# COGNITIVE COMPUTING COMMERCIALIZATION: BOUNDARY OBJECTS FOR COMMUNICATION

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**ABSTRACT:** *We are poised to embark upon commercialization of a novel neurosynaptic substrate for cognitive computing. Neurosynaptic systems promise a new kind of intelligence—in everything and everywhere, essential to a smarter planet— that will deliver enduring value for science, technology, government, business and society. Realizing this potential requires a fundamental departure from conventional understandings and expectations about computing. We enlist design thinking and design methods to interpret key points of technological differentiation, harnessing the communicative power of tangible artefacts to engage stakeholders in envisioning possible futures. We present a combination of artefacts and abstractions as a basis for boundary objects to support communication about the benefits of the technology. Composable concepts, rendered vividly and intuitively understandable in this manner, are better suited to the inherent unpredictability of radical innovation.*

## 1. INTRODUCTION

### CONTEXT

To usher in a new era of cognitive computing (Modha et al. 2011), we are developing TrueNorth, a neurosynaptic computational architecture inspired by the function, low power, and compact volume of the organic brain. TrueNorth is a versatile substrate for implementing cognitive algorithms for sensor-actuator systems, developed under the DARPA SyNAPSE project. It comprises a scalable network of configurable, neurosynaptic cores. Unlike conventional computers which constantly shuttle vast amounts of data and program instructions between memory and a processing unit via a bus (the von Neumann architecture), neurosynaptic computation densely interleaves memory, processing and communication (in the form of synapses, neurons and axons) within each core. Computation is massively parallel, mediated by spike events between neurons and cores sent over an efficient message passing network. Neurosynaptic and von Neumann computation complement one another, however the ways in which one programs and solves problems—indeed the problems one chooses to address with neurosynaptic architecture—will be very different from the approaches taken in von Neumann computation.

The innovations underlying TrueNorth flow from a synthesis of advances in neuroscience, nanotechnology and supercomputing. A number of milestones have recently been achieved, including a versatile and efficient digital spiking neuron model (Cassidy et al. 2013) and demonstration of 256-neuron cores in 45nm silicon capable of executing real-time applications (Merolla et al. 2011, Arthur et al. 2012). A hardware-

equivalent software simulator supports algorithm development and is capable of scaling the architecture to an unprecedented 2 billion cores and $10^{14}$ synapses (Preissl et al. 2012, Wong et al. 2012). A novel programming paradigm facilitates object-oriented creation and reuse of efficient TrueNorth code (Amir et al. 2013). Finally, a number of software applications have been built that demonstrate the potential of the architecture and the value of the programming paradigm (Esser et al. 2013).

Neurosynaptic systems promise a new kind of intelligence—in everything and everywhere, essential to a smarter planet—to deliver enduring value for science, technology, government, business and society. To realize this potential, neurosynaptic technology must be harnessed to solve specific problems and address latent human needs, wants and desires. The technology must also ultimately compete in the marketplace, either by increasing capability or reducing cost. Surfacing opportunities and deciding which to pursue with available resources requires engaging multiple constituencies and stakeholders with diverse knowledge and expertise across technology, business strategy, market understanding and user need.

## MOTIVATION

TrueNorth's model of computation requires new thinking, not only on the part of programmers and application developers, but also by organizational decision makers who seek to link technological possibilities to market opportunity. While incremental innovation can be achieved on the basis of existing knowledge in well-charted commercial territory, radical innovation entails far greater uncertainty, the result of fundamental discontinuities with existing technologies and markets (Garcia & Calantone 2002). Barriers to successful commercialization of technological innovations have been identified in four areas (Barnes & Houston 2003): identifying markets and value propositions for technologies,

formulating business models and predicting future revenue to calibrate investment, defining strategy and structure to execute and finally, overcoming communicative and functional boundaries. While the fourth barrier specifically highlights communicative challenges, effective communication is required to surmount the other three barriers as well. Clearly, communication is of paramount importance in commercializing innovative new technologies. The challenge for TrueNorth is to anticipate the configurations of need, technological capability and market demand that will enable creation of an ecosystem to support and ensure continued development of the technology. This involves thinking differently, and communicating effectively, in an environment of inherent uncertainty about the final forms that the technology might take and the specific end-use applications in which it will eventually flourish.

## CONTRIBUTION

As we proceed with the development of TrueNorth, we anticipate large numbers of colleagues in a world-wide organization will begin to engage in surfacing possibilities and exploring opportunities. What is needed is a compact way of articulating core concepts about the technology and a broad sense of what it is capable of, in order for this process to be productive and efficient. We seek a vivid means of communication that will engage creative thinking to expand conceptions of possibility and, at the same time, convey structured concepts to facilitate the collaborations that lie ahead. We present a combination of artefacts plus abstractions to support the communication necessary to exploit the benefits of the technology. We believe composable concepts, rendered vividly and intuitively in this manner, are better suited to navigating the inherent unpredictability of radical innovation. In section 2 we describe conceptual tools we bring together in our approach, design thinking and boundary objects. In section 3 we present key technology differentiators and their potential value. In

section 4 we motivate the use of specific design methods to address the communicative challenges we face. In section 5 we present outcomes of the process to date, in the form of concept models for applications of the neurosynaptic computational substrate. Finally, in section 6 we discuss a deep structure of technology evolution and innovation to show how this aligns with the structure of the boundary objects we seek to create, anticipating future work.

## 2. APPROACH

### DESIGN THINKING

We turn to design thinking to broaden our exploration, to facilitate the emergence of new and creative ideas, and to foreground human experience and processes of meaning, interpretation and communication alongside the technology and technical considerations. Design, articulated by Herbert Simon (1996) is an activity aimed at realizing preferred futures. Simon's metaphor of design as *search* highlights decomposition and systematic exploration of a problem space. An alternate conception of design as *conversation* (Schon 1987) highlights its emergent and dialogical character, as well as the social and interactional basis of most commercially significant design activity. Other perspectives call attention to the centrality of *meaning and interpretation* in design (Krippendorff 2006), as well as the importance of *storytelling* (Quesenbery & Brooks 2010) to promote understanding and garner support. Design thinking is fundamentally *abductive* in nature, in that it aims to expand possibilities and open up new avenues for solution (Cross 2011).

Design thinking also involves *making*. Rapid prototyping characterizes innovative organizations and creative problem solving environments (Brown 2009, Leonard-Barton 1995). Models integrate viewpoints, expose and test assumptions to accelerate learning. The creation of models and a culture of prototyping are essential means by which organizations explore alternative futures

(Schrage 2000). Part and parcel with design thinking comes a commitment to *externalize and instantiate* concepts in tangible, physical form. This serves both to expose and test ideas, and to enhance their communicative effectiveness.

### BOUNDARY OBJECTS

Boundary objects (Star & Griesemer 1989, Star 1993) form bridges between distinct communities with diverse practices and objectives. Bringing TrueNorth to market will require people in a large, distributed organization, with different functions and distinct "thought worlds" (Dougherty 1992), to communicate and collaborate to identify opportunities and decide which to pursue. Boundary objects embody the common understandings that allow people to work together. They convey enough structure to ensure alignment and coherence while preserving interpretive flexibility to accommodate different expertise and points of view. Initially conceived to account for the loose-yet-effective coordination between trappers, biologists and curators involved in founding an early California zoology museum, the concept has been applied to scientific collaboration more generally, and increasingly in the management literature to communication and collaboration in organizations. Examples of boundary objects include repositories of samples and specimens, standardized forms, categories, techniques and processes, as well as maps, models and other objects that help people share vocabulary, meaning and knowledge.

Carlile (2002, 2004) identifies models as types of boundary object that directly support knowledge transformation. He describes how, for innovation to occur, stakeholders must relax their grip on existing knowledge and forego some things they may have invested significant time and energy to learn to embrace new knowledge opportunities. However, the examples Carlile uses are not drawn from such a profound departure from convention as our neurosynaptic substrate. The question remains,

what might boundary objects look like when situated in the early stages of radical innovation, when outcomes are unpredictable and ways of framing problems require a substantial departure from conventional thinking? How can we conceive a space of possibility for TrueNorth applications, and what forms might these take? These are the questions we will explore in the remainder of this paper.

## 3. AN "ETHOS" FOR NEUROSYNAPTIC COMPUTATION

TrueNorth is a hardware substrate for fundamentally brain-like computation. We set out the following as an "ethos" to differentiate it from conventional technologies, and to highlight the application benefits that we believe are achievable.

PHYSICAL ATTRIBUTES: *COMPACT, LIGHTWEIGHT, LOW POWER*

The human brain consumes on the order of 20W, but simulating even simple neurons in a network of this scale with current von Neumann computation could require gigawatts. The ultimate DARPA goal for the SyNAPSE program is a system of $10^{14}$ synapses dissipating 1kW. The biophysical richness and 3D wiring of organic neurons are currently beyond our reach, so to meet this aggressive target we must rely on what is achievable with current semiconductor technology. The high density of CMOS logic, currently on the order of 1 billion transistors per $cm^2$, is well-suited for compact and portable devices. Compared to existing chip multi-processors, TrueNorth's neurosynaptic processing confers tremendous power advantages. Low power obviates the need for large batteries and bulky power supplies, further reducing the size and weight of potential TrueNorth-based systems.

INFORMATIONAL ATTRIBUTES: *MULTI-MODAL, SUB-SYMBOLIC, SPATIO-TEMPORAL, LOW-PRECISION, HIGH-DIMENSIONAL*

Biological computation transduces all sensory and motor signals to a common language: spikes—that is, signaling events communicated from neurons to target destinations via axons. This "lingua franca" enables the fusion of multiple sensory modalities (e.g. taste, touch, sight, sound and proprioception) into a seamless awareness and understanding. It also enables all manner of feed-forward, lateral and recurrent network connections such as, for example, between sensing and motor systems. This flow of information via spikes is referred to as sub-symbolic information—that is, raw, discrete event signals derived directly from sensors and actuators. This contrasts with symbolic information like text, high-precision numerical values and formulas that we are accustomed to manipulating in conventional von Neumann computing architectures.

Multi-layered neural networks excel at identifying patterns in sub-symbolic information that unfold over space and time, such as the movement of an image across the retina, or the patterns of vibration along the cochlea that correspond to the sound of one's name in the din of a crowded room. TrueNorth performs rapid, low-fidelity processing of high-dimensional data. Capturing correlations across space, time and sensory modalities, high-dimensional representations play an important role in reliably extracting information from noisy and ambiguous data in real world environments.

ARCHITECTURAL/ALGORITHMIC ATTRIBUTES: *PARALLEL, SCALABLE, EVENT-DRIVEN, DISTRIBUTED*

Unlike the long, sequential algorithms developed for von Neumann architecture, algorithms in TrueNorth should ideally be short and parallel. This means recognition and actuation can begin after just a few layers of neuronal activation, as opposed to thousands or millions of CPU cycles shuttling bits between processor and memory (the so-called "von Neumann bottleneck"). Computation in neurosynaptic systems is a function of the dynamics of spiking neurons and their patterns of synaptic connectivity. Processing and memory are closely intertwined, circumventing

the von Neumann bottleneck entirely. The TrueNorth architecture is extensible and tileable to handle problems at different scales; more chips allow greater input resolution and more complex computations. In contrast to armies of transistors feverishly marching in synchronous lock-step, neuronal activation is event-driven. Since neurosynaptic systems excel at detecting patterns, this means things happen quickly when interesting events occur, while systems remain largely quiescent (consuming very little power) the rest of the time. The inherent sparseness of high-dimensional representations and event-driven processing reduce power consumption and minimize the propagation of uninteresting and redundant information. This suggests a strategy of pushing computation out to the periphery of networks, so that processing becomes distributed rather than centralized, making sensors integral to the computation not just drivers of ever-increasing volumes of data to be analyzed later.

PERFORMANCE ATTRIBUTES: *REAL-TIME, ROBUST*

The proliferation of cameras and sensors in our increasingly instrumented world generates a tsunami of data that exceeds our capacity for analysis and sense-making. The neurosynaptic paradigm for cognitive computing is a real-time paradigm. Parallel algorithms operating on high-dimensional, spatio-temporal, sub-symbolic inputs, taking advantage of our scalable architecture, will be able to deliver meaning and insight when and where they are needed. Neurosynaptic computation is also suited to detecting incomplete or sparse patterns, as well as remarkably robust to noise in the sensor and the environment.

PROGRAMMABILITY ATTRIBUTES: *DISCRETE, REPRODUCIBLE, CONCURRENT, COMPOSABLE & REUSABLE*

Certain programmer-friendly attributes simplify the process of creating TrueNorth programs. Despite being event-driven, the architecture is temporally discrete. The computation operates with millisecond fidelity that gives us a 1:1 correspondence between hardware and software, ensuring reproducibility and cross-validation. This means it is possible to time step even large networks to observe and debug activity. TrueNorth follows a concurrent programming model, where every neuron computes a short, configurable set of operations every time step, in parallel. Programming TrueNorth consists of specifying (1) the computation performed at every neuron, and (2) the pattern of connectivity between neurons. A programming environment has been created (Amir, et al. 2013), that exploits object-oriented methodologies (e.g. encapsulation, inheritance, abstraction & polymorphism). This enables creation of TrueNorth programs from a library of composable, re-usable functional blocks. Operations currently implemented in the library include various mathematical functions, signal routing, signal processing, vision and machine learning algorithms.

TrueNorth is Turing complete, which means it can execute any conceivable program; however not all programs will execute with equal efficiency. The substrate will offer outstanding advantages for the types of computation outlined above, while it may be less suited for others. Good programmers will develop an intuition about the approaches and techniques that make best use of the neurosynaptic hardware. Our goal is to make this knowledge explicit and communicable as it develops.

Through this discussion we have sought to lay out some key points of differentiation; how we operationalize these abstractions and make them more consumable to stakeholders in organizational decision making is the subject we turn to next.

## 4. DESIGN METHODS AND CONCEPT MODELLING

Beyond the abstractions, what might this new technology really do for people, and what forms might it take? To bring design methods to the SyNAPSE project, a team was formed

comprising IBM industrial designers whose "day jobs" involve shaping user experience of the company's systems and technology products. These designers met in depth with technical experts in neurosynaptic computing over a period of days, then amongst themselves and with subsets of the technical team on a regular basis over a period of months.

Industrial designers are accustomed to using models and scenarios as vehicles for explanation and storytelling to convey the potential of a new technology. Models illustrate a compelling end point for a product or an idea in tangible form to which people—specialists and non-specialists alike—can relate. They render the opaque functions of technological objects more immediately and intuitively understandable. Three-dimensional models are a powerful means of communicating ideas for a number of reasons. By virtue of their physicality (size, graspability, finish details, etc.), models evoke tacit knowledge from everyday experience, triggering potentially generative associations (Mascitelli 2000) and intuitively grounding what an object might be like in interaction.

The design objective has been to align technological capability with compelling human needs, wants and desires. Concept modelling is intended to evoke interest around key attributes of the technology, reinforce this through physical experience and interaction with prototypes, and consolidate understanding with narrative and storytelling around each artefact. Embodied experience plays a central role in human reasoning and cognition (Clark 1998). Norman (2004) explains how three levels of cognition interact to shape our response to objects and products around us. Specifically, a visceral, affective reaction precedes behavioural (interaction) and reflective (rational) levels of cognition. Positive affect can serve to make people more creative, open and receptive to new ideas. The strongest impact is achieved when experience across all three levels is consonant and mutually reinforcing.

The design team has also been attuned to semantic and symbolic aspects of design (Krippendorff 2006). Metaphor, metonymy and semantic cues were used to invoke naturalistic forms and lifelike behaviours. Alternative energy sources, such as solar cells, were incorporated to exemplify the technology's low power characteristics. In other cases, formal semantics were drawn from familiar objects to establish connection to existing product categories. In brainstorming and idea generation, participants were encouraged to strike a creative balance—projecting into the future to conjure an interesting vision, grounded in feasible capabilities but not overly constrained by current limitations. The team aimed for ideas that were aspirational yet relevant, conceptually playful but not fanciful, optimistic but not delusional. Ideas were grouped and categorized to structure concept spaces, from which certain directions were selected, scenarios developed, and concepts iteratively refined.

## 5. CONCEPT MODEL DESCRIPTION

Several concepts were taken forward into physical, three-dimensional model form. These models tangibly illustrate combinations of attributes of neurosynaptic computation to convey the potential of this cognitive computing technology. The models communicate visions of possible systems. They are grounded yet optimistic projections into the future for the purpose of establishing a useful end point or vision. They do not embody engineering specifications of buildable systems in and of themselves, nor are they intended to represent commercially viable products. Rather, the understandings and interpretations they embody provide input into the ongoing work of communicating the potential of the technology and formulating a commercialization strategy.

A key attribute of TrueNorth architecture is its scalability, from single-chip systems with about as many neurons as a bee, to some of the largest hardware neural networks

contemplated. *BrainCube* (Fig. 1a) illustrates a system with hundreds of chips. It incorporates a visualization, based on simulations of spike dynamics, showing how activity might propagate through a network of this scale. Periods of quiescence are punctuated by bursts of activation that spread rapidly from multiple points, evoking the manner in which sensory input can trigger multiple memories, associations and responses. *Sensor Leaves, Conversation Flower* and *Jellyfish* (Figs. 1b,1c,1d) illustrate compact systems for intelligent sensing, with low power requirements emphasized by solar cells. The *Leaves* illustrate feature detection from different sense modalities in a lightweight, air-droppable package that rights itself upon unfolding. Transmission of detected features (via mesh networking) rather than raw signal affords tremendous reduction of bandwidth and consequent power savings. The *Flower* fuses two modalities, vision and audition, to attend and respond to people engaged in conversation around it. Recognizing features to detect faces and movement correlated with participants' voice spectral content, the *Flower* opens in response to energetic conversation; boring or one-sided monologues may cause it to go to sleep. The *Jellyfish* is a floating sensor buoy for monitoring hazards, pollution etc. in seas and waterways. Harvesting wave energy as well as solar power, it detects distinctive acoustic signatures and triangulates features between multiple units operating in tandem. The *Tumbleweed* (Fig. 1e), is a rolling search and rescue robot illustrating complex image processing and closed loop control. Driven by an internal, eccentric mass, the outer surface is studded with dynamic, switchable cameras controlled by an inertial vestibular system.

Additional models, *Vision Cubes* (Fig. 1f, 1g) and the *Vision Assistive* (Fig. 1h), embody TrueNorth's image processing capabilities in different ways. The *Cubes* (Fig. 1f) are ultra-compact, situation specific feature detectors that could operate standalone or embedded in "smart cameras" to recognize desirable or adverse events in process monitoring, transportation, health and safety situations. A composable version (Fig. 1g) allows multiple cubes to be ganged together to perform more complex recognition tasks, such as assessing the engagement of a particular demographic in a retail or advertising setting. The *Vision Assistive* (Fig. 1h) is a more complex system with additional functionality fully exploiting the potential for compact, TrueNorth-based wearable devices. It is a head-mounted, multi-camera system able to process environmental images and sound to extract useful information for visually-impaired users to aid them in daily life, for example by providing dynamic audio feedback to assist wayfinding, navigation and operation of appliances and other screen-based devices. (This type of sophisticated vision processing could give cars and robots the ability to see as well.)

Other models are situated in more familiar product categories. Healthcare is an area in which we envision great potential for TrueNorth-based systems. In addition to improved imaging and multi-modal monitoring devices, better management of chronic conditions could enhance quality of life and defray massive systemic costs associated with emergency care. This inspired a pair of models of portable home health diagnostic devices, the *Wand* and the *Pulmonary Monitor* (Fig. 1h). The *Wand* would diagnose ear, nose and throat infections on the basis of vision, temperature and olfactory analysis of off-gassing from microbial pathogens. The *Monitor* would combine volumetric measurement of respiration, oxygenation and circulation, with acoustic analysis of chest and lung sounds during breathing to aid in the management of chronic respiratory conditions. Finally, *Build-a-Brain* (Fig. 1i) is a large-scale system that could operate in conjunction with von Neumann computation in a data centre environment, for example doing real-time indexing and perceptual search across simultaneous video streams. This system draws inspiration from distinct types of connectivity in the mammalian brain: cortical folding for dense local communication, long-distance
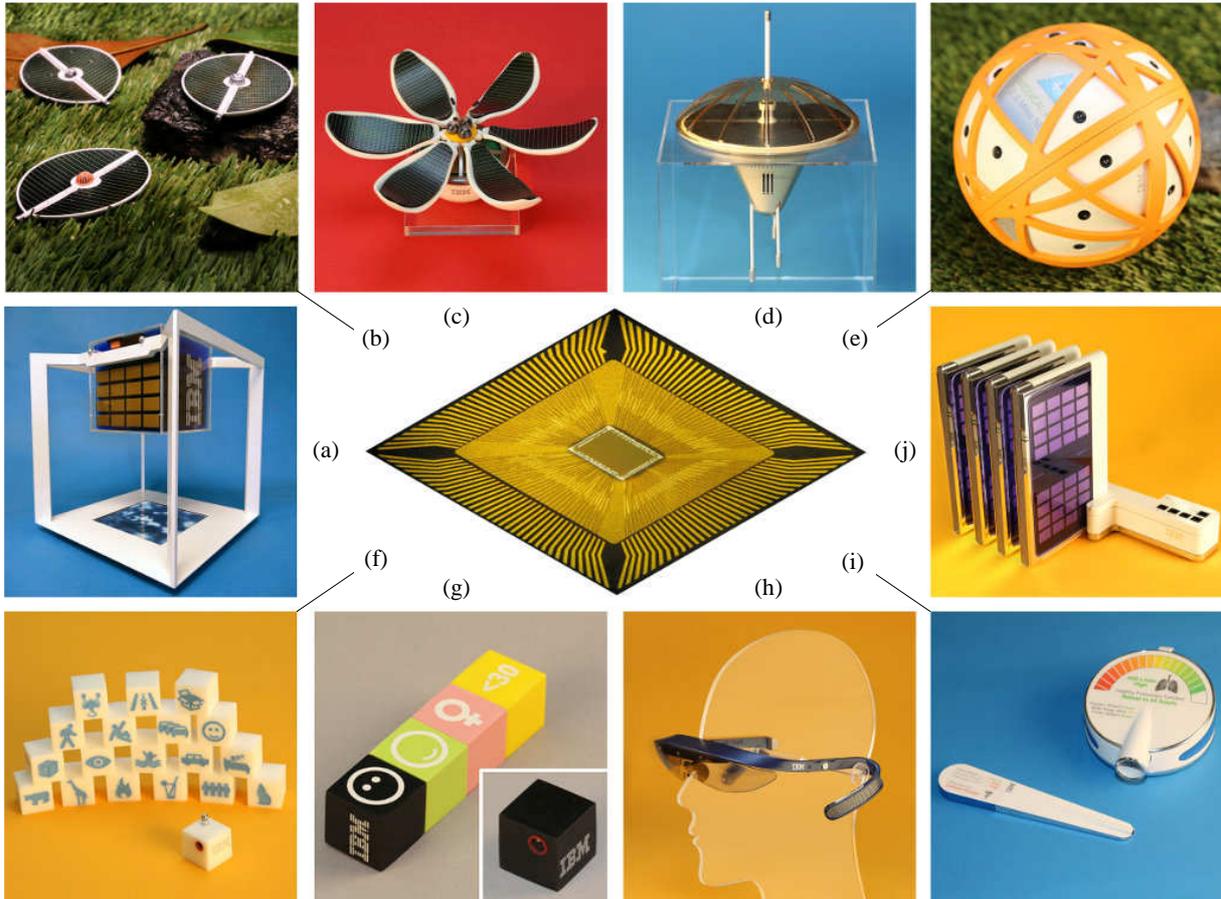
Fig. 1 Concept Models: (a) BrainCube, (b) Sensor Leaves, (c) Conversation Flower, (d) Jellyfish, (e) Tumbleweed, (f) Vision Cubes, (g) Composable Cubes, (h) Vision Assistive, (i) Home Health Wand and Pulmonary Monitor, (j) Build-a-Brain

white-matter connections linking the hemispheres, and a "thalamus" for sensor and motor connections.

These models illustrate use of different sensors and combinations of modalities in diverse environmental settings, traversing a range of processing problems from object recognition & classification to scene understanding, user interface and closed loop control. The systems envisaged cross a range of scales from single-chip to large-scale systems in stationary, mobile and autonomous applications. Even so they represent only a small fraction of the concepts discussed, and a miniscule slice of the space of the potential that can be imagined.

## 6. DISCUSSION

Neurosynaptic computation promises a new kind of distributed, embedded intelligence for smarter products, infrastructure, environments and services. It entails a fundamental departure from conventional paradigms. To identify new opportunities it will be necessary to think differently about current problems, as well as latent human needs, wants and desires. To realize the technology's potential in a commercially viable and sustainable way, it will also be necessary to bridge multiple constituencies and stakeholders with diverse knowledge and expertise. These communicative challenges span individuals, domains of knowledge, and functional boundaries in organizations. To address these challenges, we rely upon design thinking to broaden our exploration and facilitate the emergence of new ideas, as well as to prototype and instantiate concepts in physical form to enhance communicative effectiveness. We recognize boundary objects as an important class of communicative artefact that enables collaboration in open systems, but the optimal form to support commercializing a radical innovation has not been clear.

We have taken the first steps to envision end use applications for this new technology; future developments, however, are not predictable. How can we anticipate the process of matching capabilities to commercial applications? We call attention to parallels between the structure of the artefacts and abstractions we have discussed, and the deep structure of technology evolution as described by Arthur (2009). On Arthur's account, technologies are purposed systems that evolve through recombination and "re-domaining." Recombination is manifest in the novel composition of hierarchical systems and subsystems to achieve a purpose. Re-domaining is the repurposing of technological solutions from one domain of application to another. Innovation is driven by combinatorial evolution of technologies that reveal new phenomena, which are then captured (with the aid of science) and harnessed by successive waves of technology.

The ethos recounted in Section 3 is a set of abstractions that describe technical capability. These *attributes* have been embodied in concept models that instantiate them in various combinations with respect to particular *domains* and *purposes*. It is this triadic relationship that is interesting and important. The abstractions themselves, even if presented as a clear and coherent list, are only one third of the triad. It is the conceptual ethos *plus* the models—the abstractions that are embodied and instantiated—that form an effective basis for communication and collaboration. The proposition we wish to advance is that by anticipating the combinatorial space of technology evolution in the structure of the boundary objects we seek to create, the resulting communicative artefacts will be better suited to cope with the uncertainty inherent in radical innovation.

Star (2010) makes it clear that boundary objects are integrated in infrastructure and embedded in practice. At this point in time, what infrastructure will be most helpful in identifying possible TrueNorth applications and formulating a commercialization strategy?

We argue it is a compact, generative way of articulating what the technology will be good for and the value to be obtained—on the basis of foundational attributes (our ethos), illustrated with regard to a domain, for a particular purpose. These are the fundamental, reconfigurable elements that will shape the evolution of the technology. We have created reference points for conversation, but these will not constitute fully-fledged boundary objects until they are incorporated in actual practices and collaborations, within and between the communities we have mentioned. The abstractions and artefacts we describe have been assembled from the perspective of designers and developers of the technology. Boundary objects need to be completed in a reciprocal manner by contributions from other sides. We can anticipate the next steps along the path of actual collaboration required to make the commercialization of neurosynaptic computation a reality. Expertise in markets and industries will bring to *domain* specific needs, assessments of market size, likely penetration and profitability to gauge returns and calibrate investment. Expertise in technologies and user need within each domain will bring to *purpose* specific problems, challenges, performance parameters and tradeoffs. These, in conjunction with fundamental *attributes* of the technology, operationalized in each setting, will provide the basis for competitive differentiation. Strategy will prioritize certain markets and industries over others, and the whole process will proceed in an iterative and non-linear manner—which is why boundary objects are essential.

Rather than attempt precise predictions of the first commercially viable applications for this new technology, we have taken a design-led approach to refine elements of an ethos and created physical models to communicate possibilities more viscerally and intuitively. From an innovation standpoint, we are prototyping triadic combinations of attributes, domains and purposes. Incorporated in boundary objects, these composable and reconfigurable concepts will help business and

technical stakeholders navigate the commercialization decisions that lie ahead.

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