

# Calculating spatial boundaries and phenomenal capacity of conscious resonating structures in General Resonance Theory

Tam Hunt<sup>1</sup>

<sup>1</sup>Worldania

April 28, 2020

I suggest a heuristic for calculating the spatial boundaries and phenomenal capacity of conscious resonating structures in General Resonance Theory (GRT), a theory developed by Hunt and Schooler over the last decade. GRT suggests that consciousness is a product of various resonating frequencies at different physical scales. All physical structures vibrate and should be considered processes rather than static things. Resonance assists in achieving phase transitions to higher levels of complex consciousness. When vibrating structures resonate in proximity to each other they will under certain circumstances “sync up” in a shared resonance frequency. GRT suggests that a shared resonance is the key requirement for the combination of micro-conscious entities into a larger-scale macro-consciousness. This approach is, thus, a solution to the “combination problem” of consciousness. The proposed mathematical heuristic allows for a practical approach for identifying potential conscious structures and the spatial boundaries of such structures as they change over time, and for calculating the capacity for phenomenal consciousness present within the putative conscious resonating structure. The slowest-frequency shared resonance is the limiting factor for the size of any macro-consciousness. I describe some limitations of the proposed framework, and how it compares to Tononi’s Integrated Information Theory. IIT’s constellation-qualia characterization framework may be compatible with GRT and may be a useful tool to use in conjunction with GRT’s quantification framework.

## 1. Introduction

This paper builds upon the mathematical framework described in Hunt 2011, which suggested a method for calculating the phenomenal capacity of any conscious entity, by providing a new method for calculating the spatial boundaries of any conscious entity in each moment. This methodology is grounded in a panpsychist framework (Hunt 2011, Schooler, Hunt, and Schooler 2011, Hunt and Schooler 2019; Goff 2017) that assumes that all matter is associated with at least some capacity for phenomenal consciousness, albeit extremely rudimentary in the vast majority of matter. Accordingly, the General Resonance Theory (GRT) developed further in the present paper is applicable to all physical systems, rather than being limited to neurobiological or biological systems.

The notion of resonance (synchrony, coherence, shared vibrations) has a long history in neuroscience. Crick and Koch featured this concept in their neurobiological theory of consciousness (Crick and Koch 1990, Koch 2004). Fries has made the concept of “communication through coherence” (neuronal synchrony/resonance) even more widely known (Fries 2005, 2015). Dehaene 2014 highlights the role of long-range synchrony between cortical areas a key “signature of consciousness,” (as does Koch 2004). Bandyopadhyay has made the concept central to his Fractal Information Theory of consciousness (Bandyopadhyay 2019).

The resonance theory of consciousness developed in Hunt and Schooler 2019, Hunt 2011, and the present

paper, also makes resonance the key mechanism by which rudimentary consciousness combines – through shared resonance in proximity – into more complex consciousness. This is the case because resonance allows for phase transitions in information flows to occur at various organizational levels, allowing previously chaotic systems to self-organize and thus become coherent.

The primary insight offered in the present paper is that consciousness is a product of resonance chains (Fn 1) of various information/energy (Fn 2) pathways, and that the spatial and temporal boundaries of any particular conscious entity is established by the slowest frequency shared resonance within that conscious entity, for each particular information/energy pathway. Resonance frequencies and resonance chains are constantly changing in most entities; thus, the spatial boundaries of conscious entities will be constantly changing at least a little. Most combinations of consciousness, in which less complex entities combine into more complex entities, will be comprised of a nested hierarchy of conscious entities, with one dominant conscious entity in each moment, without extinction of the nested entities' consciousness, distinguishing this approach from Integrated Information Theory and other theories that assume the extinction of nested conscious entities, leaving only one macro-conscious entity left (this is IIT's "exclusion principle").

*Footnote 1. Bandyopadhyay has developed a sophisticated approach to resonance chains in a broad theory of consciousness he calls the Fractal Integrated Information (FIT) theory of consciousness (Bandyopadhyay 2019). Resonance in GRT is similar to its role in FIT, but GRT adopts a metaphysically foundational role for resonance through its general congruence with Whitehead's process philosophy and the "actual entities" that are the "final real things" that comprise the world (Whitehead 1929, Hunt and Schooler 2019, Hunt 2019).*

*Footnote 2. Information is generally defined as a subjective aspect of the physical world, whereas energy is an objective aspect; but in this context I am using these terms interchangeably because I define information as aspects of energy that we can measure. As such, all physical dynamics consist of nothing more than energy flows, but those energy flows that we can measure may be labeled "information" and quantified under established information theoretic concepts. I will, however, refer to "information/energy flows" simply as "information flows" from now on in this paper, for simplicity's sake.*

The rest of this paper provides a heuristic for calculating the spatial and temporal boundaries of candidate conscious entities, as well as the capacity for phenomenal consciousness.

## 2. Calculating spatial boundaries and phenomenal capacity in General Resonance Theory

Step 1: Inductively identify candidates for the combination of consciousness

The first step in calculating the spatial boundaries of a candidate complex conscious entity is to consider, inductively, what constituents are likely to be resonating synchronously and, as such, to be candidates for a structure that combines micro-conscious entities into a particular macro-conscious entity. We label such a candidate for combined consciousness a "putative combined consciousness" or PCC. Inductive judgments about what may constitute a PCC will necessarily be based on the human experience of consciousness and what structures we can, accordingly, expect to enjoy some degree of consciousness, based on observed behavior similar to what we see in humans and other creatures that most humans would agree are conscious. We can label these types of behaviors the "behavioral correlates of consciousness" (Tononi and Koch 2015; Hunt 2019b).

Definition 1. CC  $\equiv$  a combined consciousness, any group of two or more conscious entities that

combine to produce a higher-level consciousness.

Definition 2.  $CC_L \equiv$  the largest combined consciousness in the relevant context.

Definition 3. PCC  $\equiv$  a putative combined consciousness, based on inductive judgments about the human experience of consciousness

Some examples for applying this inductive methodology for identifying a PCC include (without pre-judging whether any of these combinations are, in fact, conscious):

- measuring EEG or MEG in the various neurons and groups of neurons that comprise human and other mammalian brains;
- measuring EEG or MEG in human coma patient brains;
- measuring chemosensory or electrochemical pathways in non-mammalian neurons like *Drosophila* or *C. elegans* (Gelperin 2014), and other means for studying comparative cognition between species;
- measuring EEG or MEG in the non-neuronal biological systems that comprise invertebrate sensory systems (jellyfish that have eyes, for example);
- biochemical communication systems in slime molds (Vallverdu et al. 2018);
- calculating information flows and speeds in computer systems that pass a Turing Test, when and if such feats become possible;
- or simply measuring information flows based on resonance chains in any artificial computer.

In each example, we may consider, as the first step in our suggested heuristic, whether the collection of entities examined may, inductively, be likely to enjoy some variety of combined consciousness. Inductive judgments about what should be considered a PCC will change over time as more data becomes available with respect to the presence of consciousness in various entities in nature and even possibly in human creations such as artificial intelligence.

Step 2: Calculate the primary resonance frequencies in the putative combined consciousness

The second step is to calculate the primary resonance frequencies of whatever information flows (chemical, electrochemical, electrical, etc.) are present in the PCC. For example, in human brains it appears that electrical and electrochemical information pathways/resonance chains are the most significant, though other pathways may also be significant (Koch 2004; Hunt and Schooler 2019; Hameroff and Penrose 2014).

The highest bandwidth information flow will generally be most relevant, but the *slowest* shared resonance frequency of the highest bandwidth resonance chain (“slowest shared resonance” or SSR) will define the boundaries of the *largest combined consciousness*,  $CC_L$ , at least with respect to that particular resonance chain. This is the case for two reasons:

- 1) Faster shared resonance frequencies will lead to nested CCs that have their own more localized awareness. In this manner, it is the “lowest common denominator” effect that leads the slowest shared resonance frequency to be the limiting factor of the  $CC_L$ .
- 2) Each resonance cycle is a snapshot that incorporates available information within each cycle, and each resonating structure at least partially resets after each cycle. Fries 2015 states: “In the absence of coherence [resonance], inputs arrive at random phases of the excitability cycle and will have a lower effective connectivity.” Conversely, inputs that arrive synced to the same excitability cycle will propagate faster and with greater bandwidth. Slower frequencies will generally travel faster (Dehaene 2014, p. 137). In the present framework, these principles apply to all resonating structures (i.e. all physical structures), not just neurons.

Accordingly, *the speed at which new information can be incorporated, within each cycle, is the limiting factor for the spatial extent (boundary) of the PCC* . Restating this as a principle:

Principle 1. The slowest shared resonance frequency (SSR) defines the spatial boundaries of the largest combined consciousness (CC<sub>L</sub>) for each information pathway

The CC<sub>L</sub> may also be described as the *dominant consciousness* , because its intentions and desires will supersede (without extinguishing) those of any subsidiary consciousness(es) that is present. The boundaries of the CC<sub>L</sub> will generally change in each resonance cycle, sometimes subtly and sometimes substantially, as we can observe in introspecting about the features of our individual human consciousness – a very immediate example of a CC<sub>L</sub>.

Parts of the resonating structure will display higher frequency resonances than the SSR, but those higher frequencies won't be shared by all regions of the CC<sub>L</sub> and thus won't define the boundaries of the CC<sub>L</sub>. Rather, they would define the boundary of a *subset* of the CC<sub>L</sub>. As such, in most biological-scale structures, each CC<sub>L</sub> is a nested hierarchy of various different resonating frequencies and smaller CCs (CC<sub>n</sub>, for “nested”). Each level of resonance will have its own type of consciousness, feeding up to the next level of consciousness to varying degrees.

Recent research has probed high terahertz-level oscillations in tubulin molecules that comprise the ubiquitous microtubule scaffolding of most cells (Craddock et al. 2017; Hunt 2019). These frequencies are far faster than those observed in EEG or MEG data. Cycle speeds and propagation velocity limit the boundary of the PCC, giving rise to the second principle:

Principle 2. Higher frequencies, all else equal, lead to smaller spatial boundaries for a given CC<sub>L</sub>

And the converse:

Principle 3. Slower frequencies, all else equal, lead to larger boundaries for a given CC<sub>L</sub>

It is important to highlight the fact that higher frequency resonances, such as those examined by Craddock, et al., 2017, may be present in many locations within a larger-scale CC<sub>L</sub>, allowing for those nested combinations of consciousness (CC<sub>n</sub>) to be subsumed into the larger CC<sub>L</sub>. Figure 1 illustrates these terms and principles using abstracted resonating structures combining into various CC<sub>n</sub> and ultimately into a single CC<sub>L</sub>.

Step 3: Calculate the boundaries of the PCC

The third step is to employ these principles to calculate the boundary of the PCC by calculating the distance, from the approximate center of the PCC, that resonating influences can travel within the relevant frequency cycles. This will be an iterative process because conclusions about the approximate center of the PCC will change with each measurement. Accordingly, this heuristic will follow a generally Bayesian logic of increasingly accurate iterations without any final “correct” answer.

Components of the PCC that are within the spatial boundary formed by this speed limit are included in the CC, in each iteration at time  $t$  , and those that are outside are not perceived and thus are not included in that moment of consciousness. Equation 1 describes this simple formalism.

$$\text{Eq. 1: } x_c = v/f$$

$$\text{which becomes: } x_c = (\text{m/s})/(\text{cycle/s})$$

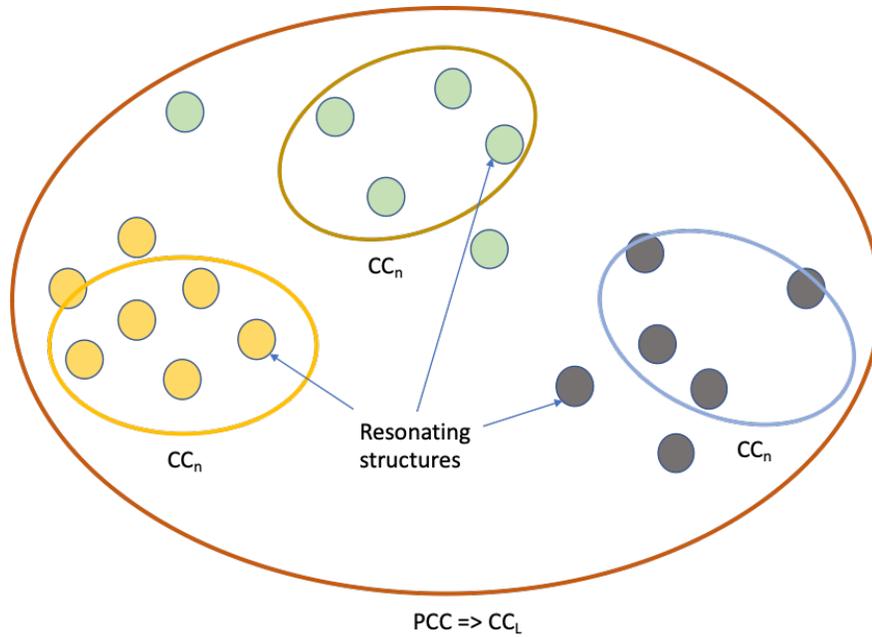


Figure 1: A PCC becomes a CCL through combination of many smaller resonating structures.

which becomes:  $x_c = m/\text{cycle}$

Accordingly, the distance from the center of the resonating structure to the furthest edge of the same resonating structure, in each direction and in each cycle ( $x_c$ ), is the velocity ( $v$ ) of the specific resonance chain (i.e., energy/information pathway, or causal interaction) divided by the frequency ( $f$ , Hz, or cycles per second). Figure 2 illustrates this step in human neocortex, which is postulated to be connected over its extent by long-range synchrony (e.g. gamma synchrony is the most commonly observed long-range synchrony in mammal cortex).

For example, if we are looking at 40 Hz gamma synchrony in a mammal brain (which is 40 cycles/s), and a velocity of electrical influence of approximately 1.4 m/s, we obtain  $x_c = 10/40 = 0.035$  meters per cycle for the maximum distance from the center of the PCC in that direction (as Bahramisharif et al. 2013 states, velocity figures for various kinds of wave propagation in cortex are generally still quite provisional since the science in this area is still new). Table 1 presents various energy pathway (resonance chain) velocities, frequencies and distance traveled in each cycle, organized from fastest to slowest velocity.

Table 1. *Various energy pathway velocities and frequencies in mammal brains.*

Energy pathway	Velocity	Frequency	Distance traveled per cycle
Terahertz-level tubulin resonance (Craddock et al. 2017)	Possibly $> c$	613 THz	0.0049 m
Electrochemical pulses through axons (Siegel and Saprú 2005)	80-120 m/s	Various	Various
Theta waves in human whole brain (Zhang and Jacobs 2015)	1-5 m/s	$\sim 5$ Hz	$\sim 0.6$ m
Gamma waves in human whole brain (Bahramisharif et al. 2013)	0.7-2.1 m/s	$\sim 40$ Hz	0.035 m
Beta waves in human whole brain (Takahashi et al. 2011)	0.23 m/s	$\sim 25$ Hz	0.0092 m
Weak electric fields (“ephaptic coupling”) (Chiang et al. 2019)	0.1 m/s	$< 1$ Hz	$\sim 0.1$ m
Gap junction sharp wave “ripples” in mouse brain (Maier et al. 2003)	0.016 m/s	200 Hz	0.00008 m

Once we calculate the maximum distance from the center of the dominant resonance frequency to its edges, and thus establish the boundary of the PCC in each direction, we can drop the “P” in PCC and describe the newly bounded resonance structure as a CC. There will generally be far more than one CC present, however, in any PCC, as discussed above, due to the nested hierarchy nature of most CCs.

As a second example, we consider the tubulin dimers and microtubules that are the focus of Penrose and Hameroff’s Orchestrated Objective Reduction theory of consciousness (Orch OR) and recently probed in

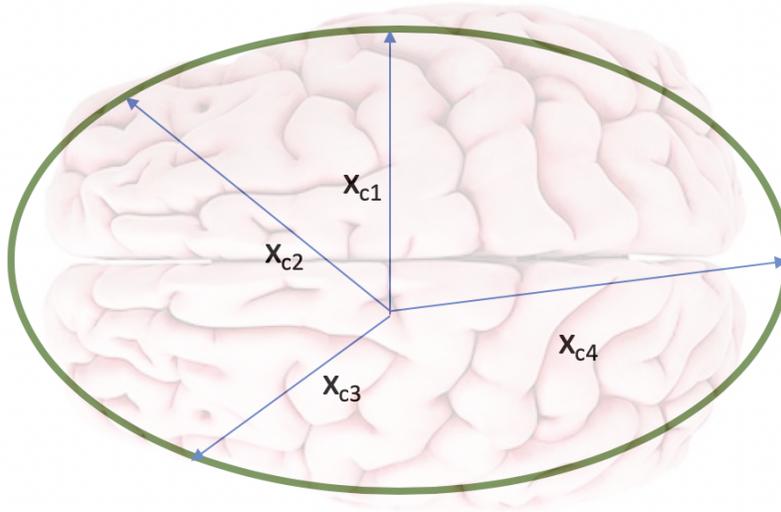


Figure 2: *Calculating spatial boundaries of a PCC using long-range synchrony in human neocortex as an example.*

The fourth step is to calculate the “perception index” (PI or  $\pi$ ) of the putative resonating structure. PI refers to the perceptual or sensory bandwidth of the PCC and is, in biological entities, based on the various biological sensory pathways such as vision, touch, etc. (Fn 3)

*Footnote 3. Perceptual bandwidth doesn't necessarily mean perception external to the brain, in the case of human complex subjects and probably for other mammalian consciousness either. For example, during dreaming there is clearly a high capacity for phenomenal content, with the “external” information supplied by certain parts of the brain instead of external perception. In the framework offered here, the parts of the brain that supply dream data to the CCL may be considered as external.*

PI represents, essentially, the connections from the  $CC_L$  to the *external* world or, in the case of dreaming, data created internally and presented to the PCC as though it were external data. Equation 2 provides a method for calculating the sensory bandwidth (PI) of any PCC.

$$\text{Eq. 2: } \pi(\text{PCC}) = \sum I(\text{PCC}, O_j^\infty)$$

In Eq. 2, the sensory bandwidth of a PCC, in each iteration, is the sum of all perceptual data between the PCC and the various objects of perception,  $O_j$ . An “object” is literally any datum presented to perception (Fn 4). This measurement will in any interesting case not be simple due to the number of causal connections between the PCC and the rest of the world, and the difficulty in measuring these causal connections.

*Footnote 4. All objects of perception are themselves subjects in a later moment, as they cycle from physical to mental poles in their own cycle times (Hunt 2019).*

We can, as a working example in applying this framework, consider fruit fly perception. Much is known about fruit flies, so they are a good candidate for fleshing out this framework. To simplify further for present purposes, let's consider the fruit fly visual system as an ostensibly separate neural system (it is, of course,

not actually separate).

Fruit flies have compound eyes with about 760 *ommatidia* (simple eyes), each of which have eight photoreceptor cells. (Hardie and Raghu 2001). If we assume 12-bit color resolution for each photoreceptor, the visual bandwidth of the fruit fly amounts to about 72,960 (12 x 760 x 8) bits, the result of applying Eq. 2 for the visual system of a fruit fly (Fn 5). As an index, this value for PI needs to be normalized, however, to avoid unnecessarily large numbers in comparing sensory bandwidth. For present purposes we can simply translate this 72,960 bit rate to a normalized value of 3 on a normalized scale from 0 to 10. The value we use for the normalized figure in this example is not particularly important at this time because it's only an illustrative example (later work will flesh out a proposed normalization scale).

*Footnote 5. Fruit flies have low spatial visual resolution compared to humans, but very good visual temporal resolution, at about 200 “frames per second.” By contrast, humans cannot experience much more than about 18 “frames per second” of visual input, though there are some exceptions.*

#### Step 5: Calculate the Connectivity Index

The fifth step is to calculate the “connectivity index” (CI or  $\psi$ ) of the PCC. CI refers to information processing power or *internal* connectivity, which is the sum of resonance chains internal to the  $CC_L$  that connect the various CCs that comprise the larger and unified resonating structure.

Connectivity in this context refers to the presence and quantity of internal energy/information pathways. Connectivity implies the transmission of something internal to the PCC and this “something” is at its root simply causal influence, something that results in a difference to the system. CI quantifies the internal connectivity of the PCC. CI scores also fall on a normalized scale between zero and ten.

A network (which can consist of literally any substance) would receive a CI score of 10 if all possible data from each node of the network could instantaneously transmit all possible data to all other nodes on the network. In other words, such a network would function as one unit because through its perfect interconnectivity it is in fact a single entity. This perfectly lubricated system is not achievable in the real world, so any actual system will at best asymptotically approach this ideal. A network with a CI score of 0 is the opposite: no information would move at all, so it's a non-functioning network, at least in that iteration.

Eq. 3 formalizes CI for any given PCC. (Fn 6)  $X_j^k$  is a subset of the PCC's possible constituents, and MI (mutual information) is a two-way information/causal flow between the constituents:

$$\text{Eq. 3. } \psi(\text{PCC}) = \sum MI(X_j^k; \text{PCC} - X_j^k)$$

*Footnote 6. Edelman and Tononi offer a similar measure (Edelman and Tononi 2001, p. 130), described as “neural complexity,” but neither this measure nor their theory more generally have a direct bearing on phenomenal content. This is the case because despite their assertions that their theory explains qualia as well as the workings of the brain, their theory is expressly materialist in nature and offers no link between functional explanations of the brain and phenomenal content/experience. They do not offer any psychophysical laws or bridging principles between the physical and phenomenal realms.*

PI and CI will entail complicated calculations in any biological structure because of the physical complexity involved in any biological structure. I discuss this limitation further below.

Looking again to the fruit fly as an example for applying the framework, the fruit fly's brain is mostly devoted to visual processing and contains about 100,000 neurons. (Rein, K., et al., (2002). Chiang, et al., (2010)).

If we assume an average 100 dendrites for each neuron, we have about 10,000,000 synapses, which are the internal connections quantified by CI in this case. We would also, to be comprehensive, have to determine what neural subunits exist in the fly brain and quantify interconnections between neural subunits in addition to the simple internal connectivity of all synaptic connections; these data are steadily being discovered in work on the various “connectomes” in different organisms. We would also need to consider other relevant information flows at the subneuronal level, as explored by Craddock et al. 2017 and Hameroff and Penrose 2014, and other publications. The complexity in quantifying these levels of connectivity is daunting.

For the purposes of this example, however, we can translate this calculation to an estimated normalized CI value of 4. Again, the specific value doesn’t particularly matter at this time since it’s only an example to show how the framework works.

Step 6: Calculate the Omega value based on PI and CI

The last step is to calculate the CC’s capacity for phenomenal content, or what we can label simply as “consciousness.” To obtain this figure we multiply PI and CI to obtain the omega value,  $\Omega$ , which is the end result of this heuristic framework for quantifying the capacity for phenomenal consciousness (Eq. 4). Omega is calculated as a simple product of PI and CI.

$$\text{Eq. 4. } \pi \times \psi = \Omega$$

Accordingly, the PCC’s capacity for phenomenal consciousness is the product of its perceptual bandwidth and its internal connectivity. This equation is a potentially powerful tool for gaining real knowledge of subjective experience because knowledge of two of the variables allows us to calculate the value of the third variable. The rationale for this equation is simple: each percept is, upon being incorporated into the CC, incorporated, at least to some degree, into all of its processing nodes. Keep in mind that the processing nodes in the CC in each iteration are determined by the spatial extent Eq.1:  $x_c = m/\text{cycle}$ .

As a simple example, we can focus on an artificial neural network consisting of 100 “neurons.” We can postulate a CI value of 2, in order to demonstrate how this equation works. A CI of 2 indicates that each node is rather slow at sending its possible data to all other connected nodes. And we assume that electrical currents are the energy/causal connection responsible for such information flow between these artificial neurons. We can also postulate a PI value of 1, based on the paucity of data we feed this information-starved mini-network. With CI=2 and PI=1 we calculate an Omega value of 2 ( $1 \times 2 = 2$ ), far down the scale from 0 to 100. Under the criteria described thus far, this simple network would have a commensurately simple phenomenal capacity.

Recalling our estimated PI value of 3 and CI value of 4 for the fruit fly’s visual system, we obtain an Omega of 12, on a scale of 0 to 100, for the same fruit fly’s visual system. In actuality, of course, there is no separation of senses in the complex entity that is a fruit fly. But, again, this is a simplified example to illustrate the formalisms offered here.

Table 2 provides a few more examples of possible Omega values. It is important to stress that these are speculative examples of how the framework may be applied in the future. All values provided are rough estimates and based on a normalized scale from 0 to 100.

Table 2. *Possible examples of various Omega values.*

Example	Omega Value
Electron	0.1
Atom	1
Macromolecule	3
Virus	5
Paramecium	8
Fruit fly visual system	12
Fruit fly	25
Rat	50
Bat	55
Cat	60
Chimp	70
Human	85
General Artificial Intelligence (based on resonance principles)	95
God?	100

Figure 3 summarizes the suggested heuristic.

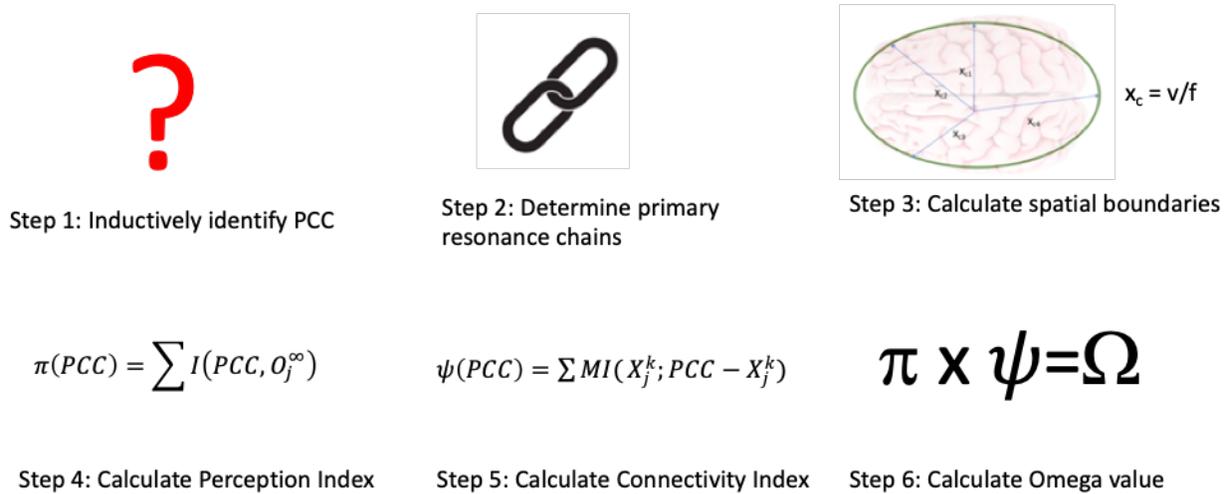


Figure 3: Summary for calculating spatial boundaries and capacity for phenomenal content.

### 3. Limitations of the approach

This mathematical approach for GRT calculates the spatial boundary of any conscious entity in each moment and a simple scalar value for phenomenal capacity of that entity. This framework may provide a useful set of tools to probe the capacity for consciousness at all scales. The main value of this approach will be to provide for comparisons across all levels of consciousness and physical complexity.

There are some limitations in employing this relatively simple approach, however, and I'll discuss the more obvious ones here.

1. A scalar value can give no indication of the different types of conscious experience available to comparably complex conscious entities, or of the different types of consciousness present in the same conscious entity in each moment.

Omega is a measure of the *capacity* for phenomenal consciousness, not a measure or characterization of any *actual* phenomenal consciousness. It is, rather, a means for measuring comparative cognition and consciousness.

Integrated Information Theory (IIT) does suggest methods for characterizing consciousness, in addition to a quantification framework (Oizumi, et al. 2014). IIT's tools for characterizing phenomenal experience – depiction of visual “constellations” for each possible quale in a given “complex” – rather than only quantifying the capacity for such experiences, may be compatible with GRT, and may be a useful addition to the tools offered here. That is, IIT's constellation-qualia characterization tools may be compatible with GRT. This is an area for future work with respect to GRT's development as an alternative or complement to IIT.

2. Calculating PI and CI in any biologically-complex entity will be difficult

As discussed above, any biologically interesting system examined in the GRT framework will be difficult to quantify accurately because of the complexity of the biological structures involved. Even relatively simple biological systems like *drosophila* or *C. elegans* have great depth that will require, at least early in the development of measures of comparative consciousness, many simplifying assumptions. However, this is the case for any theory that attempts to make sense of the biological world, and it will require, like any such theory, dedicated effort by many researchers to develop reliable simplifying tools for making meaning quantifications. Over time, such techniques will improve and more accurate quantifications will become possible. One such example has already been developed with respect to integrated information. Casarotto et al. 2016 (with Tononi as a co-author) employs a simplifying approach, the Perturbational Complexity Index, as a proxy for integrated information.

3. GRT adopts a process notion of the flow of time

GRT adopts a process time notion of time (Hunt 2014). As described in Hunt 2014, this is a notion of time that matches the human *experience* of time, which appears to entail a steady passage of time, and resolves various difficulties presented by other notions of time. So while some observers may consider GRT's adoption of process time to be a difficulty or limitation of the theory, this may be one of its strengths.

#### 4. Conclusion

The mathematical framework offered here may be useful to both researchers and philosophers in probing the nature and extent of consciousness. Various other quantification and characterization approaches have been offered, including in particular the Integrated Information Theory developed by Tononi, Koch and others. Hunt 2011 and 2014 describe how GRT and IIT differ and those differences between the theories generally remain. We acknowledge in the present paper that IIT's tools for characterizing phenomenal experience – depiction of visual “constellations” for each possible quale in a given complex – rather than only quantifying the capacity for such experiences, as is done in the present paper, may be compatible with GRT. IIT's constellation-qualia characterization tools may help to fill in key gaps with GRT.

The key difference between GRT and IIT is an explicitly process view of time in GRT, and various types

of shared resonance (and thus various phase transitions in the transmission of information) forming, consequently, the key signature of complex consciousness. IIT relies instead on an “exclusion principle” for defining the dominant consciousness (“maximally irreducible conceptual structure” or MICS) present in any collection of items (Oizumi, et al. 2014). GRT results in a nested hierarchy of conscious entities in any complex consciousness, whereas IIT results in the extinction of subsidiary conscious entities as a result of the combination of consciousness into a single larger entity. Hunt 2014 describes these differences in more detail.

This is not the place for a detailed comparison between GRT and other theories of consciousness. However, GRT was developed as a way to mitigate at least some of the difficulties posed by other theories of consciousness. The approach proposed is also a relatively simple mathematical framework, and simplicity presents some advantages.

## References

Bandyopadhyay, A. (2019, June 15), *Resonance chains and new models of the neuron* . Retrieved from: <https://medium.com/@aramis720/resonance-chains-and-new-models-of-the-neuron-7dd82a5a7c3a>.

Bahramisharif, A., Gerven, M. A., Aarnoutse, E. J., Mercier, M. R., Schwartz, T. H., Foxe, J. J., . . . Jensen, O. (2013). Propagating Neocortical Gamma Bursts Are Coordinated by Traveling Alpha Waves. *Journal of Neuroscience*, 33 (48), 18849-18854. doi:10.1523/jneurosci.2455-13.2013.

Casarotto, S., Comanducci, A., Rosanova, M., Sarasso, S., Fedchio, M., Napolitani, M., . . . Massimini, M. (2016). Stratification of unresponsive patients by an independently validated index of brain complexity. *Annals of Neurology*, 80 (5), 718-729. doi:10.1002/ana.24779

Craddock, T. J., Kurian, P., Preto, J., Sahu, K., Hameroff, S. R., Klobukowski, M., & Tuszyński, J. A. (2017). Anesthetic Alterations of Collective Terahertz Oscillations in Tubulin Correlate with Clinical Potency: Implications for Anesthetic Action and Post-Operative Cognitive Dysfunction. *Scientific Reports*, 7 (1). doi:10.1038/s41598-017-09992-7.

Crick, F.C. and Koch, C. (1990). “Towards a neurobiological theory of consciousness,” *Sem. Neurosci.* 2:263-275.

Dehaene, S. (2014). *Consciousness and the Brain: Deciphering How the Brain Codes Our Thoughts* . London, England: Penguin.

Fries, Pascal. (2005). Fries, P.: A Mechanism for Cognitive Dynamics: Neuronal Communication Through Neuronal Coherence. *Trends in Cognitive Sciences* 9, 474-480. *Trends in cognitive sciences*. 9. 474-80. 10.1016/j.tics.2005.08.011.

Fries P. (2015). Rhythms For Cognition: Communication Through Coherence. *Neuron* . 88(1):220-235. doi:10.1016/j.neuron.2015.09.034.

Gelperin, A. (2014). Comparative chemosensory cognition. *Frontiers in Behavioral Neuroscience*, 8 . doi:10.3389/fnbeh.2014.00000

Goff, P. (2017). *Consciousness and Fundamental Reality* . Oxford University Press.

Hameroff, S., and Penrose, R. (2014) Consciousness in the universe: A review of the ‘Orch OR’ theory. *Physics of Life Reviews* 11 (2014) 39–78

Hunt, T. (2011) Kicking the Psychophysical Laws into Gear A New Approach to the Combination Problem. *Journal of Consciousness Studies* 18 (11-12):11-12.

Hunt, T. (2014) *Eco, Ego, Eros: Essays on Philosophy, Spirituality and Science*. Santa Barbara: Aramis Press.

Hunt, T., Schooler, J. (2019) The "easy part" of the Hard Problem: a resonance theory of consciousness. *Authorea* . DOI: 10.22541/au.154659223.37007989.

Hunt, T. (2019a, June 10) *Resonance and process philosophy* . Retrieved from: <https://medium.com/@aramis720/resonance-and-process-philosophy-e5b801045ca6>.

Hunt, T. (2019b, July 1) *How can you tell if another person, animal, or thing is conscious. Try these 3 tests*. Retrieved from: <https://theconversation.com/drafts/115835/edit>.

Koch, C. (2004). *The Quest for Consciousness: A Neurobiological Approach* . Roberts Publishers.

Maier, N., Nimmrich, V., Draguhn, A.: Cellular and network mechanisms underlying spontaneous sharp wave-ripple complexes in mouse hippocampal slices. *J. Physiol.* 550(Pt 3), 873–887 (2003). doi:10.1113/jphysiol.2003.044602

Oizumi, M., Albantakis, L., & Tononi, G. (2014). From the Phenomenology to the Mechanisms of Consciousness: Integrated Information Theory 3.0. *PLoS Computational Biology*, 10 (5). doi:10.1371/journal.pcbi.1003588

Salart, D., Baas, A., van Houwelingen, J.A.W., Gisin, N. & Zbinden, H. (2008) Spacelike Separation in a Bell Test Assuming Gravitationally Induced Collapses, *Physical Review Letters* , **100** ( 22), pp. 1-4.

Siegel, Allan; Saper, Hriday (2005). *Essential Neuroscience* .

Takahashi, K., Saleh, M., Penn, R. D., & Hatsopoulos, N. G. (2011). Propagating waves in human motor cortex. *Frontiers in human neuroscience* , 5 , 40. doi:10.3389/fnhum.2011.00040

Tononi G, Koch C. 2015. Consciousness: here, there and everywhere? *Phil. Trans. R. Soc. B* 370: 20140167. <http://dx.doi.org/10.1098/rstb.2014.0167>

Vallverdú, J., Castro, O., Mayne, R., Talanov, M., Levin, M., Baluška, F., . . . Adamatzky, A. (2018). Slime mould: The fundamental mechanisms of biological cognition. *Biosystems*, 165 , 57-70. doi:10.1016/j.biosystems.2017.12.011

Zhang, H., & Jacobs, J. (2015). Traveling Theta Waves in the Human Hippocampus. *The Journal of neuroscience : the official journal of the Society for Neuroscience* , 35 (36), 12477-87.