PROPOSAL FOR *CENTERS OF NEUROPHYSICS* BY A. PELLIONISZ

THE AUTHOR'S MOTIVATION — Developing and promoting a conceptually and formally homogeneous, quantitative brain theory (a mathematical *understanding* of brain function) integrated with experimental neuroscience (the *knowledgebase)* and connecting to applied science & technology (to *utilize* the gained understanding).

THE CHALLENGE FOR BRAIN THEORY — A scientific-technological breakthrough is taking place with profound implications well into the next milleneum.Such major advances have significantly altered the World throughout history (inventions of roads, gun powder, steam engine, automobile, airplane, electricity, nuclear energy, rockets, genetic engineering are only a few examples). One of the latest and most significant scientific-technological breakthrough was the development of *computers*. Their importance need not be belabored here. Suffice to observe that today's World-balance depends more and more not so much on the availability of raw materials or weapons, but on the access to superior computer systems to control and automate both production (robotics), and defense (complex strategic systems). *Therefore, it is difficult to overestimate the revolution, unfolding today in brain theory, that is about to make present-day (von-Neumann type) computers, the traditional ways and means of controlling both production and defense, surpassed.*

The status-quo of brain theory, leading to neurocomputers, is determined by two fundamental factors. One is a strategic technological need. The other is an impending scientific breakthrough that makes the need fulfillable. As for the need, one might wish to recall that today's (serially-organized) computers were developed, at the time of II. World War, in a direct response to a demand of controlling fast *single* projectiles. It is rapidly becoming clear that the interdependent, optimalized control of a *vast array of defense-projectiles* poses alone a strategic challenge for developing a new breed of *parallelly* organized "computers". Adds to this demand, although not insignificantly, that the arrays of actuators and sensors used in robotic production-systems also call for *means of massively parallel computations. Brain Theory is about to find out how Nature accomplishes parallel computations, Neurocomputer Technology is well on its way to implement it.*

Terms of Neurocomputers, Neurochips, Neurobotics, Neurophilosophy signify that the scientific breakthrough, that appears to make such instrumentation possible, is likely to emerge with the cardinal help of Neuroscience. After all, this is the field of research that could reveal the principles based on which Nature has already solved the task of parallel computing. Nature's means of doing it are the vast, interconnected networks of brain cells, the neurons. The theoretical principles of how neuronal networks operate, however, have barely begun to be revealed in Neuroscience in a clear mathematical manner. A reason for this lag is, that Neuroscience has hitherto concentrated on the first step, on building up the necessary body of knowledge about the nervous system by experimentally gathering data. Therefore, thus far only an insignificant fraction of the investments was aimed at constructing a mathematical theoretical understanding of the principles underlying the function of Neuronal Networks. Today, there are mighty few theories available for even the simplest brain function such as sensorimotor operations. Their mathematical understanding, however, is essential for any kind of physical (or computer-software) implementation of brain-like machines. This is crucial, eg. for simple robotic motor effectors, let alone robots equipped with vision and other sensation, or with the prize of evolution; intelligence. *It may be an ill-spent effort to launch full-scale development of Neurocomputers without necessary understanding of the actual computing that neuronal networks do, or even what neurons and neuronal networks are.*

It is argued here that Neurophysics (similar to solid-state physics, or nuclear physics) should be made a conglomerated research-base discipline of a technology-driven field. It could introduce the attitude used in physics, and the formalism honed in mathematics, into "wet" Neuroscience. It could also communicate to the industrial and defense utilizations. Thus, it could connect a branch of basic experimental research to theoretical analysis and, in turn, would connect towards a synthesis; the instrumentation of the resolved principles. **Establishing Neurophysics Centers requires, however, both the readiness and willingness of enlightened Universities, as well as the solicitation and procurement of the necessary funding from government research and development agencies, and/or from industry and defense establishments.**

DIVERGENCES THAT SLOW CONSOLIDATION — Although the interest within the Neuroscience community for theory and application is running high, and the "Neurocomputing" community grows explosively, there are 3 major stumbling blocks on the road towards consolidation.

INTERCONTINENTAL TRIANGLE HAMPERS COOPERATION OF THE WESTERN WORLD — Since the issues of Neurocomputers, Neurochips, Neurobotics are cardinally important both for production and defense in the Western World, coordinated intercontinental cooperation of the *US, Europe and Japan* would be ideal for a consolidation of activities aimed at such goals. An inbalance of assets and somewhat divergent regional goals, however, make this problem very difficult, if not impossible, to resolve on a small-scale horizon. While the US is extremely strong in experimental Neuroscience and classical (von-Neumann type) Computer Science, it seriously neglects Brain Theory – to the degree that it is next to impossible to get adequately funded for such (outstandingly cost-effective) efforts. The situation is different in Europe, which has used to its advantage in Brain Theory its notorious favor towards lean theoretical approaches. In fact, Neurophysics Center, which is merely an idea in this proposal, is an accomplished fact eg. in the Netherlands – where it forms a strong new nucleus in any of the ubiquitous Departments of Biophysics. Robotics and advanced computer system development lags over there. Japan, however, contrasts and complements Europe by pushing aggressively not only in the field of classical computer-chips and traditional robotics, but also in creative large-scale funding of advanced R&D efforts in the outlined new direction (cf. the outlandish "Human Frontier" Program). Having participated in a string of "Neuro-computation type" world-meetings, one cannot miss to detect a deepseated desire, and an apparent lack of hope, for some kind of concerted action (eg. CERN-type collaboration) of the scientists involved throughout the Western World. Appropriate US agencies (eg. NSF) might be the only forum to lead and/or coordinate.

INTERINSTITUTIONAL TRIANGLE DELAYS ORGANIZATION OF INFRASTRUCTURE — The well-known cultural and structural divergences of *Academic- Industrial- and Defense* Institutions represent another major difficulty of consolidation, whether in form of Neurophysics Laboratories or otherwise. Nevertheless, Academic organizations, such as University Neurophysics Departments or Neurophysics Institutes could best play the neutral and accessible forum that can conglomerate the various efforts. Construction of "Neurocomputers" is a typical Research & Development issue for industrial institutions. A major consumer of the utilization of such new types of computers, again, is likely to be the defense establishment. However, such protective and restrictive environments would pull apart the growing body of research and delay the spread of utilizations – let alone that a schism between technology and academic research could repeate faults that happened to Cybernetics or AI.

INTERDISCIPLINAL TRIANGLE MAKES A PROPER UNIVERSITY-EMBEDDING DIFFICULT—The new field of neuro-computing is expanding on a territory that presently is a "no man's land" or "everybody's turf" among the three major circles of *Experimental Neuroscience & Medicine, Mathematical Computer Science & Artificial Intelligence and Physical Basic Sciences & Robotics Engineering*. Since these fields fall into different Schools; Medical, Basic Science and Engineering, the triangle handicaps those Universities that do not have all these faculties. Missing one or two of the three precludes pursuing the above goals in a fully integrated manner. The triangle hampers even full Universitites, since such emerging interdisciplinary activities are parcelled and fragmented in the 3 Schools. Having to break new grounds in between established territories, however, can be seen not only as a problem, but also as a challenge that can open up new possibilities. *Neurophysics Centers* could be formed either as divisions of existing Departments of Medical School; (eg. of Neuroscience, Biophysics, Rehabilitation Medicine, Physiology & Biophysics Depts.), or as part of Basic Science School Departments (eg. of Physics, Computer Science, even Mathematics Depts.), or as part of Engineering School Departments (eg. of Robotics, Biomedical Engineering Depts.). Best, however, Neurophysics could be established as a separate Department, *with full and optimal growing potential,* either within any of the three Schools, or in between them, in effect institutionalizing, on the dynamic neuro-platform, their often badly needed liaison.

PROPOSED MEASURE: SET UP PROGRAM TO ESTABLISH & SUPPORT NEUROPHYSICS CENTERS Tackling the problem posed by the InterContinental Triangle seems beyond the scope of a proposal as this. In that regard, the goal here is limited to the communication of this problem, and the various attitudes about it around the World, to US government agencies (eg. NSF). When their awareness of the issues at stake is sufficiently raised, they stand a chance for a good resolution. Specific proposal (deemed to be realistic) can, however, be forwarded here as to how to help resolve the other two standoffs (the InterInstitutional and InterDisciplinal triangle). **The key is in Academia; to establish a national policy and program (administered eg. by NSF) to help universities establish and support academic research & learning centers of this field; such as University Neurophysics Departments.** High-level coordination and administration of such program is necessary for a number of reasons. First, because of the national and international importance of the goals. Second, because the divergent funding systems and special interests of industry and defense cannot be coordinated from below. Last, and most important, because Universities might not be able to embark on such projects without strong assistance even if they are keen doing so.

The necessity for establishing appropriate University Departments is evident if one, again, compares the present situation to the early post-war era, the dawn of Computer Age. When a new research-based technology unfolds, the two most frequently asked and most fundamental questions are: 1) Where are the people who already *know* the state of the art of such research & technology? 2) Where can people *learn* whatever it takes to do the job? Today, it is difficult to imagine a University without a Computer Science Department. In the early fifties, it was difficult to find one that had it. In retrospect, those Universities did very well which established Computer Science Departments sooner and better. Neurocomputation, Neurobotics, Neurochip-making are long-range commitments, and it is unsound to expect uninterrupted growth without proper Neuro- background and connection to related activities. Thus, it is predicted that those Universities will do best in this field which first establish suitable Neurophysics Centers with best growing potential, with access to and from related fields, where available researchers can be concentrated, research & development can be conducted, where menpower can be educated for this national task.

Units that can serve as nuclei for such institutions can already be found at select Schools of Higher Learning. As a matter of course, the present proposal aims not only at establishing new Neurophysics Departments, but also bringing existing units, with substantial help, up to this level. Groups at MIT, Boston University, Brown University, U.Mass at Amherst, Caltech, etc. can provide examples for existing assets of the field, and also for what is missing. An existing framework can help (or limit) the potential of such units.

OUTLINE OF A NEUROPHYSICS DEPARTMENT — The Department awards B.S., M.S. and Ph.D. degrees in Neurophysics to graduates from Medical School, Basic Science School and Engineering School. It offers a Neurophysics Course, and requires students to take existing Neurobiology, Mathematics, Physics, Computer Science and (Biomedical) Engineering and/or Robotics Courses. The Neurophysics course will cover theoretical neurobiology, neuronal modeling, membrane and cell biophysics, and provides laboratory and computer programming hands-on training. The fully configured Department has 7 Laboratories as follows.

1) THEORETICAL NEUROPHYSICS LAB. Research conducted here is mathematical theory and sofware development for interpreting brain function. It may give a leading edge and a character to each of the Neurophysics Departments if each represents, and brings into full potential, *a particular school of thought of its own.* This author proposes activities centered around the concept and formalism of Tensor Network Theory of the CNS, to which the author already devoted about a decade of research. The concept that CNS expresses its function by transformations (implemented by networks) of *vectors expressed in general coordinate-systems* (that are intrinsic to the structure of the body), is based on an axiom that is not only obvious, but is more and more accepted. The formalism of vectors expressed in various general frames (tensor analysis), at the same time could become a common mathematical language of robotics and computer science (which uses Cartesian vectors) and

neurobiology (which *must* use more general frames, since Nature uses them). Also, this represents a cautious approach, strongly believing that Brain Theory should prove itself on simple and physically measurable sensorimotor operations first. Such approach results in an "evolution" of brain like robotic systems that follows natural evolution. It starts with rudimentary motor systems, later equipped with tactile and visual receptors, and evolve towards machines with intelligence. Such *sensorimotor-oriented, neuroscience-based approach* requires (and provides for) the experimental establishment of natural coordinate systems intrinsic to the structure of eg. various sensorimotor apparatus of different species. Then, the understanding of the function in terms of such general coordinate sytems is stated in a mathematical form (also implemented by suitable computer software). Thus, through a telephone-network of graphic work-stations, the experimental neuroscience-community is to be strongly coupled to such center, and the understanding gained, since it is handled by a mathematically and softwarewise homogenous formalism, could be implemented by both von-Neumann type and parallel (neurocomputer) software and hardware means. This lab is to closely cooperate with Departments of Mathematics, Physics, Neuroscience, Robotics.

2) BODY-COORDINATES ANATOMY LAB Research conducted here would be aimed at experimentally establishing the coordinate systems intrinsic to the structure and function of various CNS systems, in different species. Experience shows that such projects have peculiar features. Neuroscientists, who wish to utilize tensor theory find that the bottleneck is the lack of availability of the intrinsic reference frames. While willing to establish them (or at least contribute to such work) these workers face a slew of difficulties. It is often unknown what are the parameters which are necessary for theory, what are the methods of establishing them, and what is the format of storing and retrieving them in a manner that different sets of data are compatible. Besides, for an investigator who is interested in one system in one species, the above procedures are not worth learning, since he would use them only once. Thus, quantitative anatomy lab is to be organized for *visiting investigators,* who are provided with appropriate equipment, honed technology, technical help and computer storage & retrieving facilities to efficiently accomplish such projects. Such research would soon lead to a building up of a computerized data-bank of quantitative body-maps of different species (including human). It may be an anachronism that a computerized quantitative model of the body is not available, in the form of a data-bank that is accessible through a telephone network of graphic workstations. Such is essential in neuroscience (which is considering establishing a brain-map, without a complementing map of the *body* that the brain controls!). Also, such is important in civilian and defense ergonomy, kinesiology, sport medicine, where much quantitative information is available about physical equipment but hardly any quantitative knowledge is available of the structure of the living system that operates it. This lab is to closely cooperate with Neuroscience, Rehabilitation Medicine, Physics and Bioengineering Departments.

3) NEURO-COORDINATES ELECTROPHYSIOLOGY LAB. Existing single cell and presently developed multi-unit electrophysiological techniques (including extracellular-, muscle-EMG and motor unit recordings) are used for many purposes. They already proved their usefulness also for revealing the functional coordinate systems involved in the working of neuronal systems. Analogous to the Quantitative Anatomy Lab, research in this laboratory is aimed at quantatively revealing the *functional* reference frames that are intrinsic to CNS operation. Availability of suitable mathematical concepts eg. multidimensional geometry, and accompanying software systems, are particularly important for complex multi-unit studies (eg. for the interpretation of multichannel EMG recordings from musculoskeletal system). These studies directly connect to the work of labs #1,2, 6 and 7. The lab is organized, similarly to #2, around projects of visitor scientists. This lab is to closely cooperate with Neuroscience, Robotics and Rehabilitation Medicine Depts.

4) VON-NEUMANN COMPUTER LAB. This traditional computer center (utilizing regular von-Neumann type computers), similar to existing computer centers, serves a number of different purposes. A major novel feature is that it relies heavily on the modern concept of networking around this central node, both within the Department and scattered around, a large array of intelligent micros, serving as graphic workstations. This is necessary, since the central data-bank is to disseminate both data and

software to neuroscience research laboratories, to a large part in graphical terms. Second, the education, administration and software development in the Department are all planned to center around microcomputer-oriented modern software techniques (cf. MacTensor interactive education software already being developed). The needed cooperation within and outside of Neuroscience community, by means of efficient quantitative data- and software sharing, requires a major organizing effort not only to bring such networking into existence, but also in order to standardize data-structures and processing software techniques. This is a central responsibility of this lab, in close cooperation with Computer Science and Mathematics Departments.

5) NEUROCOMPUTER LAB. This major lab is established in order to develop *non von-Neumann* type (parallelly organized) computer-algorithms, chips and hardware, based on ideas, models and general understanding of CNS function that is worked out in this lab, in cooperation with the other laboratories. Responsibility also centers around testing different neuro-related applications of non von-Neumann computers developed elsewhere. This department is to closely cooperate Computer Science and Robotics Depts, Industry & Defense contractors.

6) NEUROBOTICS LAB. This lab is to elaborate mathematical formalisms & software systems as well as hardware prototypes to be shared by neuroscience and robotics. Particular example is to research robotic arms actuated by artificial muscles, governed by a controller that is built on the understanding and mathematical description of neuronal sensorimotor systems, such as cerebellar coordination of movements. Robotic vision, pattern recognition and tactile sensation, resolved in a brain-like manner, are also subjects of research in this lab. This lab is to closely cooperate with Robotics, Computer Science Departments and Industrial contractors.

7) NEUROENGINEERING LAB. Implementation and utilization of an understanding of brain function can lead to special Rehabilitaion Medicine & Bioengineering projects that require both extensive Engineering Research & Development, as well as a deep involvement in Neuroscience & Medicine. A particulary important and revealing project is Functional Neuromuscular Stimulation. This aims, in effect, to apply "an artificial brain" to control movements of paraplegic patients. The musculoskeltal system of these patients is intact, but the natural neuronal apparatus which controls them is defective. While research is extensive along this direction, a formidable difficulty is the present lack of understanding of natural neuronal control and coordination of skeletomuscular systems. A theoretical understanding of the functional principles of sensorimotor control, and coordination of overcomplete mucles by means of the cerebellar neuronal networks offers an excellent possibility to demonstrate the power of Neurophysics, by means of implementing a "neurocomputer"-type motor control in human. This lab is to closely cooperate with Rehabilitation Medicine, Bioengineering, Neuroscience Depts, and with University Hospitals.

WHAT DOES IT COST TO SET UP A NEUROPHYSICS DEPARTMENT?— Establishment and running of a fully configured Department is capable of absorbing megadollars. But what an asset would such a center represent for a University of today, and of tomorrow! However, *the existence of such centers does not depend on funding at all*. Many (if not all) elements of the proposals already exist; and will try to make it no matter what. Funding can only effect a single factor: *growth rate*. Of course, since all but a handful of such nuclei are presently subcritical, relegated to vegetate, an urgent infusion of funding is in effect a life or death question. Once a center is elevated beyond the critical mass, funding will control its growth-rate. This would ultimately determine the competitive edge of a particular University (or of a Nation) in the field of Neurophysics and thus in Neurocomputers and Neurobotics. It is probably a realistic estimate that given available facilities and personnel support, a Neurophysics *Division,* within an existing Neuroscience, Biophysics, or Physiology & Biophysics Department, could be established and run on a few hundred thousand dollars. The configuration and growing potential of such a unit would be very limited, perhaps to theory only. The range of establishing a full Department with all new facilities is likely to be in the millions, but an upper limit is probably nonexistent. It appears that the challenge inherent in establishing Neurophysics Centers is as great for scientists as it is for top-level scientific management.