

# A Theory of Consciousness from a Theoretical Computer Science Perspective: Insights from the Conscious Turing Machine

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## Abstract

The quest to understand consciousness, once the purview of philosophers and theologians, is now actively pursued by scientists of many stripes. We examine consciousness from the perspective of theoretical computer science (**TCS**), a branch of mathematics concerned with understanding the underlying principles of computation and complexity, including the implications and surprising consequences of resource limitations.

In the spirit of Alan Turing’s simple yet powerful definition of a computer, the Turing Machine (**TM**), and the perspective of computational complexity theory, we formalize mathematically a modified version of the Global Workspace Theory (**GWT**) of consciousness originated by cognitive neuroscientist Bernard Baars and further developed by him, Stanislas Dehaene, Jean-Pierre Changeaux and others. We are *not* looking for a complex model of the brain nor of cognition but for a simple *computational* model of (the admittedly complex concept of) consciousness.

We do this by defining the Conscious Turing Machine (**CTM**), also called a Conscious AI, and then we define consciousness and related notions *in the CTM*. While these are only mathematical (**TCS**) definitions, we suggest *why* the **CTM** has *feelings* of consciousness. The **TCS** perspective provides a simple formal *framework* to employ tools from computational complexity theory and machine learning to help us understand consciousness and related concepts.

Previously we explored explanations for the feelings of pain and pleasure in the **CTM**. Here we consider additional phenomena generally associated with consciousness, again from the perspective of the **CTM**. We start with three examples related to vision (blindsight, inattentive blindness, and change blindness), then follow with a discussion of dreams, free will and altered states. We give explanations *derived from the formal model* and draw confirmation from consistencies *at a high-level* with the neuroscience literature.

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## Introduction: Why a Theoretical Computer Science Perspective?

The quest to understand consciousness, once the purview of philosophers and theologians, is now actively pursued by scientists of many stripes. We study consciousness from the perspective of theoretical computer science (**TCS**), a branch of mathematics concerned with understanding the *underlying principles of computation*. These principles largely include the *complexity* of computation, which deals with the consequences and *unexpected usefulness* of taking resource limitations into account. This perspective has provided not only a theoretical foundation for the computer revolution but also surprising new concepts and ingenious applications stemming from considerations of computational complexity. **TCS** is our principal tool. We claim that its perspective and unique insights add to the understanding of consciousness and related concepts such as free will.

Our view is that consciousness is a property of all properly organized computing systems, whether made of flesh and blood or metal and silicon. With this in mind, we give a simple abstract *computational* model of consciousness (Chapter 1). While we are *not* looking to model the brain, *nor to suggest* neural correlates of consciousness, we do give examples of human and animal consciousness in order to clarify concepts and arguments.

We begin this introduction with a brief overview of **TCS**, its perspective, and an example of a seemingly paradoxical concept that got defined and understood by **TCS**. We then outline how the perspective of **TCS** informs our model and understanding of consciousness.

Alan Turing's seminal paper "On computable numbers" (Turing A. M., 1937) is arguably the genesis of **TCS**. The paper presents a formal mathematical definition of a "computing machine", now known as the Turing Machine (**TM**). Here, Turing defines a simple universal programmable computer that can compute any function computable by any computer or supercomputer.<sup>2</sup> Theorems are the *raison d'être* of mathematical theories, and Turing proves what might be called the first theorem of **TCS**, namely the *unsolvability* of the *Halting Problem*. In modern parlance, this theorem implies there can be no universal (debugging) program for determining which programs halt and which do not: it is just not possible to construct one. This result is equivalent to the undecidability of elementary number theory (Church, 1936) and implies a weak form of Kurt Gödel's First Incompleteness Theorem (Gödel, 1931).

Although Turing's 1937 paper was strictly a paper in mathematical logic – there were no computers at the time – Turing did intend to construct a practical programmable computing machine. In 1945, he brought with him to the British National Physical Laboratory an 86-page detailed<sup>3</sup> blueprint for an Automatic Computing Engine (ACE), a universal programable computer, which he intended to build (Turing A. M., 1945). Politics intervened and it never was built, only the less ambitious PILOT ACE (Hodges, 1992).

Before Gödel and Turing, mathematicians had the unshakable belief that with enough knowledge and work, any mathematical problem could be solved. As the mathematician David Hilbert famously said in 1930 at his retirement address (Dawson, 1997): "This conviction of the solvability of every mathematical problem is a

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<sup>2</sup> In the mathematical tradition going back to Euclid, of formulating axioms (basic premises) and proving theorems (deriving consequences), Turing identifies fundamental principles (the Turing Machine) that lead to unexpected consequences (universal Turing Machine, the halting problem, etc.) and a deep understanding of computation. Many other models of discrete computation such as the lambda calculus of Alonzo Church (Church, 1936) give rise to the same set of computable functions. This gives credence to the Church-Turing thesis that no reasonable model of computation can compute more than what a Turing Machine can compute. (See (Yao, 2003) for implications to classical physics.)

<sup>3</sup> These details include for example, the circuit design, all resistor and capacitor values, the physics and chemistry of delay line memories, the programming language, instruction cards, and even the cost in pounds to build the machine.

powerful incentive to the worker. We hear within us the perpetual call: There is the problem. Seek its solution. You can find it by pure reason, for in mathematics there is no *ignorabimus* [sic].”

After Gödel and Turing, mathematical logicians had a heyday investigating which problems were solvable, which not, as well as investigating the esoteric hierarchy of unsolvable problems.

With the advent and wider availability of computing machines in the 1960’s, it soon became clear that a number of important problems that were solvable in principle could not in fact be solved, not even with the fastest conceivable computers.<sup>4</sup> Was this a problem with the state of technology, or something deeper?

Researchers in the emerging field of theoretical computer science<sup>5</sup> realized that among natural finite (and therefore solvable) problems there appeared to be a dichotomy between those problems that were *feasibly (efficiently) solvable* and those that were not, mirroring the earlier dichotomy between solvable and unsolvable. Feasibly solvable became formalized mathematically as *solvable (by some computer program) in polynomial time (P)*. Furthermore, the realization emerged that problems solvable in polynomial time and problems *checkable in polynomial time (NP)* might not be equivalent.<sup>6</sup> Indeed, deciding the equivalence (or not) would answer the famous **P =? NP** million-dollar question (Wikipedia, P versus NP problem).

Besides defining a hierarchy of serial fast (poly time) computational complexity classes, **TCS** defines a hierarchy of parallel superfast (*polylog time*) computational complexity classes. Both hierarchies inform the definitions and choices employed in our model.

Understanding the dichotomy between *easy* and *hard*, *quick* and *slow*, and their implications launched a complexity revolution with a rich theory, reframing of ideas, novel concepts and stunning applications. Indeed, developments in computational complexity over the past 40 years have shown how to use hardness to our advantage, to deal with seemingly impossible problems. This has created a paradigm shift in mathematics, namely the ability to use hardness (of some problems) to resolve (other) problems, and provide new insights.

We illustrate with the concept of a *computer-generated random sequence* called a *pseudo-random sequence*.

On the face of it, the very idea of a *pseudo-random sequence* is so incongruous that von Neumann joked (von Neumann, 1951), “Anyone who considers arithmetical methods of producing random digits is, of course, in a state of sin.”

More precisely, a *pseudo-random sequence generator* is a *feasible (polynomial time)* computer program for generating sequences that cannot be distinguished from truly random sequences (generated by independent tosses of a fair coin) by any feasible computer program. Thus, in the polynomial time world in which we live, pseudo-random sequences are, for all intents and purposes, truly random. This understanding was impossible without the clarifications made by **TCS** and the distinctions between polynomial and superpolynomial complexity. (See (Yao, 1982) and (Yao, 2003).)

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<sup>4</sup> Suppose that when program P is run on computer C, on any input of length n, it has run time  $2^n$ . Let  $C^+$  be the same computer except that  $C^+$  runs twice as fast as C. Then program P, run on computer  $C^+$ , on any input of length  $n+1$ , will have run time  $2^{n+1}/2 = 2^n$ , which is the same running time as C on any input of length n. **TCS** considers the increased speed of  $C^+$  (and therefore  $C^{++}$ ,  $C^{+++}$ , ...) over that of C to be insignificant for running P when n is large.

<sup>5</sup> These researchers included Jack Edmonds (Edmonds, 1965), Stephen Cook (Cook, 1971), Richard Karp (Karp, 1972), and Leonid Levin (Levin, 1973).

<sup>6</sup> Solvable in polynomial time (**P**) means it is possible to find a solution in time polynomial in the size of the problem instance. Checkable in polynomial time (**NP**) means that given a purported solution, its correctness can be checked in time that is polynomial in the size of the problem instance. On the face of it, finding a solution seems harder than checking it. Properly coloring the nodes of a graph with 3 colors is hard (**NP-hard** so likely not in **P**), while checking if a 3-coloring is proper, meaning that no edge joins two nodes of the same color, is easy (in **P**).

An application of the above ideas will be to replace the use of random sequences in the Conscious Turing Machine (**CTM**) by sequences produced by pseudo-random generators supplied with (short) random seeds. In particular, if the probabilistic **CTM** has “free will”, as will be argued, then so does the deterministic **CTM**.

**Now for consciousness:** The **TCS** perspective is employed in defining the Conscious Turing Machine (**CTM**), a simple machine that formalizes mathematically (and modifies with dynamics) the Global Workspace Theory (**GWT**) of consciousness originated by cognitive neuroscientist Bernard Baars (Baars B. J., 1988) (Baars B. J., 1997) (Baars B. J., 2019)<sup>7</sup> and further developed by him, Stanislas Dehaene, Jean-Pierre Changeaux (Dehaene & Changeaux, Experimental and theoretical approaches to conscious processing, 2011) and others.

In his *Global Workspace Theory*, (Baars B. J., 1997) describes *conscious awareness* through a theater analogy as the activity of actors in a play performing on the stage of Working Memory, their performance under observation by a huge audience of unconscious processors sitting in the dark.

In the **CTM**, the stage is represented by a Short Term Memory (**STM**) that at any moment in time contains **CTM**’s *conscious content*, and the audience members are represented by a massive collection of parallel processors that make up its Long Term Memory (**LTM**) (section 1.1.1). **LTM** processors, each with their own specialty, **compete** to get their questions, answers, and information on the stage to be immediately **broadcast** to the audience (section 1.1.2). In time, some of these processors become connected by **links** (section 1.1.4) turning conscious communication (through **STM**) into *unconscious communication* (between these **LTM** processors).

*Conscious awareness* is defined formally in the **CTM** as the *broadcast* of **CTM**’s conscious content and its immediate *reception* by the **LTM** processors. While the definition is natural, it is merely a definition; it is not a proof, that the **CTM** is conscious in the sense that the term is normally used. We argue however that the definition and its explanations capture underlying features of commonly accepted intuitive concepts of consciousness. (See Chapters 2 and 3.)

Although inspired by Turing’s simple yet powerful model of a computer, the **CTM** *is not itself* a standard Turing Machine. That’s because what makes the **CTM** conscious is not its computing power nor its sequence of input-output maps, but rather *its Global Workspace architecture* (including its *competitive process* to gain access to **STM** and its *global broadcasting* of the winner to all **LTM** processors), its *predictive dynamics* (cycles of prediction, feedback and learning), *its rich multi-modal inner language* (what we call **Brainish**), and *certain special LTM processors* (**Inner Speech/Vision/Tactile Sensations, Model-of-the-World**, and others). (See Chapter 2.)

*Complexity considerations* enter into fixing the detailed definition of **CTM**. These details include, for example,

1. the formal definition of a **chunk**, which is the information that each **LTM** processor puts into the *competition* for consciousness at every tick of the clock (section 1.1.3),
2. the fast probabilistic competition algorithms that select which of the many chunks reaches consciousness (sections 1.3 and 1.4), and
3. the machine learning algorithm (section 1.6) in each processor that uses *feedback* from *global broadcasts*, other processors, and the outside world to update its processor’s competitiveness and reliability.

*Complexity considerations* play a crucial role in our high-level explanations for consciousness-related phenomena such as change blindness and the feeling of free will.

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<sup>7</sup> Baars’s **GWT** is strongly influenced by earlier work in cognitive science, much of which was done at Carnegie Mellon: (Simon, 1969), (Reddy, 1976), (Newell, 1990) and (Anderson, 1996).

As we have said, we are not looking for a model of the brain but for a simple model of consciousness, and even there, the **CTM** model can hardly be expected to explain everything: it is too simple for that. The reasonableness of the model (and its **TCS** perspective) should be judged by its contribution to the discussion and understanding of consciousness and related topics.

We end this introduction by noting briefly a historical synergy between theoretical computer science and neuroscience. Turing’s simple computer model led neuroscientist Warren S. McCulloch and mathematician Walter Pitts to define their formal neuron, itself a simple model of a neuron (McCulloch & Pitts, 1943). Mathematics forced their model to have inhibition, not just excitation - because without inhibition, loop-free circuits of formal neurons can only compute monotonic functions - and these do not suffice to build a universal Turing Machine.<sup>8</sup> The McCulloch-Pitts neuron also gave rise to the mathematical formalization of neural nets (Wikipedia, History of artificial neural networks) and subsequent deep learning algorithms (Goodfellow, Bengio, & Courville, 2016), further illustrating ongoing synergies.

In this paper, we present an *overview* of the model and *refer* the reader to (Blum & Blum, 2021) for additional formal details. Whereas that paper explores explanations for the feelings of pain and pleasure in the **CTM**, here we consider additional phenomena generally associated with consciousness. We start (in Chapter 3) with three examples related to vision (blindsight, inattentional blindness, and change blindness), then follow with a discussion of dreams, free will and altered states. We give explanations *derived from the formal model* and draw confirmation from consistencies *at a high-level* with the neuroscience literature.

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<sup>8</sup> The formal model also arose in the work of Lettvin, Maturana, McCulloch and Pitts to describe the simple neural networks that appear in “What the frog eyes tells the frog’s brain” (Lettvin, Maturana, McCulloch, & Pitts, 1959).

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# 1 CTM Model Overview

## 1.1 Basic CTM Structure & Definitions of Consciousness in the CTM

The **CTM** is defined in part to formalize Bernard Baars’s **GWT**. In the *Theater of Consciousness*, (Baars B. J., 1997) describes conscious awareness through a theater analogy as the activity of actors in a play performing on the stage of Working Memory, their performance under observation by a vast “audience” of “intelligent unconscious” processors. (See Figure 2-1 on page 42 of (Baars B. J., 1997).)

Formally, the **CTM** is defined as a 7-tuple, **< STM, LTM, Up-Tree, Down-Tree, Links, Input, Output >**<sup>9</sup>.

Here we informally discuss these components and related *definitions* of consciousness. We *refer* the reader to (Blum & Blum, 2021) for additional formal details.

We assume that the **CTM** has a finite lifetime **T**, although **T** can be arbitrarily large. Time is measured in discrete clock ticks, **t** = 0, 1, 2, ..., **T**. The **CTM** is born at time **0**.

Statements about the Conscious Turing Machine (**CTM**) are printed in black. **Statements particular to humans or animals are printed in burgundy. Burgundy-colored statements also refer to features that a human or animal would have if it were correctly modeled by CTM.**

### 1.1.1 Short Term Memory (STM) & Long Term Memory (LTM) Processors

In the **CTM**, the stage (conscious arena) is represented by a Short Term Memory (**STM**). The audience (in the unconscious arena) is represented by a massive collection of **N** powerful parallel processors,<sup>10</sup> each with their own memory, that together make up the Long Term Memory (**LTM**). We also call these **LTM** processors **Sleeping Experts**. Processors are only in **LTM**, not in **STM**, so when we say processor, we mean **LTM** processor. Certain special **LTM** processors are especially responsible for **CTM**’s “feeling of consciousness”. These include - but are not limited to - the **Model-of-the-World processor**, and the **Inner Speech, Inner Vision and Inner Sensation** processors. (See Chapter 2.)

<sup>9</sup> Coincidentally, the classical **Turing Machine** is also defined as a 7-tuple, **< Q, Σ, Γ, δ, q<sub>0</sub>, q<sub>accept</sub>, q<sub>reject</sub>>**, where **Q** is a finite set of **States**, **Σ** is the **Input** alphabet, **Γ** is the **Tape** alphabet, **δ** is the **Transition** function, **q<sub>0</sub>** is the **Start** state, **q<sub>accept</sub>** is the **Accept** state, and **q<sub>reject</sub>** is the **Reject** state.

<sup>10</sup> Here **N** is a large unspecified integer.



### 1.1.2 The Up-Tree Competition & Down-Tree Broadcast

The **Up-Tree** is an up-directed binary tree of height **h** with a leaf in each **LTM** processor and a (single) root in **STM**. The **Down-Tree** is a simple down-directed tree with a single root in **STM** and **N** edges each directed from that root to the leaves, one in each of the **LTM** processors.

**LTM** processors, each with their own specialty, compete via the **Up-Tree competition** (section 1.3) to get their questions, answers, and information onto the **STM** stage from there to be **broadcast** immediately via the **Down-Tree** to the audience of all **LTM** processors.<sup>11</sup>

### 1.1.3 Chunks, Conscious Content, Conscious Awareness & Stream of Consciousness

These questions, answers, and information are conveyed in the form of **chunks** (defined formally in section 1.2). The **chunk** that **wins** the **Up-Tree competition** and gets into **STM** is called the **conscious content** of **CTM**.<sup>12</sup> Unlike Baars's Theater, there is always exactly one and the same actor on stage. At every step in time, that actor gets handed the winning chunk as a script for immediate **broadcast** via the **Down-Tree**. We say that **CTM** becomes **consciously aware** of this content when it is received by all **LTM** processors via this broadcast.<sup>13</sup>

We have defined conscious awareness as the *reception* by all **LTM** processors of **STM's broadcast**, rather than the appearance in **STM** of the winning chunk, *to emphasize* that the feeling of consciousness arises when certain processors, such as **Inner Speech**, receive the broadcast and can act on it.

One reason to keep the number of chunks in **STM** small (exactly one in our model) is to ensure that all processors focus on the same information in the broadcast from **STM**. Another reason is to keep the model as simple as reasonably possible.<sup>14</sup>

**CTM** is constantly bubbling with the activity of chunks competing for **STM**, and winners constantly being broadcast from **STM** to **LTM**.<sup>15</sup> The time ordered chunks that are broadcast from **STM** to **LTM** form a **stream of consciousness**. This stream, as argued in Chapter 2 is part of the subjective *feeling of consciousness*.

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<sup>11</sup> For simplicity in **CTM**, all **LTM** processors submit information to the competition for **STM** and all processors receive all broadcasts from **STM**. In humans, the dorsal stream of vision is never conscious, only the ventral stream is conscious.

<sup>12</sup> For simplicity, **STM** holds only one chunk at any moment in time. In humans, the storage capacity of short-term memory is roughly  $7 \pm 2$  chunks (Miller, 1956), where a chunk can be a word, a phrase, a digit, and so on. A few chunks cycling through **STM** can simulate some aspects of an **STM** that holds several chunks. Cycling can happen via the **Up-Tree competition** and the **Down-Tree broadcasts**. In this way, **CTM** can keep thoughts alive in **STM** continuously through many cycles by sending the thought from **processor**  $\rightarrow$  **STM**  $\rightarrow$  **processors**  $\rightarrow$  **STM**  $\rightarrow$  ....

<sup>13</sup> Again, for simplicity, we stipulate reception of the broadcast by *all* **LTM** processors,

<sup>14</sup> Leslie Valiant (Valiant, 2013, pp. 127-128) asserts that limited computational resources and constraints imposed by the need to learn are the primary reason for the small size of conscious information.

<sup>15</sup> This bottom-up/top-down cycle is analogous to the Global Neuronal Workspace (**GNW**) hypothesis (Dehaene, Changeux, & Naccache, 2011) that "conscious access proceeds in two successive phases ... . In a first phase, lasting from  $\approx 100$  to  $\approx 300$  ms, the stimulus climbs up the cortical hierarchy of processors in a primarily bottom-up and non-conscious manner. In a second phase, if the stimulus is selected for its adequacy to current goals and attention state, it is amplified in a top-down manner and becomes maintained by sustained activity of a fraction of **GNW** neurons, the rest being inhibited. The entire workspace is globally interconnected in such a way that only one such conscious representation can be active at any given time ... ."

The *dynamic* of chunk submission to competition for **STM** (the stage) and subsequent broadcast of the winning chunk to the **LTM** processors (the audience) corresponds roughly to the **GNW** global *ignition* property. However, **GNW** ignition is significantly more subtle and complicated, depending, e.g., on strength (or absence) of sensory inputs, and having variable duration.

#### 1.1.4 Links & Unconscious Communication

All communications between processors *initially* occur via **STM**. For example, processor **A** can submit a query to the **Up-Tree competition** for **STM**. If the query wins the competition, it is broadcast to all **LTM** processors. Processor **B** may then submit an answer via the competition, which if it wins gets broadcast, and so on.

If **A** acknowledges that **B**'s answer is useful sufficiently often, then a bi-directional **link** forms between **A** and **B**.<sup>16</sup> In addition to processors sending chunks to the **Up-Tree competition**, processors send chunks over **links**. In this way **conscious communication** (through **STM**) between **A** and **B** can turn into direct **unconscious communication** by chunks being sent (through **links**) between **A** and **B**.<sup>17</sup> As additional links form between **A** and **B** we say the link between **A** and **B** is *strengthened*.

#### 1.1.5 Input & Output Maps: Sensors & Actuators

**CTM**'s environment (**outer world**) is a subset of  $\mathbf{R}^m(\mathbf{t})$  where **R** denotes the real numbers, **m** is a positive integer dimension, and **t**, a non-negative integer, is time. **Input** maps take (time-varying) environmental information acquired by **CTM**'s **sensors** (which for simplicity we assume are part of the **Input** maps) and send it to designated **LTM** processors. **Output** maps take command information from **LTM** processors to **actuators** (which we assume are part of the **Output** maps) to act on the environment. **Input** and **Output** maps also translate between the environmental **outer languages** and **CTM**'s **inner language, Brainish** (section 1.2).

#### 1.1.6 Summary of Connections

In summary, there are five kinds of connections in the **CTM** that provide paths and mechanisms for transmitting information. The five, also shown in *Figure 1*, are:

- 1)  $\mathbf{R}^m(\mathbf{t}) \rightarrow \mathbf{LTM}$ : directed edges from the environment via **sensors** to processors of the sensory data.
- 2)  $\mathbf{LTM} \rightarrow \mathbf{STM}$ : via the **Up-Tree**.
- 3)  $\mathbf{STM} \rightarrow \mathbf{LTM}$ : via the **Down-Tree**.
- 4)  $\mathbf{LTM} \rightarrow \mathbf{LTM}$ : bi-directional edges (**links**) between processors.
- 5)  $\mathbf{LTM} \rightarrow \mathbf{R}^m(\mathbf{t})$ : directed edges from specific processors (like those that generate instructions for finger movement) to the environment via **actuators** (like the fingers that receive instructions from these processors) that act on the environment (via the actions of the fingers from these processors).

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<sup>16</sup> Linking is different than, but reminiscent of, the Hebbian principle of (Hebb, 1949) "**Neurons that fire together wire together**".

<sup>17</sup> If the **CTM** has  $10^7$  **LTM** processors, **corresponding to  $\approx 10^7$  cortical columns in the brain**, and all processors are initially linked, there will be  $\approx 10^{14}$  links, a large possibly infeasible number of links. Worse yet, a processor with  $10^7$  inputs might need its own personal competition tree to decide what to look at. One might want some special processors linked initially, but for simplicity we choose to not have any.



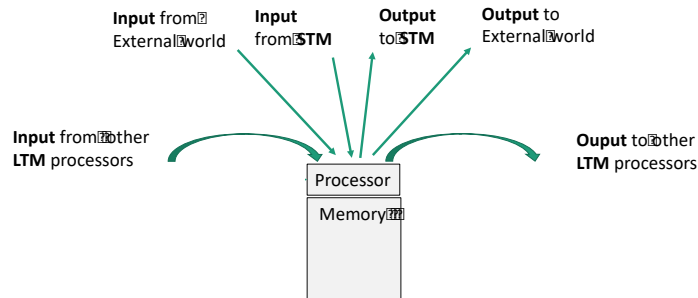


Figure 1 Connections in CTM.

## 1.2 Brainish (the CTM’s Multi-Model Inner Language), Gists & Chunks

**Brainish** is **CTM’s inner language** used to communicate *between* **processors** in its **inner world**,<sup>18</sup> whether via the competition and broadcasts or directly through **links**, which do not pass through the environment. Brainish is the language used to express **inner speech**, **inner vision**, **inner sensations**, **imaginings** and **dreams**. It includes coded representations of **inputs** and **outputs** all expressed with succinct **multi-modal** Brainish words and phrases called **gists**. A gist can hold the essence of a scene or the (high-level expandable) idea of a proof. It can be an answer to a query, an insight of some sort, a dream image, a description of pain **in a torn ligament**, and so on. Brainish is able to express and manipulate images, sounds, tactile sensations, and thoughts including unsymbolized thoughts *better* than **outer languages**. We claim, having an expressive inner language is an important component of the *feeling* of consciousness (Chapter 2).<sup>19</sup>

Information is communicated within **CTM’s** inner world by **chunks** produced by **LTM** processors.

Formally, a **chunk** is defined as a 6-tuple  $\langle \text{address}, t, \text{gist}, \text{weight}, \text{intensity}, \text{mood} \rangle$ .

Here, **address** is the address<sup>20</sup> of the **LTM** processor that produced the chunk, **t** is the time that the chunk was created, **gist** is the “small” amount of information that the processor wants to communicate, **weight** is a valanced number that the processor gives the gist, **intensity** starts off as  $|\text{weight}|$  and **mood** starts off as **weight**. At time  $t = 0$ , the weight given a gist is **1**. Weights given at a later time depend on feedback processors get from broadcasts, or directly from other process via links, and built-in learning algorithms (section 1.6).

We note that the **size** of the chunk (and hence the size of its parameters, including its gist) will necessarily be bounded by computational complexity considerations. (See section 1.4 and (Blum & Blum, 2021) for more specifics.)

## 1.3 The (Probabilistic) Up-Tree Competition: The Competition Function & Coin-Flip Neuron

The **Up-Tree competition** is the mechanism that enables **LTM** processors to get their information (in the form of **chunks**) into **STM**. At each clock tick  $t = 0, 1, \dots, T$ , the competition starts with each processor **p** putting its chunk into the node that is the processor’s leaf of the **Up-Tree**. When a chunk is submitted to the **Up-Tree**

<sup>18</sup> The language used internally by a processor may be different from Brainish.

<sup>19</sup> Representing and learning multimodal inputs is an important aspect of machine learning (**ML**). Paul Liang, PhD student in ML at Carnegie Mellon, is working to develop Brainish, **CTM’s** multimodal language.

<sup>20</sup> If the **CTM** has  $10^7$  **LTM** processors, **corresponding to  $\approx 10^7$  cortical columns in the brain**, then the address is a 7 digit number.

competition and moves up the competition tree, its **address**, **t**, **gist**, and **weight** will remain unchanged; but its **intensity** and **mood** get updated incorporating more and more global information.

Deciding whether or not (a variant of) the chunk moves up the **Up-Tree** or drops out is made by a fast tiny parallel circuit, one such circuit located in each of the non-leaf nodes of the **Up-Tree**, each making its decision in one clock tick (meaning the time between two successive clock ticks).

These circuits compute a built-in **competition function**, **f**, with the property that **f(chunk)** is a non-negative real number.

In the **probabilistic Up-Tree competition** which we discuss here, each node of the **Up-Tree** has and uses a **coin-flip neuron** (Figure 2) in its built-in circuit. A **coin-flip neuron** is a device that takes as input an (ordered) pair (**a**, **b**) of non-negative real numbers ( $a \geq 0$  and  $b \geq 0$ ), and in *one step* does the following:

if  $a > 0$  or  $b > 0$ , it outputs **a** with probability  $a/(a+b)$ , else **b**; if  $a + b = 0$ , it outputs **a** with probability  $1/2$ , else **b**.

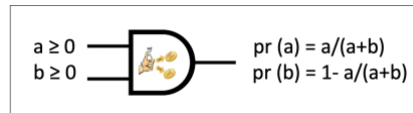


Figure 2 A coin-flip neuron on input (*a*, *b*) with  $a + b > 0$ .

At each clock tick, the circuit in a non-leaf node **v** runs a *local* competition that probabilistically selects one of **v**'s two (sibling) children based on a comparison of the chunks they contain, then moves (a variant of) its chunk into **v**. The chosen chunk is said to be the **winner of the local competition** at/for **v**.

At each level **s**,  $0 < s \leq h$ , and each node **v<sub>s</sub>** at that level, the local winner is decided **probabilistically** as follows:

- Suppose **chunk<sub>p(L)</sub>** and **chunk<sub>p(R)</sub>** are the chunks in **v<sub>s</sub>**'s left and right children respectively. Then a variant of **chunk<sub>p(L)</sub>** will move into **v<sub>s</sub>** with probability  $f(\text{chunk}_{p(L)}) / (f(\text{chunk}_{p(L)}) + f(\text{chunk}_{p(R)}))$ , or probability  $1/2$  if the denominator is 0,
- else the variant **chunk<sub>p(R)</sub>** will move up.

Suppose **chunk<sub>p,t,0</sub>** = **< address<sub>p</sub>, t, gist<sub>p,t,0</sub>, weight<sub>p,t,0</sub>, intensity<sub>p,t,0</sub>, mood<sub>p,t,0</sub> >** is the chunk that processor **p** puts into competition at time **t**.

And suppose **chunk<sub>p(L)</sub>** is a variant of **chunk<sub>p,t,0</sub>** with the same **address<sub>p</sub>**, **t**, **gist<sub>p,t,0</sub>**, and **weight<sub>p,t,0</sub>**. Then, with probability  $f(\text{chunk}_{p(L)}) / (f(\text{chunk}_{p(L)}) + f(\text{chunk}_{p(R)}))$ , or  $1/2$ , the chunk that will be in **v<sub>s</sub>** in the next clock tick will be

$$\text{chunk}_{p,t,s} = \langle \text{address}_p, t, \text{gist}_{p,t,0}, \text{weight}_{p,t,0}, \text{intensity}_{p,t,s}, \text{mood}_{p,t,s} \rangle$$

where **intensity<sub>p,t,s</sub>** = (**intensity<sub>p(L),t,s-1</sub>**) + (**intensity<sub>p(R),t,s-1</sub>**) (=  $\sum (\text{intensity}_{p',t,0})$ ) and **mood<sub>p,t,s</sub>** = (**mood<sub>p(L),t,s-1</sub>**) + (**mood<sub>p(R),t,s-1</sub>**) (=  $\sum (\text{mood}_{p',t,0})$ ), where the two super sums are over all **LTM** processors **p'** in the subtree rooted at **v<sub>s</sub>**.

**REMARK.** Updating the chunk at node **v<sub>s</sub>** consists in computing the probabilities needed to select the local winner and then to make the needed modifications of the intensity and mood. This must all be done in 1 clock tick. This puts bounds on both the *amount of computation* that can be performed in a node and on *the size* of the **chunk** in that node. (See section 1.4 and (Blum & Blum, 2021) for more specifics.)

By a simple induction, the **winner of the Up-Tree competition** (the *conscious content* of **CTM** at time **t+h**) will look like:

$$\text{chunk}_{p,t,h} = \langle \text{address}_p, t, \text{gist}_{p,t,0}, \text{weight}_{p,t,0}, \text{intensity}_{p,t,h}, \text{mood}_{p,t,h} \rangle$$

where  $\text{intensity}_{p,t,h} = \sum (\text{intensity}_{p',t,0})$  and  $\text{mood}_{p,t,s} = \sum (\text{mood}_{p',t,0})$  and the two sums are over all **LTM** processors  $p'$  in **LTM**.

Let  $t' \geq h$ . The **current mood** of **CTM** at time  $t'$ ,  $\text{mood}_{t'}$ , is defined to be the **mood** of the **chunk** that is broadcast from **STM** at time  $t'$ . Thus **CTM** becomes *consciously aware* of  $\text{mood}_{t'}$  at time  $t' + 1$ .

**REMARK.**  $\text{mood}_{t'} = \sum_{\text{all } N \text{ LTM processors } p} \text{mood}_{p,t'-h,0}$ , so  $\text{mood}_{t'}/N$  is the average mood of the chunks submitted to the competition at time  $t' - h$ .

$\text{Mood}_{t'}$  is a measure of **CTM**'s "optimism/happiness" if positive, or "pessimism/sadness" if negative, at time  $t'$ .<sup>21</sup> Similarly,  $\text{intensity}_{t'}$  is defined to be the measure of **CTM**'s level of "energy/enthusiasm/confidence" at time  $t'$ .

We say that a competition function  $f$  is **additive** when  $f(\text{chunk}_{p,t,s}(v_s)) = f(\text{chunk}_L(v_s)) + f(\text{chunk}_R(v_s))$ . Examples of additive competition functions include:  $f(\text{chunk}_{p,t,s}) = \text{intensity}_{p,t,s}$  or more generally,

$$f(\text{chunk}_{p,t,s}) = \text{intensity}_{p,t,s} + c \cdot \text{mood}_{p,t,s} \text{ for any real } c, -1 < c < +1, \text{ but not } f(\text{chunk}_{p,t,s}) = |\text{mood}_{p,t,s}|.$$

We call a **CTM** with a probabilistic **Up-Tree** competition a **probabilistic CTM**.

**THEOREM.** If the competition function  $f$  of a **probabilistic CTM** is **additive**, then every chunk submitted to the **Up-Tree competition** gets a fraction of time in **STM** proportional to its importance as determined by  $f$ . As a consequence, for additive  $f$ , the permutation chosen to assign processors to leaves of the **Up-Tree** has no effect on the sequence of broadcasts from **STM**. (See (Blum & Blum, 2021) for more specifics including the statements of these theorems and their proofs.)

In this paper, unless otherwise stated, all **CTMs** will be probabilistic.

## 1.4 Complexity of Computation & Time to Conscious Awareness

For  $t > 0$  and  $s > 0$ , the *computation* to update the chunk at node  $v_s$  in the **Up-Tree competition** consists of:

- I. two fast computations of  $f$ , a sum and division of their values, and a fast probabilistic selection,
- II. putting the **address**, **gist** and **weight** of the chunk selected into  $v_s$ , and
- III. summing the **intensities** and **moods** of the chunks associated with  $v_s$ 's children, and setting those sums to be the **intensity** and **mood** respectively of the chunk at  $v_s$

These computations, all three of which must be completed in **1 time-unit**, put a bound on both *the size* of the **chunk** in a node and the *amount of computation* that can be performed in that node.<sup>22</sup>

If **1 time-unit** is 10ms and there are  $10^7$  **LTM** processors, then the time from a chunk being placed into competition by an (unconscious) **LTM** processor to becoming **CTM**'s *conscious content* will be about 230ms. If the broadcast takes another 10ms, the total time to *conscious awareness* will be about 240ms. **Interestingly, this seems to be the order of time it takes for humans to become consciously aware of some decisions made unconsciously.** (See section 3.6 for a discussion on whether or not this delay has implications for free will in the **CTM**, or humans.)

<sup>21</sup> (Kringelbach & Berridge, 2017) argue that in humans "emotion is always valenced—either pleasant or unpleasant—and dependent on the pleasure system".

<sup>22</sup> The space required to store a chunk must be large enough to store a  $\log_2 N$  bit (or  $\log_{10} N$  digit) address, and to store a **gist** whose length is no greater than what is required to store approximately one line of English or its equivalent in Brainish, very roughly  $2^{10}$  bits.

## 1.5 Memories & The High-Level Story

We assume that each processor **p** stores in its internal memory, the sequence of tuples, ordered by time **t**, consisting of the **chunk<sub>p,t,0</sub>** that it submitted to the competition and all chunks it received at time **t**, whether by broadcast from **STM**, from **links**, or from **Input maps**. These sequences comprise **CTM's memories**. The **CTM** may require compression for this storage. (Al Roumi, Marti, Wang, Amalric, & Dehaene, 2020) discuss mental compression of spatial sequences in human memory.

This “history” provides a **high-level story** of what **p** saw and did. Periodically, this stored information may be pruned so only “salient” chunks remain, the most “salient” being those that represent terrible, unexpected, or wonderful events. High-level stories are called upon when **CTM** creates dreams (section 3.5).

In general (see section 1.6), every processor makes predictions regarding the chunks it generates, modifies, reconstructs, reconsolidates, and stores. In humans, when memories are recalled, they are generally modified before being returned to storage (Lee, Nader, & Schiller, 2017).

## 1.6 Predictive Dynamics = Prediction + Feedback + Learning (Sleeping Experts Algorithm)

Processors require **feedback** to *assess correctness* or *detect errors* in their **predictions** and to **learn** how to both boost correctness, and diminish and *correct* errors.

- **Predictions** in **CTM** are made by **LTM** processors, both within their internal algorithms and implicitly when they submit chunks elsewhere, whether to the competition for **STM**, to other processors through **links**, or to **actuators** that effect the outer world.
- **Feedback** comes from chunks that are received in broadcasts from **STM**, through **links**, and from sensors of the outer world via **Input maps**, indicating correctness or detecting errors in predictions.
- **Learning** and **error correcting** take place within processors.

There is a continuous cycling of prediction, feedback and learning within **CTM**. The **CTM** needs to be alerted to anything unusual, surprises of any kind, in order to deal with them if necessary, and to improve its understanding of the world in any case. Prediction errors (e.g., “surprises”) are minimized by this cycling.

Processors especially need to know if they were too timid or too bold in setting their |weights| so they can correct their weight-assigning algorithms. **Sleeping Experts Algorithms** are a class of **learning algorithms** employed by **LTM** processors to do just that. See (Blum & Blum, 2021) for one of the simplest versions of the **Sleeping Experts Algorithms (SEA)**.<sup>23</sup> Here is the idea:

In general, **SEA** will *embolden* a processor - raise the *intensity* it gives its chunks - if:

1. its chunk did not get into **STM**, and
2. its information is more valuable (in the SEA’s opinion) than what is in **STM**.

The **SEA** will *hush* the processor - *lower the intensity* it gives its chunks - if:

1. its chunk got into **STM**, and
2. its information is less valuable than that of some chunk that failed to get into **STM**.

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<sup>23</sup> More sophisticated **Sleeping Experts Algorithms** will be presented in an expanded monograph (Blum, Blum, & Blum, In preparation). See also, (Blum A. , 1995), (Blum A. , 1997), (Freund, Schapire, Singer, & Warmuth, 1999), (Blum & Mansour, 2007), (Luo & Schapire, 2015) and (Blum, Hopcroft, & Kannan, 2015).

**Sleeping Experts Algorithms** play a role in whether or not processors get their chunks into **STM**. They also play a role in whether or not processors “pay attention” to gists in chunks that are sent to them via **links**. The  $|\text{weight}|$  of a chunk is an indication of how important the processor thinks its gist is and this, together with prior knowledge, will influence whether or not the receiver pays attention.

## 1.7 Comparison of CTM with the Global Workspace Theory Model

We conclude this chapter with a comparison between the **CTM** and Baars’s **GWT** model (Figure 3).

Aiming for simplicity, we have eliminated or simplified many features. For example, the **CTM** has just one “actor” on stage holding just one chunk at a time. Additionally, in the **CTM**, all processors are in **LTM**. We have eliminated the Central Executive and its sequence of directions, opinions, questions, answers and so on, as all this can come from processors. In the **CTM**, **inputs** and **outputs** go directly to and from **LTM** processors, not directly through **STM**.

In the **CTM**, **chunks** compete in a *well-defined competition* to get onto stage (**STM**). *Conscious awareness* is the broadcasted reception by all **LTM** processors of the **winning chunk** (i.e. **CTM**’s *conscious content*), not an event that occurs between **Input** and **STM**. The roles of Baddeley and Hitch’s Verbal Rehearsal and Visuospatial Sketchpads (Baddeley & Hitch, 1974) are accomplished by **LTM** processors. Finally, as in the “Extended Mind Theory” of (Clark & Chalmers, 1998), **CTM** can have access to existing technology - Google, WolframAlpha, AlphaGo, NELL, and so on – in the form of **LTM** processors tasked to use these apps. This is one way to ensure that **CTM** has a huge collection of powerful processors at the start of its life, a collection that is also augmentable throughout its life.

Key features of the formal **CTM** and its dynamics resonate with properties of consciousness that (Dennett D. C., 2018) outlines:

[Neither] a Master Scheduler, nor a Boss Neuron, nor a Homunculus or Res Cogitans [govern the transitions of our conscious minds]. [What governs] must be a dynamical, somewhat competitive process of contents vying for fame, for cerebral celebrity ... or relative clout against the competition. What determines the winners? Something like micro-emotions, the strength of positive and negative valences that accompany and control the destiny of all contents, not just obviously emotionally salient events such as obsessive memories of suffering or embarrassment or lust, but the most esoteric and abstract theoretical reflections.

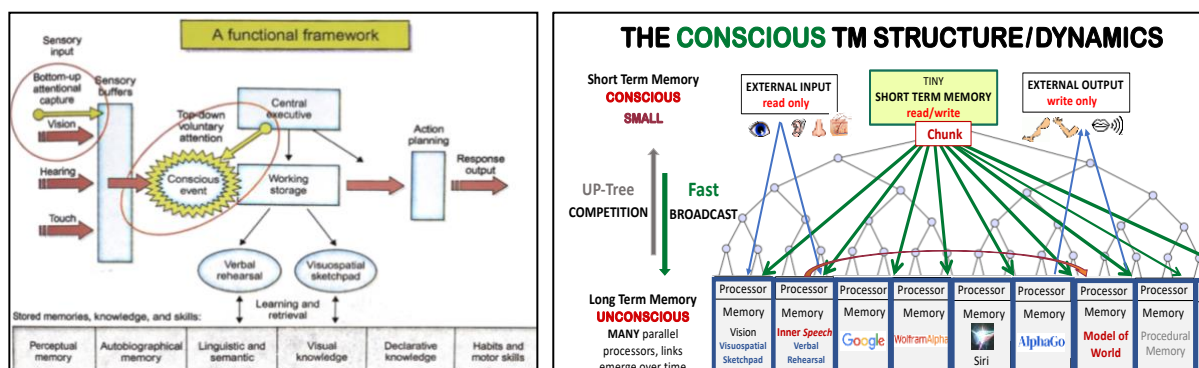


Figure 3 Baars’ **GWT** model (l); **CTM** (r).

## 2 The Feeling of Consciousness

While **CTM** is “consciously aware” *by definition* of the “conscious” content broadcast from **STM** (section 1.1.3), this definition does not explain what generates the *feeling* of consciousness in **CTM**. While we believe that the **CTM** will have the feeling that it is conscious, we cannot prove anything mathematically without a definition of the “feeling of consciousness”, which we do not have (yet).<sup>24</sup> Here we summarize arguments given in (Blum & Blum, 2021) for our beliefs. In Chapter 3 we augment these arguments, showing how the **CTM** provides *high-level* explanations for a range of properties generally associated with consciousness.

We argue that the *feeling* of consciousness in **CTM** is a consequence principally of its extraordinarily expressive *Brainish language*, coupled with **CTM**’s *architecture*, certain *special processors*, and **CTM**’s *predictive dynamics* (prediction, feedback and learning):

1. **Architecture.** This includes the *competition* to gain access to **STM** and subsequent *broadcast of the winner* to all **LTM** processors (particularly all processors that play a special role in generating the *feeling* of consciousness).
2. **Special Processors.** We single out a few such processors, which have specialized algorithms built into them at birth:
  - a. The **Model-of-the-World processor** is a collection of processors that each construct models of **CTM**’s **inner** and **outer worlds** based on information they get from stored, possibly modified, inner memories, or gotten more directly from the outside world.

These processors tag parts in their **models-of-the-world** with labels and descriptions, annotated in *Brainish*, such as actions they can perform.

This includes tagging the “**CTM**” that appears in their **models-of-the-world** as “**conscious**”, which they do when the **CTM** detects (through broadcasts) itself thinking (about its own consciousness).

These processors also tag various constituent parts of their **models-of-the-world** as either **self** or **not-self** (or **unknown**). How do they determine what is or is not self? If the broadcast of a chunk (a **CTM** thought) is immediately followed by an actuator carrying out an action in the world – and that same thought leads to the same action consistently and repeatedly – then that indicates the actuator is part of self. Again, when the **CTM** detects itself thinking, or solving problems posed to it from its outer or inner worlds, then these processors tag “**CTM**” in their **models-of-the-world** as **self**.

The **Model-of-the-World** has additional important jobs that give the **CTM** its *sense of self*, including: creating imaginings (based on information gotten from **CTM**’s inner and outer worlds); maps of, and getting around in, its worlds; helping to plan actions in the environment (outer world); helping to predict and correct actions of **self** and **not-self** in those worlds.

- b. The **Inner Speech processor** takes any speech encoded in the gist that is broadcast by **STM** and maps it to the *same locations* that the **Input map** sends gists of outer speech. The **Inner Speech processor** enables **CTM** to recollect its past, predict its future, and make plans. The gists of **inner speech** (such as occur in talking to oneself or the hearing in a dream) are nearly indistinguishable from the gists of **outer speech** (the gists created by the **Input maps**). *In humans, inner speech*

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<sup>24</sup> Integrated Information Theory (IIT) defines a measure of consciousness **PHI** (Tononi, 2004) which roughly measures the feedback in a system. The **CTM** has positive **PHI**, but we wonder if having consciousness according to this measure implies that the entity has the *feeling* of consciousness.



sounds so much like outer speech that it can be difficult, as in schizophrenia, to distinguish between Inner and outer speech (Rosen, et al., 2018).

- c. **Inner Vision and Inner Sensation processors** map whatever images and sensations are broadcast from **STM** to whatever locations the **Input maps** send outer scenes and outer sensations. The gists of **inner vision** can be barely distinguishable from the gists of **outer vision** (the visual gists created by the **Input maps**). **CTM**'s memories enable **CTM** to create the **inner images** and **sensations** that **CTM** uses to generate imaginings and dreams (section 3.5). To thwart schizophrenic hallucinations, the human brain distinguishes inner images from outer images. The brain has various tricks for doing this, one being to make dreams hard to remember.

These processors inform the “eyes” and “skin” in the **Model-of-the-World** that “sees” whatever the **CTM** recalls from its visual memory and “tactily senses” whatever **CTM** recalls from sensory memory. These “eyes” and “skin” are **CTM**'s *mind's eye* and *mind's skin*.

- 3. **Predictive Dynamics.** Additionally, we argue that **CTM**'s continuous cycling through prediction, feedback and learning (section 1.6) together with the **stream of consciousness** (section 1.1.3), play a role in **CTM**'s feelings of consciousness (see (James, 1890). The feelings are further enhanced by (parallel) predictive dynamics in **CTM**'s **Model-of-the-World** where planning and testing is constantly carried out, often before action is taken by the **CTM**. Positive feedback gives **CTM** an indication that it understands what is going on; negative feedback - unless it is about something that could not have been predicted such as an unexpectedly loud noise - gives **CTM** evidence of something that it did not know or understand.

We now look at the **CTM** from the point of view of the outside world. From outside **CTM**, we see that something about **CTM** is conscious, specifically, the **CTM** considers itself conscious. It cannot be the **Model-of-the-World processor** or any other processor, that *feels* it is conscious, as processors are just machines running algorithms - machines that have no feelings. We propose that the view that **CTM** as a whole is conscious, and *feels* that it is conscious as normally understood, is a consequence in part of the fact that the **Model-of-the-World processor** views the “**CTM**” in its **models-of-the-world** as conscious, and that this view is broadcast to all processors.<sup>25</sup>

### 3 High-Level Explanations

We now explore how **CTM** might experience a variety of phenomena generally associated with consciousness. We believe our explanations *derived from the formal model* provide a *high-level* understanding of how conscious experiences are or *might* be generated, and draw confirmation from consistencies with the neuroscience literature, again at a high-level.

Previously we explored explanations for the feelings of pain and pleasure in the **CTM** (Blum & Blum, 2021). Here we consider additional phenomena, again from the perspective of the **CTM**. We start with three examples related to vision (blindsight, inattentional blindness, and change blindness), then follow with a discussion of dreams, free will and altered states.

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<sup>25</sup> Shimon Edelman says (personal communication) “This reminds me strongly of the explanation offered by (Metzinger, 2004).



### 3.1 Blindsight

*Blindsight* provides a striking example of the difference between conscious and unconscious awareness (Striemer, Chapman, & Goodale, 2009). In blindsight, the person does not *consciously* see the outer world. When asked to fetch something across a cluttered room, a typical response is “But I cannot see.” Nevertheless, the person responds cautiously but adeptly to the request.

What is going on?

In the **CTM**, visual **Input** goes directly from the **vision sensors** to a subset of **LTM** processors that process visual input. But in the blindsighted **CTM**, due to some malfunction, perhaps a break in the **Up-Tree** or some other inability for the **Vision processors** to enter chunks competitively into the competition, this information does not get up to **STM** and hence *does not get globally broadcast*. For this reason, **CTM** is *not consciously aware* that it can see. However, information can still be communicated between (unconscious) processors via **links**. So, for example, visual information received by the **Vision processors** can be sent through links to the **Walk Processor** that controls the leg actuators.

At a high-level, this explanation is consistent with explanations of blindsight in humans given by (Ajina & Bridge, 2018).<sup>26</sup>

### 3.2 Inattentional Blindness

*Inattentional blindness* occurs when an individual fails to perceive a visual stimulus that is in plain sight. It is “the failure to notice the existence of something unexpected when attention is focused on some other task” (Jensen, Yao, Street, & Simons, 2011).

For example, in the famous *selective attention test* of (Chabris & Simons, 1999), viewers of the “invisible gorilla” film were asked to “count how many times the players wearing white shirts pass the basketball” (*Figure 4*). Nearly all viewers gave close to the correct number (15), but were stunned when asked, “Did you see the gorilla?”

**Selective attention test:**



Figure 4 Screen shots from video, “The original selective attention task” (Chabris & Simons, 1999).

What is going on?

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<sup>26</sup> (Ajina & Bridge, 2018) assert that when the primary visual cortex (V1) is damaged impairing conscious vision, blindsighted individuals still have functional connections between the lateral geniculate nucleus (which receives input from the retina and projects this information to V1) and hMT+ (the cortical area that detects motion). This functional connection was absent in V1 impaired patients without blindsight.

In blindsighted individuals, some retinal input travels (unconsciously) directly to hMT+ bypassing V1. We view it likely that this information is transferred (unconsciously) to, and acted on, by the motor cortex.

Let's suppose the **CTM** is viewing the film. The **Input** query about the white shirted players gains access to **STM** (via chunks sent by the **Inner Speech** processor into the competition for **STM**) and is then immediately broadcast to all **LTM** processors. To carry out the task, **CTM's Vision** processors assign high intensities to white shirted gists and very low (or zero) intensities to anything black. The chunk with the "gorilla" gist has no or little chance to enter **STM**. Consequently, the **CTM** does not consciously see the gorilla.

The **CTM** explanation of inattentional blindness reduces to the differential intensities given to gists, lower intensities given to irrelevant ones, and the competing advantages of chunks with higher intensities.

In humans the explanation is different but consistent. According to simulations performed by (Dehaene & Changeux, 2005), during certain "ignited" states, "spontaneous activity can block external sensory processing." They relate this blocking to the cause of inattentional blindness. In our view, blocking the "sensory processing" in human brains of black objects is roughly equivalent to the **CTM** dramatically lowering the intensity of black gists in chunks, thus lowering the chances of those chunks to enter **STM**. The effect of differential intensities in the **CTM** is also consistent with theoretical implications that inattentional blindness in humans "can serve as a filter for irrelevant information." Thus, it may also filter out unexpected events (Jensen, Yao, Street, & Simons, 2011).

### 3.3 Change Blindness

*Change blindness* occurs when individuals fail to notice large changes in pictures or scenes (Rensink, O'Regan, & Clark, 1997). It is "the failure to notice when something has changed from one moment to another" (Jensen, Yao, Street, & Simons, 2011).

An instructive fun example is the (Test Your Awareness : Whodunnit?) video. A detective enters a murder scene proclaiming, "Clearly somebody in this room murdered Lord Smythe" and immediately interrogates each in turn. The maid proclaims "I was polishing the brass in the master bedroom," the butler "I was buttering his Lordships scones," and Lady Smythe "I was planting my petunias in the potting shed." Enough information for the clever detective to solve the murder on the spot.<sup>27</sup>

But why didn't we notice the many incongruous scene morphs between the beginning screen shot and the end? (See *Figure 5*.)

#### The *Whodunnit* video:



<sup>27</sup> Detective. "Constable, arrest Lady Smythe." Lady Smythe: "But, but, how did you know?" Detective: "Madam as any horticulturist will tell you, one does not plant petunias until May."

Figure 5. Beginning and ending screen shots from video (*Test Your Awareness : Whodunnit?*, 2008).

From the perspective of the **CTM**:

In viewing the *Whodunnit* video (Figure 5) **CTM** has the impression of seeing the whole but doesn't notice the changes that take place as trench coat, flowers, painting, and so on are replaced by variants. That is because:

1. The filming is cleverly staged so that there are cuts from the whole scene to smaller ones (e.g., from the whole scene to the maid alone) eliminating transitions showing the dark trench coat replaced by the white one, the bear replaced by the suit of armor, the rolling pin by the candelabra, the dead man now with a change of clothes and raised leg, and so on. The video **Input** never signals **CTM's Vision processor** that the "scene" has been modified.
2. And more importantly, the same gist describes both the beginning and ending scenes equally well: "The living room of a mansion with detective, butler, maid, others, and a man apparently dead on the floor."

Under these conditions, the **CTM** experiences *change blindness*.

Again, the **CTM** explanation is consistent with literature on change blindness in humans. For example, according to (Jensen, Yao, Street, & Simons, 2011) confirming earlier work of (Rensink, O'Regan, & Clark, 1997):

"Given that change detection requires adequate representation of the pre- and post-change scenes as well as a comparison, any task characteristics that influence the richness of the representation or the tendency to compare representations should affect detection. The semantic importance of the changing object appears to have the biggest influence on the likelihood the subject will attend, and therefore notice, the change."

In other words, detecting change in the *Whodunnit?* video would have required significant changes in the gists describing the beginning and ending scenes. But size limitations on conscious content (and the clever scene transitions) caused the high-level descriptions to be essentially the same.

### 3.4 Illusions

Inattentional Blindness and Change Blindness might be considered examples of illusions. The **CTM** helps provide understanding of the dictum that, while "the things we see, do, and feel are perfectly real, it's the private mental versions of them, which are supposed to constitute our consciousness, that are illusory!" (Keith Frankish, personal communication.)

The **CTM** is conscious (by definition) of the gists (in chunks) that are broadcast from **STM**. (Those gists reached **STM** from **LTM**. **LTM** got them directly from **sensors** via **Input maps**, from other **LTM** processors through **links**, and from **STM** by **broadcast**.) The gists are stored in **LTM** memories for many reasons, one being to supply the processors' high-level stories (section 1.5) such as those that occur in dreams.

In **CTM**, the **stream of consciousness** is the sequence of gists broadcast from **STM** (section 1.1.3). Each visual gist at each moment gives the **CTM** the sense that it sees the entire scene before its eyes, though in truth it sees at most a tiny fraction of the scene. The illusion of the whole has several explanations, the main one being that a multi-modal Brainish gist can describe a hugely complex scene like "I'm standing before a Japanese style garden containing a brook, path, bridge and trees." Could that gist contain the details of a 12 million pixel photograph from an iphone camera, *which is what it feels like we are seeing*? The illusion of the whole is a consequence of the highly suggestive (compressed) information in a gist. The **CTM** conjures up the scene in a kind of magic act. Keith Frankish (Frankish, 2016) calls this the *illusionism theory of consciousness*.

### 3.5 Dream Creation

Dreams are the ultimate illusions. Some people claim not to dream, but most do. Their dreams may be visual, auditory, or tactile. They are often related to emotional processes (Freud, 1900), (Scarpelli, Bartolacci, D'Atri, Gorgoni, & De Gennaro, 2019). They can express great pain and fear (nightmares), or great pleasure (as in flying dreams). One can feel crippling pain in the leg and wake up to find that the pain is completely illusory: there is no pain at all. One can be lying face down and wake face up.

In the **CTM**, a **Sleep processor** keeps track of time, habits, day/night etc. and has internal algorithms to monitor the need for sleep. If and when the **Sleep Processor** determines that sleep is needed, it raises the intensity of its own chunks enough to get them into **STM** and to keep other chunks out. It also *blocks* or *greatly reduces* the intensity of various inputs (eyes and ears) and *blocks signals that activate outputs* (such as to limbs). The **CTM** sleeps. This is the **sleep state**. The **Sleep processor** continuously monitors the need for sleep, and as that need diminishes, reduces the intensity of its own chunks proportionately. This eventually permits **dream gists** (in chunks) to reach **STM**. This is the **dream state**. Finally, after releasing its (choke) hold on inputs and outputs, the **CTM** wakes up. In humans, by comparison, non-REM and REM sleep can alternate several times before awakening (Vyazovskiy, Delogu, & A., 2014).

When **CTM** is in the dream state, a processor acting as **Dream Creator** becomes active (that is, starts getting its chunks into **STM**). The gists in these chunks contain kernels of ideas (typically based on earlier **CTM** activities, concerns, imaginations). When these chunks are broadcast, *all* other processors, including most relevantly the ones that play key roles in the feeling of consciousness, compete to respond. The **Dream Creator** and the other processors take turns interacting back and forth. The conversation – the back and forth interaction – between Dream Creator and the other processors is the sequence of gists that constitutes the **dream**. This sequence is the “dream stream” of consciousness.

The sequence of back and forth broadcasts is a kind of “inner movie” that is shown from **STM**. This movie displays a range of sensory inputs (images, smells, sounds, and so on) that appear to other processors much like what might have come from the outer world.

Dreams are important for demonstrating the power of Brainish gists since they generate the sense of a surprisingly realistic world though they are fabrications manufactured by processors while **CTM** is completely divorced from external inputs: **CTM** dream creations use essentially the same gists in dreams that are created when awake, except that in dreams none of those gists come directly from **sensors**. The dream gists are drawn or reconstructed from memory and are themselves stored as high-level stories (section 1.5).

Similarly, (Zadra & Stickgold, 2021) in *When Brains Dream* refer to research by (Horikawa, Tamaki, Miyawaki, & Kamitani, 2013) demonstrating that in humans, the same neural pattern of activity occurs when one sees a face, brings the face back from memory, or when the face appears in a dream. They also point out that in REM sleep, the activation of the motor cortex in a dream, when one has the sensation of movement, is the same activation as when awake.

As discussed earlier (Chapter 2), key processors such as those for **Inner Speech**, **Vision**, **Tactile Sensation**, and **Model-of-the-World** play special roles in generating the *feeling* of consciousness in **CTM**. These processors play similar roles when **CTM** is dreaming.

Here are some examples of how processors help with dream creation:

- The **Model-of-the-World Processor** predicts the effect that **CTM**'s actions will have in the outer world. It does this from the effect of those actions in its model-of-the-world. The **Dream Creator** can use this same prediction machinery to create dreams.
- The **Inner Speech processor** culls the inner speech from the multi-modal gists broadcast from **STM** and

sends that speech to the same processor that receives outer speech.<sup>28</sup> This process causes speech in dreams to sound like outer speech. The inner vision and inner sensation processors help in similar fashion with dream creation.

When the **CTM** is asleep but not dreaming, processors cannot usually get their chunks into **STM**. Exceptions include detectors of especially loud noises, and the **Sleep processor** itself which blocks other processors from getting their chunks into **STM**. Hence, during dreamless sleep, the **CTM** is not conscious or barely so. After the **CTM** leaves the sleep state to enter a dream state, a fraction of **LTM** processors such as **Vision processors** can get their chunks into **STM**. Thus, while dreaming, the **CTM** is conscious and can experience vivid sketches. However, what **CTM** sees, hears, feels and does in a dream are necessarily *fabrications* by processors that can recall, modify, and submit their creations to the competition for **STM**. These fabrications are realistic because they use the same gists that are generated while awake, or modifications of them produced by the same algorithms that do prediction in the **Model-of-the-World**. As a consequence, they can appear so realistic that for **CTM**, as for humans (Corlett, Canavan, Nahum, Appah, & Morgan, 2014), it may become hard to distinguish dreams from reality.

Dreams also enable the **CTM** to test itself in unknown and possibly dangerous situations. In both humans and **CTMs**, dreams can be laboratories for experimenting with a variety of possible solutions. Inconsistencies, however, are *more likely* to occur and be accepted in dreams than while awake since **Model-of-the-World Processors** do not receive input from the environment in dreams. For example, In dreams the **CTM** can fly.

(Zadra & Stickgold, 2021) point out that in humans, “Dreams don’t replay memories exactly; they create a narrative that has the same gist as some recent memory and could have the same title.” They note that “REM sleep provides a brain state in which weak and unexpected associations are more strongly activated than normal strong associations, explaining how it aids in finding the remote associates and perhaps explaining the bizarreness in our REM sleep dreams.”

### 3.6 Free Will

**The Problem of Free Will** is ancient. It appears in Lucretius [*De Rerum Natura*, 1<sup>st</sup> century BC]: “If all movement is always interconnected, the new arising from the old in a determinate order – if the atoms never swerve so as to originate some new movement that will snap the bonds of fate, the everlasting sequence of cause and effect - what is the source of the free will possessed by living things throughout the earth?” (Lucretius & Ferguson Smith (translator), 1969).

**The Paradox of Free Will** is captured by Dr. Samuel Johnson’s (1709-1784) observation (Boswell, 1791): “All theory is against the freedom of the will; all experience is for it.”

Stanislas Dehaene (Dehaene S. , 2014) bestows a contemporary voice: “Our brain states are clearly not uncaused and do not escape the laws of physics – nothing does. But our decisions are genuinely free whenever they are based on a conscious deliberation that proceeds autonomously, without any impediment, carefully weighing the pros and cons before committing to a course of action. When this occurs, we are correct in speaking of a voluntary decision – even if it is, of course, ultimately caused by our genes,...”

We add to Dehaene: *computation takes time*. To make a decision, a **CTM** evaluates its alternatives, an evaluation that takes time, and during that time the **CTM** is free, indeed may *feel* free, to choose whichever outcome it deems (i.e. computes) best.

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<sup>28</sup> Spoken speech is not heard as speech until the appropriate links between speaker and hearer are created. These links would appear most likely early in the life of the **CTM** .

The **TCS** perspective thus informs our *definition of Free Will*:

**Free Will** is the freedom to compute the consequences of different courses of action – or as much of those consequences as is possible within the available resources (time, space, computational power, and information) – and choose from them whichever course of action best suits one’s goals.

This definition incorporates both *predictive dynamics* (compute the consequences of different courses of action) and *resource constraints* (time, space, computational power, and information).

Consider a **CTM** that is called on to play a given position in a game of chess. Different processors suggest different moves. The **CTM**’s main chess-playing processor (assuming one exists, else a processor that has a “hi-level” view of the game) indicates, by broadcast of the chunk in **STM**, that it recognizes it has a choice of possible moves and that the decision which move to make merits a careful look at the consequences of each move. At this point, faced with a selection of possible moves but not yet having evaluated the consequences of those moves, the **CTM** is free to choose whichever move it reckons best *within* the time constraints.

Will the **CTM** *feel* that it has **Free Will**?

1. Consider the moment that the **CTM** asks itself “What move should I make?” meaning this question has risen to the **STM** stage and, through broadcast, has reached the audience of **LTM** processors. In response, a number of those processors submit suggestions to the competition. The winner of the competition reaches the stage and gets broadcast. Because gists are short, any such broadcast is short and therefore reasonably articulable.
2. The continued back and forth sequence of comments, commands, questions, suggestions and answers that appear in **STM** and globally broadcast to **LTM** gives the **CTM** a *knowledge of its control*: If the **CTM** were asked how it generated a specific suggestion, i.e., what thinking went into making that suggestion, its processors, in particular its **Inner Speech** processor, would be able to articulate the fraction of conversation that reached the stage (though perhaps not much more than that in the short term).
3. Many **LTM** processors compete to produce the **CTM**’s final decision, but **CTM** is only *consciously aware* of what got into **STM**, which is not all of what was submitted to the competition. Moreover, much of **CTM**, meaning most of its processors, are not privy to the unconscious chatter among processors. To the **CTM**, enough is consciously *unknown* about the process that the decision appears at times to be *plucked from thin air*. Even so, although **CTM** does not consciously know *how* its suggestions were arrived at, except for what is in the high-level broad strokes broadcast by **STM**, it *knows* that its suggestions came from inside itself. The **CTM** can rightly take credit for making its suggestions (after all, they did come from inside the **CTM**), can explain some of them with high-level stories (see section 1.5), and as for what it cannot explain, it can say “I don’t know” or “I don’t remember.” It is the knowledge that there are choices, that it (the **CTM**) has knowledge about those choices – and that it has ignorance as well – that generates the *feeling* of free will.

Thus, although **CTM** is constrained by limitations of resources, it has the feeling it has free will.

How important is randomness for this explanation of the *feeling* of free will? Notice that *no quantum physics* is required in the **CTM** for the above explanation. The only randomness is that of the **coin-flip neurons** in the **Up-Tree competition** and whatever randomness, if any, the processors use in their probabilistic algorithms. It can be shown, moreover, that the above argument for the feeling of free will still applies for a *completely deterministic* albeit more complex **CTM**, e.g. one that uses pseudo-randomness, i.e. the output of a pseudorandom generator that has been provided with a random seed, in place of true randomness. It follows – and we know this will be a source of contention - that even in a *completely deterministic* world, the **CTM** will *feel* it has free will.



What is the significance of the *time delay* (section 1.4) between chunks being submitted by the unconscious processors into competition and **CTM** becoming consciously aware of the winner? This delay reminds us of the [Libet 1985] experiments showing delay between unconscious decisions and conscious actions.

There has been substantial controversy over the interpretation of the above experiments including what they mean for the existence or not of free will (Gholipour, 2019). For example, some research shows that the measured delay may be due to effects of stochastic fluctuations (Schurger, Sitt, & Dehaene, 2012), some argue that the distinction between deliberate or arbitrary decisions have to be taken into account (Maoz, Yaffe, Koch, & Mudrik, 2019). Other research on volition qualitatively corroborates the earlier results, e.g., (Fried, Mukamel, & Kreiman, 2011) and (Haggard, 2011).

While the results of the above paragraph present insight into brain dynamics, we do not view them as providing arguments for or against free will.

### 3.7 Altered States of Consciousness

Under psychedelics or meditation, humans can experience altered states of consciousness ranging from a heightened sense of awareness to dissolution of self (feelings of being “one with the world”). We agree with (Bayne & Carter, 2018) that these are *states*, not levels, of consciousness. However, we disagree with their assessment that the global/global neuronal workspace theories are too simple to explain these altered states. Indeed, the beauty of those theories lies in the significant understanding that comes of their simplicity.

Here we show how the **CTM** might experience a simple form of *dissolution of self*. We start by describing **CTM**’s Mindful Meditation Processor:

The conscious decision to meditate is the concern of a **Mindful Meditation Processor (MMP)** that creates and submits a sequence of chunks to the competition for **STM**. Through repeated practice, this processor gains strength and increases the intensity of its chunks. It can be surprisingly difficult for an **MMP (Mindful Meditation Processor)** to keep other chunks from entering **STM**. The difficulty is not in the sense of lifting a heavy weight or proving a difficult theorem, but in the sense of demanding focused concentrated attention and practice. (Rathi, 2021) explains how the **CTM**, using the *Mantra* meditation technique, accomplishes this.

When the **MMP** is successful, its chunks get into **STM** and are broadcast. Those broadcasts generally contain feedback that other processors use, through their *Sleeping Experts Algorithm*, to *hush* their self-evaluations (section 1.6). Thus during successful meditation, the **MMP**’s chunks get the lion’s share of time in **STM**.

Additionally, during successful meditation, chunks that get communicated via **links** from all processors except the **MMP** get hushed – by the incoming broadcasts from **MMP** - and thus processors are unlikely to pay their usual attention to the chunks they receive through links.<sup>29</sup>

This “hushing” or diminishing of functional connectivity is observed in studies on effects of psychedelics and meditation. For example, brain imaging and electromagnetic studies on effects of certain psychedelics

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<sup>29</sup> In effect, this diminishes communication through links and, in particular, the **Model-of-the-World** processor’s ability to communicate to others what is **self** and what is **not-self**.

Neuroimaging studies on various forms of meditation from distinct traditions share some common neural correlates, see (Millière, Carhart-Harris, Roseman, Trautwein, & Berkovich-Ohana, 2018). Importantly, the latter report that in several forms of meditation there is “attenuation for either activity or functional connectivity” in the medial prefrontal cortex and in the posterior cingular cortex, key nodes of the so-called default mode network (DMN). The DMN is active when a person is daydreaming or mind-wandering. It is also active when a person is thinking about others or themselves, remembering the past, or planning for the future, see (Buckner, Andrews-Hanna, & Schacter, 2008) and (Lieberman, 2013). Thus attenuation of functional connectivity in these areas may also account for dissolution of self.



(psilocybin) suggest that the dissolution of self (“ego-dissolution”) is due to “disintegration” of functional connectivity (Calvey & Howells, 2018).<sup>30</sup> This decreased connectivity accounts in part for the sense of dissolution of spatial boundaries, which in turn leads to the feeling of being “one with the world”.

## 4 Summary

We consider consciousness from the perspective of theoretical computer science. To this end we define a formal model, the **Conscious Turing Machine (CTM)** inspired by Bernard Baars’s *Theater of Consciousness* and Alan Turing’s simple yet powerful model of a computer, the Turing Machine (**TM**). We formally *define* “conscious content”, “conscious awareness”, and “stream of consciousness” within the model. We claim it is the architecture of a system (including basic processes and dynamics) and the expressiveness of its inner language that give rise to consciousness. One purpose of our model is to argue this claim. Another is to provide a theoretical computer science foundation for understanding consciousness.

The **Conscious Turing Machine** aka **CTM** is *defined formally* (Chapter 1) as a 7-tuple, **< STM, LTM, Up-Tree, Down-Tree, Links, Input, Output >**. The theory includes a precise definition of **chunk**, a precise description of the **competition** that decides which (**LTM** processor’s) chunk will gain access to **STM**, and a precise definition of **conscious awareness** in **CTM**. **Links** between processors that *emerge* in the life of the **CTM** enable conscious processing to become unconscious. **Input/Output** maps enable communication between **CTM**’s outer and inner worlds. Other features of the model can be found in (Blum & Blum, 2021).

We argue (Chapter 2) that the *feeling* of consciousness arises in **CTM** as a consequence of:

1. the global workspace *architecture*, which enables all processors, including *especially those that are particularly responsible for consciousness* - **Inner Speech, Inner Vision, Inner Sensations** and **Model-of-the-World** – to be privy to the same (conscious) content of **STM**,
2. the *expressive power* of *Brainish* (**CTM**’s inner language for describing all elements of both its outer and inner worlds),
3. the close correspondence between *gists* of outer speech (what we say and hear in the world), outer vision (what we see in the world), and so on, to gists of inner speech (what we say to ourselves), inner vision (what we see in dreams), and the like, and
4. *predictive dynamics* (prediction, feedback, and learning), which helps maintain the user’s connection to the world.

We argue (Chapter 3) that the *feeling* of free will in the **CTM**, like the *experiences* of illusions and dreams, are direct consequences of **CTM**’s *architecture*, certain *special processors*, the *expressive power of Brainish*, and its *predictive dynamics*.

The paper (Blum & Blum, 2021) and an expanded monograph (Blum, Blum, & Blum, Towards a Conscious AI: A Computer Architecture Inspired by Cognitive Neuroscience, In preparation) cover the topics presented here in

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<sup>30</sup> Referencing (Carhart-Harris, et al., 2016), (Calvey & Howells, 2018) suggest that this “disintegration” is due at least in part to decreased connectivity between the parahippocampal place area (PPA) and the retrosplenial complex (RSC). According to (Epstein, 2008), the PPA is “concerned with representation of the local visual scene” while the RSC is “more concerned with situating the scene within the broader spatial environment.”

considerably more detail, including especially **Brainish**, the **Sleeping Experts Algorithms**, and the **Hard Problem** (Chalmers, 1995) for **pain** and **pleasure**.

## 5 Relation to Other Theories of Consciousness

The **CTM** is an abstract computational model designed to consider consciousness from a **TCS** perspective. It is not intended to model the brain nor the neural correlates of consciousness. **Nevertheless, the CTM is both inspired by, and has certain features in common with, neural, cognitive, and philosophical theories of consciousness.**

The **CTM** is directly influenced by Baars' **GWT**, which is supported by (Dehaene & Changeux, Experimental and theoretical approaches to conscious processing, 2011), (Dehaene S. , 2014) and (Mashour, Roelfsema, Changeux, & Dehaene, 2020) in their investigation of neural correlates of consciousness, known as the Global Neuronal Workspace Theory (**GNWT**). Like the **LIDA** model of cognition (Baars & Franklin, 2007) and (Baars & Franklin, 2009), **CTM** is architectural.

*Predictive dynamics* (the ensemble of prediction, feedback, and learning) is an additional key feature of the **CTM**. It is related to the notion of predictive processing (**PP**), see (Lee & Mumford, 2003) (Friston, 2003) (Friston, 2005) (Cleeremans, 2014) (Clark, 2015) (Seth, 2015) (Hohwy & Seth, 2020).

We see a kinship between the **CTM** and the self-aware robots developed by (Chella, Pipitone, Morin, & Racy, 2020). We also see a kinship between the **CTM** and the Global Latent Workspace (**GLW**) proposed by (VanRullen & Kanai, 2021) for deep learning.

Philosophically, we align with much of Daniel Dennett's functionalist perspective (Dennett D. C., 1991) **except we don't agree with his view that we are the only species to have consciousness (Dennett D. C., 1978) and more recently (Dennett D. C., 2019). As for animal consciousness, we agree with (Mumford, submitted 2019) that consciousness is a matter of degree. Here he cites (Merker, 2007) that consciousness does not need a cerebral cortex: it arises from midbrain structures. We would also cite other studies, e.g., (Slobodchikoff, 2012).**

We do not see the *explanatory gap* (Levine, 1983) between functional and phenomenological consciousness as insurmountable. This viewpoint aligns closely with Baars (see (Kaufman, 2020) interview) and (Dennett D. C., 2016). Indeed, we see the **CTM's** ability to tag and test features in its **Model-of-the-World** as playing a role in the feeling of "what it is like" (Nagel, 1974).

As in Michael Graziano's Attention Schema Theory (**AST**) (Graziano, Guterstam, Bio, & Wilterson, 2020), **CTM** is consciously aware of both external and internal events. Basic **AST** is similar to **GWT**: its i-consciousness (i for information) aligns somewhat with **CTM's** conscious awareness.<sup>31</sup>

We do not agree with Graziano et al. that **GWT** "leaves unexplained how people end up believing they have subjective experience" i.e., that it leaves an explanatory gap. Instead, we argue that the feeling of subjective experience in the **CTM** arises when "winning chunks" from imaginings and dreams, for example, are received by the same (unconscious) processors that receive chunks directly from the environment via **Input maps**.

Additionally, the **Model-of-the-World processor** incorporates the information gotten from the winning chunks (i.e., the **conscious content** of the **CTM**) into its **model(s)-of-the-world**, as appropriate, tagging the "**CTM**" in all **models-of-the-world** as "conscious". Fuller discussion is in Chapters 2 and 3, and in (Blum & Blum, 2021).

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<sup>31</sup> Full **AST** has three neural networks (**A** for receiving information, **B** for constructing an attention schema, and **C** for reporting to the outside world) to obtain a system which purportedly thinks it has subjective experience (m-consciousness, m for mysterious).

Both **AST** and **CTM** appear to embody illusionist notions of consciousness proposed by (Dennett D. C., 2019) and Keith Frankish (Frankish, 2016). Saying that the feeling of consciousness is an illusion does not deny the existence of that feeling. As a familiar example, the fact that a movie is made up of (many) discrete still images does not affect the feeling of continuity one gets from viewing it. The feeling of continuity is an illusion.

By utilizing existing technology (or apps) to supplement its supply of **LTM** processors (section 1.7), **CTM** incorporates elements similar to those advocated by (Clark & Chalmers, 1998)’s “extended minds”.

Integrated Information Theory (**IIT**), the theory of consciousness developed by Giulio Tononi, (Tononi, 2004) and supported by Koch (Tononi & Koch, 2015), proposes a measure of consciousness called **PHI**, defined using Shannon’s information theory that essentially measures the amount of feedback in a system. Thus, “consciousness is not input-output information processing but the intrinsic ability or power of a neuronal network to influence itself.” This is consistent with **CTM**’s *intrinsic* predictive dynamics (of predication, feedback and learning). Tononi proposes five “axioms” (properties) necessary for any causal system to have consciousness.<sup>32</sup> Given a detailed specification of a **CTM**, one could in principle compute its **PHI** and compare it to the **PHI** of any other precisely defined causal system. It turns out that many causal physical systems have non-zero measures of **PHI**. **IIT would validate animal consciousness.**

With regard to the “adversarial collaboration” between advocates of **GNWT** and **IIT**, (Reardon, 2019) and (Melloni, Mudrik, Pitts, & Koch, 2021), the **CTM** shares features of both basic theories, as pointed out above. Our view is that both theories add to the discussion of consciousness. The adversarial aspects between the theories arise mainly from the advocates’ differing views on brain regions primarily responsible for consciousness –prefrontal cortex for **GNWT**, posterior cortex for **IIT**. We note however, it is possible to have some **level** of consciousness without a cerebral cortex at all (Merker, 2007) and suspect that in such cases, as in the **CTM**, aspects of the basic **GWT** and **IIT** are still in play.

Our view on **free will** (section 3.6) is close to Dehaene’s (Dehaene S. , 2014). Our explanation of the *feeling* of free will in the **CTM** incorporates additionally and *especially* resource limits imposed by computational complexity considerations.

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<sup>32</sup> In (Koch, 2019), Christof Koch outlines the axioms: “[E]very conscious experience has five distinct and undeniable properties: each one exists for itself, is structured, informative, integrated and definite”.

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