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What Is the Fundamental Nature of Consciousness? [Excerpt]

Giulio Tononi

23-29 minutes

*This chapter [from PHI: A Voyage from the Brain to the Soul](#), by [Giulio Tononi](#) (Pantheon, 2012) describes Tononi's theory of consciousness as a measure of information. The brain, Tononi postulates, consists of billions of neurons: think of them as if they were transistorlike bits that, when tallied, sum to equal more than their parts. That increment above and beyond—Tononi calls it *phi*—represents the degree to which any being, whether human or mule, remains conscious.*

From the forthcoming book *PHI: A Voyage from the Brain to the Soul*, by Giulio Tononi

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Integrated Information: The Many and the One

In which is shown that consciousness lives where information is integrated by a single entity above and beyond its parts

When is an entity one entity? How can multiple elements be a

single thing? A question simple enough— but one, thought Galileo, that had not yet been answered. Or perhaps, it had not been asked.

The sensor of the digital camera certainly had a large repertoire of states— it could take any possible picture. But was it a single entity? You use the camera as a single entity, you grasp it with your hands as one. You watch the photograph as a single entity. But that is within your own consciousness. If it were not for you, the observer, would it still be a single entity? And what exactly would that mean?

While musing such matters, Galileo was startled by a voice. J., a man with the forehead of an ancient god, addressed him in a polished tone: “Take a sentence of a dozen words, and take twelve men, and tell to each one word. Then stand the men in a row or jam them in a bunch, and let each think of his word as intently as he will; nowhere will there be a consciousness of the whole sentence. Or take a word of a dozen letters, and let each man think of his letter as intently as he will; nowhere will there be a consciousness of the whole word,” J. said.

Or take a picture of one million dots, and take one million photodiodes, and show each photodiode its own dot. Then stand the photodiodes well ordered on a square array, and let each tell light from dark for its own dot, as precisely as it will; nowhere will there be a consciousness of the whole picture, said Galileo. “So you see that, Galileo,” J. continued. “There is no such thing as the spirit of the age, the sentiment of the people, or public opinion. The private minds do not agglomerate into a higher compound mind. They say the whole is more than the sum of its parts; they say, but how can it be so?”

An image came to Galileo. An astronomer was watching the sky in Padua, during an eclipse, and precisely at the same moment, another astronomer was watching the night sky at the antipodes. Would there be a single consciousness contemplating, in one great image, the entire dome of the sky, the austral and boreal skies joined seamlessly at the horizon? A single image of the entire sky, experienced within one consciousness? That was absurd, thought Galileo, and its absurdity had nothing to do with the distance between the scientists. Whether the two were separated by the diameter of the earth, or by a fraction of an inch, like two photodiodes on the camera sensor, made no difference. Because in both cases, the two parties could not interact. And if they could not interact, they could not form a single entity, and they could not have a single, unified conscious experience.



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“Of course,” agreed J. “A blind man and a deaf man cannot compare sounds and colors. One hears them and the other one sees them, but could they compare them if they are together? Not even if they were to live in the same house forever, not if they were conjoined twins.” Like Ishma and El, thought Galileo.

“Nice words,” said Alturi, standing next to Galileo. “But what’s the point? We were arguing about the information in a camera, and you saw that, if the camera is large enough, it can be as much or more than the information generated by a brain. Which shows that information, as S. was saying, has little to do with consciousness. Isn’t it so?”

Galileo hesitated. If one measured information the way S. did, a camera was better than a brain: the larger the repertoire of states available to a system, the greater the reduction of uncertainty—the greater the information generated by the particular state the system was in. But was this the right way of measuring information? He thought of what J. had said, of the scientists in the northern and southern hemispheres, of Ishmael's left and right hemispheres. So he tried:

It should make a difference if the information is generated by a system that is one, rather than just a collection of parts.

"Quite possibly," said Alturi. "And how would one show the difference?" He smiled, as if he knew that Galileo could not provide an answer.

"I wish I knew," said J., as if he knew there could not be an answer. Galileo paused, as if lacking for words, then turned to J., and asked:

If, with an extraordinarily thin and sharp blade, old Occam's razor, say, one were to split in two the sensor of the camera, in such a way that half a million photodiodes lie on one side, and the other half a million on the other side, what would then happen to the image seen by the camera?

"Nothing would happen, of course," answered J. "The camera would go on working just as well, taking full pictures, the pictures could be sent over the air, stored and replayed at will, and no one would notice any difference."

Galileo held up the camera, and took a picture, with the split sensor, of what was now on the screen before them. It was an Italian word, *SONO*, the word for "I am," and *SONO* was

seamlessly displayed.

Indeed, said Galileo to J. As long as the sensor is in place, nothing will change, because every one of the million photodiodes will go on reporting its own separate dot, unaware of what its peers are seeing.

But what if, with a thin and sharp blade, one were to split in two a brain? Recall Ishmael's brain, in the crypt of Prince Venosa, when Salerno froze the connections between his two hemispheres.

Would nothing change, as with the camera? You know it already, said Galileo without waiting for an answer. Ishmael split into Ishma and El, and Ishma saw the lady, and El the brute, but no one saw them both—there was no Ishmael who could see the adultery, as long as the two hemispheres were split. But when the hemispheres embraced again with warmth, there was Ishmael again, and Ishmael saw the couple joined.

You know the answer then: Ishma would see *SO*, the Italian word for “I know,” El would see *NO*, the word for “no,” but there would be no Ishmael who would see *SONO*, and say, “I am.” Unlike the camera image, the blade would split the conscious image and consciousness itself would be divided.

J. and Alturi remained silent, so Galileo went on. But if the connections between the hemispheres are warm, as they are in your own brain, you can try as hard as you may wish to split your experience in two, to see *SO* independently of *NO*, but you will not succeed. Just as you will not succeed in seeing the shape of things without their color, or their color without their shape—you will remain one J., one experience, one consciousness.

“Impregnable logic,” said J. “One plus one equals two, but not

quite,” he added.

One thing is certain, said Galileo: there is nothing it is like to be the sensor of a camera—consciousness cannot live there, because the sensor is not a single entity, though it may be rich with a million photodiodes. Just like there is nothing it is like to be two scientists, one in the northern and one in the southern hemisphere. Nothing it is like to be a row of twelve men, each thinking of a different letter.

“I see it,” said J. “The camera may be large, but is less than poor in consciousness: it owns none and lacks existence in the realm of experience. Compared to it, even a photodiode is richer, it owns a wisp of consciousness, the dimmest of experiences, one bit, because each of its states is one of two, not one of trillions. Yet being a photodiode is more than not being at all. I wonder,” J. went on. “What if one splits the brain into a million parts? First left and right, then front and back into four quarters, then with a hundred other cuts through its white matter, into a million separate grains, as separate as the grains on a cob, or the photodiodes on the camera sensor: Would consciousness disintegrate?”

“Never mind,” said Alturi. “Galileo hasn’t shown a difference in number. If consciousness lives on information, one must squeeze money out of a formula, the formula of S.”

Allow me, said Galileo at once, without raising his eyes. If we cut the camera sensor into its one million parts, the array of photodiodes, how much information is generated by each photodiode?

“One bit, of course,” answered Alturi. “That’s what the formula of S. tells us.”

Now, said Galileo, how much information is generated by the

camera sensor?

“What a question,” said Alturi. “Being constituted of a million photodiodes, it will generate one million bits.”

Il right, said Galileo. How much information is generated by the camera sensor above and beyond its parts? Beyond its one million photodiodes, I mean.

“Zero, of course,” said Alturi after a while, not expecting he would be questioned this way. Precisely, said Galileo, feeling he was usurping Alturi’s role. The camera does not generate any more information than the sum of its parts. Therefore, at least with respect to information, we have no need to invoke the camera above its parts. We might as well drop it from the catalog of useful entities, cut it with Occam’s razor, and stick with a million photodiodes. *Entia non sunt multiplicanda praeter necessitatem.*

“That’s just a matter of perspective,” intervened Alturi, who seemed busy tipping the smoldering tobacco in his pipe onto the floor. “You like to talk of photodiodes and ban the camera, I may prefer the camera and spurn the photodiodes.”

Not so, not so, hurried Galileo, think of Ishmael. He would have seen SONO and understood “I am.” But after the connections between his two brains were frozen, and Ishmael had disappeared, nobody would be left who could see and understand SONO, “I am.” Ishma and El together could never make up for it, for one saw SO and understood “I know,” the other saw NO and understood “No.” In this case, unlike with the camera, the whole is more than the sum of its parts and cannot be reduced to them; Ishmael is more than Ishma and El, and SONO cannot be reduced to SO and NO.

“I think I see the point,” said J. “The information generated by the whole above and beyond its parts— call it integrated information—is what distinguishes Ishmael from a camera. Does this seem right, Alturi?”

“What would be right?” exclaimed Alturi, who was busy grounding the tobacco out with his heel. “Is it right that a distribution of system states, if it cannot be factorized into a product of distributions of its parts, is not reducible? Of course, but SO what? What’s special about this? There are all kind of things that cannot be factorized, that cannot split without a loss, but why would any of this matter for consciousness? Besides, there are many ways to divide a system into parts, of factorizing distributions, and you will get a different answer depending how you cut it into pieces.”

“True,” said J. “If integrated information has something to do with consciousness, it should not change depending how you divide a system into parts. Isn’t it so, Galileo?”

The crucial cut, said Galileo, is the minimum cut, the cruelest cut of all— the cut through a system’s weakest link, the cut that divides it into its strongest parts— those that generate as much information as possible by themselves, leaving as little as possible for the whole.

“Excellent,” said J. “Integrated information is the information generated by a system above its parts, where the parts are those that, taken independently, generate the most information. Now that we have a definition, we need a symbol for it.”

“If you need a symbol, it should be Φ ,” said Alturi. “That is the symbol of the golden ratio— the right way of dividing something into parts. And the minimum cut, which reveals how much

information is integrated information, is the right way of dividing a system into parts, is it not? You should call it Φ .”

That would be interesting, said Galileo. After all, the golden ratio was studied by a fellow Pisan, the good old Fibonacci.

“It is better than that,” said J. “ Φ is like Phenomenology, like experience, which is what consciousness is.”

Better than that, said Galileo. Φ has an I, for information, and an O, a circle, for integration. Let’s call it Φ , then.

“Splendid,” said Alturi. “Now that you have your quantity and your symbol, let’s see what follows. Clearly, every time some elements interact, you’ll have some integrated information: a whole that does not reduce to its parts. Then, if integrated information has something to do with consciousness, as you seem to think, what follows is quite simple: it follows that consciousness is like an onion.

“Take me and the neurons in my brain. Somewhere inside my brain there is me, of course, but I am not alone. If you peel me away, neuron by neuron, you’ll find other me, millions of me, each lacking some part, but all conscious to some extent. I am just the most conscious of my many me, but those diminished selves would be right in claiming their own rights, except that I don’t hear them, but they are along for the ride. “

Then take my body. No doubt my body, too, is made of interacting parts, a whole that cannot be reduced to its parts— either physically or informationally— in fact the brain itself is just one of those parts. So the body, too, is yet another consciousness, an even larger onion than I thought I was. Its Φ may be much less than mine— its minimum cut quite weak, say across my neck— but

it, too, is carrying on its own limited existence. A multiplication of selves, a proliferation, of which I know nothing at all, and they know nothing of me.

“But it does not stop there. Then there is the two of us talking, nay, the three of us, interacting as a whole that cannot be reduced merely to the three of us taken independently. A Holy Trinity thinking its little Trinitarian thoughts.

“And then a city, a country, or the entire world, all layers of the universal onion, and each of them conscious, some more and some less.”

“I see your point,” said J. “And yet consciousness seems to reside just once inside my head, your head, and Galileo’s head. Then Φ cannot be the answer.”

The onion, too, must be peeled with Occam’s razor, said Galileo. And when you do so, that will leave only its core—the core where integrated information reaches its maximum—the core that holds together while the rest peels off.

“So consciousness is not an onion, it is an onion’s core! This is quite some progress,” said Alturi. “But if you and I talk, what then? Don’t you and I, talking as we are doing now, form a larger core?”

Occam’s razor, once again, answered Galileo. You just said: “You and I, talking.” “You and I, talking” is much simpler, physically or informationally, than a would-be chimera mingling you and I. That monster has no holding power and would break down at its seams, you and me, where reality is carved into individual entities. Think not of monsters but of raindrops. Inside a drop of rain, molecules interact more strongly than with the air outside, and so a surface forms. The drop is a single entity and is contained within a border.

When two droplets meet, either they bounce and remain separate, or they fuse and become a single, larger drop. There are no overlaps, nor drops within other drops. So it may be with consciousness: consciousness lives within a system where integrated information reaches a maximum, inside its own drop.

“So what you have understood is this,” said Alturi: “Experience cannot be reduced to anything less than it is. Impressive indeed.”

Ignoring Alturi, J. turned to Galileo. “If you are right, we should have a name for a system for which the information generated by the whole above its parts reaches a maximum, the onion core, the raindrop of consciousness. A complex, perhaps?”

Let’s call it so, said Galileo— a complex.

“So a complex is where consciousness lives,” said J. “There consciousness raises its house, erects its walls, and you are what’s inside, the rest of the world is what’s outside. The house of consciousness is one and cannot be shared: there is only one, only one owner, and it excludes all others.”

It was not clear whether Alturi liked this, but then he said: “I guess when you apply this analysis to the sensor of the camera, it will break down into complexes that are individual photodiodes, each of them distinguishing between just two states, on or off, but there will be no integrated entity— a complex— corresponding to the sensor. But when you analyze your brain, you will find inside it a set of nerve cells that form a large complex: one that can distinguish among a large repertoire of states in a way that its parts cannot; and one that does so maximally, more than any other set of nerve cells, more than the entire body, than any crowd of men, than the world itself.”

Precisely, said Galileo.

“Then I have something for you,” said Alturi, and handed Galileo some notes. The notes were from Frick and were full of diagrams representing parts of the brain. There was the cerebrum: without it, Copernicus had lost his consciousness forever. Galileo remembered when he and Frick had compared the cortex and thalamus to a great city. The diagram showed that a large expanse of the cerebral system formed a single complex of high Φ . This was because its elements, different groups of neurons, were specialized for different functions, and yet these specialists talked to each other—they were integrated within a single great complex that could distinguish among a vast number of different states, one for each experience.

There was the cerebellum, which had even more elements, but they were separated into many small modules that did not talk to each other. Each of them formed a small, separate complex, and for each little complex Φ was low. Like a collection of photodiodes, thought Galileo, and remembered Poussin: the painter’s hand trembled without a cerebellum, but his mind was rich and full.

Then there were diagrams explaining why your eyes may be blind but your consciousness can have inner vision, like the blind painter in front of his great allegory. They showed how the visual inputs reached the cerebral cortex, influenced its functioning, but did not become part of the great complex of high Φ that gave rise to consciousness.

And there was his friend M., too, showing that all the nerves reaching out of the great complex, though necessary to speak and act, did not participate in it and thus did not contribute to his

consciousness. There were Galileo's muses, the poetess and the gamba player, with loops going out and into the great complex, but the loops themselves remained outside. This was why, thought Galileo, so many neural processes that make us understand speech, or find the right words, or say them, or remember them, perform marvelous feats, but still remain outside the special sphere of consciousness.

And finally there was Ishmael, with the nerve fibers linking the right and left hemisphere split, and the great complex splitting in two and yielding two consciousnesses with similar values of Φ , Ishmael and El. Other, smaller splits, might explain why Teresa could see and yet did not know it, thought Galileo. And surely Φ was low during the frenzy of seizures, or the deep waves of unconscious sleep, because the repertoire of distinguishable brain states was bound to shrink.

"You think this might explain it?" asked J. after a while.

Consciousness is such a lofty bird that it must be caught with an equation, said Galileo. First catch the concept, then dress it in the language of mathematics. Then, and only then, knowing how it can be measured, would one truly know what it is. It may be, said Galileo, it may be that the essence of consciousness is integrated information.

And this may be a way this concept can be grasped— a way to catch this bird: a way to find what entity is a single entity, a nucleus of experience.

"Something still perplexes me," J. said pensively. "The brain is inconceivably complex, so much so that trying to understand its mysteries through a network of equations is like trying to collect the

sea with fishing nets. The brain has more trees than the jungle, more streets than a great city, is more plastic than the desert's sand, more changeable than the waves of the sea. And who would hope to reduce the endless wavering of the dunes, the bustling traffic of the market, the tangle of leaves and animals in the jungle canopy, to a series of equations, or worse, to a set of numbers? Mathematicians may weave their networks, but in the end, I am afraid, they will catch nothing."

"Do not be afraid, since there is beauty in principles," said Alturi's voice from a distance, and J. turned to question Galileo.

But Galileo too was far away. For he had read something at the end of Frick's notes, something he recognized from long before:

Philosophy is written in this grand book—the universe I say—that is wide open in front of our eyes. But the book cannot be understood unless we first learn to understand the language, and know the characters, in which it is written. It is written in the language of mathematics, and its characters are triangles, circles, and other geometric figures, without which it is humanly impossible to understand a single word of it; without these it is like wandering in vain in an obscure labyrinth.

So Galileo felt, for the first time in a long time, that he must write what he had learned. And this is what he wrote:

Integrated information measures how much can be distinguished by the whole above and beyond its parts, and Φ is its symbol. A complex is where Φ reaches its maximum, and therein lives one consciousness—a single entity of experience.

Notes "The whole is more than the sum of its parts" is an expression that comes from Aristotle's *Metaphysics*, which Galileo

knew well. William James thought that integration was a key to consciousness and fought hard to understand it, as revealed by some excerpts from his *Principles of Psychology* integrated into this chapter. Unfortunately he never succeeded and eventually gave up amid doubts and denial, writing an essay with the revealing title “Does Consciousness Exist?” James’s photograph is from the Houghton Library, Harvard University. The all-sky night photograph of the Northern Galactic Hemisphere (on the left) was taken by Tunç Tezel at the Canary Islands; the Southern Galactic hemisphere (on the right) was taken by Stéphane Guisard in the Acatama Desert. The picture obtained by joining the horizons of the two all-sky images was the Astronomy Picture of the Day on July 30, 2011 (A Tale of Two Hemispheres). If integrated information, measured by Φ (the Greek letter phi), is indeed the weighty concept at the heart of consciousness that it is claimed to be, this chapter introduces it in a rather light-weighted manner. Perhaps the author was trying to avoid equations at all costs, but the result is far from satisfactory. Versions of Φ dressed in equations, but in the end just as unsatisfactory, are found in Tononi and Sporns, *BMC Neuroscience* (2003); Tononi, *BMC Neuroscience* (2004); *Biological Bulletin* (2008); Balduzzi and Tononi, *PLoS Computational Biology* (2008); Tononi, *Archives italiennes de biologie* (2010, 2011). Information was defined as “a difference that makes a difference” by Gregory Bateson, in *Steps to an Ecology of Mind* (University of Chicago Press, 1972). *The Ripe Harvest* by Klee is at the Sprengel Museum, Hanover, Germany. The last portrait is by Arcimboldo (disliked by Galileo and modified in bad taste, if not bad faith) and is known as Adam (Eve’s counterpart, private collection).