BIOMEDICAL ENGINEERING AT NORTHWESTERN UNIVERSITY

by
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To define the field of biomedical engineering precisely is difficult, but at least two components are easily recognized. One is biomedical tools, that is, the development of instruments, devices and systems that contribute to the quality and sophistication of patient care and to the techniques used in clinical and research laboratories. A second area may be described as the interaction -- in the classroom and in the laboratory -- between engineers and life scientists who together seek detailed, quantitative descriptions of the dynamic properties of biological systems.

The origins of biomedical engineering at Northwestern can be traced back to 1943 when Paul E. Klopsteg, President of Central Scientific Company, made a donation to Northwestern for the purpose of making possible "certain developmental activities at the University." Several passages in the document that outlines the purpose and administration of these funds clearly show that Klopsteg foresaw the potentials of interaction between physics and engineering on the one hand and biology and medicine on the other, in teaching as well as in research. The passage which suggests that it would be valuable to introduce "a course in physical laboratory methods, and the use of instruments and apparatus in the measurements and control of physical phenomena, with reference to experimental problems in chemistry, biology, medicine and other sciences" constitutes but one example of Klopsteg's suggestions for biomedical engineering endeavors at Northwestern. Somewhat later, Paul Klopsteg became Professor of Applied Sciences and Director of Research at Northwestern's Technological Institute, and in 1945 he became involved in prosthetics research (1), one form of biomedical engineering.

However, if asked today when and how Biomedical Engineering at Northwestern's School of Engineering took hold, the nineteen fifties and Richard W. Jones, professor of electrical engineering at Northwestern from 1941 to 1971, immediately come to mind. A flavor of the spirit in which Professor Jones initiated biomedical engineering in Northwestern's Engineering School, can be gleaned from a passage in a talk he gave in 1966 at the meeting of the American Academy of Physical Medicine and Rehabilitation:

> "To many individuals the ideas to which we have referred" (the interaction between engineering and life sciences) "connote instruments, recorders, and computers, devices that have appeared in profusion in clinical research. Of possibly greater importance, however, are the concepts, the theoretical structures, that diffuse between disciplines to profoundly affect our ways of thinking about biological processes. This flow of ideas has led to many refinements in our view of physiological systems, and to the introduction of mathematical models and what might be described as theoretical physiology."

It was in this field of "theoretical physiology" that biomedical engineering at Northwestern started and grew during the first few years. Medical instrumentation "joined the club" somewhat later and the two components then flourished side by side.

Shortly after the end of the second World War the chairman of the Electrical Engineering Department, Dr. John F. Calvert, arranged a series of demonstrations of the analog computer facilities on the Evanston Campus. These demonstrations were directed towards the Medical School faculty because Dr.Calvert felt that there might be some areas of common interest between the two schools. Among the members of the Medical School faculty who attended were Professors John Gray and Fred Grodins of the Department of Physiology; Professor Jones was one of the participating engineers.

Drs. Gray and Grodins were involved in quantitative physiological studies (something rather unique in those days) of the mammalian respiratory system. They had acquired a large amount of data pertaining to the effect of changes in the external environment upon the physical variables of the different components of the respiratory system, and they hoped that computers might help them understand the flow of signals through the system as a whole. One of Professor Jones' fields of expertise was feedback control, and the interaction with Drs. Gray and Grodins led him "to become interested in the feedback aspects of the respiratory system inasmuch as it appeared to have many similarities to industrial regulators and servos" (1). The collaboration between these members of the Engineering and the Medical School faculties led to a 1954 publication of a theoretical analysis of the respiratory system, treated as a nonlinear biological regulator (2).

An even more important outcome of the early collaboration between these three outstanding scholars was an embryo that eventually matured into the present Department of Biomedical Engineering at Northwestern's McCormick School of Engineering and Applied Sciences. The road for biomedical engineering at Northwestern from a program to departmental status was long -- 25 years -- and at times rather bumpy.

The beginning: The Physiological Control Systems Laboratory

In 1957 an ophthalmologist (the late Julia Apter), then working towards a master's degree in the Physiology Department at the Medical School, drew Professor Jones' attention to two studies; the topic of both these papers was the response of the human papillary reflex to light which was temporally modulated in a sinusoidal fashion. To quote Professor Jones (1): "These ground-breaking studies seemed to open up a whole new field in which sinusoidal techniques from engineering offered new ways of characterizing physiological behavior, and even predicting the onset of instability." The interaction with Gray and Grodins and the potential of applying engineering approaches to biological problems prompted Professor Jones to encourage his graduate students to choose life-science oriented thesis topics. And so, by the academic year 1958-59 several of his graduate students in electrical engineering conducted experiments on the human papillary reflex, eye fixation and accommodative reflexes, as well as on animal photoreceptors.

The group operated on a shoestring budget based on a modest faculty research grant from the University. Two of the lab tables on which "home made" visual stimulators and recording equipment were mounted are still used in the present Biomedical Engineering Department. They are labeled: "Physiological Control Systems Laboratory" which was the name given to this very first phase of biomedical engineering at Northwestern. Another relic from this period is a "tech-

wide" announcement of the first meeting held on Oct.1, 1959 by The Physiological Systems Group for the purpose of discussing micro electrodes and measurements of signals from retinal neurons, and the presence of noise in retinal signals.

In 1983 Dudley Childress organized a symposium at Northwestern to honor Professor Jones. Peter Dallos, one of the first to receive a Ph.D. degree in Professor Jones' biomedical engineering program made some remarks that better than any statements I can make reflect both the atmosphere that existed within the Physiological Control Systems Group, and the major reason for the early growth and success of biomedical engineering at Northwestern, namely Richard W. Jones. I quote:

> "Northwestern was a very different place 25 years ago than what it is now. Graduate programs were small appendages to undergraduate training, some professors loudly proclaimed the immorality of taking federal money to support research, and publications by professors were only occasional and by graduate students almost unheard of. Disciplinary lines in the Technological Institute were tightly drawn. Within this low-key, small-scale, somewhat complacent atmosphere the seeds of an entirely new mode of operation were germinating. Among these was the realization by one of the electrical engineering professors that living systems are made up of a jumble of biological control loops, and that studying these was a major challenge. Thus a new avenue of study opened up for graduate students: the mathematical and engineering analysis of biological control systems. The time was ripe for these ventures to arrive in Evanston. The work of Wiener and Shannon was very fresh, Hodgkin and Huxley had just barely published their series of papers. Some of us graduate students were caught in the excitement, communicated by Professor Jones, about the new frontier of cybernetics.
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> The first thesis efforts by C.C.Li and Andy Meyer were on mathematical analysis of neural coding. Emphasis, emanating from Professor Jones, soon shifted to the visual system and Dan Green, Jay Warshawsky and myself analyzed various control loops for papillary reflexes, accommodation and eye fixation. Dr Enroth-Cugell was attracted to Evanston and set up a laboratory for visual neurophysiology. Bob Pinter was the first to take advantage of this development and he ventured into "wet" physiology to the great consternation and hilarity of the rest of us. He worked on the horseshoe crab, Limulus, which was inedible even for graduate students. From the initial efforts of one visionary professor and a few misfit graduate students grew one of the largest bioengineering programs in the country.
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> How was it to be one of Dick Jones' students? In one word, dignified. He treated us like colleagues, not as minions or slave laborers. He did not force his attention or criticism upon us, but was always available for consultation. His spoken and written communication was precise, and his use of the English language inspiring. He is the only man I know who could describe a given pole-zero configuration in poetic language. I still find myself using certain sentence constructions that I

> learned from his finely crafted classroom lectures. Even he, however, could not prevent the rest of my sentences from being rough translations from the Hungarian.
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> He instilled in us the necessity of completing a project including the publication of results, but insisted on dotting all the i's before sending out a manuscript. He taught us the importance of publication but discouraged the submission of bits and pieces. He favored putting together the complete story and did not approve of the now fashionable habit of printing the "least publishable unit of research".

Dick was a perceptive supervisor of research but he also knew when not to ask questions. I was putting together my research apparatus to measure human eye movements before any grant support or financial backing was available for building equipment. Consequently, I used to range the dead storage rooms and depots of Tech after the midnight hour to "requisition" what was needed. Soon an entire room was filled with shiny brass constructions and jerry-rigged electronics. Dick did not ask where it all came from. I suspect that he knew."

Today Peter Dallos is a Professor in the Department of Communicative Sciences and Disorders and The Department of Biomedical Engineering at Northwestern. He is a world leader in his field, auditory physiology, and his laboratory attracts investigators from near and far. In 1966 another early "graduate from the Physiological Control Systems Laboratory", Dudley Childress joined Northwestern's Department of Orthopedic Surgery and the Department of Electrical Engineering. His activities have been concentrated on the development of modern technological systems for disabled individuals. He too is a world leader in his field and he has contributed immensely to the development and success of his branch of biomedical engineering.

Although biomedical engineering originated in the Electrical Engineering Department, Professor Jones felt quite strongly that similar cooperation between life scientists and other engineering disciplines would be equally valuable. He appeared before the faculty of each department in the Engineering School, describing the activities in the Physiological Control Systems group and suggesting to his fellow engineers that "problems and opportunities for cooperative investigations between other engineering departments and the life sciences were equally great." (1). At first interest was minimal but with time these efforts bore fruit and biomedical-type projects were soon under way in biofluid mechanics, diffusion and transport, biomaterials and biomechanics, thus making the program a truly interdepartmental one.

One of the many strengths of Professor Jones was his conviction that if biomedical engineering was to "fly" and become an important discipline at Northwestern, engineers and life scientists had to be thoroughly "blended"; both by working together in a research laboratory and to the extent that each partner had to have some knowledge of the other's field. Consequently he looked for one or several Northwestern biologists with an interest in the kind of studies that he and his students were already pursuing in the Electrical Engineering Department. At this time -- in the late nineteen fifties -- an engineering approach or training in physics and mathematics, were not considered important for biological research. There was very little interest in the new developments in the engineering school. However, during a scientific meeting in Washington DC in either the fall of 1958 or spring of 1959, Professor Jones met Dr. Fergus Campbell from the

Physiological Laboratory of the University of Cambridge. Dr. Campbell, a physician specializing in ophthalmology, expressed considerable interest in the work in Professor Jones' group, and he was already knowledgeable in, not to say infatuated with, Fourier analysis and sinusoidally modulated stimuli as applied to the study of various visual functions. Dr. Campbell's enthusiasm had been ignited earlier by the work of two engineers. One of them, O.H.Schade (3), measured the human visual response to spatial sinusoidal modulation of the stimulus luminance. The other one, K.H.de Lange (4), used temporal sinusoidal luminance changes to study human vision. As a result of the contact between Professor Jones and Dr. Campbell, the latter spent one quarter as a visiting professor in the Physiological Control Systems Laboratory in the fall of 1962, and he thereby became the first biologist to receive an appointment in a Northwestern engineering department. During his brief tenure in the Electrical Engineering Department as a representative of the "bio" component of biomedical engineering he did experiments with the students working on the visual system. The value of his participation was enhanced by his ability to converse with the students in their own language, and thus he helped them shore up their confidence in the future of the unorthodox field they had chosen. He also gave a course in vision which was the very first biology course at Northwestern specifically designed for engineering students.

In 1959 Professor Jones obtained a research grant from The National Institutes of Health to continue his work on various aspects of the visual system. It was the very first grant application submitted to the National Institutes of Health by an engineer and the study section which reviewed it was initially somewhat suspicious. One of the projects in Professor Jones' overall program was mathematical modeling based on experimentally determined dynamic properties of single visual neurons. To accomplish this Professor Jones needed someone trained in visual neurophysiology who was willing to collaborate with engineers. By coincidence I then held a research position in the Ophthalmology Department on the Chicago campus, and I had just been awarded a research grant from The National Institutes of Health to study individual cat retinal ganglion cells, that is, the output neurons of the retina. I gave a seminar and spent a day with Prof. Jones' group and shortly thereafter was invited to set up my laboratory in the Electrical Engineering Department instead of in the Medical School, an offer which I gratefully accepted. Experimental collaboration with Professor Jones and serving as an unofficial graduate student advisor in matters biological was a most valuable learning experience for me. I became the first life science faculty member permanently located in the Engineering School.

As the new decade dawned it became abundantly clear that the engineering school's biomedical program, which Professor Jones had almost single-handedly initiated, was recognized far beyond Northwestern University, both in this country, in Europe and even "down under." In the beginning of 1963, "Science" published a lead article entitled "Systems Theory and Physiological Processes," jointly authored by Richard Jones and John Gray. In England, at the University of Cambridge, one of the members of the Department of Physiology had been charged with compiling a pamphlet to guide British students in their search for institutions where they could pursue graduate study in quantitative physiology with an engineering flavor. Northwestern's Control Systems Laboratory was included in that booklet with Professors Jones and Gray mentioned as possible advisors. In Sydney, Australia, an electrical engineer heard about Professor Jones' group and came to Northwestern to obtain a Ph.D degree under Professors Jones and Gray.

The Biomedical Engineering Center

In the early nineteen sixties there were important administrative developments. In 1960 the University made a formal commitment to biomedical engineering by establishing a Biomedical Engineering Center, thus greatly enhancing the presence of this field at Northwestern. Professor John Jacobs was appointed to the Department of Electrical Engineering as the Director of the Center. Under his leadership a group of faculty members applied for and were awarded the nation's first Biomedical Engineering Center Grant from The National Institutes of Health, as well as an NIH Training Grant in Biomedical engineering. The Center provided seed funds for new projects in various departments on both campuses, thereby bringing more graduate students into the field. A Biomedical Instrumentation Laboratory was established in The Medical School to support research there. Initial support for new faculty members, salaries for visiting faculty members, as well as funds for inviting seminar speakers also became available. The Center played an important role in establishing connections between the engineering school and clinical units such as the Childrens Memorial Hospital and the Department of Orthopedic Surgery. Professor Jacobs' own field of expertise was medical instrumentation and his arrival at Northwestern initiated a boom in this branch of biomedical engineering on both campuses.

From some of Professor Jones' written recollections about the early years of the Physiological Control Systems Laboratory to the day of his retirement in 1971 (1), it is clear that although he was frustrated at times with some administrative attitudes towards the fledgling biomedical engineering program, his efforts did receive very considerable University support. One clear expression of this support was the new facilities given biomedical engineering in 1963 when a new wing in the North East corner of the Technological Institute building was completed. A large proportion of those involved in biomedical experimental research were given contiguous laboratory and office space, and space was also assigned to the offices of the Biomedical Engineering Center. Thus, from the fall of 1963 almost all of the third floor was "biomedical engineering territory." This does not, however, imply that biomedical engineering was restricted to that space as we entered the nineteen seventies.

The development (and decline) of a life science curriculum for engineers

During the early years of the nineteen-sixties graduate students engaged in interdisciplinary research were urged to take some of the life sciences courses that were available on the Evanston campus. But these courses were almost totally descriptive and thus did not serve engineering students very well. An alternate plan, taking courses in the Medical School, was met with little favor as noted by Prof Jones: "Strong arguments were put forth by the administration to have engineering students go to the Chicago Campus for Medical School courses even though they were not of the character desired, and the travel problem seemed severe" (1). There was little understanding at the administrative level of the need for a life science curriculum designed for and controlled by the engineering school. Professor Jones' suggestion that one, or ideally several, life scientists with a strong quantitative background be appointed to an engineering department, even if they did not have an engineering degree, was steadfastly opposed. Somehow these difficulties were circumvented and a life science curriculum suitable for engineers slowly developed. In 1962 Professors Gray and Grodins offered a course on the Evanston Campus

aimed at engineering graduate students and delivered in engineering language. The title of this course, which covered the respiratory and circulatory systems, was "Homeostatic Physiology". Professors Gray and Grodins offered this course on an entirely voluntary basis. Shortly after the "Homeostatic Physiology" course was introduced another course was added to the emerging life science curriculum in the engineering school. Dr. J. Randall, a biophysicist with an interest in a quantitative approach to biology, joined the faculty of the Physiology Department. He developed a course entitled "Cell biophysics", that was given on the Evanston Campus. It admirably prepared students with minimal life science backgrounds for the "Homeostatic Physiology" course. When Dr. Franklin Offner became a professor in the Electrical Engineering Department in 1963, another quantitative biology course, membrane biophysics, became available to engineering graduate students. My own course, covering basic neurophysiological concepts, was given for the first time in 1963. Although not presented with an "engineering-math" orientation, it was specifically aimed at the engineering students who worked on different aspects of neural function. In 1965 Dr.Robert Gesteland, an M.I.T trained engineer and neurophysiologist, was appointed jointly to the Department of Electrical Engineering and the Department of Biology, and another highly quantitative biology course, this one dealing with all of the mammalian sensory systems, was added to the electrical engineering curriculum. In 1962 Dr. Peter Dallos was appointed to the faculty of the Audiology Department in the School of Speech and in 1966 he also became a member of the Electrical Engineering Department. His physiological acoustics course was yet another biology offering that served engineers very well. By this time Electrical Engineering was no longer the only department within the Technological Institute participating in the biomedical engineering program. In 1967 Professor Lyle Mockros of the Civil Engineering Department began his contribution to the biologically oriented graduate curriculum, with a course in biofluid mechanics. Together all of these courses provided a foundation for the highlight of the nineteen-sixties "engineering-biology" courses, "Control Systems in Biology", taught by Professor Jones. Thus, by the middle of the nineteen-sixties a reasonable choice of quantitative biology courses for biomedical engineering graduate students was available in spite of administrative reluctance to support the development of such biology courses within the engineering school. Disciplinary lines within the Technological Institute were indeed tightly drawn in those days.

In 1961 both the Electrical Engineering Department and the Physiology Department on the Chicago Campus added a Biomedical Engineering option to their Ph.D programs. In 1969 the Graduate School approved an interdisciplinary masters and a doctors degree program in biomedical engineering to be administered by a committee appointed by the Dean of the Graduate School. In the spring of 1971 an interdisciplinary undergraduate program in biomedical engineering was approved by the Tech Curriculum Committee.

In spite of the fact that biomedical research had grown remarkably in several engineering departments, and that by 1965 a reasonable choice of quantitative biology courses had been "patched together" on the Evanston Campus, several faculty members felt that to secure stability of the curriculum and future growth in research, a Department of Bioengineering and Biophysics should be established in the engineering school. Such a department was envisaged as having the autonomy to appoint biologists and biophysicists, who might not have an engineering degree, to its research faculty and to oversee the curriculum. However the Central University Administration did not support this suggestion at that time and no action with regard to the

establishment of a Biomedical Engineering Department was taken in the nineteen sixties. An independent full-fledged department of Biomedical Engineering was established in 1985.

Regrettably, by the end of the nineteen-sixties a large part of the curriculum created earlier had disappeared. Drs. Grodins and Randall had left Northwestern, Dr. Gray had chosen not to continue teaching on the Evanston Campus, Dr. Gesteland gave up his affiliation with the Engineering School and Professor Jones retired in 1971. Thus the struggle to assemble a suitable life science curriculum for engineering graduate students had to begin once again, and, now the task at hand included the creation of a biomedical engineering undergraduate curriculum, not just options in other engineering departments. Such curricula were developed and "non-engineer" quantitative physiologists were appointed to the Engineering School during the nineteen seventies, but the details of these and subsequent developments are beyond the scope of these historical notes.

In conclusion, when the decade of 1970 began, Northwestern's biomedical engineering youngster was very much alive, had acquired experience from the "school of hard knocks" and was thus prepared for, and did exhibit, continued growth and maturation.

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