7 The Complementary Nature of Coordination Dynamics: Toward a Science of the In-Between

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7.1 Introduction: Whither a Science of the In-Between?

My take-off point in this brief essay is the following comment from the introductory material that all the participants received for the conference on "Uncertainty and Surprise." It reads:

> *Instead of* viewing social systems as machines whose Newtonian-like dynamics are to be uncovered and then controlled, we now see social systems as self-organizing systems whose properties emerge from interactions between *agents.* (italics mine)

One is, of course, sympathetic to this view in general (Kelso 1995, 2001a). At the same time, however, it does not seem necessary to cast the benefits of self-organizing dynamics as an alternative to Newtonian mechanics in an either/or fashion. As James Gleick (2003) remarks in his recent book *Isaac Newton* (see also the even more scholarly *Never at Rest* by Richard Westfall), Newton himself never succumbed to the fantasy of pure order and perfect determinism. Newton already saw that chaos could emerge in the interactions of many bodies. "Unless I am much mistaken" Newton said, "it would exceed the force of human wit to consider so many causes of motion at the same time, and to define the motions by exact laws which would allow of an easy calculation" (cited in Gleick 2003:137). Any developments in self-organizing dynamical systems rest on the shoulders of Newton, or at least they have his fingerprints all over them. We do not need to throw out determinism merely because we embrace uncertainty (consider, to boot, the huge field of study dealing with *deterministic* chaos). The main general point here concerns the habit we have of putting things in terms of dichotomies. More specifically, I believe we need a science that embraces not only the extremes, but also the vast world of the in-between (Kelso and Engstrom 2005). That science is emerging and has gathered a good deal of impetus in the last 25 years or so. In the literature, it has a name: it is called *coordination dynamics*. The term *agents* also italicized in the quotation at the beginning of this chapter, and the issue of how agency arises from and directs or steers self-organizing dynamics is addressed elsewhere (Kelso 2002; Kelso and Engstrom 2005).

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Ask yourself: Why do we talk about "instead of" and "versus" all the time? Why do we partition the world into pairs, contrasting, for example, the genotype and the phenotype, the discrete and the continuous, the individual and the collective, the orderly and the random, the qualitative and the quantitative, the internal and the external, the persistent and the changing, the gradual and the abrupt, the reductionist and the holist - and yes, the certain and the uncertain. The list goes on and on. It is pretty obvious, one intuits, that both represent polarized extremes, and that reality must lie somewhere in between. One might even say that we categorize things and ideas in this polarized fashion in order to be sure that what we are really after will be captured in between. One might even say that all science is about the in-between. One might, indeed. Few have.

Such thinking raises several questions. Is it something about our own brains that makes us categorize things in either/or terms? If so, how do we understand that? And what if we were to view things from the perspective of "both/and" rather than "either/or" (see how insidious is the habit to dichotomize!). Let me say that again: What if we were to embrace *both* the either/or and the both/and, *and* everything in between? What would such a science look like? At the very least, such a science, I submit (e.g., Kelso 1995, Chap. 4; Kelso and Engstrom 2005) would have to include *both* the language of states, in which polarized extremes may be seen as stable states (stationary attractors) of a dynamical system, *and* the language of tendencies or dispositions, in which there are no states (stable or unstable) at all. In fact (and I use the word "fact" carefully), the science of the in-between - like a James Joyce narrative - consists *of multiple tendencies coexisting at the same time.* The science of the in-between - and importantly, the philosophy that motivates and accompanies it - thus represents a strange kind of complementarity (Bohr 1935). We call it The Complementary Nature (Kelso and Engstrom 2005).

On first blush, all this may seem rather obscure, philosophical and speculative, so let's ground it in an example. In fact, let's take a nontrivial example, one that lies close to the very issue of why we might split the world into pairs in the first place. The example concerns our understanding of the brain and - when the brain is embedded in its world - the behavior it gives rise to.

Historically, there are two (!) main theories of how the brain works (see Finger 1994 for an excellent historical account). One is that the brain works as a coordinated, integrated entity. The other is that it is segregated into highly specialized parts that are localized for particular functions. Why, a reasonable person asks, could the brain not be both? We could all agree, "Of course! Let's have both." Instead of viewing integration and segregation as conflicting processes (and theories), let's view them as complementary. That sounds grand, but what does it really look like? What would be the manifestation of having both segregation and integration in the brain, or for that matter in any naturally complex system like a society? (Ask your favorite politician). In what way might integration and segregation be construed and understood as complementary?

To come to grips with these questions, we have to take a short sojourn into coordination dynamics, a theory of how coordinated patterns of behavior arise in a self-organized fashion, and how they adapt, persist and change according to internal and external circumstances (see Jirsa and Kelso 2004 for a sampling of recent work in this field). Coordination dynamics aims to characterize the nature of the coupling *within* a part of a system, *between* different parts of a system and between *different kinds of systems*. Moreover, it explicitly addresses the connection between different levels of description (see e.g., Kelso et al. 1999). Ultimately, coordination dynamics is concerned with how things come together in space and time, and how they break apart - bringing us back full circle to the integration~segregation issue.

From now on, by the way, we'll use the squiggle or tilde (~) as part of a convenient syntax for complementary pairs (Kelso and Engstrom 2005). The squiggle does not represent a glue or a bridge. Rather it is to acknowledge, in a world replete with either/or dichotomies, that complementary aspects are inextricably related, yet each may retain their singular character.

7.2 Coordination Dynamics

Consider the large scale spatiotemporal dynamics of the brain. Measures of brain activity using current imaging techniques such as EEG, MEG and MRI all depend on synchronous activity in populations of neurons, so-called neural ensembles. Without the basic cooperative effect of synchronization among approximately 10^5 neurons, no signal would even be observable. Synchronization, of course, is a classic example of self-organized coordination (Kelso 1995; Haken 1996 for reviews) and may be described by a model of N globally-coupled nonlinear oscillators (Kuramoto 1984), here the neurons themselves:

$$\frac{d\phi_k}{dt} = \omega_k + \frac{K}{N}\sum_{j=1}^{M} \sin(\phi_j - \phi_k). \qquad (7.1)$$

Eq. (7.1) describes the evolution in time of the oscillator phases ϕ_k. A critical coupling parameter K determines different modes of synchronization, and is a function of the dispersion of individual oscillator frequencies, ω_k.

Segregation means that neural ensembles in different regions of the brain fire independently of each other. Integration means that there is some kind of coordination between different regions - often across large distances - thereby implying patterns of functional connectivity that evolve in time (Sporns and Tononi 2002). Without going into details, there are both experiments (e.g., Daffertshofer et al. 2000; Fuchs et al. 2000; Kelso et al. 1992, 1998) and theory (e.g., Haken, Kelso and Bunz 1985; Jirsa et al. 1998; Kelso et al. 1990) that show that the brain's coordination dynamics may take the form of transient phase-locking within and between different neural regions (see Varela et al. 2001 for review). The basic idea is that phase-locked oscillations in different brain areas such as the cerebellum, hippocampus, thalamus, olfactory cortex and neocortex can serve a "binding" function. For example, perception may arise as a result of temporary episodes of phase-locking at the γ-frequency (approx. 40 Hz) in the brain thereby linking stimulus features into a coherent, coordinated Gesthalt. Phase-locking synchrony appears to be a universal process of communication that transcends several levels of neural information processing. There is even evidence that individual neural spikes encode information about the synchronization process, a kind of basic "temporal coding" (Ermentrout and Kopell 1998).

Given that different regions in the brain may fire at different frequencies (there are Greek names for them, alpha, beta, delta, mu and theta, all tied to various functions such as sensorimotor processing, remembering, attending, and so forth) and given that the brain has mechanisms for regulating these frequencies (which it does) the synaptic connectivity among neural pools is captured best by the relative phase, ϕ_{ij} between the *j*th and *i*th oscillating regions. Here again, many experiments have shown that different phase relations are possible among interacting brain areas and that abrupt transitions may occur as relevant parameters are varied (e.g., Mayville et al. 2000; Meyer-Lindenberg et al. 2002).

A simple, but essentially nonlinear dynamics that captures coordinative stability and switching between coordinative states in both brain and behavior is:

$$\dot{\phi} = -a\sin\phi - 2b\sin 2\phi, \tag{7.2}$$

where ϕ is the relative phase or natural phase difference between the component parts, $\dot{\phi}$ is the derivative of ϕ with respect to time, and *a* and *b* are control parameters, the ratio of which (*b*/*a*) specifies the coupling among the interacting components. An equivalent formulation of Eq. (7.2) is

$$\begin{aligned} \dot{\phi} &= -\partial V(\phi)/\partial\phi \text{ and} \\ V(\phi) &= -a\cos\phi - b\cos 2\phi. \end{aligned} \tag{7.3}$$

In the literature, this is called the HKB model of coordination, after Haken, Kelso and Bunz (1985) who formulated it as an explanation of observed multistability, phase transitions and hysteresis in the coordinated movements of human beings (Kelso 1984). For the record, Eqs. (7.2) and (7.3) have two stable *fixed point attractors*, corresponding to coordinative phase-locked states at $\phi = 0$ and $\phi = \pm\pi$ rad. Thus, two (and, in general, multiple) coordinated states may *coexist* for exactly the same parameter values, the essentially nonlinear feature of *bistability*. Which one is observed, of course, depends on initial conditions that set the system into a particular basin of attraction. As the coupling (*b*/*a*) in Eqs. (7.1) and (7.2) varies, the coordination states at $\phi = \pm\pi$ rad. become unstable and switch - fully in line with experiments at both behavioral and brain levels (op. cit.).

Very many extensions and elaborations of this elementary coordination dynamics have occurred in the last 20 years (see Jirsa and Kelso 2004), but there is one key one that will turn out to be crucially important for seeing the connection between the language of states and the language of coexisting tendencies. It concerns *broken symmetry*. Notice that Eqs. (7.2) and (7.3) are *symmetric*: the coordination dynamics is 2π periodic and is identical under left-right reflection (ϕ is the same as minus ϕ). This means that in-phase and anti-phase belong to the same (spatio-temporal) symmetry group, and assumes that the individual components are *identical*, a condition in living things that is seldom, if ever, satisfied. As already pointed out, neural oscillators are divided into pools or ensembles according to their different natural frequencies. In general, nature thrives on *broken symmetry*.

To accommodate observations of broken symmetry, Kelso et al. (1990) introduced a term $\Delta\omega$ into the dynamics as follows:

$$\dot{\phi} = \Delta\omega - a\sin\phi - 2b\sin 2\phi \text{ and}$$
$$V(\phi) = -\Delta\omega\phi - a\cos\phi - b\cos 2\phi \tag{7.4}$$

for the equation of motion and the potential respectively. $\Delta\omega$ represents intrinsic differences between the components, i.e., in their natural frequencies, and attests to the heterogeneity of the interacting components. Small values of $\Delta\omega$ shift the attractive fixed points of the coordination dynamics in an adaptive manner, adjusting system behavior to the intrinsic properties of (and differences between) the individual components For larger values of $\Delta\omega$ the attractors disappear: no coordination between the components occurs. That is, the individual parts behave as separate, autonomous entities.

There is, however, an enormously interesting régime *in between* the idealized states of full cooperation and the total independence of the component parts from each other. This is the *metastable régime* in which there are no attractors or repellors (fixed points of the coordination dynamics) but there is still *attraction* to where the attractors used to be (Kelso 1991). The reason is that intrinsic differences ($\Delta\omega$) between the individual component parts are sufficiently large that they do their own thing, while the coupling is sufficient to hold the parts together so that they still retain a *tendency* to cooperate. Thus, the relative phase between the components drifts, but is occasionally trapped near remnants or ghosts of where the coordinated states used to be (i.e., near $\phi = \pm\pi$ and $\phi = 0$). This, I propose, is how global integration, in which the component parts tend to be locked together in harmony ("binding"), is reconciled with the tendency of the parts to function locally as specialized autonomous units. Because of broken symmetry in its coordination dynamics, the brain is able to exhibit a far more variable, plastic and fluid form of coordination in which integration and segregation tendencies *coexist at the same time,* metastable coordination. Metastable coordination dynamics is characteristic of successful organizations, and is especially evident in the human brain (Kelso 1995; see Bressler and Kelso 2001 for a recent review). Elsewhere, I have argued, this is where a certain kind of flexibility and stability (metastability) gives rise to the creation of information (Kelso 2001b).

7.3 Discussion

Gathering these results together and returning to the business at hand, we see two extremes in coordination dynamics - even in its most elementary form. One is for the component parts to be coupled together in coherent (self-organized) coordinated states. These are stable states: stationary attractors of a dynamical system. These stable states correspond to “pure” integration. The other extreme is for the component parts to be completely independent, doing their own thing. There is no coordination or interaction among the parts whatsoever, total segregation. Only two (!) factors are running the show here: the strength of the coupling between the parts (*b*/*a* in Eqs. (7.2), (7.3), and (7.4)) and the intrinsic differences between the components, a complementary pair consisting of coupling~components.

In between, however, is the huge territory of tendencies and dispositions (In this regard, one is reminded of the Oxford philosopher, Gilbert Ryle, who, in his 1949 book *The Concept of Mind*, considered beliefs, intentions, desires as dispositions toward behavior depending on context.). Notice that this “in between” is chock full of complementary pairs: Individual component parts coexist with the collective (individual~collective); cooperation coexists with competition (competition~cooperation) - the component parts competing with each other in order to retain their autonomy while also trying to cooperate; in the flow of the dynamics, the tendency to converge toward attractive fixed points (phase-locked states) and the tendency to diverge to (coexisting) repelling fixed points (convergence~divergence) (see Kelso 1995:104-114 for pictures of this); qualitative change (phase transitions) produced by quantitative variation of parameters, and accompanied by quantitative consequences such as enhancement of fluctuations (qualitative~quantitative); and, of course, the tendency to integrate coexisting with the tendency to segregate, thus allowing us to see - through the window of coordination dynamics - how we might in fact have a science that embraces both the both/and *and* the either/or. In other words: A science that undergirds both polarization and reconciliation.

Let me finish this brief essay with just a few more points (from a very wide range of possibilities). The first concerns our notion of complementary pairs, which is as old as the days and goes back at least to the Ionian philosopher Heraclitus (540 B.C.-480 B.C.). Heraclitus, the reader will remember, said the world would not exist without the clash of opposing currents. This theme of opposing “contrarities” (Samuel Beckett’s lovely word, or is it Joyce’s?) runs through the history of ideas and the men and women who generated them (Plato, Aristotle, Aquinas, Kant, Hegel, Marx, De Beauvior….). Science too has struggled (and still struggles) with its complementary pairs and how to reconcile them (discrete and continuous, space and time, mass and energy, electricity and magnetism, gradualism and saltationism, nature and nurture, genotype and phenotype, central controls and laissez-faire, individual and collective, etc., etc.).

In more modern times, the notion of contrasting opposites is central in the writings of the theoretical physicist-mystic, Fritjof Capra (2000):

The notion that all opposites are polar - that light and dark, winning and losing, good and evil are merely different aspects of the same phenomenon - is one of the basic principles of the eastern way of life. Since all opposites are interdependent their conflict can never result in the total victory of one side, but will always be a manifestation of the interplay between two sides... (p. 146)

Capra goes on to say that the notion of dynamic balance is essential. It is never a static entity but always a dynamic interplay between two extremes: "The dynamic unity of opposites can be illustrated with the simple example of a circular motion and its projection (onto a line, my words)….The circular movement will appear as an oscillation between two opposite points, but in the movement itself the opposites are unified and transcended..." (Capra 2000:147).

This is a pretty image of Capra's - the Tao is in the middle of the circle and the two extremes of the line are yin and yang. As the ball goes around in the circle it moves up and down on the line. From this (metaphorical) image of the dynamic unification of opposites, Capra proceeds to the microscopic realm. His reason is because "our classical notions derived from our ordinary macroscopic experience are not fully adequate to describe this subatomic world [which] appears as a web of relations between the various parts of a unified whole" (p. 159).

"Contrarities" are all around. They are ubiquitous. Contrarities are complementary (as Bohr's coat of arms says: *Contraria sunt complementa*). But the scientific basis of complementary pairs and what it means for them to be dynamical is either metaphorical (the "dynamic" interplay of opposites) or rests on an interpretation of how the subatomic world behaves, viz., the Copenhagen interpretation of Quantum Mechanics. Coordination dynamics lies - you guessed it - somewhere in between the classical world of Newtonian mechanics with its forces, masses and motions and the weird, but highly successful world of Quantum Mechanics with its probabilistic waves and particles. Here, in coordination dynamics - which deals in the currency of coordination variables like phases and amplitudes of brain and behavioral and social activity - we offer an explanation/interpretation of complementary pairs that is neither metaphorical nor (solely) quantum mechanical in origin. Coordination dynamics ties "polar opposites" like integration and segregation to essential nonlinearity (bistability in the simplest case) and their mutual interplay to coexisting tendencies that arise in the metastable regime of the dynamics. I find it amusing that Newton saw the self motion that God gave animals "beyond our understanding without doubt" (not so the motions of inanimate bodies, at least for him!), yet the coordinated movements of human beings, which most of us take for granted, happen to be the primary stimulus for the development of a science of coordination. For living things, it seems, we must move from a mechanics of motion to a dynamics of coordination.

A second and related point concerns the relationship between coordination dynamics and Quantum Mechanics. Elsewhere I have addressed this connection, in particular the metastability inherent in both that is necessary for the creation of information (Kelso 2001, 2002). We owe to Niels Bohr, of course, the great philosopher~scientist that he was, the Copenhagen interpretation of Quantum Mechanics - that a full description of light and matter relies on complementarity.

Complementarity, according to Bohr, means that the use of certain concepts in the description of nature automatically excludes the use of other concepts, which however, are equally necessary for a description of the phenomenon. Despite its subtleties, complementarity, as John Archibald Wheeler (1994) emphasizes, is battle tested. There is no going back on it. It says, for instance, that one cannot find the position of an electron and the momentum of an electron at the same place and time. The measurement of one has unpredictable consequences for the other. The interaction of the measuring device (the brain?) and the object being measured (the world?) is never nil.

The complementary nature of coordination dynamics - with its built-in, essential nonlinearity - is different, and perhaps just as strange as Quantum Mechanics. It says that two opposing tendencies are complementary and do coexist at the same time. Measures such as the distribution of dwell times (how long the system hangs around a given tendency before it leaves) and its complement (how long it escapes for, when it leaves) open up ways to address the strength of the coupling among components relative to their independence, their individual freedom. More generally, the simultaneous presence of convergence and divergence in the flow of the coordination dynamics attests to its truly non-stationary, transient nature. In my view, here is where the science of the “in-between,” the science of tendencies and dispositions, puts the language of stationary attractors (chaotic and otherwise) and the notion of “brain states” in appropriate relief.

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