

## A CELESTial MANIFESTO

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Why is a Center with a research structure like that of CELEST appropriate, and even necessary, to understand how the brain works? There are several reasons for this:

### **BRAIN EVOLUTION IS GUIDED BY BEHAVIORAL SUCCESS**

First, there is the crucial observation that “Brain evolution is guided by behavioral success.” Even if a brain’s individual nerve cells, or neurons, are beautiful, if they cannot interact together to generate successful adaptive behaviors, Darwinian selection will eliminate that individual brain, and the entire species that possesses a brain like it. Thus, in order to understand brain *design*, one must discover and study the organizational level that can compute indices of behavioral success, and that drives the evolutionary selection process.

### **STUDY BOTH BRAIN AND BEHAVIOR TO UNDERSTAND EITHER ONE**

Progress can certainly be made by studying brain or behavior separately. However, in order to deeply understand either brain or behavior, in particular how the brain’s organizational principles and mechanisms achieve behavioral success, one must study both brain and behavior simultaneously. One needs to understand how a brain gives rise to a mind. Said in a more classical way: How can we solve the Mind/Body Problem? Although there has been enormous experimental and theoretical progress on understanding brain or mind, establishing a mechanistic link between them has been very difficult, if only because the gap between how a brain looks and how we consciously experience the world seems to be so enormous. Yet establishing such a link between brain and behavior is crucial in any mature theory of how a brain or a mind works.

### **WHY WE STUDY NEURAL NETWORKS AND SYSTEMS**

What is the brain *level* that can compute indices of behavior success? Forty years of modeling have shown that this is the network or system level. That is why people study “neural networks.” This fact might immediately raise the following concern: Does study at the network and system level imply that individual neurons are unimportant? Emphatically not! One must study how the individual neurons are designed, and how they are connected, to understand how their interactive, or emergent properties, which are the properties that directly control behavioral success, can successfully adapt to environmental challenges.

Thus, one of the reasons that brains are so hard to understand is that one must simultaneously study multiple levels of brain organization (neuron, network, behavior) in order to understand how the brain works.

Without a link between brain and behavior, the *mechanisms* of the brain have no functional significance, and the *functions* of behavior have no mechanistic explanation. In order to coherently bring together insights about both mechanism and function, on multiple levels of organization, one needs to have a Center with scientists who have interdisciplinary expertise that can cross and unify these levels.

One also needs a theoretical method that is powerful enough to bridge across multiple levels of description. As in all scientific endeavors, such a method requires rigorous models that are expressed in terms of an appropriate mathematical language.

### **WHY IS THIS THE RIGHT TIME TO FUND A CENTER LIKE CELEST?**

There are a rapidly growing number of models available that can quantitatively simulate the neurophysiologically recorded dynamics of identified nerve cells in known anatomies *and* the behaviors that they control. In this restricted sense, the Mind/Body Problem is at last being understood. Most of these brain/behavior modeling breakthroughs have been pioneered by CELEST scientists, and CELEST scientists have been building infrastructure for the last twenty-five years in order to be able to systematically lead this major scientific revolution. CELEST is a Center of Centers, whose individual Centers have gradually been formed over the years to meet this interdisciplinary challenge.

### **BOTH MECHANISM AND FUNCTION ARE NEEDED TO UNDERSTAND BRAIN AND TO CREATE NEUROMORPHIC TECHNOLOGY**

*Mechanism* tells us how something works. *Function* tells us what it is for. Both mechanism and function are needed to design and build new algorithms or machines for technology. By providing an analysis of brain and behavior, one provides the type of information that a technologist needs to transfer basic science studies about mind and brain into novel engineering and technological tools for solving outstanding societal problems.

There are obvious benefits of designing new technologies in a biologically-inspired way: Biologically-inspired technologies have a better chance to enjoy seamless human-machine interfaces and to thus work better under the direction of their human overseers.

There is, however, a deeper reason why brain-inspired technologies are so desirable. This reason also clarifies why study of the brain represents a truly revolutionary step forward in science.

### **LEARNING IS KEY: AUTONOMOUS ADAPTATION TO A CHANGING WORLD**

Forty years of modeling have shown that the brain is designed to achieve *autonomous adaptation to a changing world*. In other words, human and other advanced brains are unparalleled in their ability to rapidly, and on their own, adapt and learn from changing and unexpected environmental contingencies, and often do so with only the world itself as their teacher. Previous scientific revolutions in physics and other natural sciences have often clarified aspects of an unchanging, or *stationary*, world. In contrast, a human brain, as we well know from personal experience, is always developing and learning at a remarkably fast rate. The challenge of understanding how brains work is, on a technical level, the challenge of understanding how an intelligent system can so rapidly and stably self-organize its successful behaviors in response to an unpredictably changing, or *non-stationary*, world. Other revolutions in science will also need to face the challenges of dealing with uncertainty and change. The brain is a paradigmatic example of an advanced natural system that is unparalleled in realizing such a property.

Most successful technologies have been developed to work in, and to control, a stationary world. Many of the most urgent unsolved engineering and technological problems are about systems that need to autonomously adapt to a changing world. The combination of providing both mechanism and function for systems that are capable of autonomous adaptation to a changing world make brain-inspired technologies very valuable.

## **NONLINEAR, NONLOCAL, AND NONSTATIONARY FEEDBACK SYSTEMS**

What sorts of systems are used by the brain to achieve autonomous adaptation to a changing world? They are typically *nonlinear, nonlocal, and nonstationary feedback systems*. This sort of system cannot be understood without mathematically sophisticated modeling of a new type:

*Nonlinear* means that the whole is not the sum of its parts. For example, the brain can deal with rapid changes in processing load that require fast nonlinear compensation. This compensation can be at the receptor level, where rapid changes in the intensity and composition of light or sound can occur through time. They can also be at a higher information processing level, where environmental demands can require a rapidly changing combination of brain regions to solve each environmentally-imposed problem.

*Nonlocal* means that the brain uses widespread interactions, often interactions that connect other neurons that are in different parts of the brain. For example, the brain typically computes context-sensitive and spatially distributed *patterns* of information to control successful behaviors. These patterns may include the synchronous processing of millions of neurons in different brain regions.

*Nonstationary* means that the brain is continually changing its structure through fast development and learning in order to adapt successfully to changing and unpredictable environmental contingencies.

*Feedback* means that there is two-way traffic between neurons, as well as two-way interactions between individuals and their world. Such feedback interactions are needed to realize the nonlinear, nonlocal, and nonstationary properties of intelligent behavior.

Thus, to understand how the brain works, one needs to have modelers who are proficient in the concepts and mathematical methods than can clearly express the kinds of nonlinear, nonlocal, and nonstationary feedback dynamics that brains undergo at every waking moment.

## **COMPLEMENTARY COMPUTING: HOW BRAIN SPECIALIZATION IS ORGANIZED**

The manner in which the brain is specialized to carry out its intelligent behaviors also requires a Center-level coordinated interdisciplinary analysis. CELEST contains five basic science research Thrusts. This Thrust organization reflects the fact that different types of learning and memory need to be characterized by different research Thrusts. Indeed, recent experimental and modeling studies, notably modeling breakthroughs by CELEST colleagues, show that *no single type of learning and memory* accomplishes a broad spectrum of behavioral tasks.

In particular, perceptual and cognitive learning, by the cortical What processing stream, has qualitatively different properties than spatial and motor learning, by the cortical Where processing stream. In fact, these two sorts of learning exhibit computationally *complementary* properties: The ability of each stream to successfully compute some properties prevents it from computing other, complementary, properties. Complementary properties are related to one another much like two puzzle pieces fit together. Each piece helps to solve the puzzle, but the puzzle cannot be solved without both pieces and their seamless fit. In summary, brain specialization carries out *Complementary Computing*. This represents a revolutionary computational paradigm whose impact on society has not yet been felt. One needs an interdisciplinary Center to understand and put together the various parts of a system that operates by Complementary Computing.

Complementary Computing provides an alternative to the classical view that our brains are

proposed to possess independent modules, as in a digital computer. In such a view, vision occurs by processing perceptual qualities such as form, color, and motion using these independent modules. The brain's organization into processing streams supports the idea that brain processing is specialized, but it does not, in itself, imply that these streams contain independent modules. Independent modules should be able to fully compute their particular processes on their own. Huge perceptual data bases argue against the existence of independent modules. Indeed, strong interactions are known to occur between perceptual qualities. For example, changes in perceived form or color can cause changes in perceived motion, and conversely; and changes in perceived brightness can cause changes in perceived depth, and conversely. How and why do these qualities interact? An answer to this question is needed to determine the functional and computational units that govern behavior as we know it. CELEST is providing this answer.

As noted above, Complementary Computing implies that the properties of each processing stream are related to those of a complementary stream much as a lock fits its key, or two pieces of a puzzle fit together. One consequence of this fact is that the mechanisms that enable each stream to compute one set of properties prevent it from computing a complementary set of properties. As a result, each of these streams exhibits complementary strengths and weaknesses.

How do these complementary properties get synthesized into a consistent behavioral experience? It is proposed that *interactions* between these processing streams overcome their complementary deficiencies and generate behavioral properties that realize the unity of conscious experiences. In this sense, *pairs of complementary processing streams* are the functional units because only through their interactions can the brain compute complete information about key behavioral properties. These complementary interactions are being used to explain many of the ways in which perceptual qualities are known to influence each other. Thus, although analogies like a key fitting its lock, or puzzle pieces fitting together, are suggestive, they do not fully capture the dynamism of what complementarity means in the brain.

Why does the brain often need several processing stages to form each processing stream? Accumulating evidence suggests that these stages realize a process of *hierarchical resolution of uncertainty*. "Uncertainty" here means that computing one set of properties at a given stage can suppress information about a different set of properties at that stage. These uncertainties are proposed to be overcome by using more than one processing stage to form a stream, as in the What and Where cortical processing streams. Overcoming informational uncertainty utilizes both hierarchical interactions within the stream and the parallel interactions between streams that overcome their complementary deficiencies. The computational unit is thus not a single processing stage; it is, rather, proposed to be an ensemble of processing stages that interact within and between pairs of complementary processing streams.

According to this view, the organization of the brain obeys principles of uncertainty and complementarity, as does the physical world with which brains interact, and of which they form a part. CELEST models propose how these principles reflect each brain's role as a self-organizing measuring device *in* the world, and *of* the world, wherein it can detect even small numbers of photons and phonons. Appropriate principles of uncertainty and complementarity may better explain the brain's functional organization than the simpler view of computationally independent modules.

## **PERCEPTION-COGNITION-EMOTION-ACTION BEHAVIORAL CYCLES**

Why not study just one learning process? In order to mechanistically understand human learning and behavior, decades of data show that behavior is organized into

perception/cognition/emotion/action *cycles*. It is only through understanding interactions of the brain with its environment, cyclically through time, that real-time behavior can be deeply understood. The fact that perception/cognition vs. spatial/motor mechanisms obey complementary laws shows that, in order to understand even one behavioral cycle, one needs to integrate, or fuse, complementary computational properties. In particular, understanding a perception/cognition/emotion/action cycle involves *multi-dimensional What-Where learned information fusion*. In summary, multi-dimensional learned information fusion of complementary properties is needed to compute the complete information with which the brain solves functional behavioral problems. This insight of CELEST modelers has introduced the new paradigm into computational science that is called Complementary Computing. Our experimental and modeling teams have been carefully constructed both to further explain the complementary subsystems and to assemble them into complete functional systems.

The above concepts can be illustrated through two simple examples. In the first example, suppose that a child's task is to learn how to visually find and pick up a cup in order to drink her milk. To do so, the child needs to spatially orient to the cup, see it, recognize it, want to pick it up, and direct a movement that picks it up. The child's spatial orientation is primarily organized by the Where stream, cup perception and recognition by the What stream, and cup reaching and picking up by the Where stream. Thus, just drinking one's milk requires a complex temporal sequence of What-Where alternations. It also requires What-Where learned information fusion because recognition mechanisms tend to be size-invariant and spatially-invariant to prevent a combinatorial explosion of recognition codes. However, the object, such as the cup, that is recognized through such an invariant representation also needs to access the spatial representations that enable the child to know where the cup is so that it can pick it up. A child who can do this task in a fluent way must use learned perceptual, recognition, spatial, and planning representations within the visual, inferotemporal, parietal, and prefrontal cortices, as well as multiple subcortical brain regions.

In the second example, a child orients to her mother's voice and says a simple sentence like: "Mommy, give me milk." Such a deceptively simple action also requires a complex combination of What and Where processes ranging from early auditory filtering and source localization to speaker identification, speech perception, speech production, and language understanding that involve multiple cortical and subcortical brain regions.

Understanding how we learn even the simplest tasks on which our lives depend thus requires a system-level approach. CELEST science is organized to model such brain systems. The Center has enabled the types of scientific collaborations to form to accomplish this goal.

## **LAMINAR COMPUTING: HOW DOES THE CEREBRAL CORTEX WORK?**

The mammalian neocortex is the seat of higher intelligence in all modalities of perception, cognition, and action. For a century it has been known that many areas of the cerebral cortex have a characteristic organization into six distinct cortical layers. These layers include circuits that form functional columns in cortical maps.

Why does the neocortex have a ubiquitous laminar organization?

How does Laminar Computing give rise to biological intelligence?

In particular, how are bottom-up, top-down, and horizontal interactions organized within the cortical layers to generate adaptive behaviors? Because this six-layer laminar design is found ubiquitously, with suitable variations and specializations, in many perceptual and cognitive cortical areas, success in understanding how it contributes to behavior in one part of the brain should provide valuable cues to how it works elsewhere. An interdisciplinary Center is needed to understand how each of these laminar neocortical systems works and how variations on a shared laminar design can support seemingly very different types of biological intelligence.

Stephen Grossberg published a breakthrough article in 1999 which introduced the LAMINART family of models to illustrate how Laminar Computing works within the visual

cortex. This breakthrough is very relevant to the goals of the Science of Learning Center program, and is one of the reasons why CELEST organized itself to meet the scientific challenges of realizing this breakthrough. The breakthrough showed how bottom-up, top-down, and horizontal interactions are organized within cortical layers of the visual cortex to realize:

(1) the developmental and learning processes whereby cortex can rapidly and stably shape its circuits to realize successful behavior in a changing world;

(2) the binding process whereby cortex groups distributed data into coherent object representations; and

(3) the attentional process whereby cortex selectively processes important events.

A major model result, which permeates all the CELEST projects, is that the mechanisms governing (1) in the infant lead to properties (2) and (3) in the adult.

In other words, the mechanisms which enable the cortex to develop its circuits in a stable way and to alter them through learning later on in life in response to changing environmental inputs force key properties of visual information processing in the adult. Such a model begins to unify several different fields of psychology and neuroscience by showing how to mechanistically link the processes of infant cortical development to those of adult learning, attention, and perception.

Since the introduction of the Laminar Computing paradigm, and accelerated by CELEST funding, increasingly rapid progress has been made to being to classify how variations and specializations of laminar circuits can embody all of the types of intelligence that neocortex supports. In addition to many projects which clarify how laminar computing controls how the visual cortex sees, recent work clarifies how the prefrontal cortex organizes cognitive information processing, notably the storage of event sequences into a short-term working memory, the learning of sequential cognitive plans from the stored working memory items, and the control of sequences of planned actions that are controlled by these learned plans.

Having the scientific infrastructure to be able to make and coordinate discoveries in various parts of the cerebral cortex requires an interdisciplinary center like CELEST. One might argue further that the brain sciences, one of the last and greatest frontiers in the history of science, are ready for a much larger coordinated research program than CELEST. But certainly interdisciplinary Centers like CELEST are necessary to realize the potential that our present knowledge allows and even insists that we pursue.

## **LAMINAR COMPUTING: A REVOLUTIONARY COMPUTATIONAL PARADIGM**

As a new computational paradigm, Laminar Computing promises to realize revolutionary new possibilities:

(1) *Feedforward and Feedback*: The system runs as fast as it can in a feedforward mode when data are unambiguous. It spontaneously slows down when processing ambiguous data until it can make the best decision, given the uncertainty of the data, and then speed up processing again to express that decision. The system uses its internal feedback loops to reduce uncertainty and make such a decision. It operates like a real-time probabilistic hypothesis testing machine that can operate stably and adaptively in the non-stationary domain.

(2) *Analog and Digital*: The system's key property of *analog coherence* combines the stability of digital computing and the sensitivity of analog computing.

(3) *Pre-attentive and Attentive*: The system contains decision interfaces where bottom-up data-driven automatic pre-attentive processing combine with top-down goal-driven volitional attentive processing to make the best behavioral decisions, given the data.

We believe that this paradigm will have far-reaching consequences both in understanding brain and behavior and in providing a revolutionary new way to do intelligent computation.

When Laminar Computing models become sufficiently mature, they will provide a blueprint for VLSI chip designers to try to design a universal laminar chip set whose variations can support many different types of intelligence. These chips will, moreover, be manifestly self-consistent for integration within a larger system controller, say for an autonomous adaptive mobile robot, due to the fact that they have all been fashioned from the same underlying design, and will all connect in a stereotyped manner.

## **UNDERSTANDING MENTAL DISORDERS**

One great promise of brain and behavioral modeling is to better understand how prescribed breakdowns in normal brain function give rise to particular mental disorders. Recent work by CELEST modelers has led to proposals about how such major mental problems as autism, schizophrenia and amnesia may arise, and are providing growing insights into Parkinson's disease and attention deficit hyperactivity disorder.

It is certainly true that there is no substitute for pharmacological and biochemical research that can lead to the discovery of new drugs that help people who are afflicted with mental diseases. However, just knowing that a certain binding site is not working well in a given part of the brain does not explain how that malfunction gives rise to the behavioral symptoms that characterize the disorder. Nor does it explain how many different types of brain insults can lead to similar behavioral symptoms, how multiple brain regions can interact together to generate and perpetuate abnormal behavioral symptoms, or how these symptoms can be understood as variations of normal mental mechanisms.

Only rigorous models that describe system-level linkages between multiple levels of behavioral and brain organization can provide such an understanding. Such models can also best clarify how mechanisms of normal behavior break down during a mental disease. This can be achieved by performing model experiments to demonstrate how the normal behaviors are generated, and then showing how abnormal behaviors result from unbalancing or lesioning normal mechanisms

## **CREATING A NEW CURRICULUM THAT INCLUDES THE PERSON**

Education and technology are currently dominated by knowledge about how the external world works. There is a major imbalance in educational curricula, which often include subjects that describe how the external world works, but do not include information about how our own minds work. But what can be more interesting to students than understanding how their own minds work, and how their minds experience the world? On a societal level as well, what can be more important for a modern society to understand than how human intelligence develops, learns, and adapts to unexpected environmental challenges?

CELEST believes that using models of brain and behavior in a wide range of curricula can partially redress this balance. Such curricula can inspire students in multiple ways to become interested in new careers in science, medicine, and technology. CELEST is developing such curricula, both on the web and in print, with an aim to reach all levels from high school and the general public through the professional level. This is a very challenging goal, and CELEST resources are very limited to achieve it, but initial progress in this direction is already promising.