Lab Notes

Blending Physics, Math, And Psychology

FAU's Center for Complex Systems

Boca Raton, FL - During WWII, "Rosy the Riveter" corps used to plug up shrapnel holes in damaged war planes here on an airstrip where now sits an isolated cluster of temporary structures in which scientists attempt to plug holes in our understanding of nature's most complex system, the human brain and its relation to behavior. In a war against the mysteries that underlie mental illness and nervous system dysfunction, a small international, interdisciplinary group of researchers — including physicists, engineers, psychologists, neuroscientists, mathematicians, and computer scientists — is united in its quest for answers to some of the most interesting questions confronting psychology today.

Housed in a modest pair of dual house trailers connected by a corpus-callosum-like tangle of communications and power wires, these researchers are part of Florida Atlantic University's (FAU) four-year old Center for Complex Systems, a unique scientific research and research training environment. The outward appearance of the Center does not betray the state-of-the-art research apparatus, graphical display equipment, and computer facilities within. And, while the 40-odd researchers and graduate students do not directly focus on applications of their work, spin-offs could have significant impact on medical and technical areas such as prosthetics, pattern (including speech) recognition, flexible robots, and computer network design. A number of important clinical applications (e.g., in movement and communicative disorders) also exist.

The Beginnings

Center founder and Co-director Dr. J. A. Scott Kelso spent time recently with *Observer* Editor Lee Herring to describe the Center and its research and training programs. Kelso is on the faculty of the FAU Psychology Department and received his doctorate in 1975 from the University of Wisconsin-Madison. He received his hard knocks during an early career as an international rugby player in Northern Ireland and has the dubious distinction of scoring the first ever touchdown for the United States against England at Twickenham in 1977.

Q. How did you come to be founder of the Center and how did the Center begin?
KELSO: With a fair amount luck and pure chance, I was offered the FAU position of Eminent Scholar in Science in September 1985 which I promptly accepted and began building the Center. Normally, a science chair such as this would be offered to a chemist or physicist.

Colleague (and wife) Betty Tuller, Ph.D., and I were the two initial full-time faculty of the Center, and Drs. Gonzalo DeGuzman and Gregor Schoner (both physicists) were Research Assistant Professors. We spent the first year or so seeking federal research grant support from various agencies including NIMH; the Office of Naval Research; the National Institute of Neurological, Communicative Disorders and Stroke; and the National Institute on Deafness and Communication Disorders. We were fortunate to receive such support.

Q. What's an Eminent Scholar in Science, a State effort to attract scientists?
KELSO: Indeed, it's an endowed chair supported by the state of Florida which provides a 50% match of private funds.

Growth of the Center

Q. So the Center has been a federal grant success story?
KELSO: I would say that in tough times and coming to a relatively obscure institution such as FAU that we have been lucky. Both Tuller and I were in 'soft money' positions at Haskins Laboratories on the Yale campus and Cornell Medical College, respectively. So we had a good idea as to what a grant proposal should contain. Also, FAU's institutional support has been considerable in terms of facilities and initialization of our research.

I am excited that our research has now expanded to include a pedagogical component. We have recently received the first training program grant from NIMH's new National Training Program in Complex Systems and Brain Sciences. This is an explicitly interdisciplinary program for pre- and post-doctoral fellows. Its goal is to produce a different

Continued on Next Page

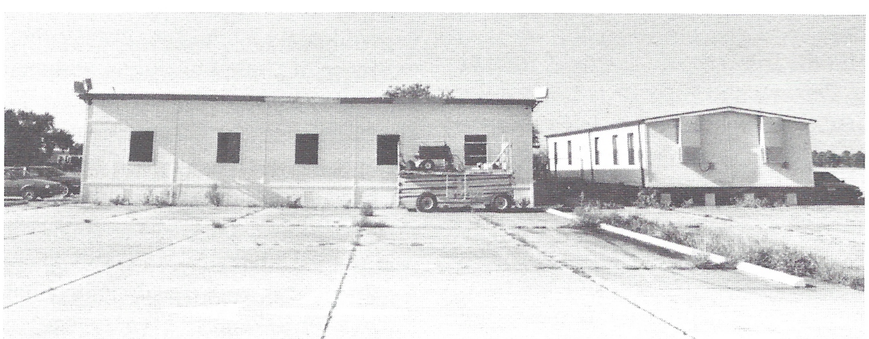

Photo by William Watkins, FAU

The Center for Complex Systems at Florida Atlantic University

Continued from Previous Page

kind of brain scientist, one who can blend mathematics and computation with hands-on experimental research in neuroscience and behavior.

Q. There are other centers of similar name, no?

KELSO: Yes. Someone told me there are about 17 around the United States by identical or similar name, some of them in major universities. Five years ago there weren't many, if any. There has been a lot of talk recently for a 'reintegration of the sciences' under the umbrella of a science of complexity. Interdisciplinary linkage has often been promoted at universities — administrators love it — but the disciplinary boundaries can be too high and thick. The FAU Center was interdisciplinary from its conception. People were brought in specifically for that purpose. It wasn't a matter of recruiting existing faculty from different departments to form a Center. That can be very complicated and doesn't always pan out. I wanted to create a group of bright young people that would work together from the beginning, sharing ideas and doing research. It's been fantastic for our students, in psychology, for example, to be exposed to different fields.

Another unique feature is that the FAU Center, through the NIMH training program, is the hub of a national network that includes four other distinguished universities: Berkeley, Cornell, UC-San Diego, and the Medical College of Pennsylvania. This network complements our existing international collaborations, most notably with Professor Hermann Haken, Chair of Theoretical Physics at Stuttgart University and Co-director of this Center, and Hiroshi Shimizu, Professor of Biophysics, from the University of Tokyo, whose group has interacted with ours through our international exchange program.

Q. Has the "Decade of the Brain" figured in the Center's success?

KELSO: Without a doubt. In fact, Japan also passed a similar national resolution, the Human Frontier Science Program, that is endorsed by the seven major Western nations to coordinate international, large-scale basic research on behavior and the brain. We are hopeful that this will promote our international exchange program.

Microscopic and Macroscopic

Q. What about your specific research interests?

KELSO: I've collaborated for eight years with Haken and his group on how complex, biological systems containing very many components generate coordinated, spatiotemporal patterns of behavior. The coordinated movements of humans and animals are an example. Keep in mind the number of *potential* degrees of freedom involved is enormous, *a priori* . . . over 700 muscles, 100 joints, 10^{14} neurons and *neuronal connections in the brain.* So, regardless of what level of description you choose, there is complexity. Nevertheless, one of the most fundamental, but least understood, features of living things is the high degree of cooperation among the system's many parts. There are always *patterns* which means that the interaction among the components is not arbitrary but is coordinated somehow.

I'm interested in the form that the interactions take more than the material composition of the components themselves. Of course, the only way to understand the cooperative dynamics is to study specific experimental model systems. This is why an explicit theory-experiment relation is so crucial.

Q. Can you elaborate?

Well, Haken and others had shown that in a large number of physical and chemical systems, nonequilibrium phase transitions are at the core of pattern formation. The patterns are formed in a self-organized fashion. Unless one's a vitalist, one has to believe that biology and behavior are self-organized. I was interested in whether nonequilibrium phase transitions are present in behavior, and that requires the invention of experimental model systems.

To do that, I had to devise a particular experimental system, demonstrate the existence of phase transitions, and then develop specific theoretical models. I emphasize here the importance of a dialogue between theory and experiment. So, I did the initial experiments that later involved students (especially John Scholz, now at the University of Delaware) and the theoretical work was done in collaboration with Haken and his associate, Schoner. In recent years, nuclear physicist DeGuzman, has elaborated and modified the theoretical picture significantly.

Q. Nonequilibrium phase transitions? Self-organization?

KELSO: Working at Haskins Labs with Michael Turvey and Peter Kugler in the late 70s, we realized that this language might be central to understanding coordinated behavior. The word 'synergy' has been around the field of motor neurophysiology and neurology at least since Sherrington, and Haken coined the related term 'synergetics' in the 70s to define an interdisciplinary field to study cooperative phenomena in nature. The task was to see if synergetic concepts were relevant to human behavior. Nonequilibrium? . . . let's just say we are open systems — this is true of any living system. The scientific problem is to characterize the generation of the dynamic patterns of these systems.

Photo courtesy of Boca Raton News, 1990

Scott Kelso wearing helmet designed to provide visual feedback of speaker's vocal track events.

Most behavior involves a spatiotemporal pattern of some sort. There's an orderly relation among the components that when measured continuously yields beautiful dynamic patterns. How do you capture the essence of these patterns? Through nonequilibrium phase transition theory. Theory has shown over and over that near transition points, where patterns are formed or changed spontaneously, there is an enormous reduction of degrees of freedom. Thus, very high dimensional systems form patterns whose dynamics, however, are low dimensional.

But another crucial piece of this is that these low dimensional dynamics — simple equations of motion for the patterns — turn out to be nonlinear. The behavioral patterns generated thus can be simple or extremely complex depending on the equation parameters. Thus a theme emerges for all living things: Materially complex systems, as long as they are open and not at equilibrium, form self-organizing patterns. The laws that describe the pattern formation are simple, but because they are nonlinear, they generate behavioral complexity. Thus, we journey from material complexity to behavioral complexity *through the laws of nonequilibrium* phase transitions and the mathematical language of nonlinear dynamics.

Q. How do you tie this to human behavior?

KELSO: You can see analogous phenomena throughout biology and psychology. Animal locomotion is a case in point — you have different gaits, ordered spatiotemporal patterns among the legs (walking, trotting, pacing, galloping). And, although not all behavior is rhythmic, that's where the foundation of all behavior rests, and we must have experimental windows into principles of ubiquitous biological self-organization and rhythmical behaviors like locomotion.

So, I decided to look at coordinated human finger motion. Schoner and I discovered that when humans are asked to move their fingers rhythmically at the same frequency, only two forms of coordination are performed stably: In-phase motion (homologous muscles contracting together) and anti-phase motion (homologous muscles contracting alternately). We discovered a phase transition (sometimes called a bifurcation) as the frequency of movement increased. The anti-phase pattern loses stability and spontaneously switches to an in-phase pattern. An essential point is that the pattern formation and spontaneous change occur through the change of a single, nonspecific parameter, the oscillation frequency.

What variable captures the ordering relations among the actively moving components? Research by us and others shows that in a large number of cases in a variety of systems, the phasing relation is the 'order parameter,' or collective variable. *En route* to transitions, all of the predicted features of nonequilibrium phase transitions were seen experimentally. So we may have the first demonstration of the most primitive form of self-organization in human behavior, a phase transition.

Thus, in an article published in *Science* [25, March, 1988, **239,** pp. 1513-1520] we showed that once patterns are characterized at the neural (microscopic) level it is possible to link them lawfully to patterns at the behavioral (macroscopic) level. We claim that the long-sought link between neuronal activities and behavior may reside in collective effects, the formation of a pattern at the microscopic level that *creates macroscopic order (and disorder).* Thus, our theoretically and experimentally based operational approach to study finger motion allowed us to link the different levels (kinematic, electromyographic, and neuronal) by means of stochastic nonlinear dynamic modeling.

The stability and change (i.e., patterns) of behavior are predicted successfully by nonequilibrium phase transition theory, synergetics. The parameters of the system that govern the qualitative change from order to chaos or vice versa can be described, thus, by focusing on the phase transitions, the point at which the patterns evolve.

Q. Neuronal-level investigations alone are insufficient to explain these transitions?

KELSO: We showed experimentally that transitions occur at the neuromuscular level as well. But the key point is to use phase transitions as a way to demarcate collective variables for patterns of activity at whatever level of description you choose. When you find these bifurcations, you can map the observed patterns onto attractors of a dynamical model. Then you can derive the pattern dynamics by cooperative (nonlinear) coupling among the active components, thereby effecting your micro- to macro- relation. Again, it's at the transition point that self-organization becomes apparent: different patterns arise as stable states of the coupled nonlinear dynamics. But if you don't know the pattern dynamics (the laws at the pattern level), you don't know what to derive! So, once the patterns are characterized at the neuronal level, it is possible to link them lawfully to behavioral-level patterns.

I stress that evidence supports more and more that the neuronal level of description is no more or less fundamental than the behavioral level. No single level of analysis has ontological priority over any other. Neuronal pattern generation research shows the same kind of phenomena as my finger research and as recently and beautifully demonstrated by Schmidt, et al. [*JEP: HP&P*, 1990, **16**, p. 227) with coordinated motions between two people.

I argue that the linkage across levels is by virtue of shared dynamical laws of coordination not because neurons are more basic than joints. Fundamentally, elements on all levels interact and *interactions generate behavioral patterns.* The dynamics of these patterns are nonlinear, so you see a rich diversity of behavior, including bifurcations, hysteresis, multistability, intermittency, even chaos. The patterns generated in a wide variety of systems, from invertebrates to hippocampus and visual cortex, often take the form of phase attraction and frequency synchronization. There is the strong impression that no matter where you look in complex biological systems, many of the degrees of freedom are suppressed and only a few (though, not too few) contribute to behavior. Only a few degrees of freedom are needed to sustain the vital mix of stability and adaptability necessary for many biological and behavioral functions. We live near the edge of chaos, so to speak, but not in it. That' where we can learn, adjust to the environment, and

SEE **FAU** ON PAGE 48

Editor's Note: Space limitations regretably preclude an exhaustive review of research activity of the Center. The Center also relies on the special expertise of FAU faculty in electrical engineering, computer science, ocean science, mathematics, physics, chemistry, and biology departments.

What follows is a list only of those FAU resource faculty associated with the Center who have ties to the psychology department: David Bjorklund (cognitive development), Wilson G. Bradshaw (neuroendocrinology of sexual behavior), Steven Bressler (human brain physiology), Howard Hock (vision), Ingrid B. Johanson (developmental psychobiology), Phillip S. Lasiter (neuronal/developmental aspects of gustatory regulation), Arnold Mandell (biological dynamics), Allan J. Nash (electropsychophysiology), Gary W. Perry (neural regeneration/development), Lewis Shapiro (neurolinguistics), Betty Tuller (speech perception/production), Robert P. Vertes (brainstem and forebrain, and sleep), and David L. Wolgin (psychopharmacology and brain damage recovery).

FAU FROM PAGE 21

switch from one action to another.

Bridging the Levels of Analysis

Q. You're working toward an "Esperanto" for neuroscience and behavior?
KELSO: There is a language barrier (much like the disciplinary barriers) among scientists who observe complex systems at different scales of analysis. As Poincare said, that's because we tend to study things rather than the relations among them. Psychology, as a behavioral science, hasn't done a very good job of identifying dynamical laws of behavior. Often we resort to other levels of description rather than obtain an adequate description at the level we are observing. A much richer language is available now, and if we develop it, maybe the gap *between brain and behavior will narrow. But, remember, the issue is not matter* versus process, reductionism versus wholism, or even rampant emergentism! Rather, the issue is to find an adequate level of description to enable us to abstract the essential, lawful aspects of the system under study.
Q. Well, I'm certainly fascinated.
KELSO: In humans, at least, fundamental behavioral functions like vision, audition, speaking, learning, remembering, making choices, have to be understood on their own terms. Single neuron studies won't help. Neuroscientists need to know about the orchestration of many neurons distributed throughout the brain. Again, there is always cooperativity, and the people that come to the Center want to understand its nature. To paraphrase our MacArthur Fellow, Arnold Mandell, "Tell me about the brain that hates my mother-in-law and not this point-to-point, ankle bone is connected to the knee bone stuff."
Q. This sounds like it might be called an "everyday" level of analysis!
KELSO: Mandell has expressed concern about the insufficiency of reductionistic approaches to understanding complex and irregular systems. We need a higher level of information, as I've described today, to understand how such systems behave as a whole.
Q. Are you also investigating perception?
KELSO: Yes, and we have found identical phase transition phenomena as in motor processes. A most fascinating area *is perceptual instabilities, for example the Necker Cube phenomenon, and detection* of motion in random-dot kinematograms. We are hoping to do some functional brain imaging (magnetoencephalography) work on perceptual dynamics.

Research Applications

Q. What about applications?
KELSO: Well, we're doing similar work in speech production and perception, and have discovered a wonderfully intimate coordination between temporal changes in articulators and speech perception. As part of the work, we have developed a helmet designed to present, to the wearer, graphical display of lingual dynamics and positioning during speech. It has enormous potential for speech rehabilitation in stroke victims and other persons with speech deficiencies. Our work may lead to designing realistic speech recognition systems.

Human Learning

Q. Do these principles of pattern formation hold for human learning processes?
KELSO: We have some beautiful data on manual learning and intentional learning supporting the notion that there are system stabilities and instabilities operating that cause differential ability to learn tasks that have differing phase relationships to the *person's intrinsic monostable phase dynamics, or attractors, in a mathematical* sense. *Postdoctoral researcher Pierre* Zanone of Switzerland and I have modeled this. Our work has the advantage of using the single subject as the unit of analysis and allows predictions of learning rate based on the person's intrinsic constraints.

The same ideas may apply to cellular learning: the temporal pattern dynamics turn out to determine whether long term potentiation or depression is observed in the hippocampal pathway. ♦

American Psychological Society
APS Observer
1511 K Street, NW, Suite 345
Washington, DC 20005-1401

NON-PROFIT
U.S. POSTAGE
PAID
PERMIT NO. 4224
Washington, DC

Is your address correct?

Please make corrections to your mailing label and return the original or a photocopy to APS at the address above.