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Becoming Knowledge: Cognitive and Neural Mechanisms That Support Scientific Intuition

SANJAY CHANDRASEKHARAN

> "... *a guy who just had a sense of intuition about these kind of aerodynamics problems. He sort of feels what the air wants to do.*"
> Colleague commenting on how aerodynamics researcher Richard Whitcomb developed the Area Rule, a design principle for minimizing shock waves in supersonic flight.
> (Ferguson, 1983, p. 54)

Intuition, whichever way the process is defined, has a significant biological component, simply because intuition exists in, and for, organisms. An effort to characterize this biological component would be useful in understanding the nature and function of intuition. However, similar to the case of consciousness, such a mechanism description will not provide an exhaustive account of the intuition process. Acknowledging this limitation up front, my objective here is to develop an account of the possible mechanisms underlying one specific type of intuition – the ability to accurately gauge/ predict the nature/behavior of complex external entities, particularly their underlying mechanisms and other inanimate components, often using indirect means of perception, such as instruments and models.

The practice of science is the major domain of this type of intuition, so my analysis will focus on the possible cognitive/neural mechanisms that support this process in science. As I use the term in the context of science, "intuition" refers to the *cognitive process* that underlies the discovery of new aspects of complex entities in the world. This cognitive process is not available for articulation, and its critical role is the *integration* of explicit and implicit results emerging from standard elements of the scientific methodology (such as observation, taxonomy, experimentation and modeling), which, by themselves, do not lead to the discovery of complex mechanisms and structures. A process integrating

the results of these methods, into a cohesive pattern, is crucial for discoveries.

The key features that delineate the scientific intuition process I am interested in are thus: 1) its implicit nature (unavailability for articulation), 2) integration of disparate inquiry elements, and 3) its ability to accurately predict the nature of complex, inanimate, and dynamic structures that are often not available to perception. The mechanism account I develop in the next two sections will help outline some more aspects of this type of intuition, and this is the objective of developing this account. The third section summarizes my mechanism account. The final section outlines how this mechanism account informs our understanding of intuition.

OUTLINE AND AIMS

My starting premise is that an implicit cognitive process is involved in integrating results from different scientific methods. This integration, which requires some common cognitive thread that allows connecting the different methods, leads to new, and accurate, understanding about the behavior of entities in the external world, such as an understanding of "what air wants to do." What kind of neural/biological mechanisms supports this implicit process? This is not a purely theoretical question.

In August 2010, *Nature* published a paper where roughly 200,000 players of a Web-based videogame were included as authors. The paper (Cooper, Khatib, Treuille, Barbero, Lee, Beenen, Leaver-Fay, Baker, & Popović, 2010) reported how the re-representation of the protein-folding problem as a multiplayer videogame, *Foldit*, allowed the generation of many novel protein-folds by Web-based groups of ordinary people. Using *Foldit*, a 13-year-old boy with no background in biochemistry was able to develop an intuitive (i.e., implicit and integrated) sense of the mechanics of protein folding, and emerge as a protein-folding prodigy, whose solutions were judged better than the best biochemists' in the top international competition on protein folding. When the researchers asked him how he knew which folding structures were good, he shrugged and said, "It just looks right" (Bohannon, 2009).

One way to think about this response is to consider Foldit as a platform that makes it possible for non-scientists to understand, in an implicit and integrated fashion, what "proteins want to do." The *Nature* paper proposed that such harnessing of people's visual and spatial reasoning abilities (which are procedural skills and therefore implicit) using model-based games could be a new method to solve challenging scientific problems. Supporting this view, Foldit players have now made some remarkable discoveries, including,

in a couple of weeks, the structure of a protein causing AIDS in rhesus monkeys, a problem that scientists could not solve for 15 years (Khatib, DiMaio, Foldit Contenders Group, Foldit Void Crushers Group, Cooper, et al., 2011). The game is currently being refined, to support the development of new drugs by the players. A recent spinoff of Foldit, EteRNA, allows gamers to design molecules of ribonucleic acid (RNA). Some of the designs, when found promising by the EteRNA game community, are physically synthesized in a Stanford biochemistry laboratory, and the results are fed back to the designers to improve their designs. This closed loop process has led to gamers discovering fundamental principles underlying RNA structure (Koerner, 2012). Another game, Phylo, tries to solve the problem of optimizing DNA sequences. EyeWire is a game from MIT in which users model how neurons are wired. Astronomy has a similar crowdsourcing effort for classifying data from Hubble and other probes, named Galaxy Zoo, which has resulted in at least 30 peer-reviewed science papers, and a new astronomical object (Hanny's Voorwerp) named after the Dutch schoolteacher who identified it.

These games mark a fundamental shift in the practice of science, particularly an acknowledgment of the implicit component of scientific cognition. The games also mark a shift in the direction of knowledge, which has traditionally been implicit to explicit. For instance, in many areas of biology, the effort is to capture implicit procedural knowledge (such as flight patterns and navigation) in explicit declarative terms (such as aerodynamics and signaling). In physics, procedural knowledge (such as the qualitative understanding of force) is considered to lead to misconceptions, and declarative knowledge (such as Newton's Laws) is used to explain many aspects of phenomenal experience. Given this procedural-to-declarative trajectory of scientific knowledge, the case of Foldit and other games is unique, as they re-represent declarative knowledge using a manipulable interface so that naive participants can use their procedural knowledge to discover novel patterns. This process raises the question of what mechanisms allow this re-representation (and back), and what is the nature of the relationship between declarative and procedural knowledge, such that this translation is possible, and new discoveries could emerge from this process. At a more applied level, how could the visual and tactile manipulation of model elements on screen, by groups of non-scientists, quickly lead to discoveries about imperceptible molecular entities they have never encountered, especially discoveries that have eluded senior scientists for many years? What cognitive and biological mechanisms support this process of "crowd-sourced" discovery using manipulable models? How can these

mechanisms be harnessed to develop other collaborative games/interfaces that address more complex and abstract problems with wider applicability, such as, say, developing bacteria that can break down plastic waste? These questions provide a pressing pragmatic context to the problem of understanding the cognitive and neural mechanisms that allow humans to develop accurate understanding about entities in the external world.

In this chapter, I review some recent theoretical and experimental results from cognitive science and neuroscience, which, I will argue, suggest mechanisms that underlie this type of knowledge and discovery. Roughly, these results indicate a *participation* relationship the body develops with entities in the world, and I argue that this participation is a common thread that runs through all scientific methods, and is part of the process that allow us to develop accurate knowledge about external entities, as well as make discoveries about their structure and behavior. This participation mechanism, based on actions and movements, is what is exploited in developing the video game, which involves turning the declarative knowledge (about protein folding, RNA, neurons, galaxies, and so on) into a set of action procedures. The participation mechanism also accounts for how nonscientists could make veridical discoveries using the game. "Participation" and "mechanism" are usually considered to be mutually exclusive categories of analysis, but this distinction breaks down in my account, as the notion of participation is critical to the account I develop, while the nature of participation I propose is similar to resonance, which makes it closer to a mechanism.

Instead of just reviewing the experimental results to develop my account, I will take an application approach, using Michael Polanyi's concept of "indwelling" (Polanyi, 1958, 1966) as a starting point and "vehicle" for my account, and illustrating how the emerging experimental results could be used to develop a mechanism account of this particular notion of scientific intuition. Indwelling is a good starting point and vehicle because it focuses on all the three features of the intuition process I am interested in: 1) implicit nature of scientific understanding, 2) the role of integration in discovery, and 3) accurate understanding of external entities. I follow this application approach for four reasons. One, the most difficult part – developing a descriptive-level characterization of the implicit process leading to scientific discoveries – has already been done by Polanyi. This original, and highly influential, account makes a lot easier the problem of trying to understand the cognitive and biological mechanisms underlying scientific discovery, as it provides a good framework to think about, and bring together, the cognitive mechanisms. Two, an account of indwelling contextualizes the

embodied cognition results I report, and this would allow readers to more clearly understand the relevance of these results to the problem of scientific intuition, and intuition in general. The application to indwelling also provides an illustration of the wide theoretical possibilities offered by these results. Third, developing this account helps me think through the connections and interactions between the different results, and thus allow these to be made explicit as well. Finally, since Polanyi considered indwelling as the process by which scientific knowledge is developed, a mechanism account of indwelling would illustrate the close interconnections between rational thought and intuition.

I would like to emphasize here that I am using the indwelling concept as a starting point, a vehicle to illustrate my mechanism account. The mechanism account I offer is, thus, not intended as a definitive account of the mechanism underlying the indwelling process.

I will use the following description of indwelling offered by Polanyi to develop my account, as it offers the clearest connections to the cognitive science literature. The emphases (in italics) are mine.

> My body is the only thing in the world I normally never experience as an object. Instead *I experience my body in terms of the world to which I am attending from my body. I continuously rely on my body as a subsidiary means for observing objects and other comprehensive entities outside* and for using these entities for my own purposes.
>
> *The kind of knowledge I have of my body by dwelling in it is the paradigm of knowing particulars subsidiarily with a bearing on the comprehensive entity formed by them.* Hence when I rely on my awareness of particulars for attending to a whole I handle things as I handle my body. In this sense *I know comprehensive entities by indwelling their functional parts, as if they were parts of my body. Such is my conception of knowing by indwelling.*
>
> *Through indwelling I participate in comprehensive entities,* from my own body and the objects I perceive, to the lives of my companions, and *the theories we employ to understand inanimate matter* and living beings. *I partly transform myself in that which I am observing and thereby extend my range of knowing to include knowledge of all the hierarchies* – from inanimate matter to the frameworks of our convivial settings and the firmament of obligations which supervene the operations of our intelligence within these frameworks.
>
> . . . .
>
> *Our view of life must account for how we know life; biological theories must allow for their own discovery and employment.* Theories of evolution must provide for the creative acts which brought such theories into

existence. *Beginning with our own embodiment our theory of knowledge must endorse the ways we manifestly transcend our embodiment by acts of indwelling and extension into more subtle and intangible realms of being,* where we meet our ultimate ends.   (Michael Polanyi, 1970)

Indwelling is a very complex concept, and I focus only on some of its aspects, particularly the italicized sections in the previous quote. I read these as making the following statements:

1. The body is not known as an object – it is known through its interaction with entities outside it.
2. New knowledge of external entities can be considered to arise in an interactive fashion similar to this knowledge one develops of one's own body.
3. Just as one dwells in one's body and know it, one can dwell in external entities, particularly inanimate ones, and know them, especially how the interactions of components relate to how the components cohere as a whole.
4. Such indwelling (of external entities) is a gradual process, where one participates in external entities, and know them by transforming one's body in relation to them.
5. Indwelling allows us to transcend our embodiment, by extending us into more subtle and intangible realms of being.

I will focus on numbers 3, 4 and 5, and outline recent results from cognitive science and neuroscience that suggest mechanisms which allow this type of knowing by gradual participation. These results are only indicative of such mechanisms, and do not rule out other mechanisms. They support three types of knowing – physical, perceptual and imaginative. Together, they offer mechanisms of "knowing by becoming," similar to the account of indwelling offered by Polanyi above, where one cognizes entities in the world by making them part of oneself, in a comprehensive fashion, and using the body to resonate these entities' abilities/properties/dynamics.

MECHANISMS THAT SUPPORT INDWELLING

I will outline the possible mechanisms underlying indwelling in three sections. The first section outlines evidence showing how external entities (primarily objects) are physically incorporated into the body schema, and how this revised schema leads to changes in cognition. The second section outlines evidence showing how movements of external entities could be

made part of the body schema through perception (i.e., without physical incorporation), and how this leads to changes in cognition. The third section outlines evidence showing how movements of external entities are made part of the body schema through imagination (i.e., without either physical incorporation or perception), and how this leads to changes in cognition.

Incorporating Objects into the Body Schema

A number of studies in monkeys have shown how the body schema is extended to incorporate external objects, particularly tools (for a review, see Maravita & Iriki, 2004). One influential study (Iriki, Tanaka, & Iwamura, 1996) examined the firing of bimodal neurons before and after a monkey learned to use a stick to gather food. Bimodal neurons in the intra-parietal cortex respond to both somato-sensory and visual input on or near the hand. That is, the bimodal neurons coding for the hand area will fire when the hand is touched, as well as when a light is flashed on the hand. Interestingly, this firing happens when the light is flashed not just on the hand itself, but also in the space close to the hand ("peripersonal space"), indicating that the neurons code for the space of *possible activity*, rather than just the hand. Iriki et al. examined whether this firing pattern changed when the monkey started using a stick as a tool. This investigation was done in three phases. In the first phase, there was no stick and the light was flashed on and near the hand, and the bimodal neuron fired. In the second phase, the monkey passively held the stick, and the investigators flashed the light near the monkey's hand, as well as at the end of the stick. The bimodal neuron fired only when the light was flashed near the hand. In the third phase, the monkey used the stick to retrieve food from a location that was not reachable by its hand. Immediately after this intentional action, the investigator flashed the light on the hand as well as at the end of the stick. The bimodal neuron now fired for light flashes near the hand as well as at the end of the stick, showing that the peripersonal space (the area of possible activity coded for by the neuron) had been extended to include the area covered by the stick. The intentional action led to the stick being incorporated into the body, and the monkey's peripersonal space (possible activity space) now extended to the entire area, and objects, reachable by the stick. I will term this "active" incorporation, as the extension occurs only through intentional action. This extension of peripersonal space is important, as it shows that such incorporation is not just about adding an external entity to the body schema. Incorporation expands the range of possible activities the monkey can do – in terms of

location of activity, other entities involved, nature of activity, the number of activities, and the permutations and combinations of activities. This expanded range also extends the monkey's understanding/knowledge of the stick, as well as the space around it, which is now understood in relation to the stick. The monkey's cognitive capacities are thereby expanded. Similar incorporation of external entities into the body schema has been shown with humans as well (Farne, Iriki, & Ladavas, 2005).

An interesting variation of this incorporation effect (which I term "passive" incorporation) is the rubber hand illusion (RHI, Botvinick & Cohen, 1998). In this experiment, one hand of the participant is placed on a tabletop, and is visible to the participant. The other hand is placed on the participant's knee, under the table, and is not visible to the participant. The experimenter then places a rubber hand on the tabletop, above and parallel to the unseen hand, and next to the seen hand. The wrist end of this rubber hand is covered with a cloth. The experimenter then touches the unseen hand (under the table) and the seen rubber hand, synchronously, using a brush. After some time, the participant feels the rubber hand as part of his body, and he feels physically threatened if a knife is brought near the rubber hand. This feeling of threat is indicated by a raised galvanic skin response. When the stroking of the unseen hand and the rubber hand is asynchronous, the participant does not report feeling the illusion, and the heightened skin response does not occur. The RHI has recently been extended to induce the feeling of having three arms (Guterstam, Petkova, & Ehrsson, 2011), and also an "invisible hand effect" when a hand is felt when empty space in front of the participant is stroked in synchrony (Guterstam, Gentile, & Ehrsson, 2013).

The incorporation of the rubber hand into the body is similar to the incorporation of the tool by the monkey, but it is also different, as the incorporation occurs not through intentional action, but through a dissociation of visual and tactile inputs. One way to understand the relation between passive and active incorporation is to consider the passive as a faint case of the active, where the perceptual effect appears similar to the effect of using a tool, even though no intentional action is executed. In the tool case, the tactile input is seen and felt in a distant manner, but it occurs in synchrony with the visual input of the tool moving. This synchrony could be one of the factors that lead to the tool being incorporated as part of the body schema. In the passive case, a similar synchrony is detected, with no tool present. The brain then "fills-in" the missing tool, by incorporating the locus of the synchrony (the external entity) into the body schema, even though there is no intentional action executed with the entity. Recent results show that such passive

incorporation also has cognitive effects. For instance, when asked to bisect a horizontal line midway, most people show a leftward bias (pseudoneglect), which is attributed to the dominance of the right brain hemisphere. This bias is reduced after the rubber hand illusion. This compensatory effect is specific to individuals who report having vividly experienced the illusion (high responders) as opposed to individuals who do not (low responders). Also, pseudoneglect was eliminated after RHI application only to the left hand (Ocklenburg, Peterburs, Rüther, & Güntürkün, 2012). This suggests that passive incorporation changes the nature of actions that follow, as well as the cognitive events related to such actions. The extension of the peripersonal space after such incorporation has not been investigated, though the following study seems to suggest that such a change could occur following passive incorporation.

In a further variation of the RHI effect, a remarkable new study has shown that a similar synchronous splitting of the visual and tactile inputs can lead to the feeling of being out of one's body, and owning another body of a different size (van der Hoort, Guterstam, & Ehrsson, 2011). In this experiment, participants lie down, with their head looking toward their feet, while wearing a virtual reality headset that shows the legs of a mannequin lying next to them. An experimenter then simultaneously strokes the participant's legs, as well as the legs of the mannequin, with a rod. This simple manipulation creates a sensory dissociation similar to the RHI: the stroking is felt in one's own leg, but it is seen as happening synchronously in the mannequin's leg. Similar to the RHI, the synchronous dissociation creates the feeling that the feet of the mannequin are the participant's own. Interestingly, the participants then feel like they themselves are the size of the mannequin, and they feel threatened if the mannequin is attacked. This 'out-of-body' experience has remarkable cognitive effects. If the incorporated mannequin is small, the subjects feel short, and when asked to use their hands to judge the size of small boxes shown to them, participants judge the boxes as quite big. Conversely, if the incorporated mannequin is huge, participants feel they themselves are huge, and thus judge really large boxes as small.

Extending this effect further, a similar synchronous dissociation has been shown to create the feeling of being out of one's own body, and being in a point of space outside. This happens when the participant feels the tactile input in her chest, but sees the visual input in a point in space behind her, an illusion achieved using virtual reality goggles. This leads to the incorporation of this (empty) space into the body schema, and the shifting of the visual perspective to that point in space. This effect is quite remarkable, as

it shows that the perceptual synchrony can lead to a form of idealized incorporation, where empty space is incorporated into the body (similar to the invisible hand illusion), by shifting the visual perspective to that point in space. This incorporation also has cognitive effects, such as a different judgment of the distance one needs to walk to reach a target (Ehrsson, 2007; Lenggenhager, Tadi, Metzinger & Blanke, 2007). This experiment shows passive incorporation at the level of the whole body, and this type of incorporation seems to alter the nature of cognitive activities performed by the subject, and the space and perspective associated with these cognitive activities. How this global-level incorporation affects possible actions/activities and extension of peripersonal space is not clear, as this has not been explored yet.

These experiments indicate that: 1) Objects are incorporated into the body schema when used as tools, 2) Objects resembling body parts are easily incorporated into the body schema through a synchronous dissociation mechanism, and such incorporation has cognitive effects, 3) Space outside the body can easily be incorporated into the body schema, and this leads to cognitive effects. These results show the possibility of extending your body schema to incorporate external entities and perspectives (and thus knowing them by participation), and how such incorporation can lead to cognitive changes. These are early and indicative results, but taken together with the tool-use case, and the ease with which incorporation occurs, they suggest that such incorporation is possible, and it is very common. The cognitive effects illustrated by these experiments also suggest that such incorporation of external entities and space into the body schema could be a mechanism through which we understand/know external objects – via the new activities, perspectives, or the different ways of doing/examining old activities, which the objects and their features make possible.

Incorporation at a Distance

Polanyi proposed that indwelling could be a way in which scientific understanding develops. Physical incorporation, and the resulting extension of the "action space," is one possible mechanism that could account for the way in which scientific understanding develops through the development and use of new instruments (Hacking, 1983) and physical and computational models (Chandrasekharan, 2009; Chandrasekharan & Nersessian, 2011; Chandrasekharan & Nersessian, In Press; Nersessian, 2008). The mechanism of passive incorporation (through synchronous dissociation), and a resulting extension of the action space, may account for how discoveries arise from the

building and use of models and visualizations (Chandrasekharan, 2009), as well as discoveries based on video games such as Foldit and EteRNA.

However, this type of incorporation, where an external object is physically made part of the agent's body schema, does not account for the way scientists in many disciplines understand external entities, as much scientific practice deals with entities that are very big (such as stars and tectonic plates), or very small (such as cells, DNA, atoms). Also, these entities interact at many time-scales, and most are beyond human perception and action (light years/nanoseconds). This means these entities cannot be made physically part of an agent's body in the ways described in the previous section, as these entities are accessed only through secondary/derivative perceptions and models. The perception of these entities is usually based on indirect indicators (such as spectra) that capture the entities' features. This means entities investigated by science can be incorporated into the body only if there exist ways in which features of such entities could become integrated into the agent's body schema while perceiving indirect indicators, such as spectra. In this section, I outline experimental evidence suggesting that perception of external entities leads to some of the entities' features, primarily movement (which is a core feature for science, as scientific explanation relies heavily on dynamics), being replicated by the body. Much of this evidence deals with replication of biological movements, but I will extend these results to nonbiological movements using some theoretical arguments and indicative results.   '

Common Coding

Recent research in cognitive science and neuroscience shows that when humans perceive and imagine movements, particularly actions, the motor system is activated implicitly. In the other direction, perception/imagination is improved by execution of movements. This two-way influence is explained using the common coding hypothesis, where the perception, execution, and imagination of movements share a common representation (common coding) in the brain. The origins of the common coding idea could be traced to the ideomotor principle outlined by William James.

> *Every representation of a movement awakens in some degree the actual movement which is its object; and awakens it in a maximum degree whenever it is not kept from doing so by an antagonistic representation present simultaneously in the mind.*   (James, 1890, 526)

The ideomotor effect is explained by common coding: a common neural representation connects an organism's movement (activation of motor

representations), observation of movements (activation of perceptual rep-
resentations), and imagination of movements (covert activation of motor
and perceptual representations). First articulated clearly by Prinz (1992),
this common neural representation allows any one of these movement
representations to automatically trigger the other two movement represen-
tations (Prinz, 2005; Sebanz, Knoblich, & Prinz, 2005; also see Decety, 2002;
Hommel, Müsseler, Aschersleben, & Prinz, 2001).

One central outcome of common coding is a body-based "resonance" –
the body instantly replicates all movements it detects, generating an internal
representation that is dynamic, and based on body coordinates. This repli-
cation generates a dynamic trace, which can play a role in later cognition.
All the replicated movements are not overtly executed or responded to.
Most stays covert, as the overt movement is inhibited. A common instance
of this replication, or "motor simulation," process is familiar to cinema
goers: while watching an actor or car moving along a precipice, viewers
move their arms and legs or displace body weight to one side or another,
based on what they would like to see happening in the scene. Similar effects
are seen in sports fans and novice video game players. Such "simulation" of
others' actions underlie our ability to project ourselves into different char-
acter roles as well. For instance, this effect explains why we are emotionally
moved by a dramatic film scene: we simulate the characters' movements
using our own system, and thus implicitly recreate their emotional states.

The basic argument for common coding is an adaptive one, where organ-
isms are considered to be, fundamentally, action systems. In this view, sensory
and cognitive systems evolved to support action, and they are therefore
dynamically coupled to action systems in ways that help organisms act
quickly and appropriately. Common coding, and the resultant replication
of external movements in body coordinates, provides one form of highly
efficient coupling. In this view, common coding (of execution, perception
and imagination of movements) is not surprising, and is to be expected, as
evolutionary trajectories are influenced by already developed systems, and
there is a strong bias toward reusing existing systems for new functions.

In implementation terms, common coding can be thought of as an
artificial neural network encoding both action and perception elements,
where the activation of one type of element automatically activates the other
(associative priming), similar to connectionist implementations of semantic
priming (Cree, McRae, & McNorgan, 1999). Imagination of movement, in
this view, would be a form of implicit activation of the action network. It has
been proposed that such common coding could arise from Hebbian learn-
ing (Heyes, 2005). Modeling work has shown how such common coding

could arise purely through agent-environment interactions, when agents
move from not using any traces (being purely reactive) to a strategy of using
stored memory structures in the world/head. In this view, common coding
is a key feature of memory, and it can arise from both evolutionary and
within-lifetime learning (Chandrasekharan & Stewart, 2007).

In operational terms, common coding implies that there are interactions
between execution, perception, and imagination of movement. I review
experimental evidence for different types of such interactions below. Most
of the behavioral evidence for common coding (as in the case of embodied
cognition in general) is based on interference effects, where movements in
one modality (say perception) leads to a difference in reaction time or
accuracy in another modality (say execution). This behavioral evidence is
supported by neurophysiological experiments, including imaging, Trans-
cranial Magnetic Stimulation (TMS), and patient studies.

Resonating Perceived Movements
If common coding holds, perception of movement should interfere with
execution of movement. Brass, Bekkering, and Prinz (2002) showed that
when participants execute an action A (say tapping fingers on a flat surface),
while watching a noncongruent action on a screen (say another person's
finger moving in a direction perpendicular to the tapping), the speed of
performed action A slows down, compared to the condition when the
participant is watching a congruent action on screen. This is because the
perceived opposite movement generates a motor response that interferes
with the desired tapping pattern. Establishing the common coding hypoth-
esis further is the reverse of the above, where actions influence perception.
Blindfolded subjects, after learning a new sequence of movements based just
on verbal and haptic feedback (Casile & Giese, 2006), visually recognized
the learned movements faster, compared to recognition of other movement
sequences. Further, recognition performance correlated strongly with the
accuracy of the execution during learning.

Supporting this behavioral data is a range of neuroimaging experiments
that show that action areas are activated when participants passively watch
actions on screen (Brass & Heyes, 2005 provides a good review). Perceiving
an action has been shown to prime the neurons coding for the muscles that
perform the same action (Fadiga, Craighero, Buccino, & Rizzolatti, 2002;
Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995). Expert performers of a dance
form (such as ballet and capoeira) when watching video clips of the dances
in which they are experts, show strong activation in premotor, parietal and
posterior STS regions, compared to when watching other dance forms.

Non-dancer control participants do not show this effect. Similar motor activation has been shown for expert piano players watching piano playing. When we observe goal-related behaviors executed by others (with effectors as different as the mouth, the hand, or the foot) the same cortical sectors are activated as when we perform the same actions (Gallese, Ferrari Kohler, & Fogassi, 2002). In contrast, motor areas are not activated when humans watch actions not part of human repertoire (such as barking). The neuronal populations that support such blurring of first person and third person views have been termed "mirror neurons" (Fadiga, Fogassi, Gallese, & Rizzolatti, 2000). These neurons were identified using single-neuron studies in monkeys, and a similar system is now considered to exist in humans.

The replication of observed actions suggest that common coding could stretch across individuals in shared tasks, as each would replicate the other's actions. A series of studies of joint actions, where two participants performed reaction time tasks alongside each other, have shown that each actor's performance was influenced by the other's task movements (Sebanz, Knoblich, & Prinz, 2005; Welsh, Lyons, Weeks, Anson, Chua, Mendoza, & Elliott, 2007; for a review see Knoblich & Sebanz, 2006). Such sharing, supported by the action replication system, emerges even when such sharing leads to a decline in one's own performance. Common coding thus allows people to coordinate task performance (say in a multiplayer game) because perceiving the other's actions activates one's own action system, leading to an intermingling of perception and action across players (Knoblich & Sebanz, 2006).

The above results clearly show that the body replicates perceived biological movements. This could be considered a type of incorporation at a distance, where a central feature (movement) of perceived biological entities in the world is replicated and made part of one's body schema. To account for indwelling, such incorporation by replication should also exist in the case of nonbiological movements. The evidence for this is indicative, but there are four compelling theoretical reasons why perception of nonbiological movements would be coded along with biological movements, thereby supporting possible replications of nonbiological movements by the motor system.

1. **Integration and Reuse:** Many biological movements, particularly joint actions, require integrating movements of external objects (such as tools, vehicles, weapons, sticks, balls, Frisbees, kites, and so on) with biological movements (one's own and others') quickly. The resonance mechanism would be the most elegant and efficient way to do this integration, both from a functional perspective (integrating

two different mechanisms would be inefficient and costly) as well as an evolutionary perspective (developing a separate mechanism would be costly, and violate the reuse principle).

2. **Hebbian Learning:** The common code is considered to originate through Hebbian learning (Chandrasekharan & Stewart, 2007; Heyes, 2005), where networks that track the perceived outcome of actions fire (and wire) together with the networks for executed actions. Once this common wiring/coding emerges through such learning, it supports action plans, as intended outcomes can now automatically activate the appropriate motor sequences. Since this type of association learning is very general, it is unlikely that a separate coding would develop only for nonbiological stimuli, especially given the first point above.

3. **Imagined Movements:** When nonbiological movements are imagined (for instance, mentally rotating objects), parts of the motor system are activated, particularly effectors that approximate the imagined movements, such as hands in the case of mental rotation (see review in next section). These studies indicate that imagination is the off-line activation of the perception-action common code, which can occur only if perception of nonbiological movements triggers similar movements supported by the motor system, through a common code connecting these two movements.

4. **Action-Centered Attention:** Related to the above, recent work suggests that attention is modulated by the actions to be performed. For instance, preparing for some movements enhance the perception of characteristics of objects that are related to the to-be-performed movement (Lindemann & Bekkering, 2009). Preparing to grasp enhances the detection of targets that vary across the size dimension, while preparing to point enhances the detection of targets that vary in the luminance dimension (Wykowska, Schubo, & Hommel, 2009). Also, covert shifts of attention occur before saccadic eye movements (Deubel and Schneider, 1996) and overt shifts of attention are tightly coupled to manual aiming movements (Helsen, Elliot, Starkes, & Ricker 1998, 2000). Such results, in combination with neuroanatomical studies that show tight links between attention and motor centers (Rizzolatti, Riggio, and Sheliga, 1994), have led to the development of action-centered models of attention (Rizzolatti, Riggio, Dascola, & Umilta, 1987; Tipper, Howard, and Houghton, 1999; Welsh and Elliott, 2004). This modulation of attention by the action system is mostly shown using nonbiological stimuli. Since perception and attention are closely coupled in the actions executed in such studies,

the modulation from the action system also influences the perception of nonbiological stimuli. This suggests a common code connecting perception of nonbiological stimuli and the motor system.

Apart from these theoretical reasons, there is empirical evidence that perception of nonbiological movements, particularly ordered sequences, trigger the activation of the motor system. At the level of everyday experience, attending to rotating objects for some time makes us dizzy, suggesting that the rotation movement is replicated by our motor system. Listening to music often leads to overt motor activation, including spontaneous dancing and keeping the beat with finger tapping or head movements, and it has been shown that music and movement share a dynamic structure (Sievers, Polansky, Casey, & Wheatley, 2013). Neuroimaging studies support this recruitment of the motor system in music perception (Bengtsson, Ullén, Ehrsson, Hashimoto, Kito, Naito, Forssberg, & Sadato, 2009; Chen, Penhune, & Zatorre, 2008; Kornysheva, von Cramon, Jacobsen, & Schubotz, 2010). The visual perception of ordered sequences also recruit the motor system, particularly the ventral premotor cortex (Schubotz & van Cramon, 2004), which is involved in the processing of action observation and imagery. Even the sudden appearance of single objects are covertly replicated. For instance, Welsh and Elliott (2004) showed that movement trajectories of participants veer away or toward the location of competing non-target objects, suggesting that the sudden appearance of the objects exerts a competing "pull" on the movement. Closer to the biological replication, actions are primed by objects that "afford" the execution of such actions (Tucker & Ellis, 2004), and this result is supported by a series of neuroimaging studies (Beauchamp & Martin, 2007). Further supporting this result, canonical neurons fire both when a monkey grasps an object and when it observes a "graspable" object (Oztop, Kawato, & Arbib, 2006), indicating a common coding between action and perception of action affordances (Gibson, 1977, 1979). Such object-based coding of actions is also indicated by "utilization behavior" in some neurological patients, where they reach out and start using objects in the environment in an automatic manner (Archibald, Mateer, & Kerns, 2001). Recent work shows mirror neuron areas are also activated during the presentation of object movements (Engela, Burkea, Fiehlera, Biena, & Röslera 2008; Gowen, Bradshaw, Galpin, Lawrence, & Poliakoff, 2010). Based on such results showing replication of object movements, Schubotz (2007) has proposed a model where abstract nonbiological stimuli are replicated by the motor area that codes the movement properties closest to the perceived movements. For instance,

the perception of a rotating object would be replicated by the area coding for the hand, as the hand can execute the movements closest to the observed rotation movements. This replication of perceived patterns may have an even deeper physiological basis, as flickering stimuli evoke an oscillatory brain response with the same frequency as the driving stimulus, called the steady-state visual evoked potential (Walter, Quigley, Andersen, & Mueller, 2012), and object representations along the ventral temporal cortex are related to their real-world size (Konkle & Oliva, 2012).

These results suggest that the body replicates perceived external movements. This replication could be considered one way of "incorporation at a distance," of movement and dynamics, of the distant perceived object or pattern. Similar to the extension of peri-personal space by physical incorporation, this replication could provide knowledge about the action possibilities of the object and extend the action space of the body, and this could lead to cognitive changes. This account provides one way of understanding how external objects perceived through probes such as microscopes could be understood using the body. However, this account does not capture how the body could incorporate very small or distant objects, which are perceived using indirect indicators such as spectra. The dynamics of such objects were, until recently, presented using static elements, such as graphs and equations. How could the body replicate such "frozen" movement, where a dynamic behavior is perceived using static elements?

Resonating Movements Encoded in Static Traces
There is evidence that the motor system is used while generating dynamic information embedded in static images (such as system drawings, see Hegarty, 2004) and vice versa. Common instances of this generation include: judging the sense of speed of a vehicle from its tire marks (or judging tire marks given speed), judging the sense of force from impact marks (or judging impact marks, given force), sense of movement speed from photos of action (say soccer), sense of movement derived from drawings, cartoons, sculptures etc. Experimental evidence for the use of the motor system in this process comes from the work on the Two-Thirds Power law for end-point movements such as drawings and writings. The law relates the curvature of a drawing trajectory with the tangential velocity of the movement that created the drawing/writing. The human visual system deals more effectively with stimuli that follows this law than with stimuli that do not. When the curvature-velocity relationship does not comply with the power law, participants misjudge the geometric and kinematic properties of dynamic two-dimensional point-displays (Viviani and Stucchi, 1989, 1992). In addition, the

accuracy of visuo-manual and oculomotor 2D tracking depends on the extent to which the target's movement complies with the power law. This relation allows humans to judge the speed in which something was drawn, using curvature information, and vice versa (judge curvature given speed). This capacity is presumably what we use when we judge speed from tire marks, and also evaluate drawings and paintings. Recent experimental evidence shows that observers simulate the drawing actions of a painter while observing paintings (Taylor, Witt, & Grimaldi, 2012). There is also evidence that object-related hand actions are evoked while processing written text (Bub & Masson, 2012).

Such predictions can also work the other way, where given a dynamic trace, we can imagine and predict the static sample that comes next. In one experiment, dynamic traces of handwriting samples were shown to participants. They were then shown some samples of written letters (such as *l*, *h*, and so on), and asked to judge which letter came next to the shown trace. Participants could identify the letter following the trace more accurately (Kandel, Orliaguet, & Viviani 2000) when the trace followed the Two-Thirds power law, that is the angular momentum of writing was related to curvature in a way laid out by the law. Accuracy went down significantly for traces that did not follow this relation. Based on this and other experiments, Viviani (2002) argues: "In formulating velocity judgments, humans have access to some implicit knowledge of the motor rule expressed by the Two-thirds Power Law."

Here again, much of the experimental evidence is about the replication of biological movements, but everyday experience (such as the tire mark case) suggests that nonbiological movements are also replicated from traces. Also, the theoretical arguments for the replication of nonbiological movements outlined in the previous section apply here as well.

Incorporation of Imagined Entities

Static traces are only one aspect of the problem of capturing the behavior of unperceivable entities. A significant chunk of scientific work involves imagining and developing mental models of the movements and features of such entities (Nersessian, 2008). Such mental models are developed and used often in conjunction with traces such as spectra, as well as physical and computational models. In this section, I will provide evidence that imagination of movements involve a replication by the motor system. I will use mental rotation research to illustrate this case, primarily because such rotation usually involves nonbiological movements similar to the ones

studied by most scientists, though the interaction between imagination and action has been shown in biological movements as well.

If imagination and execution of movement shares a common code, imagining a movement should affect the execution of movement. Wohlschlager (2001) showed that while imagining a mental rotation, if participants plan another action, or move their hands or feet in a direction non-compatible to the mental rotation, their performance suffers. This effect is reversed for compatible movements. Unseen motor rotation leads to faster reaction times and fewer errors when the motor rotation is compatible with the mental rotation, and speeding/slowing the compatible motor rotation speeds/slows the mental rotation (Wexler, Kosslyn, & Berthoz, 1998).

Supporting the common coding view further, it has been shown that the time to mentally execute actions closely corresponds to the time it takes to actually perform them (Decety, 2002; Jeannerod, 2006). Responses beyond voluntary control (such as heart and respiratory rates) are activated by imagining actions, to an extent proportional to that of actually performing the action. When sharpshooters imagine shooting a gun, their entire body behaves as if they are actually shooting (Barsalou, 1999). Similarly, imagining performing a movement helps athletes perform the actual movement better (Jeannerod, 1997).

Links between imagination and action have also been found by experiments investigating mechanical reasoning, such as how people imagine the behavior of pulleys, gears etc. (see Hegarty, 2004 for a review). Children who learn fractions by actually executing movements on blocks learn the fraction concepts better than others who do not perform such movements (Martin & Schwartz, 2005). Imaging experiments support these behavioral results, and show that premotor areas are activated while participants do mental rotation (Vingerhoets, de Lange, Vandemaele, Deblaere, & Achten, 2002, also see Schubotz, 2007; Schubotz, & von Cramon, 2004).

In the other direction, common coding would suggest that our action possibilities restrict imagination of novel actions and movements. Kosslyn (1994) reports that participants need more time to perform mental rotations that are physically awkward. People with writer's cramp (focal hand Dystonia) take more time to do mental rotation of hand pictures, and people have difficulty mentally rotating manually difficult hand movements, such as right-sided stimuli at 120 degrees and left-sided stimuli at 240 degrees (Fiorio, Tinazzi, & Agiloti, 2006).

In biological movements, according to common coding, we understand another person's actions by reenacting those actions using our own motor system. An example would be judging the weight of an object by watching

how a person lifts a heavy object. Bosbach, Cole, Prinz, and Knoblich (2005) recently showed that people with compromised ability to activate their body, such as deafferented individuals, cannot make such predictions, suggesting that the action system is used in such judgments. Ramenzoni, Riley, Davis, Shockley, and Armstrong (2008) showed that estimated judgments of how high an actor could jump-and-reach were influenced by the observer wearing a weight in his ankle. The weight led to a reduction in estimated heights, but only when the observer walked around with the weights. Similarly, wearing a weight changes estimates of whether an action can be executed, and physical execution of the judged-action makes such judgments more accurate (Chandrasekharan, Binsted, Ayers, Higgins, & Welsh, 2012).

Together, these experiments show that imagination of both nonbiological and biological movements are based on replicating these movements using the motor system. One way to think about this replication process is to consider it as extending the body schema, to incorporate *possible* movements of unperceivable entities. In science, movements embedded in traces such as spectra are used to guide the execution of possible movements in imagination, the traces gradually constraining the possible movements, until only one imagined dynamics resonates with the movements encoded in the traces. In this instance, the dynamics inherent in the graphs/equations is integrated with the dynamics generated in the imagination (see Chandrasekharan, 2009; Chandrasekharan & Nersessian, in press), so the replication is not entirely generated from the static elements.

Aside from imagining dynamics using static graphical and mathematical elements, scientists also imagine external systems using language-based concepts, particularly theoretical models, descriptions of experimental protocols, and descriptive accounts involving dynamics. Many of these linguistic components have significant elements of metaphors and analogies. There is now rich evidence showing that motor replication is involved in the processing of language and concepts involving movement. Motor activation has been shown while imagining words encoding movements, and processing sentences involving movements (Barsalou, 1999; Bergen, Chang & Narayan, 2004; Glenberg & Kaschak, 2002; Holt and Beilock, 2006). When processing sentences that involve upward-motion, like *The ant climbed*, participants take longer to perform a visual categorization task in the upper part of their visual field. For downward-motion sentences like *The ant fell*, the processing is longer for the lower half of the visual field (Bergen et al., 2004). Similarly, participants reading sentences depicting

fictive motion (such as *The road runs through the valley*) have lower response latencies when the sentences were about fast travel, short distances and easy terrains (Matlock, 2004). Critically, this effect did not occur when they read non-fictive sentences (such as *The road is in the valley*). When participants perform a lexical decision task with verbs referring to actions involving the mouth (e.g., chew), leg (e.g., kick), or hand (e.g., grab), areas of motor cortex responsible for mouth/leg/hand motion show more activation (Pulvermüller, 2001). Similar effects have now been shown for verb production (Hirschfeld & Zwitserlood, 2012) and the processing of grammatical aspect (Bergen & Wheeler, 2010). Motor activation is also involved in metaphor processing (Wilson and Gibbs, 2007). These studies indicate that imagining systems using linguistic concepts encoding movement also involves a replication of the movement using the motor system.

BECOMING KNOWLEDGE

In the above sections, I have outlined a set of mechanisms that could allow the body to have a participatory relationship with entities in the world. These mechanisms allow the incorporation of an entity's movements into the body schema when the entity is in: 1) direct physical contact with the body, or in indirect contact through synchronous tactile input, 2) perceived at a distance directly, or perceived through derivative traces, and 3) when manipulated in imagination, or imagined using descriptions based on language. These components (physical contact, perception, and imagination) and their combinations together account for a significant chunk of the way in which we gain knowledge of an external entity, particularly scientific knowledge. Given this, the above mechanisms together provide a possible cognitive and neural basis for Polanyi's account of indwelling, specifically his proposal that we come to know an external entity comprehensively the way we come to know our body – by dwelling in it, and interacting with the world from this perspective.

The mechanisms I have outlined offer a way in which sustained study of an external entity leads to movements of the entity being replicated by the body. This replication process *gradually* creates a participatory relationship with the external entity, which leads to an expansion of the scientist's understanding of the possible 'action space' of the entity (similar to the extension of the peripersonal space, outlined in section 2.2.1). This extended understanding of the action space allows the scientist to develop probable hypotheses about the entity's behavior, which are tested using experiments. The results from the experiments lead to a refined replication of the entity's

movements, and this leads to a closer incorporation of the entity. This cycle continues, and eventually leads to new discoveries about the entity, as the scientist's understanding of the entity's action space gets more and more constrained, to the point where she can accurately predict its behavior.

In this view, scientific discoveries emerge through a process where the scientist's body, particularly her motor system, is used to replicate, and incorporate, an external entity's dynamic behavior in a comprehensive fashion. Discoveries thus arise from a 'becoming' process, where the scientist and the external entity becomes a coupled system through movement replication. This process closely parallels Polanyi's description of how new knowledge arises: "I partly transform myself in that which I am observing and thereby extend my range of knowing to include knowledge of all the hierarchies – from inanimate matter to the frameworks of our convivial settings." Since veridical knowledge is accrued from this participation process, my account suggests a "resonance-based realism", where internal and external representations allow scientists to replicate the dynamic behavior of real-world entities, and discover/predict unknown behavior based on such participation in the world. This participatory realism view is quite different from correspondence-based realism, which posits a structural isomorphism or analogical relationship between representation states and world states. Such structural accounts are limited in explaining the process of discovery (Chandrasekharan, 2013), compared to process accounts such as the participation account sketched here (also see Chandrasekharan, 2009; Chandrasekharan & Nersessian, in press). Further, correspondence accounts are limited because they do not identify the biological mechanisms that enable veridical knowledge. The participation account, and the mechanisms that allow participation, provide insight into the inherent dynamic nature of knowledge, how this dynamic nature helps us incorporate external entities, and how this incorporation allows making accurate predictions and discoveries.

Importantly, this becoming, the participatory relationship with the external entity, is not automatic or given; it emerges *gradually*, and is based on sustained attention and a large range of interactions with the entity, involving execution/perception/imagination of movements. This process of participatory knowledge crucially involves a "coherence" element, where many different movement replications are integrated during the incorporation process, and the external entity's action space is predicted based on this coherent extension of the body schema, and not individual movements. This integration process is in tune with Polanyi's view that "the kind of knowledge I have of my body by dwelling in it is the paradigm of knowing particulars subsidiarily with

a bearing on the comprehensive entity formed by them." This coherence aspect of indwelling, and the way it fits (well) with the incorporation account sketched above, requires deeper discussion that is beyond the scope of this chapter (see Chandrasekharan & Nersessian, in press).

The incorporation account is based on the idea that organisms are action systems, and cognition emerged to support action. Declarative knowledge, in this view, is considered as derived from procedural knowledge. This approach is supported by evolutionary models, as most organisms only have procedural knowledge. Even in the human case, declarative knowledge emerges later in development, and only after learning language. Also, the declarative form of science, as we know it now, emerged very recently in evolutionary history even in our species. These factors, as well as the critical role played by dynamics in scientific accounts, suggest that the mechanisms involved in scientific discovery would be procedural (and dynamic) in nature. The account thus assumes a "primacy of the procedural," similar to the "primacy of the implicit" articulated by Reber (1993) while developing his account of implicit learning, which, he suggested, is close to Polanyi's account of tacit knowledge. Finally, while not evidence, the following reflection by Albert Einstein (and other scientists' and mathematicians' reflections about their thinking process, reported in Hadamard, 1945) also suggest that scientific thinking is primarily procedural:

> The words or the language, as they are written or spoken, do not seem to play any role in my mechanism of thought. The psychical entities which seem to serve as elements in thought are *certain signs and more or less clear images which can be voluntarily reproduced and combined*... *The above-mentioned elements are, in my case, of visual and some of muscular type.* Conventional words or other signs have to be sought for *laboriously* only in a secondary stage, when the mentioned *associative play* is sufficiently established and can be reproduced at will.
>
> (Albert Einstein, quoted in Hadamard, 1945, 147–148, emphasis added)

BECOMING KNOWLEDGE AND THE NATURE OF INTUITION

What insights do the mechanism account sketched above offer toward understanding the function and nature of intuition, particularly intuition related to science?

One central insight is that the intuition process could be distributed, across time (the participation relationship develops over time) and across space (the participation relationship could be with far away or molecular

objects, and is itself mediated by instruments and representations). These two features mean that the gradual nature of the process through which intuition develops, and the external components involved in the development (instruments, representations, results), could be available for introspection and description, even manipulation. However, the intrinsic nature of the intuition process, particularly the way the different components are integrated across time and space, is still unknown and implicit.

Second, in the account presented, the incorporation process is mediated by movement, which suggests that intuitions based on incorporation can only be about features and aspects that exhibit some dynamics. One possible implication of this is for models of intuition where (participatory) knowledge about the world arises by making the mind still. Such models usually do not focus on knowing the structure and dynamics of external entities, and their interplay. This does not rule out the still mind providing an understanding of structure and dynamics of external entities, but the process by which such understanding could occur through stillness, if it occurs, would be different from the incorporation process sketched here.

Third, the Foldit example (and the other games) suggests that explicit knowledge can ·be translated into formats where naive participants can interact with such knowledge in an implicit fashion, and this interaction can generate novel and accurate understanding of complex external entities such as proteins and RNA. In the participation account, this translation and discovery process is both based on incorporation of the external structure, using which: 1) the explicit knowledge was generated originally, 2) explicit knowledge is translated to design the game, and 3) novel discoveries are made by naive participants. This means incorporation acts as a common meeting ground – for explicit and implicit understanding, as well as for expert and novice participants. This intuition-as-common ground view is quite different from the rational thought versus intuition dichotomy that is dominant in the psychology/philosophy literature.

Four, the above common ground, as well as the crowdsourcing results from Foldit and other games, also implies that the participation mechanism supports an intuition process that could be distributed across people with some level of uniformity, and this could be one way in which consensus could be reached about discoveries. This view, that intuition could be a consensus-promoting mechanism, is different from the standard view that intuition is an arbitrary process, and therefore undependable (but see also point six).

Five, the gradual incorporation process advances through coherence, that is, new knowledge elements are made to cohere with existing knowledge,

and this coherence is what slowly advances the process of incorporation. In this view, intuition is gained through the mechanism of coherence. Since coherence itself is *achieved*, and is not a given, in the incorporation account, this proposal suggests a deeper relationship between coherence and intuition, where the two are connected by an agentive/volitional process. This suggests it is not an accident that coherence is a feature/aspect of intuition.

Six, the body and its extension is central to the incorporation account, and the core proposal is that knowledge of an entity requires participating in that entity. All channels of awareness (perception, cognition, action, proprioception, interoception, the vestibular sense, language, external representations) are viewed as mechanisms that advance coherence and the participation relationship. In one reading of this view, everyday intuition would be seen as a byproduct, or an intermediate process, that emerges during the wider effort to achieve participation. All results of everyday intuition, in turn, help advance the wider participation process. In another reading, everyday intuition would involve 'micro' versions of the wider participation, where the participation is local, with the coherence process limited, and the domain of its operation contained. This raises the question: is there one big intuition or many small ones? In the mechanism description, this would be rephrased as: is there one participation process or many?

My view is that these options are not mutually exclusive – the global striving, the effort, toward coherence and participation could be one, but many local participations would be what is achieved, depending on the coherence-requiring elements the person encounters. This of course does not definitively answer the one/many intuition question, as participation may not be applicable to all cases of intuition. However, if the participation process is found to be wider than the scientific intuition case it is develop for here, this view could provide an avenue to answer the one/many intuition question in a non-exclusive fashion.

Seven, as the participation account promotes 'the primacy of the procedural', it suggests that intuition is a procedural mechanism, similar to implicit learning of skills. In such a view, it would be hard to see how intuition could have evolved for any particular function. It is similar to associative learning, which is also not focused toward any particular function. That said, I would like to end with the provocative suggestion that it is worth considering whether intuition could be its own function. This is possible in the participation account, as the coherence process, and the resulting participatory knowing of entities in the external world, could be a satisfying, and liberating, end in itself. This end may have downstream effects in terms of control over phenomena, and many adaptive advantages

may have resulted from this control, but the participation mechanism does not exist because of, or for, these ends. It exists for becoming, and knowing through becoming.

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