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On the Measurability of Consciousness: Perspectives from Product Design and Philosophy

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ABSTRACT: With recent advances in the science of consciousness, there is an increased interest in the measurement problem of consciousness (MPC). The development of consciousness measurement systems (CMS) is still in its infancy without a formal framework and established design approach. This article presents a novel consciousness measurement framework that uses measurement workflow, design principles, the concept of observability, consciousness theories and technologies, and philosophical arguments. The framework proposes measurability criteria, applies them to different use cases, and identifies whether existing theories and technologies can measure consciousness attributes for specific use cases. Researchers and engineers can use the framework to develop CMS for individual use cases without being bogged down by the complexity of unknowns in the field of MPC.

KEYWORDS: consciousness, measurement problem of consciousness (MPC), consciousness measurement system (CMS), problem space analysis, process workflow, MPC use cases.

1 INTRODUCTION

The only thing you know for sure is that you are conscious. All else is inference, however reasonable. There is something in your brain that feels, experiences, makes sense of the external world, and contemplates beyond the limits of the senses. It even knows that it knows, feels the feelings, and experiences the experiences. The nature of consciousness makes it, by definition, a wholly private affair (Koch, 2019). Your experience is exclusive to you, and nobody else has any access to this experience except your external behavior, including what you choose to report verbally or through other behavior. With the advent of Large Language Models (LLM), chatbots like Bard/Gemini and ChatGPT, and generative models, artificial intelligence (AI) is changing the way we understand, think, and interact with the world around us (Dean, 2023). Machines and systems are starting to simulate human-like behavior, such as intelligence and creativity. It may not be far away when machines exhibit behaviors resembling human emotions and feelings. With the adoption of these technologies, it is quite often asked if these AI systems are actually conscious or just simulating conscious behaviors. What about animals? Which animals have consciousness, and which ones do not? How do we know if coma victims or patients in a vegetative state are conscious? How can a family know when a patient in a minimally conscious state is truly conscious?

The basic question is how to know if any person, animal, or anything is actually conscious and not just simulating various aspects of consciousness. This question is not new. It seems to be around in some form forever, yet neither philosophy nor science has been able to provide an acceptable answer. We have seen great progress in neuroscience and consciousness studies over the last several decades. Yet, the study of consciousness remains one of the most challenging contemporary scientific endeavors and confronts several methodological and theoretical challenges. Some of these challenges are the scientific modeling of feeling or experience, the distinction between phenomenal and access consciousness, whether consciousness is a continuous stream of percepts or it is discrete, and the relationships between consciousness and self (Raffone, 2021).

With recent advances in brain scanning technologies such as functional MRI (fMRI), magnetoencephalography (MEG), and electroencephalography (EEG), there is an increased interest in the measurement problem of consciousness (MPC). There are two key aspects of consciousness that make it challenging for measurement (Raffone, 2021).

- **Subjectivity** – Consciousness is subjective and can only be accessed by the person experiencing it. Researchers often rely on the study subject's reports, which can be unreliable. Subjective methods also can't be used with animals who can't verbally report.
- **Indirect measurement** – Consciousness can not be measured directly. It can only be measured indirectly through observation of its effects, such as changes in behavior or physiology.

These aspects of consciousness create several challenges for MPC, which are typically absent in other measurement systems, e.g., devices to measure electric current, the speed of a car, or the mass of an object. Some of these challenges are (Browning & Veit, 2020; Gamez, 2014):

- **Indicator validity problem** – Most methods evaluate the presence of consciousness in humans and attempt to extend them to nonhuman cases. The indicators developed using the differences between conscious and unconscious humans do not necessarily apply to other conscious or nonconscious organisms.
- **Extrapolation problem –** This is a problem when extrapolating indicators developed in humans or other biological organisms to artificial systems.
- **Theory-neutrality** – Without a widely accepted theory of consciousness, a CMS can have wider acceptability only if it can be theory-neutral.
- **Distinguishing between mechanisms** – It's important to distinguish between the neural mechanisms that give rise to consciousness and those that enable its subjective report. In the absence of a subjective report, we don't know whether it is due to issues in reporting or issues with consciousness.
- **Measuring all relevant experiences** – A measure of consciousness should measure all relevant subjective experiences and be immune to influences from unconscious knowledge.

Consciousness studies have rapidly progressed in the last three decades; many scientific and philosophical theories of consciousness have been proposed. Some of the theories are worldly discrimination theory (Eriksen, 1960), Integrated Information Theory (IIT) (Tononi, 2008), panpsychism and cosmopsychism (Keppler & Shani, 2020), and yogic theory of consciousness (Tripathi & Bharadwaj, 2021). A recent review paper by Sattin et al. (2021) assessed 1130 consciousness-related articles published between 2007–2017, analyzed 68 selected articles, and identified 29 theories of consciousness. These theories, along with recent progress in neuroscience and brain scanning technologies, have resulted in several proposals for measuring consciousness. Seth *et al.* (2006) have formally analyzed three quantitative measures of dynamical complexity in the neural systems underlying consciousness: neural complexity, information integration, and causal density. They find that no single measure fully captures the multidimensional complexity of conscious neural systems and conclude that "a satisfactory measure is likely to be one that combines both qualitative and quantitative elements." Hunt et al. (2022) examine several categories of tests for making reasonable inferences about the presence and complexity of consciousness. They label them as the measurable correlates of consciousness (MCC), which includes three subcategories: (a) neural correlates of consciousness (NCC), (b) behavioral correlates of consciousness (BCC), and (c) creative correlates of consciousness (CCC).

Since consciousness can only be measured through first-person reports, one has to address the problems associated with the accuracy of first-person reports, the possibility of non-reportable consciousness, and the causal closure of the physical world. Gamez (2014) proposed a framework that starts with the idea that reports about consciousness from reference systems are functionally connected to the reference systems' consciousness. This enables consciousness to be measured during experiments on the neural correlates of consciousness. In another study, Kim *et al.* (2018) used measurements from a multichannel electroencephalogram (EEG) to estimate consciousness in the human brain using Tononi's (2008) integrated information theory (IIT). The study represents "a new practical approach to the application of IIT, which may be used to characterize various physiological (sleep), pharmacological (anesthesia), and pathological (coma) states of consciousness in the human brain."

Technologies are becoming available to measure the presence and complexity of consciousness. However, the development of consciousness measurement systems (CMS) is still in its infancy, with many outstanding challenges and without a formal framework for design and development. This article uses product design principles, e.g., measurement process workflow and problem space analysis, to define a novel design framework for developing CMS. The framework proposes measurability criteria, applies them to different use cases, and identifies whether the required attribute of consciousness in a use case can be measured by existing theories and technologies.

The design framework defines several CMS functions within the measurement workflow. These are: (1) modeling of consciousness states and outputs, (2) validation of sensor input signals, (3) sensing, (4) model-based state estimation, (5) interpretation, and (6) CMS calibration. Each CMS function requires different theories and technologies for its implementation. For example, the sensing function can be based on behavioral, neurophysiological (e.g., EEG, MEG, fMRI, etc.), computational (e.g., IIT), and other measurements. Measurability criteria for each CMS function are established and applied to different use cases that are identified using a product design technique called "problem space analysis." The application of measurability criteria helps identify CMS functions that can or can't be designed for individual use cases using existing theories and technologies. For example, the absence of an acceptable model for the subjectivity of consciousness should not be a problem for measuring consciousness in use cases involving human clinical applications. Currently, available technologies can be sufficient to measure consciousness in these use cases. However, without a well-defined consciousness model, we cannot develop a CMS to determine if a humanoid robot has consciousness.

Consciousness is unique among all the things that can be measured. It is all around us. We know about our own consciousness. But, the subjectivity in the consciousness of others is only an inference, however reasonable. Therefore, one might ask whether subjectivity, which can be experienced or felt only by the subject, is measurable. This paper uses concepts from mathematical logic (e.g., Gödel's incompleteness and Tarski's undefinability theorems) and philosophy (e.g., method of agreement-disagreement in the Indian Nyaya system) to understand the measurability of subjectivity. Based on the preliminary analysis done so far, this paper argues that subjectivity is not measurable like other attributes of consciousness using currently available theories and technologies. This is a major area of study by itself and will be taken up as a future project.

The key contribution of this paper is a novel CMS design framework that uses measurement workflow, design principles, theories and technologies from neuroscience, and arguments from philosophy. The framework provides a precise understanding of the measurability of different CMS functions. Researchers and engineers can use the framework to develop CMS for specific use cases without being bogged down by the complexity of unknowns in the field of MPC.

The paper is organized as follows: Section 2 describes the conceptual framework for measuring consciousness. Section 3 provides details on validating different MPC functions. Section 4 proposes the measurability criteria for different use cases, followed by discussion and summary in Sections 5 and 6, respectively.

2 FRAMEWORK FOR MEASURABILITY ANALYSIS IN MPC

Increased focus in MPC has resulted in a new wave of interest in the philosophical foundations of measurement that looks into the basic questions like what measurement actually is, what conditions have to be fulfilled for a process to be accepted as a measurement (aka measurability), and what are the basic assumptions required for a measured quantity to be meaningful, etc. (Mari et al., 2021). This section introduces a novel framework to define measurability criteria for different MPC use cases. The framework uses concepts from product design, e.g., process workflow, problem space analysis, and the idea of observability from system theory, to identify different use cases and define measurability criteria for these use cases.

2.1 MEASUREMENT PROCESS WORKFLOW

The measurement process workflow consists of several components that interact with each other through the exchange of information (aka signals) to perform specific functions (Figure 1). Depending on the task, the workflow can be broken down into constituent parts in different ways. For example, the workflow breakdown by Bentley (2005) consists of input sensing, signal conditioning, signal processing, and data presentation to produce output signals of sensors. This workflow breakdown is helpful for the design of sensors for physical systems. We proposed a more general workflow breakdown (Figure 1) for end-to-end system-level analysis of the measurement system where sensing is considered as a sub-system.

The act of measurement presupposes the existence of a component called the “object of measurement,” having states or attributes that we want to know about. These internal states may or may not be measurable. The object of measurement produces specific signals or outputs (aka measurands) that are functions of the internal states and can be measured. The relationship between the outputs and the states is established by a mathematical function defined as part of modeling. The outputs of the object of measurement can be fed as input into another component called the “sensor” that measures the measurands. The sensor measures any signal that is provided as an input. It does not distinguish between scenarios where the sensor input comes from the real “object of measurement” or some simulated system. Therefore, we need to ensure that input to the sensor is truly the measurand that we want to measure. This function is performed by a component called “input validator.” The input validation is typically performed by a conscious agent (e.g., human) or guaranteed during system design by ensuring that the sensor is explicitly connected to the object of measurement. However, input validation cannot be guaranteed in all measurement scenarios, particularly when humans are not involved, and sensors are not explicitly connected to the object of measurement. Therefore, we have “input validation” as a separate component between the object of measurement and the sensor.

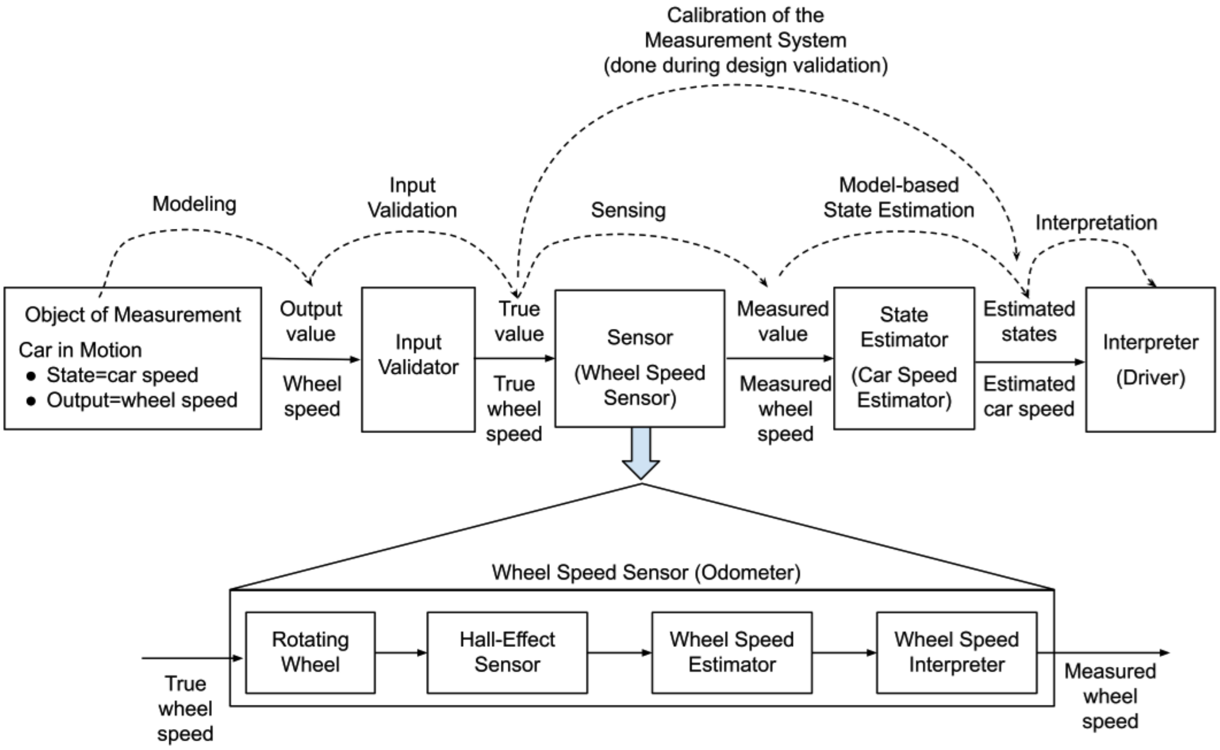

Fig. 1. Components, signals, and functions in a measurement workflow with the example of an odometer.

The input to the “sensor” is the “true value,” which is the output of the “input validation” function, and the output of the sensor is the measurement of this “true value.” The measurement can then be processed by another component called a “state estimator” to calculate the values of the states or attributes of the object of measurement. The estimated states are then interpreted by the “interpreter,” the last component in the measurement workflow. In addition to these functions, the measurement system must be calibrated against a reference system for the interpreter to make sense of the estimated states. This process is typically done during design validation before the measurement system is used in real life. The schematic diagram of all components, signals, and processes in the measurement workflow is shown in Figure 1. In addition, the figure also shows an example of a car speed measurement workflow using an odometer. Details of this example will be discussed in other sections to analyze different components of the workflow and derive measurability conditions.

2.2 MEASURABILITY CRITERIA

A measurement process is meaningful only if the interpreter can interpret the measured value to make sense of the states of the object of measurement. In other words, the states are called “measurable” (i.e., can be measured) only if there is a measurement workflow where the interpreter can interpret the “measured value” to make sense of the “states.” This can be achieved only if each of the components in the workflow (Figure 1) performs its own function accurately. The set of criteria for accurate functioning of each component is called “measurability criteria” and can be defined as given below.

- **Interpretability –** The interpreter must be capable of “interpretation” to understand the measured value in terms of the states of the object of measurement.
- **Observability** – The state estimator should be able to estimate the states or attributes using sensor outputs.

This is called “observability” in system theory (Kalman, 1960). The simplest observable system is where the system output (i.e., measurand) is the same as the system state (e.g., measuring the height of a person). The odometer in a car and the 3-dimensional attitude estimation of a spacecraft are examples of more complex state estimators. The car speed estimator uses the measurement of the wheel’s rotational speed to estimate the car’s linear speed (Figure 1). In the spacecraft example, the 3-dimensional attitude of a spacecraft is estimated using the measurement of the earth’s magnetic field (Psiaki et al., 1990). The observability of complex systems depends on the mathematical model used to describe the system output in terms of its states.

- **Sensor Calibrability** – It is the ability to calibrate the sensing system by successfully correlating the sensor outputs with the sensor inputs. This process requires the availability of a reference standard for sensor calibration and needs to be done prior to the act of measurement by a capable agent or an autonomous system.

- **Input Validability** – The sensing system measures any acceptable signal that is provided as an input. It does not have any way to know whether the input is coming from a real object of measurement or some simulated object. Therefore, something or somebody outside the sensing system needs to validate the source of the input signal. The "input validation" may sound trivial in most real-life scenarios where a conscious agent performs the measurement. However, it is an essential function of the measurement workflow that needs to be carefully implemented for autonomous systems.
- **Ability to Model** – The states or attributes that describe the behavior of a system may not always come out of the system as output and, therefore, may not be directly measured by a sensor. Therefore, we need a mathematical model to define the output in terms of system states. This model is essential to reconstruct system states using output measurement. To put it differently, we cannot construct system states without a model.
- **System Calibrability** – We make sense of measurement only by comparing it with a previously established reference. This requires the availability of a reference and the ability to correlate the measurement with the reference. It is similar to sensor calibrability but at the system level.

2.3 PROBLEM-SPACE AND USE-CASES IN MPC

Like any other engineering problem, the development of a consciousness measurement system is a design problem that involves a sequence of steps (Goel & Pirolli, 1992):

- Exploration and decomposition of the problem (i.e., analysis);
- Identification of the interconnections among the components;
- The solution of the subproblems in isolation;
- The combination of the partial solutions into the problem solution (i.e., synthesis).

This is a formal problem-solving approach where the first step is the problem-space analysis that involves exploration and decomposition of the problem. This step is performed before any other step and is done to gain more insight into the problem we are trying to solve. *The Problem Space* is the problem and everything associated with the problem, including the stakeholders, history, and philosophy of the problem. The stakeholders include those who contribute to the problem, those who benefit from the problem, and those who feel the problem most deeply as pain (Maedche et al., 2019). The *Solution Space,* in contrast, constitutes the products, services, and policies that help address a particular problem. Defining *the problem space* and writing a problem definition are the first steps to solving a problem. In other words, "what" the product needs to accomplish for users or customers is the *Problem Space*. Meanwhile, "how" the product would accomplish it is the *solution space*. A schematic representation of the problem and solution space is given in Figure 2.

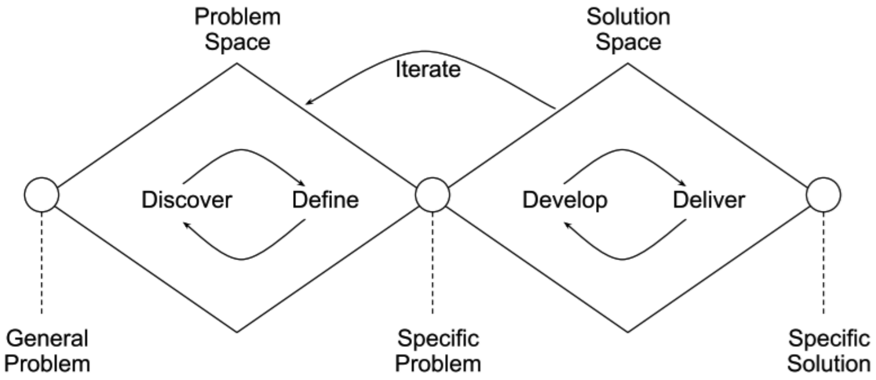

Fig. 2. Problem space and solution space in product design.

For the problem space analysis of the MPC, we can start with a list of questions that the consciousness measurement system is expected to answer. The following is a sample of questions asked by researchers (Browning & Veit, 2020; Hunt et al., 2022; Seth et al., 2008).

- How do we determine the presence and properties of consciousness?
- How can we know if any person, animal, machine, AI, or anything is conscious and not just simulating various aspects of consciousness?
- Are artificial intelligence (AIs) actually conscious or just simulating conscious behavior?
- How do we know if coma victims or patients in vegetative states are conscious?
- How can a family know when a patient in a minimally conscious state is truly conscious?

- Do animals have consciousness? Which animals have consciousness, and which ones do not?
- How do we measure the level of pain and suffering in animals involved in animal agriculture and animal experimentation?
- How can we measure whether and to what extent a particular motor, sensory, or cognitive event is consciously experienced?

By carefully reviewing these questions, we can divide the MPC problem space into three categories or use cases. Each use case consists of a set of questions that may require distinct technology to solve.

- *Potentiality of Consciousness* – This use case addresses questions about whether the object of measurement has the potential to be conscious. The objects of consciousness include every possible system, including humans, AI systems, animals, biological organisms, silicon-based machines, and extra-terrestrial autonomous systems (if and when we find them).
- *Presence of Consciousness* – Once we know or assume that the object of measurement is capable of having consciousness, the next question is whether the object is actually conscious during measurement. This measurement can be used to find if a coma patient or a person after a traumatic injury is actually conscious.
- *Degree of Consciousness* – If the object of measurement is conscious, the question is to find the degree of consciousness. Note that the previous use case for the presence of consciousness is a boundary condition of this use case, which covers the following questions.
  - How do we know if coma victims or patients in vegetative states are conscious?
  - How can a family know when a patient in a minimally conscious state is truly conscious?
  - Can we find the type of consciousness of a patient after an accident? These types may include coma, vegetative state, sleep, etc.

The presence and degree of consciousness can be considered as one use case. However, given the primitive state of technology for measuring consciousness, it may be worthwhile to design a measurement system that can give a binary output (present or absent) for the presence of consciousness. Note that this paper presents a simple problem space analysis to demonstrate the framework for the measurability of consciousness. The actual design of a CMS may include many other scenarios such as phenomenal and access consciousness (Block, 1997), different neurological conditions, e.g., synesthesia, phantom limb syndrome, and Capgras syndrome (Ramachandran, 2004), and animal behavior (Safina, 2016), etc.

3 VALIDATION OF MPC FUNCTIONS

The measurability criteria for consciousness are derived from conditions that validate each measurement function described in Figure 1.

3.1 MODELING

A scientific model is a physical or mathematical representation of real-world phenomena. It includes a set of attributes or states to represent the real-world phenomena, a number of outputs (aka measurands) of the phenomena that can be observed or measured, and the relationship between the states and the outputs. In the example of the odometer (Figure 1), the speed of the car represents the motion of the car in the real world, the rotational speed of the wheel is the observable output (aka measurand), and the equation relating the wheel speed with the car speed is the relationship between the state and the output. The model for the odometer can be defined as:

Car Speed = Wheel Speed × Tire Diameter × π × CF

where π is the circle constant (π = 3.14) representing the ratio between the tire's perimeter and diameter, and CF is a constant factor for unit conversion. In this example, the model is based on the universally accepted theory that relates the wheel's rotational speed with the car's translational speed. However, in the case of consciousness, there is no accepted theory to develop such a mathematical model. Some of the available theories on consciousness are summarized below.

Materialistic worldview has been the basis of several theories of consciousness, e.g., worldly discrimination theory (Eriksen, 1960), integration theory (Edelman, 2003), and Higher-order thought theories (Seth et al., 2008). This worldview proposes that phenomenal subjectivity, e.g. feeling and experience, is a consequence of neuronal activity in the brain.

It is assumed that consciousness emerges from the underlying biological processes in the brain and can be represented by the complexity of conscious neural systems (Seth et al., 2006). This is an appropriate approach when measuring the degree or complexity of consciousness of human subjects (e.g., persons in a coma or vegetative state), who are assumed to be conscious under normal conditions. However, if we are trying to know if a system (e.g., a humanoid robot) has the capability or potential to be conscious, assuming that the system is capable or not capable of being conscious becomes a circular argument.

Other theories, such as panpsychism (Chalmers, 2016) and cosmopsychism (Keppler & Shani, 2020), attempt to overcome this limitation by considering the mind or a mindlike aspect as a fundamental and ubiquitous feature of reality. The study by Gasparri (2019) proposes an alternative positioning of the Vedantic theory of consciousness within the contemporary debate on monism and panpsychism. The detailed review of these and other theories of consciousness is outside the scope of this study. A brief overview of these theories is presented below to facilitate discussion on the measurability of consciousness in later chapters.

Worldly discrimination theory – This is perhaps the simplest theory that impacts the experimental literature on consciousness and states that any mental state that can express its content in behavior is conscious (Eriksen, 1960). This theory, called the worldly discrimination theory (WDT), assumes that continuous information available for discrimination is necessarily the content of conscious states. This theory captures one property of the conscious mental state, namely that it enables choice behavior. However, rightly or wrongly, it does not represent other properties, e.g., experience or feeling, associated with consciousness (Seth et al., 2008).

Integration theories – According to the core idea of integration theories, "a mental state is conscious if it provides a sufficiently informative discrimination among a large repertoire of possible states, in which successful discrimination requires both differentiation and integration" (Seth et al., 2008). This idea has been used to develop several theories, such as unified field theory, global workspace theory, process dissociation framework, etc. (Edelman, 2003; Seth et al., 2008). There are many critiques of the information-based theory of consciousness. Notable among them is Searle, who argues that information-based theories of consciousness are circular; that is, they seek to explain consciousness with a concept–information, that presupposes consciousness (Horgan, 2015).

Higher-order thought (HOT) theories – According to these theories, a mental state is conscious when a person is actually aware or disposed toward being aware of being in that state. The mental state is achieved by either perceiving it or thinking about it. HOT theories differ from WDTs in that it is the ability of a person to discern their mental state rather than the state the world is in, which determines whether a mental state is conscious (Seth et al., 2008). In the context of measurement, this theory depends on the person's ability to report being conscious.

PanPsychism and Cosmopsychism – Panpsychism considers that the mind or a mindlike aspect is a fundamental and ubiquitous feature of reality. The consciousness at the fundamental level can combine to form other, more complicated conscious minds. The question is, then, how does this occur? This problem is called the combination problem of panpsychism (Chalmer, 2016; Seth, 2021). Some of the concerns of panpsychism can be addressed by cosmopsychism, which relies on the central idea that the universe is imbued with a ubiquitous field of consciousness (UFC) (Keppler & Shani, 2020; Lamme, 2018).

Advaitic and Yogic Theory of Consciousness – Consciousness has been fascinating Indian philosophers for thousands of years. Richly sophisticated varieties of cosmopsychism can be found in the Advaitic theory of consciousness (ATC) described in ancient Sanskrit classics, the Upaniṣads, and more particularly by those Vedānta philosophers who provide interpretations of these texts (Ganeri & Shani, 2022; Vaidya & Bilimoria, 2015). Another study by Tripathi and Bharadwaj (2021) formulates the yogic theory of consciousness (YTC), which allows us to model the external states, internal states of meditation, "samadhi," and even the disorders of consciousness.

3.2 INPUT VALIDATION

The sensor in the measurement system can measure any measurable signal that comes as an input. It cannot distinguish between the sources of the input signal. Therefore, for the overall measurement to be valid, it is necessary that the input signal to the sensor comes from the true object of measurement. For example, if the odometer sensor (Figure 1) is mounted on the door of a car (instead of the wheel shaft), it will tell us zero car speed when the car may actually be moving at 50 kilometers per hour. The input validation function may seem obvious or trivial in most measurement processes where conscious agents (e.g., humans) perform the measurement. However, it may not be so apparent for use cases where the measurement is done by autonomous systems (e.g., humanoid robots). The input validation may be a simple activity like a visual inspection to ensure the sensor is placed on the actual object of measurement, or it may require a complex process to validate that the input signal is coming from the actual object of measurement. The details of input validation vary from case to case and need to be designed for individual use cases.

3.3 SENSING

The outputs of the object of measurement (aka measurands) are measured by the sensing function, which depends on the current state of technology. Three broad categories of sensing technology are currently available for consciousness measurement: behavioral, neurophysiological, and computational measurement. A summary of these measurements is given below.

Behavioral Measurement – Before the advent of brain scanning technology, the use of measurable behaviors was the only methodology available to measure and understand consciousness. In fact, the world's first recorded map of consciousness in Vedantic literature from the seventh century BCE or earlier used three observable states of consciousness – the waking state, the dreaming state, and the state of dreamless sleep (Thompson, 2015). Later texts added a fourth state called the state of pure awareness. More recently, behaviorism has been widely used in the study of psychology and consciousness since the nineteenth century (Lashley, 1923). With the recent advances in brain scanning technology, behavioral measures and associated consciousness reports have been used to calibrate neurological brain measures (Seth et al., 2008; Gamez, 2014).

Neurophysiological Measurement – The Neural Correlates of Consciousness (NCC) have received the most scientific attention as a means for measuring the complexity of consciousness. The term was first coined by Crick and Koch (1990) to determine what parts of the brain are necessary and sufficient for conscious experience. The NCC is defined as “the minimal neuronal mechanisms jointly sufficient for any one specific conscious percept” (Crick & Koch, 1990). They have been used to develop tests for consciousness in patients using various neuroimaging tools such as electroencephalography (EEG), magnetoencephalography (MEG), functional MRI (fMRI), and transcranial magnetic stimulation (TMS) (Dehaene, 2014). A measurement framework using NCCs, along with the behavioral correlates of consciousness (BCCs) and creative correlates of consciousness (CCCs), has been proposed by Hunt et al. (2022) to develop consciousness measurement systems.

Computational Measurement – The computational model of consciousness is based on the proposition that phenomenal experience is a consequence of neuronal activity in the brain. Neural complexity defines the extent to which a system is dynamically segregated and integrated (Tononi et al., 1994). The neuronal activities can be measured by three different models: neural complexity, information integration, and causal density, which explicitly attempt to quantify the balance between integration and differentiation exhibited by a neural system (Seth et al., 2006). The actual measurement of consciousness using integrated information has been reported by Oizumi et al. (2016), Mediano et al. (2018), and others.

3.4 MODEL-BASED STATE ESTIMATION

As the name suggests, the state estimation function uses the sensor output (i.e. measured value) to estimate the state or attribute of the object of measurement. In the simple example of an odometer (Figure 1), the state estimation function estimates the car speed using the wheel speed measurement from the sensor (see Section 3.1). For complex dynamic systems, the state estimation function needs to use a multidimensional mathematical model. The validity of the state estimator in these dynamic systems is measured by mathematical conditions called "observability criteria" (Kalman, 1960). In the context of CMS, we do not have any consciousness model that provides a mathematical relationship between states and outputs of the object of measurement. Therefore, the validity of the state estimator will depend on the use case and needs to be defined qualitatively until a mathematical model of consciousness is available.

3.5 INTERPRETATION

Interpretation is the last step in any measurement process and is typically done by a conscious agent (e.g., a human being) or an autonomous system (e.g., a computer). Sometimes, both humans and computers may be engaged in interpretation at different levels in a complex measurement process. In the odometer example, the human driver is the final interpreter of the car’s speed. At the same time, the onboard computer is the interpreter for measuring wheel speed, which is used to calculate the car speed. The goal of the interpretation process is to understand the measurement for the specific use case and make it worthwhile for the end user. The design of the CMS needs to explicitly address the details of how interpretation needs to be done. The details of interpretation depend on the use case and available technologies.

3.6 CALIBRATION OF CMS

Every measurement system must be calibrated to establish the accuracy of the device. In measurement technology, "calibration is the comparison of measurement values delivered by a device under test with those of a calibration standard of known accuracy" (Wikipedia-1). The calibration standard for engineering systems is typically defined by a national or international standard. Like other measurement systems, the CMS should also be calibrated before it is used in real-life applications. However, the challenge is the availability of a calibration standard to compare the results from a CMS system. There is not much work done in the area of CMS calibration standards. The study by Gamez (2014) proposes to create a standard for calibration using verbal and other behavioral reports from human agents, who are assumed to be conscious. This standard can be used to develop CMS for use cases where the object of measurement can have consciousness. There is no measurement standard currently available to develop CMS for other use cases. The calibration standard for CMS is in a very early development stage and has a long way to go.

4 MEASURABILITY OF CONSCIOUSNESS

Using the measurement framework discussed in Sections 2 and 3, we can now look at the measurability of consciousness for different use cases (Table 1). Modeling, the first CMS function, is the foundation of any measurement system. The physical and mathematical model of the object of measurement is essential in defining the states, the measurands, and the state estimation algorithm. The existing philosophical theories, e.g., higher-order thought theories, panpsychism, and the Advaitic theory of consciousness, provide a conceptual definition of consciousness. The computational model of consciousness (e.g., IIT) provides a mathematical model that can measure the complexity and degree of consciousness. None of these theories provide a mathematical model for experience or feeling. The absence of a mathematical model for experience and feeling is a limitation only for the use case that measures the potentiality of consciousness.

However, it is not an issue for use cases on the presence and degree of consciousness (e.g., human clinical application), where the object of measurement (i.e., the human being) is capable of being conscious.

As discussed in Section 3.3, there are different behavioral, neurophysiological, and computational technologies available for sensing function. There is no general feasibility issue for sensing. It is a question of choosing the right technology from a set of available technologies for the specific use case. As new technologies are developed over time, they can be incorporated into the design and development of CMS. Similarly, there is no basic feasibility challenge related to the CMS function, such as validation and interpretation. These two functions can be considered as design problems where functional capabilities can be developed using available technologies for specific use cases.

Table 1. Measurability of consciousness for different use cases

Measurement Function	Potentiality of Consciousness	Presence of Consciousness	Degree of Consciousness
Modeling	There are philosophical theories like higher-order thought theories, panpsychism, and the Advaitic theory of consciousness. But, there is no mathematical model for experience or feeling.	If we assume that the object of measurement (humans or animals) has consciousness, then the sensing technology will define the model for consciousness.	
Input Validation	There is no fundamental challenge. Details depend on available technology and use cases.		
Sensing	Different behavioral, neurophysiological, and computational technologies are available for sensing. The exact sensing technology for CMS depends on the use case.		
Model-based State Estimation	We can't define a state estimation algorithm without having a mathematical model for experience or feeling.	The model of consciousness can be used to develop state estimation algorithms.	
Interpretation	There is no fundamental challenge. Details depend on available technology and use cases.		
Calibration of CMS	It is not possible to define a calibration standard without a quantifiable definition and mathematical model for experience and feeling.	If the object of measurement is capable of having consciousness, the calibration standard can be defined with respect to some reference point.	

Calibration is a standard process in developing every measurement system where the measured output is compared with a calibration standard to establish the accuracy of the device. The calibration process for CMS is similar to the calibration of any other measurement system. However, the very nature of consciousness makes it challenging to develop a calibration standard for CMS. The nature of consciousness makes it, by definition, a wholly private affair. Your experience is exclusive to you, and nobody else has any access to this experience except what you choose to report verbally or through other behavior (Koch, 2019). This aspect of consciousness makes it almost impossible to develop a calibration standard for the use case on "potentiality of consciousness." Researchers are starting to develop calibration standards for use cases where it is assumed that the object of measurement has the potential to be conscious and can provide consciousness reports (Gomez, 2014). The measurability conditions for different use cases are summarized in Table 1.

5 DISCUSSIONS

As discussed in Section 4, there are two unique challenges in MPC. These are related to the calibration standard and modeling of experience and feeling. These challenges affect the measurability of consciousness for the use case called the "potentiality of consciousness." A calibration standard in the science of measurement (aka metrology) is an object, system, or experiment that has a defined relationship to a unit of measurement of a physical quantity. The units of measurement are defined in relation to internationally standardized reference objects, which are maintained under controlled laboratory conditions to define the units of mass, length, electrical potential, and other physical quantities (Wikipedia-2). All existing calibration standards in metrology are about measuring physical quantities, not for experience or feeling, which are fundamental to consciousness. There has been an attempt to create a consciousness measurement standard using a first-person report from "a physical system that is assumed to be associated with consciousness some or all of the time" (Gamez, 2014). The physical system that can provide the first-person report is essentially a human being assumed to have consciousness. This approach can create a calibration standard to measure the presence and complexity/degree of consciousness. Since this method assumes that the physical system is capable of providing first-person reports, it can not provide a calibration standard for measuring the "potentiality of consciousness."

The mathematical modeling of experience and feeling is the other open question that has not yet been addressed by researchers. Consciousness, particularly experience and feeling, is a fascinating area of study where nobody denies its existence and subjective nature. We all experience it and feel it. But, nobody is able to provide an acceptable model, and there is no way to measure it. The key challenge in modeling and measuring consciousness is associated with subjectivity (feeling or experience). Chalmer (1995) refers to this as "the hard problem" of consciousness and asks the following basic questions:

> *It is widely agreed that experience arises from a physical basis, but we have no good explanation of why and how it so arises. Why should physical processing give rise to a rich inner life at all? It seems objectively unreasonable that it should, and yet it does.*

These questions are still unanswered even after significant progress in technology, neuroscience, and consciousness studies over the last several decades (Horgan, 2023). Consciousness is the basis of everything we know and do. Neither can I write, nor can you read this paper without consciousness. It is consciousness that enables us to know that we have consciousness. It is pervasive all around us. But, it remains the most private aspect of a conscious being. We cannot measure or know that somebody else has consciousness. We can only assume that other humans and animals with similar biological and behavioral characteristics as ourselves have consciousness. The key difference between consciousness and other scientific problems is that consciousness is the basis of all knowledge, including the knowledge of itself and the knowledge of the knowledge.

Given the uniqueness of consciousness, one might ask if subjectivity, which can be experienced or felt only by the subject, is measurable or knowable. One may wonder if measuring the subjectivity of consciousness is beyond our ability to know. There are many examples of unknowable, incomplete, and undecidable problems in math, science, and philosophy. Rescher (2009) describes a class of problems as logical, conceptual, or in-principle unknowables. For example, “it is in-principle impossible to know when and by whom the word ‘mother’ was first used in English.” Similarly, there are examples of incompleteness and undecidable problems in mathematics. For example, Gödel’s incompleteness theorems in mathematical logic are concerned with the limits of provability in formal axiomatic theories. The first incompleteness theorem states that for any consistent formal system, “there will always be statements about natural numbers that are true but unprovable within the system. The second incompleteness theorem, an extension of the first, shows that the system cannot demonstrate its own consistency.” (Wikipedia-3). There are also undecidable problems in computability theory that include the field of logic, abstract machines, combinatorial group theory, topology, etc. These are “types of computational problems that require a yes/no answer, but where there cannot possibly be any computer program that always gives the correct answer; that is, any possible program would sometimes give the wrong answer or run forever without giving any answer” (Wikipedia-4). The nature of reality is another area where there are open questions on what we know and what we can know. The mathematical formulation of quantum physics has been very effectively used by the scientific community to model our physical world. However, there are competing and completely different theories, e.g., collapse theory, pilot wave theory, and many world theories, to explain what that physical reality is (Maudlin, 2019). In philosophy and logic, the knowability of consciousness was discussed by different Indian philosophical schools. Using the method of *Anvaya-Vyatireka* (or method of agreement-disagreement) logic of the Indian Nyaya system, Dṛg Dṛśya Viveka concludes that sense organs, brain, and mind are all objects of perception and the unified pure consciousness is the only subject that perceives (Nikhilananda, 1931). The undifferentiated pure consciousness is “unknowable” and is the eternal reality that manifests into the known and knowable universe (Shimi & Behera, 2018). This paper does not attempt to conclude anything related to the unknowability of consciousness. This is an area we will take up as a separate study.

6 SUMMARY

This paper presents a formal framework to define and analyze the measurability of consciousness using product design principles, e.g., measurement process workflow, problem-space analysis, and the concept of observability. The framework defines several CMS functions within the measurement workflow. These are: (1) modeling of consciousness states and outputs, (2) validation of sensor input signals, (3) sensing, (4) model-based state estimation, (5) interpretation, and (6) CMS calibration. Each CMS function requires different theories and technologies for its implementation. For example, the sensing function can be based on behavioral, neurophysiological (e.g., EEG, MEG, and fMRI, etc.), computational (based on integration information theory (IIT), and other measurements. Validation or measurability criteria for each CMS function are established and applied to different CMS use cases that are identified using a product design technique called "problem space analysis." The objective was to identify CMS functions that can or cannot be designed for different use cases using existing theories and technologies. For example, the absence of an acceptable mathematical model for experience and feeling should not be a problem for measuring consciousness in use cases involving human clinical applications. However, without a well-defined consciousness model, we cannot develop a CMS to determine if a humanoid robot has consciousness.

Consciousness is unique among all the things that can be measured. It is all around us. We know about our own consciousness. However, the subjectivity in the consciousness of others is only an inference, however reasonable. Therefore, one might ask whether subjectivity, which can be experienced or felt only by the subject, is measurable. This paper uses concepts from mathematical logic (e.g., Gödel’s incompleteness and Tarski’s undefinability theorems) and philosophy (e.g., method of agreement-disagreement in the Indian Nyaya system) to understand the measurability of subjectivity. Based on the preliminary study done so far, it may be possible that subjectivity is not measurable like other attributes of consciousness. This is a major area of study by itself and will be taken up as a future project.

The key contribution of this paper is a novel consciousness measurement framework that uses measurement workflow, design principles, theories and technologies from neuroscience, and arguments from philosophy. The framework provides a precise understanding of the measurability of CMS functions for individual use cases. Researchers and engineers can use the framework to develop CMS for specific use cases without being bogged down by the complexity of unknowns in the field of MPC.

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