Research Statement

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I am a theorist at the borders of computation and cognition, with research within theoretical biology, neuroscience, cognitive science and artificial intelligence.

Theorists are quite rare within these fields, and can be mistaken for a few other specializations. I am ***not*** a computational neuroscientist (although I have experience). I am ***not*** a physicist who got bored with physics and now publishes excessively mathematical and unreadable articles in theoretical physics journals about biology that has no connection to the data and that no actual biologist ever reads. And I am ***not*** the applied mathematician type who is connected to a wet lab that mostly just does their analysis.

Rather, I use my background in mathematics, physics and computer science to build *rigorous, groundbreaking, and often grand unifying theories* about the function and design of biological and/or cognitive systems. All my work has *new data*, either acquired myself or compiled across sometimes hundreds of papers within the relevant literature. And, despite the mathematical foundations of my theories, my papers are *readable and relevant* to the questions biologists and cognitive scientists care about; and in some cases my work appears in my books designed for both academics and the general public.

As a theorist, my research style is fundamentally different from that of most scientists in the field, who are experimentalists. Experimental science usually requires a large dose of incrementalism, and iterations of large, multi-year grants on a similar topic. For theory, once I make a major theoretical breakthrough, including initial acquisition of data to provide support, the probability of making a second major breakthrough in the same area is vanishingly small. My expertise as a theorist can only be leveraged by looking into new areas. Had I stayed within one field my whole career, I would still have just one theoretical breakthrough. But moving as I have to so many areas within the biological and brain sciences over the last 25 years, I have allowed my brain the opportunity to make more and more discoveries.

As a theorist, it can therefore be difficult to extrapolate where my next research direction will be. I can't force it to be within some particular direction, lest I risk failure of not finding anything. Nevertheless, by describing the sorts of research I have done over the last 25 years, you may be able to extrapolate the sorts of research I am likely to move to next.

On the kinds of funding I will acquire, for each of my existing research directions there *is* further theoretical and empirical work to be done, ripe for undergrads, grads and postdocs, and I will apply for grants for many or all of them.

But my main plan is to acquire funding for novel and revolutionary ***applications*** *of the ideas with market potential*.

I am not only a rare theorist in the field, but am also rare in having spent considerable time in the business world. For the last ten years I have been VP of Research and Development of my own research and incubator lab (2ai Labs, http://2ai.org), where I have both continued my fundamental research but also transformed my ideas into business opportunities. My farthest along business project is a medical device startup, VINO Optics (http://vinooptics.com), emanating from my 2006 discovery on the origins of primate color vision. I also have consulted for several dozen companies over the last decade with my Human Factory (https://www.humanfactorylab.com/), bringing cutting edge insights from the cognitive and brain sciences to the next generation of human-centered technology. I have thereby acquired significant experience with transforming raw ideas into real technologies the marketplace desires.

In this light, I will get closely involved with the university's incubator and business development resources, helping new patents to be filed, and -- much more important -- being actively involved in getting the technology built, licensed, or bought.

I have tried to cluster my various research areas below into five research lines, and I have listed them in roughly chronological order (although there are significant temporal overlaps) to help communicate the progression.

1. LOGIC and COMPUTATION

Some of my earliest work concerned logico-philosophy. I have a long contribution to *Synthese* on the foundations of the riddle of induction, another in *Synthese* on why natural language is vague, and research in this line on why eureka/aha! moments are expected for any computational agent (and an easier to read version). I also have a couple papers in recursion theoretic learning theory on the computational limits of learning. Some of these research areas were part of my first book, ***The Brain from 25000 Feet*** (Kluwer, 2003). I have research now within this broad domain concerning the mathematics underlying new kinds of parimutuel markets. I do not foresee myself aiming for funding within these domains, but mentioning them helps communicate my mathematico-philosophical origins, which perhaps explains how I ended up the sort of rigorous, foundations-oriented theorist I am today.

2. THEORETICAL MORPHOLOGY and COMPLEXITY

I have a variety of research on why biological and cognitive structures are organized as they are. In one study I asked why animals have as many limbs and digits as they do, and discovered a "limb law" across seven phyla showing how the number of limbs relates to the length of the limbs (relative to the body size); we can explain why we humans have five fingers per hand, and thus ten fingers total (and base 10), as a special case of this limb law. I have research on the morphology of arteries and neurons, showing that they have nearly volume optimal connection networks for reaching out to their "leaves", and that they manage to do this via a simple physical heuristic (because the general problem is NP-hard). I have a variety of research papers on why the micro- and macro-anatomical properties of mammalian neocortex change as they do in larger brains, why animals have the number of cortical areas they do, and why the visual cortex has as many levels as it does. In another paper I asked, how is greater behavioral complexity accommodated across mammals? Do they do it by combining the same muscles into more complex combinations? Or, instead, do they have similarly complex combinations, but have more muscle types (akin to the "words" of a behavior) to choose from? I was able to acquire behavioral repertoire size, and total number of muscles, from across the mammalian order and show that behavioral complexity rises in the second of two ways I just suggested above. This paper was also the first to document that behavioral complexity does *not* correlate with brain size (but only with brain-body ratio, specifically, with something called the encephalization quotient). Such research directions also sometimes are purely cognitive, such as my research asking whether the mental lexicon (at least as it is characterized by dictionaries) is organized as a "web" or instead as a hierarchical network defined ultimately by a small set of lowest-level, primitive words. I was able to show that dictionaries are in fact hierarchically organized, and that the specific nature of the hierarchical organization minimizes the total number of needed words in the network. More recently I provided evidence that our pruney wet fingers have the optimal morphology for rain treads to prevent hydroplaning; that is, we get wrinkly fingertips when wet because they become "rain treads" for primates in rainy conditions. I will apply for funding on the following topics.

- **Neocortex scaling**. Since the time of my publications on how the mammalian neocortex scales in size there have been a wealth of new data that have been published, some via novel techniques. I will apply for government grants based on testing my theories of brain scaling in collaboration with the labs involved in these new data sets.
- **Organization of the mental lexicon**. Since the time of my publication on how dictionaries are near-optimally hierarchically organized, dictionary network data has become much more highly accessible, allowing much finer tests, and examination of much finer predictions from the theory.
- **Pruney fingers are rain treads**. The evidence I currently have for my "rain tread" hypothesis of pruney fingers is mostly morphological: that the actual shape of the wrinkly fingers is consistent with the peculiar shape they should have if

they are drainage networks for channeling (and squirting) out water during a grip in wet conditions. I will apply for government grants to test behavioral predictions (which have to be done with whole-body behaviors, like parkour, and will collaborate with an appropriate lab) and phylogenetic predictions (concerning which primates are predicted to, and not to, have rain treads).

3. VISUAL PERCEPTION

My discoveries that have gotten the most attention have been in visual perception. For example, despite the community believing for a century that primate red-green vision evolved for finding fruit or leaves in the forest, I was able to provide evidence that in fact our peculiar variety of red-green vision has exactly the peculiarity needed for seeing blood under bare skin, so that we can detect emotions, state and health. I have a research sub-line on why we see illusions, providing evidence that a tremendous range of illusions are explained by our brain's attempt to compensate for neural delays. And, again rebuffing century-old accepted wisdom, I was able to provide evidence that the evolution of forward-facing eyes is not "for predators" (nor for several other variants on this), but is for seeing better within cluttered forest habitats. Also in this category might be my work showing how to trick the visual system into carrying out arbitrary computations (and a longer version online). Some of these research directions were talked about in my books, especially ***Vision Revolution*** (Benbella, 2009), which was widely read, appeared in six languages (including Chinese, and to have a second printing in 2021 in Japan), and had reviews such as "...one of the best works of theoretical vision science since Gibson," Dan Simons, author of *The Invisible Gorilla*, "...a book full of invention and originality..." Peter Lucas, Professor of Anthropology, and a great review in the *Wall Street Journal*.

- **Color vision and blood augmentation**. By virtue of understanding the tight connection between the design of our color vision mechanisms and the physiology of our blood, there are many potential medical applications. (My startup VINO Optics, http://vinooptics.com, concerns one such application.) In addition to funding from the government and industry, I believe that there are foundations potentially interested, because it is possible to build blood and vein augmentation technology that requires no battery or electricity, and so there are potential disproportionate advantages in the third world.
- **Forward-facing eyes**. The forward-facing-eyes research has applications for novel kinds of human-machine interfaces in automobiles and heavy machinery, and I believe I can get funding from automobile companies in this regard. (I have worked, for example, with Yamaha Motors on something related to this.)
- **Visual computation**. Might it be possible to harness our visual computational powers for other tasks, perhaps for tasks cognition finds difficult? I was the first person to devise ways of converting digital logic circuits into visual stimuli -- "visual circuits" -- which, when presented to the eye, "trick" the visual system into carrying out the digital logic computation and generating a perception that amounts to the "output" of the computation. That is, the technique amounts to

turning our visual system into a programmable computer. This is not the first time scientists have attempted to make use of biological computation; this was first tried with DNA, tapping into the computational prowess inside cells. My research is the second kind of biological harnessing that has been attempted for computation, aiming to commandeer our very brains. I will apply for government and industry funding. (In fact, I have been approached by venture capital firms interested in making progress along these lines.)

4. NATURE-HARNESSING

Perhaps my most important contribution will have been -- in my view -- my work on how humans came to have language and writing. Rather than humans having evolved to have a language instinct, and rather than humans simply learning to do deeply complex tasks such as language without an instinct, I argue it is neither. Instead, cultural evolution has over time shaped the sounds of speech and look of writing to be "like nature," thereby harnessing existing event and object recognition systems for the new tasks of speech and writing. My first paper along these lines concerned measuring how writing systems accommodate greater complexity, and I was able to show that, whether a writing system has 15 or 200 letters, the average number of strokes per character, and redundancy, tends to remain constant. And in a later seminal paper I was the first to show that the shapes of letters across more than a hundred writing systems, and across Chinese characters, match the topological contour combinations occurring in natural scenes, thereby co-opting the visual object recognition system for reading. I then published my third book, ***Harnessed*** (Benbella, 2011), where I provided evidence that the sounds of speech have culturally evolved to sound like physical events amongst solid objects, thereby "hacking" our event recognition system for speech processing. And in that same book I make the case that music sounds like something else we already have innate recognition mechanisms for: the sounds of human movement. That book was among the "Top 10 Books of 2011" at *New Scientist* Magazine, and engendered reviews such as "...this book might hold the key to one of humanity's longstanding mysteries..." Stanislas Dehaene, author of *Reading in the Brain*, and "I'd be amazed if everything he says is right; but at this point I'd be even more surprised if his main ideas, which crack open riddles that have annoyed me for years, aren't on the right track." Frank Wilczek, Recipient, Nobel Prize in Physics, 2004. It also is the topic of my book, ***On The Origin of Art*** (MONA, 2016) with co-authors Steven Pinker, Geoffrey Miller and Brian Boyd, and hybrid novel ***Human 3.0: What's Next, After Human*** (Human Factory, 2012).

- **General Harnessing Grants**. These "nature-harnessing" principles I have uncovered are crucial for how we became the "human 2.0s" we are today, astronomically more intelligent than our human 1.0 biological selves without the cultural additions. But these cultural evolutionary processes are ongoing, and almost assuredly occurring now faster than ever. I will apply for government and foundation funding for large grants to further study these ideas, and to study the extent to which culture *today* is actively engaged in these processes. Note that, in a sense, the mechanisms behind these processes are more artistic than scientific, and there are ways of pitching these ideas within the arts foundations communities that are romantic and exciting, with the arts at the lead in transforming what it means to be human.

- **Human-Computer Interfaces**. We may not initially think about, say, the shapes of letters being a kind of "interface", but that is basically what it is. By shaping letters and characters in just the right way (namely, like nature), writing is able to efficiently and seamlessly interface with our innate perceptual mechanisms. We now have comparatively infinite powers to create interfaces, but the real question is, What is the optimal design? That's what HMI, HCI and UX care about, but I believe that having these principles in hand, the ones that drove the cultural evolution of writing and language, can help us design much better interfaces. I will apply for government funding, and forge industry relationships (e.g., Yamaha and Facebook).

5. EMOTIONAL ARTIFICIAL INTELLIGENCE / AFFECTIVE COMPUTING

My most recent research direction concerns a first principles grand unified theory of emotional expressions. The theory makes a four-dimensional pattern of predictions concerning the structure and meaning of emotional expressions as a poker-like signaling system allowing social animals to engage in compromise-seeking negotiation. And the pattern of predictions appears to fit the actual structure and meaning of emotional expressions we possess. The power of the theory goes way beyond any to date, and I believe it is the backbone of what is needed to drive advancement in emotionally intelligent AI, affective computing, and emotion-machine interfaces. It will be published in my next book for around 2021, tentatively titled *The Poker Origins of Emotional Expressions*. I foresee my greatest push for funding will be within this domain, as the drive today in the marketplace for incorporating emotions into technology is greater than ever. New intellectual property of use in the marketplace is almost certain.

- **Affective computing**. There has recently been an explosion of interest within industry for reading and comprehending the emotional expressions of their users. However, existing understanding of what emotional expressions actually *mean* in terms of what the user is "saying" is very poor. It does no good to devise clever ways to measure the user's emotional expression if all one can say is, "she's angry to level 0.7". My theory provides a revolutionary new rigorous understanding of emotional expressions, and their structure and meaning. I will apply for government funding, and especially work with industry partners.
- **Emotional artificial intelligence**. My new theory of emotional expressions also makes clear the class of algorithms that must be used in order for artificial intelligence to comprehend emotions, recognize them, and to display them in intelligent ways. I will again apply for government funding, and to industry partners.