Foreword

At the Interface of Photonics and Neuroscience

"Neuromorphic Photonics," by Paul R. Prucnal and Bhavin J. Shastri (CRC Press/Taylor & Francis, 2017), is a book about photonic neural networks, which enjoy a number of unusual and salutary features. They can be highly interconnected and robust in the presence of noise. The number of interconnections among spike-processing elements can be scaled indefinitely, with large fan-out, by using wavelength multiplexing, a technique similar to that used for the fiber-optic networks that serve the internet. Spike processing benefits from both the bandwidth efficiency of analog pulse encoding and from the on/off nature of the spikes themselves.

Neural systems are largely immune to amplitude noise because information, rather than being encoded in amplitude, is encoded in the form of fresh, unitary action potentials (neural spikes) that are repeatedly regenerated at each synapse along the transmission pathway. As with cascaded digital transistors, amplitude noise in photonic neural networks does not propagate, enabling them to scale in size nearly indefinitely. The intriguing features of these new photonic neural networks, such as bandwidth efficiency, large interconnectivity and fan-out, and cascadability, offer promise as a platform for the next generation of signal-processing and computing systems.

The manner in which the story unfolds in "Neuromorphic Photonics" is, to me, a tale of d*éjà vu*, as will become clear from my own personal chronicle at the interface of photonics and neuroscience.

At Columbia in the 1940s and 1950s

In 1942, Hecht, Shlaer, & Pirenne (HSP) carried out a classic psychophysics experiment at Columbia University designed to determine how few photons the human eye could perceive under the best possible conditions [1]. Psychophysics, which dates from the 1860s, has traditionally been a branch of psychology that relates sensory perceptions to the physical stimuli that give rise to them. Dark-adapted subjects viewed a sequence of dim flashes of different mean energies, randomly interspersed with blanks, and were asked to report whether each trial was 'seen' or 'not seen'. Accepting data only from 'good subjects' who reported zero false positives in response to the blanks, HSP concluded that the sensation of seeing required the confluence of 7 or more photons at the retina, a fixed number they designated as the 'visual threshold.' They also suggested that the shapes of the frequency-of-seeing curves (plots of flash detectability vs. mean flash energy) were determined by the intrinsic Poisson photon-number fluctuations [2] of the stimulus flashes, rather than by sensory-system variability inherent in the observer. This conclusion was startling in its day and their findings had a profound impact on the contemporary community of visual scientists. HSP's noiseless conception came to be called 'threshold detection theory.' The existence of a sensory threshold was a central concept in classical psychophysics.

In the 1950s it was recognized that noise was inherent in essentially all detection systems and a signal-detection approach accommodating additive

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noise was developed [3]. This approach was based on statistical decision theory, which had been conceived in the 1930s and 1940s as a model for understanding choice in the presence of uncertainty. This point-of-view set electrical communications on a firm mathematical footing. Its introduction into sensory psychology, which took place during the same time frame, resolved a number of key problems in psychophysics and came to be called 'signal detection theory' (SDT). In particular, Horace Barlow [4] argued that visual thresholds should be construed as signal-to-noise discriminations rather than as fixed numbers, and he developed a version of SDT with additive retinal 'dark noise' that was in very good agreement with the data collected by Hecht, Shlaer, & Pirenne.

At about the same time, a detection researcher at MIT Lincoln Laboratory named William J. McGill, who was enamored of the work of Hecht, Shlaer, & Pirenne, joined Columbia's Department of Psychology as a young faculty member. While he heartily endorsed Barlow's approach, McGill believed it was also important to incorporate into the detection model at least a rudimentary trace of the neural processing mechanisms that lie behind the eye in the brain. He conceived a simple, but prescient, model in which the Poisson photon-number fluctuations of the stimulus flashes served to modulate the rate of an idealized collection of neural spikes traveling up the optic nerve; this collection, presumed to be a sparse superposition, would itself exhibit Poisson neural-number fluctuations [5]. McGill's result [6] was both remarkable and durable: he had constructed a doubly stochastic Poisson conception identified as the Neyman Type-A (NTA) counting distribution [7], originally set forth in 1939 in the context of entomology by the famous statistician Jerzy Neyman. This counting construction was subsequently extended to a point process, the shot-noise-driven doubly stochastic Poisson process (SNDP), which retains the hallmark NTA counting statistics [8].

At Columbia in the 1970s

In a chance encounter on the campus of Columbia University in the spring of 1974, 30 years after Hecht, Shlaer, & Pirenne's seminal work, I happened to notice an announcement for a talk to be given at the *Columbia University Seminar on Mathematical Methods in the Social Sciences* [9] by William McGill, who had by then become the President of Columbia. I was a young faculty member in the Electrical Engineering Department at the time and wondered what the President of Columbia, a 'mathematical psychologist' working in an arcane area of auditory sensory perception, might have to say about a topic he called 'signal detection theory.' After all, my own research was also concerned with signal detection theory — but in the domain of the photodetection of laser light.

Listening to McGill's talk that March afternoon, it began to dawn on me that the two 'signal detection theories' might, in fact, be closely related. At the end of the seminar I brashly approached the President, whom I had never met before, and asked him what he thought about that prospect. He replied that he had, quite by chance, recently come across a journal article on 'laser energy detection' and had himself begun to ruminate about the mathematical connection between the perception of bursts of sound and the detection of pulses of laser light.

Immediately following the seminar McGill invited me to his office and we began a collaboration that lasted for many decades. After numerous meetings, we discovered that the two seemingly unrelated constructs, his for auditory sensory detection and mine for laser energy detection, were, in fact, mathematically identical. Both 'signal detection theories' related to the detectability of weak signals embedded in noisy backgrounds. And both had grown out of a common antecedent: statistical decision theory. McGill's work in auditory sensory detection was cast in the form of a neural-counting model, whereas my work in laser energy detection took the form of a photon-counting model. It took us some time to show that the two outcomes were mathematically identical since he had chosen a combinatorial form for his neural-counting statistics whereas my photon-counting statistics had been cast in polynomial form [10]. Recognizing that such an identity existed was extraordinarily satisfying because each of us had unexpectedly found another who had struggled with the same problem, but in a very different context. Not long thereafter, McGill had a chance to recount this story to a particularly appreciative audience: a meeting of lightwave communications researchers that convened at Columbia in 1977 [11].

All of this was occurring just as a young Paul Prucnal began his graduate studies at Columbia, after having received his Bachelor's degree at Bowdoin. I persuaded Paul to join my group as a Ph.D. student. The first task he carried out was to mathematically demonstrate that the classical binary detection problem using a likelihood-ratio test often reduces to a simple comparison of the number of events with a single threshold; this showed that simple neural machinery could often suffice for reaching a decision [12, 13]. Prucnal and I, together with Bill McGill, Giovanni Vannucci, and Michael Breton, then proceeded to carry out a modern version of the HSP experiment using a laser source and an acousto-optic modulator [14]. In a deliberate deviation from the protocol used by HSP, on certain experimental runs we encouraged our subjects to report seeing the stimulus flash even if they weren't absolutely sure of its presence. Under these conditions, our subjects reported a minimum detectable number of photons considerably lower than 7; however, this was accompanied by a false positive rate substantially greater than zero. The number of photons at the retina required to elicit the sensation of seeing was evidently not fixed at 7 as suggested by HSP; instead it was found that sensitivity and reliability were traded against each other as an internal criterion was voluntarily modified by the subject. It turned out that even a single photon at the retina could be perceived, provided that the false-positive rate was allowed to become sufficiently large. On average, our four subjects were able to detect a single photon at the retina with 60% frequency of seeing, at the expense of a 55% false-positive rate.

We refined our results by collecting data in accordance with a carefully established protocol [15], and further confirmed them by conducting experiments that made use of super-Poisson light flashes generated by triangularly modulating the intensity of a Poisson light source [16]. Prucnal and I had previously determined the statistical properties of photon-counting distributions for intensity-modulated sources [17]. We also obtained theoretical results for experiments designed to make use of photon-number-squeezed (sub-Poisson) light, even though no such source was available at the time [16].

In 1979, Paul Prucnal delivered an outstanding dissertation [18] and completed all of the requirements for the degree of Doctor of Philosophy in Columbia University. He assumed a faculty position at Columbia, where he remained for nearly a decade before joining the faculty at Princeton, where he currently resides.

At Columbia in the 1980s and 1990s

The underpinnings of the results obtained from HSP-type experiments can be investigated by neurophysiologically tracing the stimulus as it propagates through the visual system in the form of action-potential sequences. Both additive and cascade neural noise turn out to be present. The neural-counting statistics at the level of the retinal ganglion cell are found to be well-described by the NTA distribution [19], just as McGill predicted [6]. The neural spontaneous (dark) discharge takes the form of additive noise, which is manifested as a non-zero false-positive rate in the psychophysical domain.

Neural amplification, which is ubiquitous in the brain, is manifested as cascade (multiplicative) noise. The retinal rod functions as a chemical photomultiplier, amplifying a single-photon detection into a macroscopic current pulse [20]. The visual-system neural network fed by the rod exhibits multiple stages of amplification at its waystations. A concatenated series of NTA-type amplifiers, in the limit when the number thereof becomes large, can be modeled as a birth-death-immigration (BDI) branching process, comprising amplification, loss, and the ingress of spontaneous action potentials, respectively. The net result is that the absorption of a single photon at the retina gives rise to a vast collection of action potentials that permeate the brain's visual nuclei [21]. Branching detection theory transcends both the noiseless conception of threshold detection theory and the additive-noise construct of traditional signal detection theory. The branching model predicts a tradeoff between sensitivity and reliability at the inception of vision that accords with both neurophysiological and psychophysical observations.

Indeed, the visual-system neural amplifier behaves very much like a photonic traveling-wave amplifier, yet another example at the interface of photonics and neuroscience. The branching of photons in a fiber-optic amplifier is described by a BDI branching process comprising stimulated emission, absorption, and spontaneous emission, respectively [22].

The story is not yet over. At longer time scales, action-potential rates recorded at the waystations of the visual pathway universally exhibit distinct fractal behavior, revealing a functionality for which there is currently no satisfactory explanation [23].

At Princeton in the 2010s

The book "Neuromorphic Photonics," a narrative about photonic neural networks, provides yet another bridge that draws together the domains of photonics and neuroscience. The research underlying this book emerged from a joint discovery by an electrical engineer and a neuroscientist. In the summer of 2008, Prucnal delivered a seminar on nonlinear optical signal processing at Lockheed Martin. This event led him and neuroscientist David Rosenbluth to begin a year-long series of meetings to explore potential interfaces between photonics and neuroscience. During one of these meetings, they came to the realization that the differential equations that govern the behavior of lasers operating in the excitable regime (by virtue of their built-in saturable absorbers) are identical to those that govern the behavior of integrate-and-fire neurons, thereby offering an all-optical realization of a neuronal construct [24]. Both exhibit spiking dynamics. The significant, and interesting, distinction is that the time scales at which the two systems operate differ by a factor of roughly one billion; so-called "photonic neurons" have a time scale of roughly one picosecond whereas biological neurons have a time scale of roughly one millisecond.

These findings suggested the possibility of interconnecting individual photonic neurons to create photonic spike-processing neural networks. The authors of "Neuromorphic Photonics" offer a thorough treatment of the theory, development, and fabrication of photonic spike-processing networks that interconnect excitable lasers and tunable micro-ring resonators (implementing synaptic weights) via optical waveguides on silicon chips. The idea is to capitalize on bio-inspired processing through the medium of ultrafast optical processors that offer the capacity to perform the kinds of tasks at which biological systems excel: image recognition, decision-making, and learning, to cite a few examples. These tasks can be performed in a bandwidth-efficient manner, because broadband signals from the physical environment, such as radio signals and inputs from cyber-physical sensors, can be directly transduced by photonic neurons into pulse-position modulated optical-spike sequences, without incurring the coding loss of analog-to-digital conversion.

The authors have embarked on a bold and exciting venture. I look forward to the denouement.

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