips which dynamical characteristics shared by complex systems, complexity theorists have employed a variety of qualitatively distinct kinds of model. Some of these models are abstract *mathematical models* – models characterized by systems of *dynamical equations* (for example, a system of coupled ordinary differential equations). Nonlinear dynamics – popularly known as chaos theory – has turned out to be a fertile source of such abstract models. Smith (1998) provides a mathematically accurate, yet readable introduction to chaos theory and philosophical issues raised by the use of mathematical models in this context.

Other kinds of model consist of actual complex systems – and these must not be confused with abstract mathematical models. Such complex systems are real-world systems consisting typically of many interacting parts. These systems change over time, exhibiting patterns of dynamical activity, in ways that reflect interactions among the component parts. When a real complex system itself is employed *as a model* for other complex systems, it plays this role because it exhibits dynamical behaviors that can be used

to model patterns of activity in these other (perhaps less tractable) systems. These other complex systems may be based on very different substrates from the model system – they do not have to be 'made up' of the same stuff.

In what follows, I shall try to characterize what is involved when we claim that the BZ reaction constitutes a complex chemical system that can be used to model complex, biological systems. Models play many roles in scientific inquiry, and while the BZ reaction has received a lot of press in its own right, little has been done to sort out and clarify what is going on when it is used as a model of biological systems. First, some chemical preliminaries.

2. THE BZ REACTION

The BZ reaction was first observed in the 1950s, when B.P. Belousov, a Russian chemist, was attempting to simulate the Krebs (citric acid) cycle *in vitro*. Belousov's work remained obscure, and western observers came to know of the reaction through the work of A.M. Zhabotinsky in the 1960s (Winfree, 1984). Today the BZ reaction refers to a set of chemical reactions in which an organic substrate is oxidized in the presence of acid by bromate ions in the presence of a transition metal ion (Tyson, 1994, p. 569).

The Krebs cycle that Belousov was initially trying to model consists of an interconnected sequence of pathways, and is called a cycle because the pathway sequence goes round in a loop (it is in fact a biochemical oscillator). It is fundamental to the metabolism of aerobic organisms. When Belousov ran his *in vitro* reaction, he got a surprise. He found that his test tube contained a chemical oscillator which subsequent work revealed also consists of a reaction sequence that forms a loop or cycle.

In the decades that followed, scientists elucidated the central features of the chemical mechanism of the BZ reaction, discovered other chemical systems that exhibited similar dynamical behaviors, developed mathematical models describing the BZ dynamics, and discovered applications of these models to biological systems (Tyson, 1994). The BZ reaction is thus worthy of study for reasons that cross traditional disciplinary boundaries.

There are several distinct recipes for BZ-type reactions (Tyson, 1994, p. 573), but one I have used has the following ingredients: potassium bromate, malonic acid, potassium bromide, cerium ammonium nitrate, sulfuric acid. Like the Krebs cycle it is intended to model, this reaction involves the oxidization of an organic substrate in the presence of acid. When the reaction is run in a test tube, oscillations in color are observed as the chemical system cycles through its component reaction pathways. What does this mean?

Suppose the system initially has a high concentration of bromide ions. In the first group of reactions, bromate and malonic acid are used in a slow reaction to produce bromomalonic acid and water. Bromous acid, one of the reaction intermediates in this pathway, is consumed as the reaction proceeds. Since the cerium present is in the cerous state, the reaction medium remains colorless for this phase of the cycle. As the reaction proceeds, the concentration of bromide ions decreases to a point at which some bromous acid is present to initiate another mechanism to produce bromomalonic acid and water.

Here, in a fast reaction, bromate, malonic acid, bromous acid (a reaction intermediate of the first pathway) and cerous ions produce ceric ions, bromomalonic acid and water. The reaction medium turns yellow as cerium enters the ceric state. This pathway also contains an autocatalytic step in that one mole of bromous acid produces two moles of bromous acid. As the cerous ions are consumed and ceric ions accumulate, a critical threshold is achieved at which time a third pathway opens which consumes bromomalonic acid, malonic acid and ceric ions to produce carbon dioxide and bromide ions, and to regenerate cerous ions (thus turning the reaction medium clear), and setting the system up for the beginning of a new cycle (Babloyantz, 1986, pp. 158–159).

The system will oscillate in color until equilibrium is achieved – in typical demonstrations, we have observed regular oscillations for more than an hour. The frequency of oscillation is a function of temperature and initial concentration of constituents. Indicators such as ferroin can be used to enhance color changes.

If the reaction is run in a continuously stirred tank reactor – essentially a reaction chamber whereby the operator can vary rates

of input of reactants and output of products – precise control can be exercised over the distance of the BZ system from a state of chemical equilibrium. For some distances from equilibrium the system will behave as a chemical clock, and a skilled operator can set it to music! For other distances from equilibrium, qualitatively new behaviors – chaotic behaviors – appear as the system enters new dynamical regimes.

It is also instructive to consider what happens when the BZ reaction is run with just a thin film of reactant in a petri dish. Waves of color change, in the form of concentric ring patterns, propagate out through the medium away from the centers where they are initiated. The color changes are brought about by waves of oxidation propagating through a reduced medium.

The waves propagate out, away from centers of initiation, because of diffusion of bromous acid ahead of the wave front and its autocatalytic production just behind the advancing wave front (Tyson, 1994, p. 579). As these events take place, reactions occur which inhibit the production of bromous acid, leaving a reduced medium behind the advancing wave front. This reduced medium is in a temporary refractory state which will not support wave propagation. This is why waves propagate out, and not back to centers of initiation. It is also why they propagate out in the form of concentric rings – the time-intervals between successive waves reflect the recovery time for the medium through which they propagate.

While the waves may start propagating in the form of concentric rings (target patterns), disturbances in the medium (for example the introduction of an inhomogeneity by tapping the medium with a toothpick) lead to the production of rotating spiral patterns. In essence, the wave of oxidation rotates around the inhomogeneity, and since spirals have a geometry that is more efficient than rings at inducing the next wave of oxidation in the recovering medium, then in due course the spiral patterns displace the concentric rings in the medium. In addition to this, three-dimensional scroll waves have been observed to propagate in three-dimensional gels of BZ medium (Babloyantz, 1986, pp. 170–172; Winfree, 1994).

The BZ reaction manifests the phenomenon of *self-organization*. That is to say, the *invisible hand* of the dynamics of the reaction – the subject of the mathematical model to be discussed below –

results in the formation of complex, ordered states of matter in the form of non-random spatial and temporal patterns. This last point will be discussed further when I discuss the concept of *excitable media* below.

3. THE OREGONATOR MODEL

Producing a mathematical model of the complex dynamical behaviors exhibited by the BZ reaction is not a trivial matter. The central dynamical model for the BZ reaction is the famous *Oregonator Model* (Babloyantz, 1986; Tyson, 1994).

The Oregonator model may be understood in terms of the following schema (Tyson, 1994, p. 576):

$$
\begin{aligned}
(O) \quad & A + Y \rightarrow X + P \\
& X + Y \rightarrow 2P \\
& A + X \rightarrow 2X + 2Z \text{ (autocatalytic step)} \\
& 2X \rightarrow A + P \\
& B + Z \rightarrow hY + Q
\end{aligned}
$$

Here, $A = BrO_3^-$, B = bromomalonic acid, P = HOBr, $Q = CO_2$, $X = HBrO_2$, $Y = Br^-$, $Z = Ce^{4+}$, and h is a constant.

In the Oregonator, A, B and P are held constant since they enter and leave the reaction medium at constant rates. By contrast, the concentrations of X, Y and Z change with time. The model can be expressed in terms of three coupled ordinary differential equations that describe the complex dynamics of the reaction process (Tyson, 1994, pp. 576–577):

$$\mathrm{d}X/\mathrm{d}t = AY - XY + AX - 2X^2 \tag{1}$$

$$\mathrm{d}Y/\mathrm{d}t = AY - XY + hBZ \tag{2}$$

$$\mathrm{d}Z/\mathrm{d}t = 2AX - BZ \tag{3}$$

From these equations it can be seen that the Oregonator model is a nonlinear dynamical model. (In the case of the oscillations observed

when the reaction is run in a tank reactor, a simpler, two-variable model, known as the *Brusselator*, can be employed. See Babloyantz, 1986, p. 175.)

The Oregonator is a model of the BZ reaction in terms of which we can explain changes of chemical state over time. Being an abstract mathematical model of the dynamics of the reaction, it can be used – *with appropriate reinterpretation of variables* – to describe behaviors of a given type – let us call these behaviors *BZ-type behaviors*. BZ-type behaviors have been found in many systems, including biochemical and biological systems, though the substrates and products in these systems are very different from those in the BZ reaction.

The Oregonator Model begins with an idealized understanding of the hypothetical BZ mechanism and works back to an abstract mathematical model that saves the dynamical phenomena. For example, the version of the BZ reaction described above actually involves more than 20 chemical species (which is why my sketch of it is somewhat incomplete). A model reflecting the actual complexity of the reaction would involve more than 20 differential equations (and empirically determined rate constants). Commenting on this situation, Babloyantz notes:

> . . . a theoretician must simplify his problem. He tries to determine the most important intermediate steps of the reaction mechanism, those which are likely to determine the behavior of the system. With these elements, he constructs an abstract mechanism, a model much simpler than reality, but exhibiting the global properties of the original scheme. A model must be simple enough to be handled analytically or at least not require expensive computer analysis (1984, p. 173)

So the Oregonator Model involves extensive idealization and simplification of the details of real-world chemistry.

The Oregonator derives part of its philosophical interest from the fact that it is very useful, while not being a literally true reflection of real-world chemistry. The situation here in chemistry is similar to that observed in physics, where workable models typically involve extensive idealization (see Shanks (Ed.) 1998). Considering the situation in physics, with respect to modeling the behavior of lasers, Nancy Cartwright asks the following question:

> Is a helium – neon laser really a van der Pol oscillator? Well, it is really a mix of helium and neon atoms, in about the ratio nine to one, enclosed in a cavity with

smooth walls and reflecting mirrors at both ends, and hooked up to a device to pump neon atoms into their excited state. It is not literally a triode oscillator in a d.c. circuit. If we treat it with van der Pol's equation for a triode oscillator, we will be able to replicate a good deal of its behavior above threshold, and that is our aim. The success of the model depends on how much and how precisely it can replicate what goes on (1983, p. 153).

In other words, successful models do not have to be literal mirrors of reality. It is enough that they capture the phenomena we are interested in.

But there is more going on here than meets the eye, for both the BZ reaction (as an experimental test system) and its Oregonator Model (as an abstract mathematical model) have themselves been used as models of phenomena observed in complex biological systems. The rest of this essay is aimed at clarifying exactly what sense of *model* is involved in these applications of the chemical reaction and the Oregonator.

4. BIOLOGICAL EXAMPLES

Biologists are clearly interested in the BZ reaction and the Oregonator model. But how does this reaction turn out to be so useful? Once again, the situation is analogous to that seen in physics. Thus, to follow up on the discussion of the helium–neon laser in the last section, Cartwright observes, in a discussion of Wilfrid Sellars' analysis of modeling in science:

What is important . . . is not sharing of properties, but the sharing of relationships among properties . . . The helium – neon laser and a real triode oscillator need have to properties in common. What is relevant is that the properties each has behave in similar ways, so that both can be treated by the same van der Pol equation (Cartwright, 1983, p. 157).

Now consider the Oregonator model. Because the variables in the model can be re-interpreted in terms of other substrates and products, it is possible to extend the model to cover other systems of interest, including biochemical and biological systems.

Underlying these extensions of the Oregonator to biological systems are observations concerning some general functional similarities between the BZ reaction and biological systems. Biological

systems may be based on different substrates from the BZ reaction studied in chemistry, but they have components that are related to each other, and behave, in similar kinds of ways. Here are two examples to illustrate what is going on.

4.1. *The dynamics of slime mold*

When food gets scarce (perhaps in a petri dish), slime mold amoebae of the species *Dictyostelium discoideum* aggregate as the result of chemotaxis. In this process the amoebae signal to each other using waves of cyclic adenosine monophosphate (cAMP). These waves propagate by a diffusion-autocatalysis process analogous to that found in BZ waves, and with the same dynamical properties. The slugs are able to exploit the chemical dynamics for aggregation and differentiation, leading to dispersal, and subsequent replication. BZ-type dynamics are an integral part of their survival strategy.

An amoeba under stress emits a pulse of cAMP. This diffuses out into the surroundings, and stimulates amoebae nearby to emit pulses of cAMP. This then diffuses out, stimulating still other amoebae, and so on. In this process, cAMP plays a role parallel to that played by bromous acid in the classic BZ reaction. The wave of cAMP propagates out from the center of initiation of two reasons. First, the amoebae secrete an enzyme – phosphodiesterase – that destroys cAMP, and this means that the substance only has a brief lifetime in any location. Second, an amoebae that has emitted a pulse of cAMP goes into a refractory state, in which it cannot emit another pulse, even if stimulated. (See Goodwin, 1994, pp. 48–59).

In these conditions we observe concentric rings of cAMP propagate out from centers of initiation, as well as spiral patterns (forming around inhomogeneities in the medium). The dynamics of these waves can be described by the Oregonator, with variables in the equations suitably re-interpreted (to reflect the role played by cAMP, rather than bromous acid, for example. See Tyson, 1994, p. 582).

4.2. *The onset of ventricular fibrillation*

Winfree (1994) has shown how waves of contraction (electrochemical BZ waves) propagate in heart tissue, with the switch from concentric ring patterns to spiral waves being associated with the

onset of ventricular fibrillation. Waves of contraction are initiated at the sinoatrial node, and propagate out, ultimately to muscle tissue in the ventricles. After contraction, the tissues go into a temporary refractory state in which they will not respond to another electrical stimulus. Thus the waves propagate away from centers of initiation, and the heart beats normally.

Problems arise if there are inhomogeneities in the heart tissue. Even a small infarct (heart tissue that is damaged and unresponsive to stimulation) can cause a dynamical disaster. Infarcts can act as sites for the initiation of spiral waves of contraction – spirals that can alter the normal beating action of the heart and send the ventricles into a state of fibrillation.

Winfree has suggested that these dynamical phenomena might be usefully studied using the BZ reaction itself:

> A simpler analogous experimental system is the Belousov–Zhabotinsky chemically excitable medium. It is simpler in that it is strictly uniform and strictly continuous. It is analogous in that the local state of the medium is determined by two quantities, both chemical concentrations, only one of which is observable by its color changes, and in that its dynamical equations are in essential respects equivalent to the cable equation of electrophysiology combined with local excitability near a unique attracting fixed point. (Winfree, 1994, p. 150)

Thus there are functional similarities between the BZ medium and heart tissue. There are also dynamical similarities with respect to abstract mathematical models.

The specific dynamical properties exhibited by the BZ reaction, and modeled in the Oregonator (or the simpler Brusselator), have also had applications to the onset of oscillations in the concentration of glycolytic intermediates in yeast cells as they oxidize sugar (Babloyantz, 1984, p. 255). There are many other examples, ranging from the role played by analogs of BZ waves in the assembly of key intracellular structures known as microtubules (Hess and Mikhailov, 1994; Tabony, 1994), to the organization of important aspects of developmental processes (Goodwin, 1996). All of this interest in the BZ reaction by biologists only serves to focus attention on the following question: how can a chemical reaction outside biology, along with its mathematical model, be biologically relevant? An answer to this question will throw some interesting new light on the nature of the boundaries between chemistry and biology.

5. THE BZ REACTION AS BIOLOGICAL MODEL

In the literature one encounters strong claims about the biological relevance of the BZ reaction. For example, Tyson (1994, pp. 583–584) comments:

> The deep underlying mathematical similarity between the BZ reaction and these biological examples... means that they share the same phenomenological features, and that the BZ reaction can serve as a simple chemical model of the invariably more complicated biological systems. Experiments that would be impossible or impractical in the biological setting can often be performed with ease in the BZ reaction. Furthermore, before drawing hasty conclusions about biological control, our theoretical ideas about oscillations, chaos, and wave propagation can be tested on the BZ reaction, where we have a good handle on the molecular mechanism and a wealth of experimental facts to challenge the theories.

This passage highlights two important points: (1) mathematical models for the BZ reaction can be extended to biological systems because of phenomenological similarities in the *behavior* of these systems; (2) the BZ reaction can be used to explore causal hypotheses about biological systems because we have a good grasp on the molecular mechanism underlying the reaction (see also Winfree (1994)).

These two points, taken together, raise some interesting issues about the status of the BZ reaction as a model of biological systems. Scientists use the word 'model' in several different ways. For example, *analog models* are heuristic devices, often used in the early stages of inquiry, to enable a theorist to get an initial handle on a subject. Watson, for example, used the analogy of spiral staircases in his early thinking about the structure of DNA (see Giere (1991) pp. 23–24; LaFollette and Shanks (1995) have an extended discussion of the role played by analog models in biomedical research). Another example is the planetary model of the atom, in which electrons are viewed as orbiting a nucleus by analogy with planets orbiting a star. Such models can be useful stimulants to further inquiry – for example, if electrons are like planets, what are their orbital velocities, what are the shapes of the orbits, etc. (Giere, 1991, p. 24).

The BZ reaction, however, is clearly not intended to be a mere heuristic device, where, for example, it might be supposed that it is helpful to think of biological systems *as if* they were examples of

the BZ reaction The BZ reaction is clearly intended to be more than a crude analogical device to help us conceptualize what is going on in biological systems – a device to be abandoned, perhaps, as our thinking about such systems matures. If Tyson, Winfree and other theorists are right, the BZ reaction can be thought of as a test bed for causal hypotheses about biological systems of interest – and the causal details concerning molecular mechanisms underlying the reaction matter from the standpoint of modeling.

But if the BZ reaction is a *causal model* (in some sense yet to be clarified), it is not like the *usual* causal models employed in biology either – where it might be claimed that mice, for example, are good causal models for men because of similarities with respect to substrates (biochemical makeup) and causal, evolutionary histories – both are mammals (see discussion in Lafollette and Shanks (1995) for a detailed discussion of the use of such models in biomedical research). Typical BZ substrates are very different from those found in the biological systems they model – the reaction is a causal model *despite* material differences in constitution and composition with the systems it models. Insofar as the BZ reaction models complex biological systems, it appears to constitute a kind of model very different in general characteristics from traditional models found in the biological sciences.

But this merely brings to the fore the issue we began with. It will emerge below that the molecular details of the BZ reaction and the systems it models do matter. It is not enough that the BZ reaction generates dynamical phenomena similar to that observed in a range of biological systems, thereby *saving appearances*. It will emerge below that the real interest in the BZ reaction as a biological model lies in the *way* it generates the phenomenological similarities.

6. THE MEDIUM IS THE MODEL

If the BZ reaction is a causal model for biological systems of interest – despite the fact that it differs in constitution and composition from the systems it models – there must nevertheless be causally significant similarities between the model and the systems it models. The relevant causal similarities are to be found in the fact that the

BZ reaction and the systems it models generate the same *type* of *excitable medium* (Goodwin, 1996, pp. 51–52).

But what exactly is an excitable medium? Discussing the BZ reaction and the biological system it models, Goodwin points out that:

> These examples show that what counts in the production of spatial and temporal patterns is not the nature of the molecules and other components involved, such as cells, but the way they interact with one another in time (their kinetics) and space (their relational order – how the state of one region depends on the sate of neighboring regions). These two properties together define a field. . . What exists in the field is a set of relationships among the components of the system. . . (Goodwin, 1996, p. 51)

This field is known as an excitable medium. Like the case of the helium–neon laser and the triode oscillator discussed above, the BZ reaction and the systems it models have relevant dynamical similarities at the level of relationships among the parts of the system. As in the case of the laser and the oscillator, these relational similarities support the application of equations modeling one system to other systems of interest.

Films of BZ reagent, lawns of slime mold and sheets of heart tissue are all examples of the same *type* of excitable medium. This is why the BZ reaction can be used to model these differently constituted systems. Excitable media are complex dynamical systems whose parts (molecules in a film, individual amoebae in a lawn of amoebae, or cells in a sheet of heart tissue) stand in certain relationships to each other. Initially – prior to any excitation – such media are homogeneous – there are no discernible patterns, spatial or temporal. In this sense, the media exhibit spatial and temporal symmetry.

Excitation (i.e., disturbance of the medium through the introduction of an initial inhomogeneity) at a particular location breaks spatial and temporal symmetry by inducing excitations in adjacent parts of the medium, which in turn induce further excitations which propagate out, leaving recently excited regions in a temporary refractory state. As the excitations propagate through the medium, the relationships among the components of the medium result in the formation of characteristic spatial and temporal patterns. The

points initiating excitations of the medium are known as *pacemakers* (Babloyantz, 1986, p. 160).

In the BZ reaction itself contaminants, such as dust in the petri dish, can initiate excitations. (Indeed, Tyson cautions that with very clean glassware, waves will not appear spontaneously but may have to be initiated by the investigator with the aid of a needle or toothpick). In a lawn of amoebae, a single amoebae under stress can cause excitation by emitting an initial pulse of cAMP. In heart tissue the natural pacemaker is in the sinoatrial node. Electrodes can also be used.

If the BZ reaction is run in a continuously stirred tank reactor (or amoebae are mixed in suspension) the medium may be homogeneous spatially, but exhibit temporal patterns of varying degrees of complexity, ranging from steady states, to oscillations to chaotic behaviors (see Goodwin, 1996, p. 53). Thermodynamically speaking, all excitable media are non-equilibrium systems. At thermodynamical equilibrium, they lose their characteristic excitability.

Excitable media are of the same type when the interactions among the parts of the respective media, consequent upon initial excitation, give rise to similar spatial and temporal patterns. The relevant similarities, then, are in terms of the relationships that hold between the parts of the respective media. When these similarities exist, the interaction dynamics internal to each medium will generate similar spatial and/or temporal patterns. The BZ reaction can be used to model biological systems that are examples of the same type of excitable medium.

Because the patterns resulting from the breaking of spatial and/or temporal symmetry in an excitable medium result from specific kinds of dynamical interactions among the parts of the medium, the patterns are a manifestation of the phenomenon of *self-organization*. That is, the patterns result from the 'invisible hand' of the interaction dynamics internal to the medium. The patterns are not imposed on the medium from outside by a visible (or invisible) *deus ex machina*. The environment in which an excitable medium is embedded does its dynamical job by providing initial excitations of the medium.

7. BZ REACTION AS FUNCTIONAL MODEL

The hypothesis that I wish to consider here is that the reason the BZ reaction can be used to model differently structured and constituted biological systems is that it, like the biological systems it models, is sufficiently complex to admit of *functional descriptions*. If this is correct, then the BZ reaction is a functional model of relevant biological systems, and to say that the systems instantiate the same type of excitable medium is simply to say that these systems are functionally equivalent with respect to given range of phenomena.

Functional descriptions and explanations are useful in contexts where it makes sense to say that two systems (perhaps very differently structured and constituted systems) are doing the same thing, but are doing so in very different ways. The idea has proved useful in debates about artificial intelligence (A.I.), for example, where the brain (an evolved computer made of meat), might be said to have the same functional states as a cleverly designed supercomputer based on silicon. If so, then the computer might be used as a model to simulate the behavior of the brain.

For example, both a brain and a computer may be capable of performing relevantly similar computational feats, but the precise way in which each does so will differ. Even if there is much we do not know about the precise connections between functional states and lower level properties, similarities with respect to functional states between systems may nevertheless advance our understanding of those systems.

Since I plan to draw a parallel between the role of computer simulations in the context of modeling human cognitive processes, on the one hand, and the role of the BZ reaction as a model of biological processes on the other, it will help to discuss two important theses that crop up in discussions of A.I. Analogs of these distinctions find a place in the discussion of the BZ reaction.

The relevant claims are the *strong* and *weak* A.I. theses. Searle explains the differences between these theses as follows:

> According to weak A.I., the principle value of a computer in the study of the mind is that it gives us a very powerful tool. For example, it enables us to formulate and test hypotheses in a more rigorous and precise fashion. But according to strong A.I., the computer is not merely a tool in the study of the mind; rather, the appropriately programmed computer really *is* a mind, in the sense that computers given

the right programs can be literally said to *understand* and have other cognitive states. In strong A.I., because the programmed computer has cognitive states, the programs are not mere tools that enable us to test psychological explanations; rather, the programs themselves are the explanations. (Searle, 1981, p. 353)

According to weak A.I., cognitive processes (in humans, for example) can be studied with the aid of computer models that have similar functional characteristics. By contrast, according to strong A.I., computers can be said to have minds, or be cognitive agents, if they have functional characteristics relevantly similar to systems (humans, in the context of the *Turing test*) antecedently known to have minds.

Weak A.I. is relatively uncontroversial, whereas strong A.I. has been the subject of much philosophical debate. Since both these theses require that objects can be described in functional terms, it will help to say something more about this kind of description.

In explaining this idea, Moody compares a modern radio based on a solid state tuner and integrated circuits, and an antique radio of yesteryear based on vacuum tubes and coils. Both can detect electromagnetic energy and convert it into sound energy:

If we confine ourselves to a physical description of what they are and what they are doing, it is clear that they do not have much in common. They are made of different materials, and those materials are configured as parts in very different ways, and the physical interactions between those parts are also very different. At a higher level, however, we might just look at various parts of the system and describe them in terms of what they do. This part detects the radio signal; this part amplifies it; this part works the speakers. At that level of description, there is a correspondence between what the two devices are doing. (Moody, 1993, pp. 43–44)

Thus we see there are different ways in which a system can be described. It can be described in terms of *what* it is made of and *how* it generates outputs. Or it can be described in terms of *what* it does. The former type of description is a *constitutive-mechanistic* description, the latter is a *functional* description.

Following Moody, we may say that any device that detects electromagnetic energy and turns it into music is *functionally equivalent* to any other such device. Our two radios may be said to be in functionally equivalent states when they accept the same kind of input and process it to produce the same output. When it is claimed

that lawns of slime mold, sheets of heart tissue and the BZ reaction are examples of the same type of excitable medium, what is being claimed is that these systems are functionally equivalent. Validating the BZ reaction as a model for these other systems rests on establishing the correctness of the claim to functional equivalence.

In the BZ reaction, lawns of slime mold, and sheets of heart tissue, energy is fed into the system and the outputs are spatial and temporal patterns. In all three cases waves propagate through the respective media by exciting the medium ahead of the advancing wave, and leaving the medium behind the advancing wave in a temporary refractory state. The constitutive-mechanistic descriptions of these systems differ, yet each cycles through the same sequence of functional states, which is to say that the functional descriptions of the pattern-making processes are the same.

For the BZ reaction to serve as functional model for biological systems what is required is that functional analogs can be found in biological systems, of the structures and processes found and operating in the BZ reaction. And what we find is that when described in functional terms, the systems all exhibit the same kinds of causal connections between inputs (energy) and outputs (spatial and temporal patterns). Similarities can be found with respect to the functional roles played by structures and processes causally linking inputs and outputs. The validation of the BZ reaction as a model for very differently constituted and organized biological systems hinges crucially on an identification of similarities with respect to functional roles.

Consider radio again. The radio made with vacuum tubes can be used as a model for the radio based on solid state circuitry because the functional roles of the parts can be identified, and further similarities exist with respect to functional roles of sequences of events causally linking inputs to outputs. A cassette player, by contrast, might draw energy from the environment and play the same tune as either radio. But it would not serve as a functional model for either radio system since it would exhibit relevant differences with respect to the functional roles of the parts and with respect to sequences of events causally linking inputs to outputs.

It is at this point that it is possible to distinguish between theses analogous to strong A.I. and weak A.I. I propose to introduce two

theses which I will term *strong chemical thesis* and *weak chemical thesis*. According to the weak chemical thesis, chemical systems (e.g. the BZ reaction) can be used to study biological systems and processes because it is possible to identify relevant functional similarities between the very differently constituted and organized systems. According to the strong chemical thesis, living biological systems can be characterized in terms of the possession of a suite of functional characteristics, and any chemical system possessing this suite of functional characteristics can be as justifiably described as a living system.

The discussion of the role of the BZ reaction as a model of biological systems in this essay requires only a commitment to the (relatively uncontroversial) weak chemical thesis. What about the strong chemical thesis? The issue does not really arise since the BZ reaction is arguably lacking numerous important functional characteristics found in biological systems commonly acknowledged to be alive – for example subsystems playing a similar role to that played by the genomes of living systems.

8. CONCLUSIONS

The BZ reaction emerges as a complex system in the domain of chemistry that is sufficiently complex and rich and admit of functional descriptions. This means the reaction is able to serve as a model of biological systems because it can be established that these latter systems, though different at the level of constitutive-mechanistic description, are functionally equivalent in relevant respects.

Yet there is something special about the BZ system as a model for biological systems. Aside from anything else it shows that chemistry can illuminate biological phenomena at the level of functional descriptions and dynamical analysis – and not merely by elucidating the specific substrates and products underlying the biochemical constitution of living systems.

Moreover, the case of the BZ reaction shows that chemistry can illuminate biological phenomena without overtones of *reductionism* – without claiming that living systems are *nothing but* chemical systems based on *these* particular substrates and products.

While biologists recognize that biological systems are ultimately physicochemical systems from the standpoint of constitution, they have argued that living systems, because of their organizational complexity, have functional characteristics as integrated wholes that cannot be *reduced* to the (chemical) properties of the parts (Mayr, 1988, p. 15; 1997, pp. 19–20).

The basic issue is *degree of complexity*. In this regard, biologist Ernst Mayr has noted an important difference between living and non-living systems:

> The world's weather system or any galaxy is also a highly complex system. On the average, however, organic systems are more complex by several orders of magnitude than inanimate objects. Even at the molecular level, the macromolecules that characterize living beings do not differ in principle from the lower-molecular-weight molecules that are the regular constituents of inanimate nature, but they are much larger and more complex. This complexity endows them with extraordinary properties not found in inert matter (Mayr, 1988, p. 14).

Well, the BZ reaction is not a living system. But complexity, as Mayr notes, is a matter of degree. It is clear from this study that the BZ reaction constitutes a sufficiently complex, inanimate chemical system to not only have functional states, but to have functional states similar in important respects to those found in more complex, highly organized biological systems. These similarities enable it to serve as a valuable model for the behaviors exhibited by those systems.

Biologists have already benefited from studying the dynamical characteristics and mechanisms of the BZ reaction. But the case of the BZ reaction as a model of biological phenomena is of value to chemists as well. For, as Whitesides and Ismagilov have recently pointed out:

> On of the opportunities in fundamental chemical research is to learn from biology and to use what is learned to design nonbiological systems that dissipate energy, replicate, and adapt. Whether such systems would model life is moot; they would unquestionably be very interesting and probably very important. (Whitesides and Ismagilov, 1999, p. 92)

If these opportunities are to be exploited, then chemical engineers will have to design chemical systems, perhaps based on novel substrates, that are functionally equivalent to biological systems.

Perhaps then the issues raised by the *strong chemical thesis* will have to be confronted.

But the first step is to build bridges between chemical and biological systems. The BZ reaction, while providing a functional model of biological systems of interest, also feeds biological insights back into the domain of chemistry. Consistent with my *weak chemical thesis*, I propose to give Tyson the last word:

> For these and other reasons it is not pretentious to suggest that the BZ reaction be given status as an *honorary organism*, somewhere between viruses and bacteria! (Tyson, 1994, p. 584, my italics)

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