



# **The Miph of Consciousness**

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**The Mathematics, Informatics, and Physics  
of Consciousness and its Place in Nature**

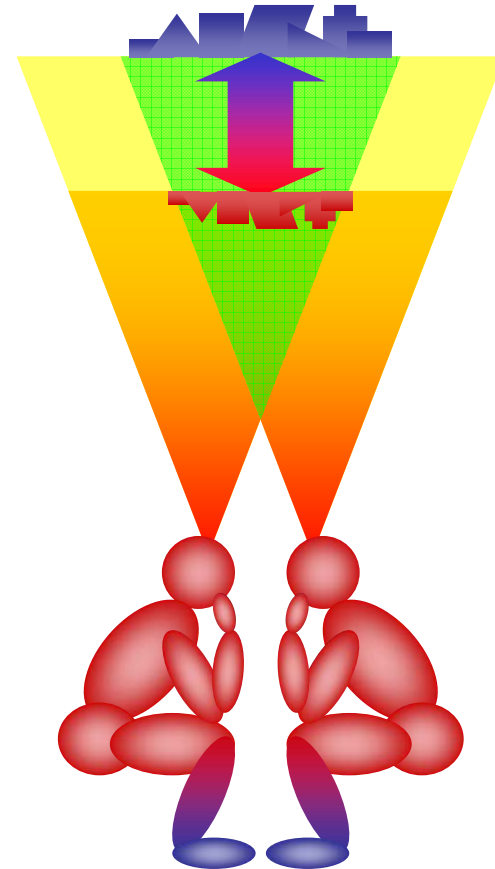
**J. Andrew Ross**

**Toward a Science of Consciousness  
7-11 August 2001, Skövde, Sweden**

# The miph of consciousness 1



- Introduction
- Formal logic
- Computation
- Set theory
- Possible worlds
- Quantum theory
- Consciousness
- Open questions
- Conclusion

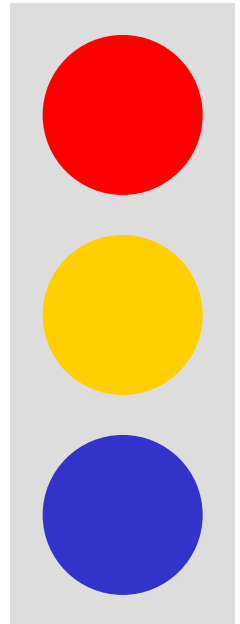


# What is consciousness?

## C O N S C I O U S N E S S

- Is a state of
  - Phenomenal awareness of qualia
  - Being inside a universal reality
  - Being in a landscape of things
- Is a process of
  - Becoming aware of changing qualia
  - Experiencing new states of awareness
  - Sensing the ebb and flow of things
- Is essentially
  - Extended over a space of things
  - Rooted in a history of changes
  - Part of an ongoing logical process

Color  
qualia



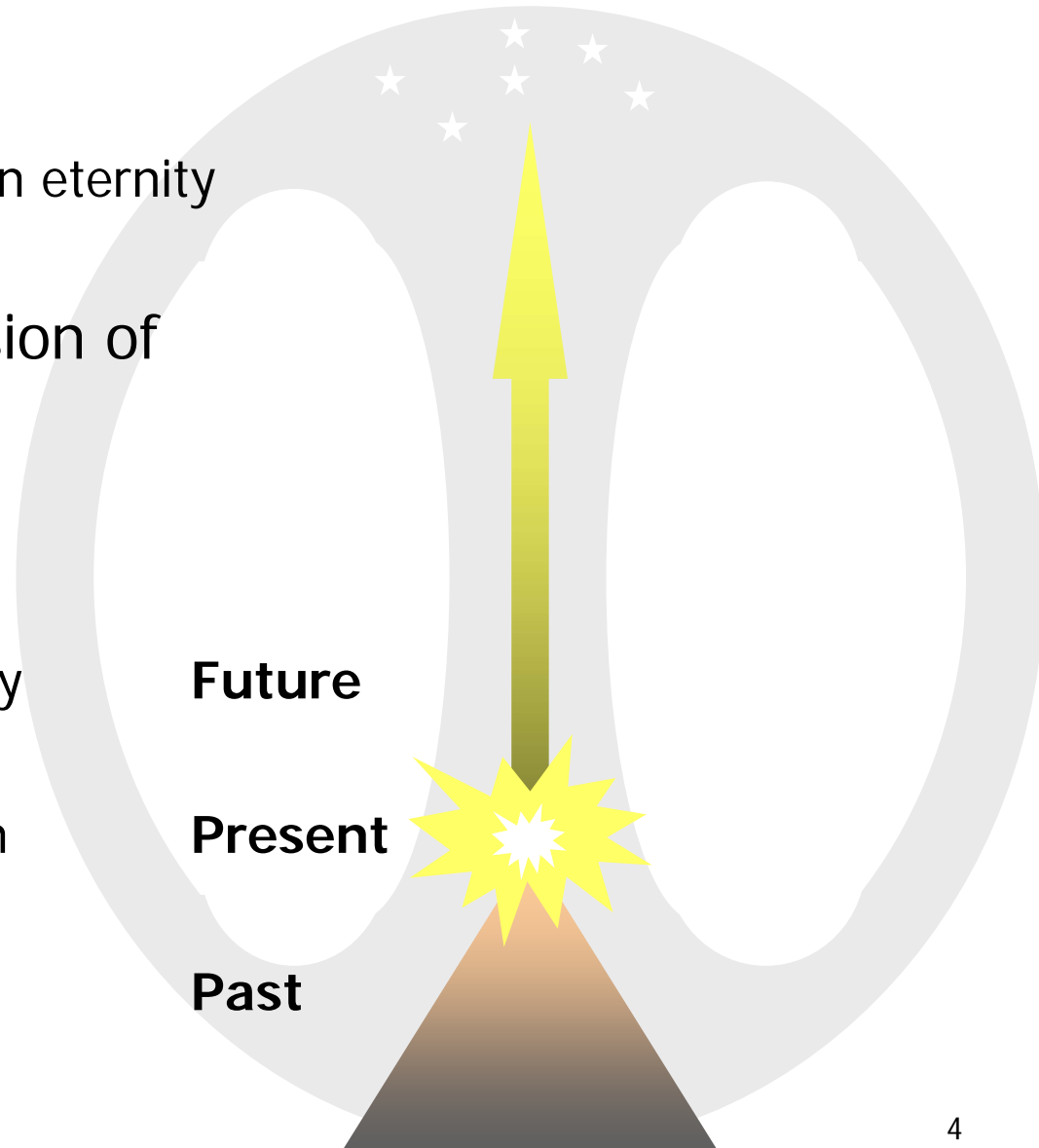
# Flow logic

- Fundamentally
  - We are immersed in eternity
  - We change in time
- Time is the dimension of
  - Growth
  - Change
  - History

Fountainhead of possibility

Crucible of transformation

Accumulation of facts





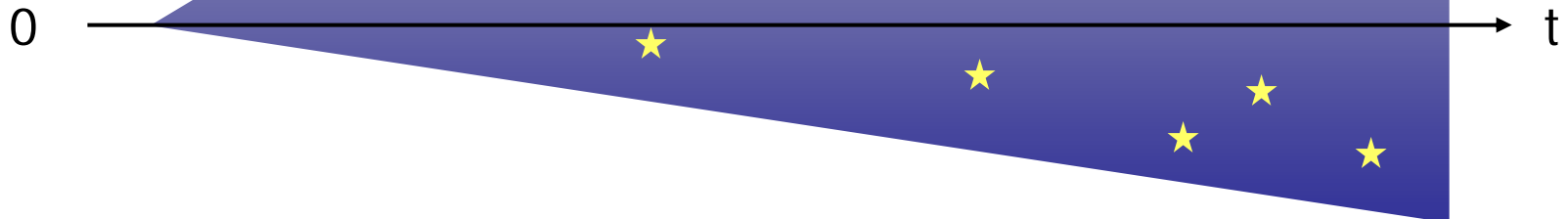
# A creation myth

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- At time zero, all was calm
- In the Planck instant before the big bang, the physical universe had perfect symmetry
- The first symmetry to break open the primal egg was the complementarity of **0/1** and **1/0**
- Bit states 0 and 1 started out equal and opposite
- The first moment of **time** broke the symmetry

# Time and evolution

- As time advanced,
  - Successive symmetries were broken
  - From 11 compact dimensions 4 expanded
  - The universe cooled and matter condensed
  - Atoms aggregated in a sea of photons
  - Symmetries broke randomly and entropy increased
  - Phase changes created concentrations of order
  - Ordered states became more complex
  - DNA life evolved on Planet Earth

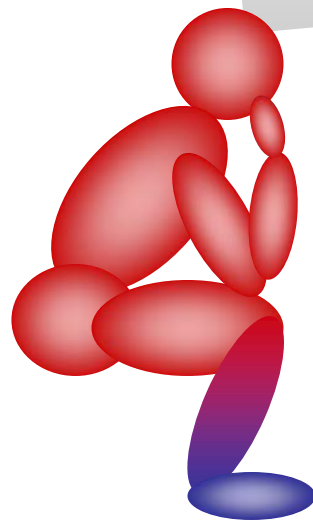


# Knowledge and reality

- In the last few million years BP,
  - Biological organisms such as human beings evolved subjective consciousness
  - Consciousness grew to recognize increasingly complex objective domains

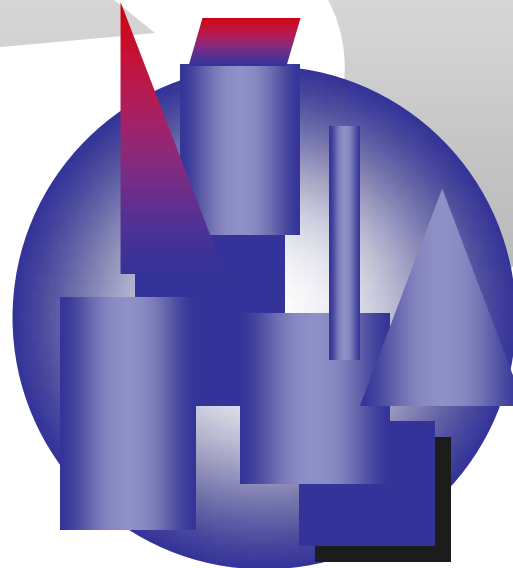
Epistemic  
subject

Realm of  
knowledge



Ontic  
domain

Realm of  
reality

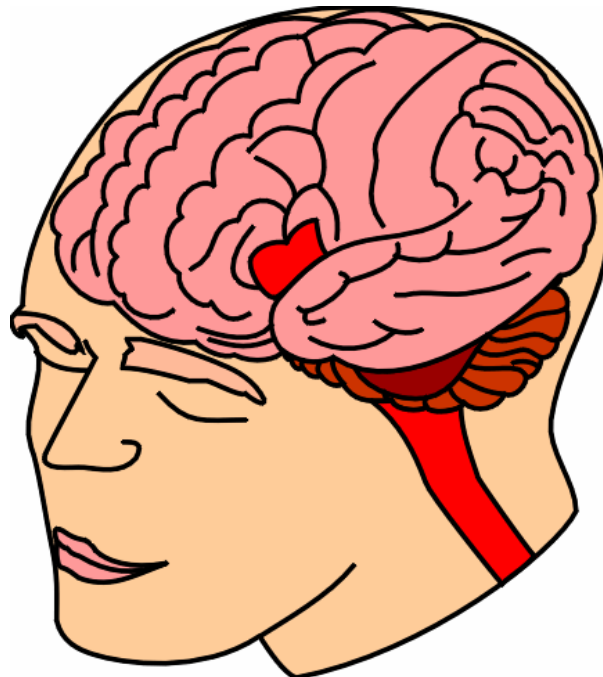


# Knowledge and the brain

- Some facts:
  - Knowledge is generated by conscious human beings
  - Human consciousness is generated by brain activity
  - Conscious states are correlated with brain states

## The body

Transition to  
objectivity

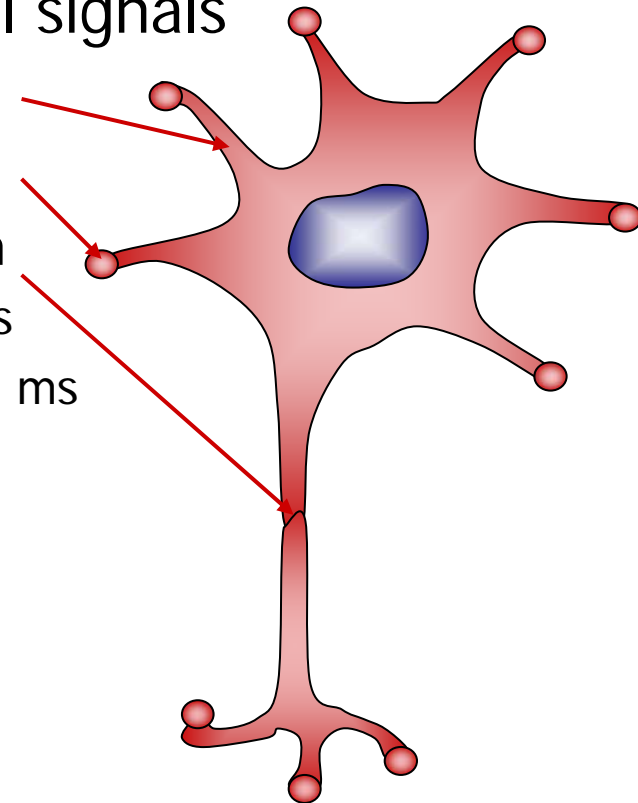
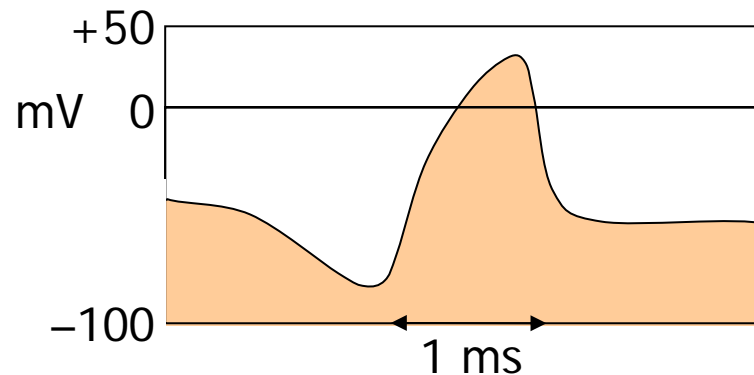


## The brain

The seat of  
subjectivity

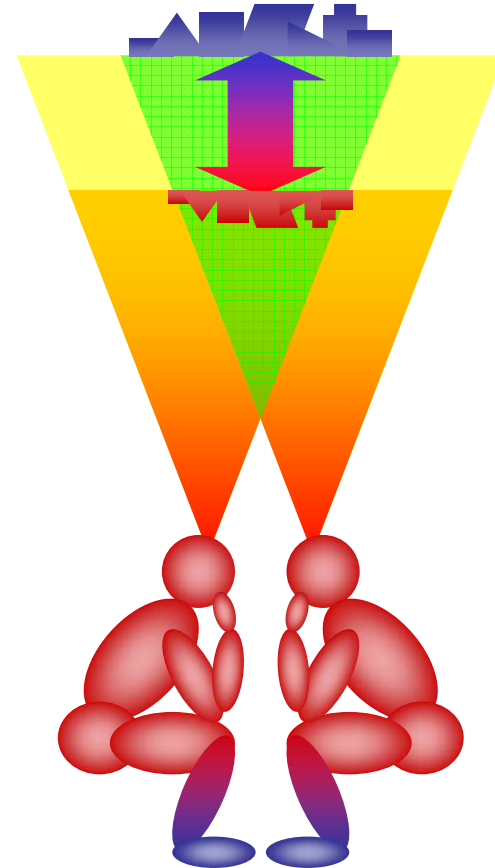
# Brains are neuronets

- The human cerebral cortex contains  $\sim 10^{10}$  neurons
  - On average, a neuron connects with  $\sim 10^4$  other neurons
  - The neurons are connected in layers to form sheets
- Neurons receive and emit electrical signals
  - They receive signals along **dendrites**
  - The dendrites terminate in **synapses**
  - A neuron emits signals along its **axon**
    - The signals are called action potentials
    - They are  $\sim 100$  mV spikes that last  $\sim 1$  ms



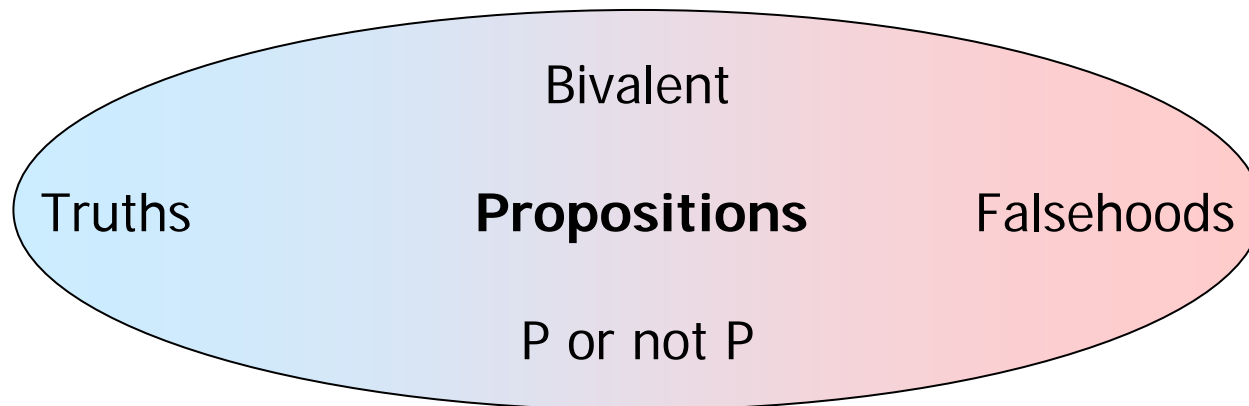
# The miph of consciousness 2

- Introduction
- **Formal logic**
- Computation
- Set theory
- Possible worlds
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# Propositional knowledge

- The contents of consciousness are knowledge states
  - Epistemology is the theory of knowledge
  - Ontology is the theory of what exists
- Knowledge states are propositional
  - True propositions state what is the case
  - False propositions state what is not



# Propositional logic

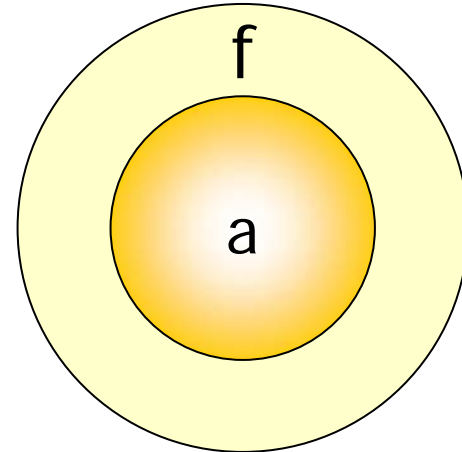
- Bivalent propositions form classical logic
  - True propositions  $P$  have truth value 1:  $v(P) = 1$
  - False propositions  $P$  have truth value 0:  $v(P) = 0$
  - Valid inference from  $P$  to  $Q$  preserves truth:  $v(P) \leq v(Q)$

TRUTH TABLE		Not $P$	$P$ and $Q$	$P$ or $Q$	If $P$ then $Q$	$P$ iff $Q$
$P$	$Q$	$\neg P$	$P \wedge Q$	$P \vee Q$	$P \rightarrow Q$	$P \leftrightarrow Q$
1	1	0	1	1	1	1
1	0	0	0	1	0	0
0	1	1	0	1	1	0
0	0	1	0	0	1	1

# Objects and concepts

Propositions have inner structure

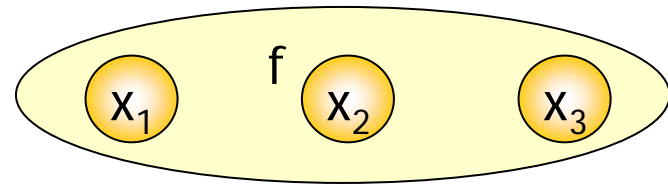
- $P = f(a)$ 
  - Syntax
    - $f$  = predicate
    - $a$  = name
  - Semantics
    - $f$  = concept or class
    - $a$  = object or element
  - $P$  states that
    - Object  $a$  falls under concept  $f$
    - Element  $a$  is a member of class  $f$
- $P = f(a_1, \dots, a_n)$ 
  - $P$  states that  $a_1, \dots, a_n$  fall under  $n$ -ary relation  $f$



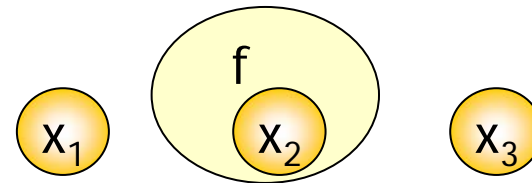
# First order logic

- General propositions use quantifiers and variables

- For **all** objects  $x$ ,  $f(x)$   
 $(\forall x)f(x)$



- For **some** objects  $x$ ,  $f(x)$   
 $(\exists x)f(x)$



- Unquantified,  $f(x)$  is an open sentence and  $x$  is free
- In classical first order logic,
  - For all  $x$ ,  $f(x)$  iff there is no  $y$  such that not  $f(y)$   
 $(\forall x)f(x) \leftrightarrow \neg (\exists y) \neg f(y)$

# Valid inference

- Propositional inference
  - *Modus ponens*  
 $P, P \rightarrow Q \Rightarrow Q$
- Quantifier inference
  - For free variable  $u$ ,  $f(u) \Rightarrow (\forall x)f(x)$
  - $(\forall x)f(x) \Rightarrow f(z)$  for any  $z$
  - For any  $z$ ,  $f(z) \Rightarrow (\exists x)f(x)$
  - $(\exists x)f(x) \Rightarrow f(c)$  for new constant  $c$
- Different axioms and rules give different systems
  - Nonclassical systems often deny bivalence

## Implication

$A, \dots \Rightarrow C$  is valid  
iff conclusion  
C is true  
whenever  
all the premises  
 $A, \dots$  are true

## Consistency

First order theory  
T is consistent  
iff, for all  
sentences  $s$  of T,  
not both  $T \Rightarrow s$   
and  $T \Rightarrow \text{not-}s$

# Models

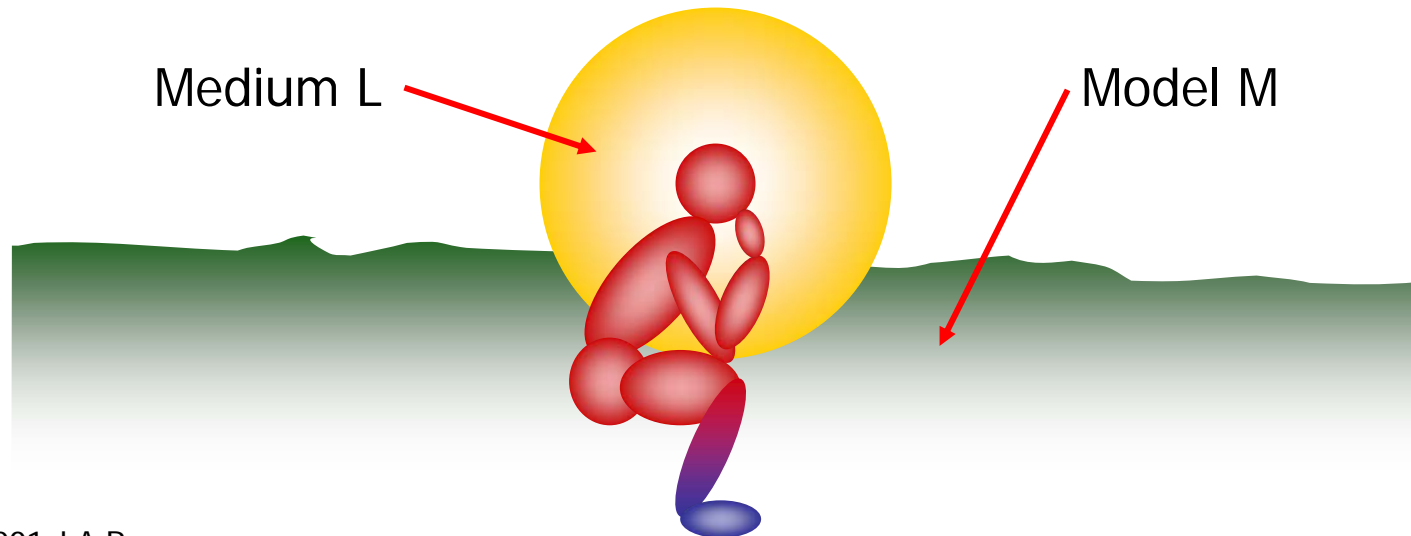
- A first order theory  $T$ 
  - Is a set of sentences  $s$  in a first order language  $L$  with a distinguished set of axioms and theorems
  - Theory  $T$  **implies** L-sentence  $s$ :  $T \Rightarrow s$
- A model  $M$ 
  - For a first order theory  $T$  is a set  $\langle O, R \rangle$  where
    - $O$  is a set of objects denoted by terms in  $T$
    - $R$  is a set of relations between objects in  $O$such that, when  $L$  is interpreted in  $O$  and  $R$ , the axioms and theorems of  $T$  are true
  - Model  $M$  **satisfies** L-sentence  $s$ :  $M \models s$
- Completeness: for all  $s$ ,  $T \Rightarrow s$  iff  $M \models s$



Semantics

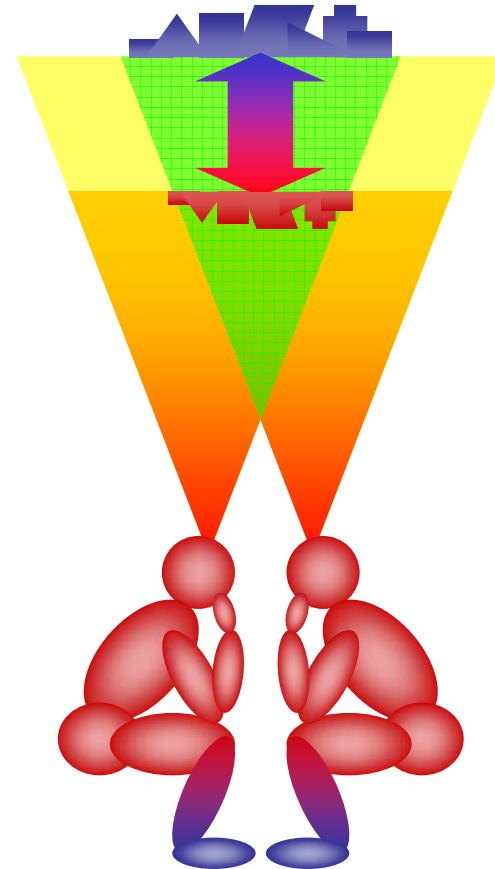
# Logic and consciousness

- L can be any symbolic interaction medium used by a conscious subject
  - L can be neurally hardwired, acted, spoken, written, embodied in tokens, coded as bits, ...
- M can model any world that embeds the subject
  - M can be the world denoted by an actual or potential conscious state of the L-using subject



# The miph of consciousness 3

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# Mathematical forms

- The realm of mathematical forms is
    - Eternal, outside time
    - Perfect and incorruptible
    - Invisible to the vulgar senses
  - Numbers are eternalized abstractions of
    - Arbitrary physical things
    - The pure intuition of time
  - Number theory is a prototype for
    - Any first order theory
    - Any computable theory
    - Any algorithmic process
    - Any virtual reality
- Plato
- Kant
- Gödel
- Turing
- Chaitin
- Deutsch

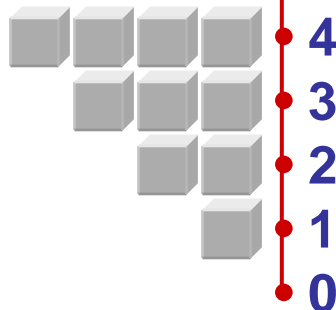
# Informal arithmetic

- Arithmetic is the theory of the natural numbers

Onward to the limit  $\omega$  of the natural numbers

$\mathbf{N} = \{0, 1, 2, 3, \dots\}$

$\mathbf{N}$  = the infinite set of natural numbers



$\mathbf{S}(n)$   
 $n$

$\mathbf{S}(n)$  = the successor of  $n$

Basic operations  
Addition +  
Multiplication \*



# Formal arithmetic

- The axioms of formal arithmetic **FA**

For all  $x, y, z \in \mathbf{N}$ ,

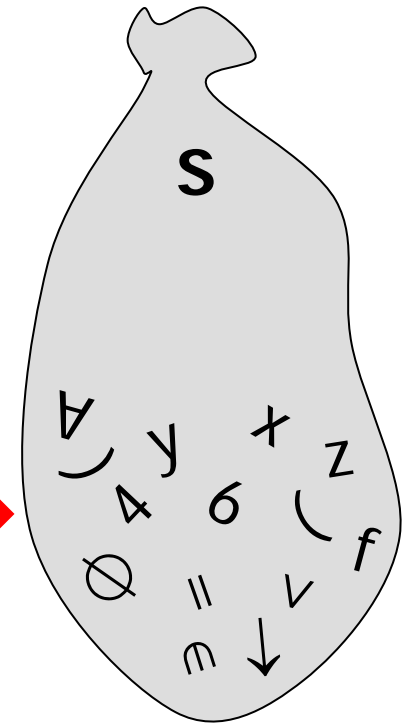
- $x = y \rightarrow (x = z \rightarrow y = z)$
- $x = y \rightarrow S(x) = S(y)$
- $0 \neq S(x)$
- $S(x) = S(y) \rightarrow x = y$
- $x + 0 = x$
- $x + S(y) = S(x + y)$
- $x * 0 = 0$
- $x * S(y) = (x * y) + x$

For any **FA** predicate  $A( )$ ,

- If  $A(0)$  and  $(\forall x)(A(x) \rightarrow A(S(x)))$  then  $(\forall x)A(x)$

# Theory and metatheory

- A theory is an epistemic construct  $T$ 
  - $T$  is a set of interpreted propositions
  - The propositions define a knowledge state
- A theory refers to an ontic domain  $M$ 
  - $T$  is interpreted in natural model  $M$
  - $M$  satisfies the axioms and theorems of  $T$
- A theory has a syntactic structure  $S$ 
  - $S$  is made of uninterpreted formal symbols →
- A metatheory of  $T$  has the model  $S$ 
  - Every theory  $T$  has a metatheory  $MT$
  - $T, MT, MMT, \dots$  can share the same  $S$





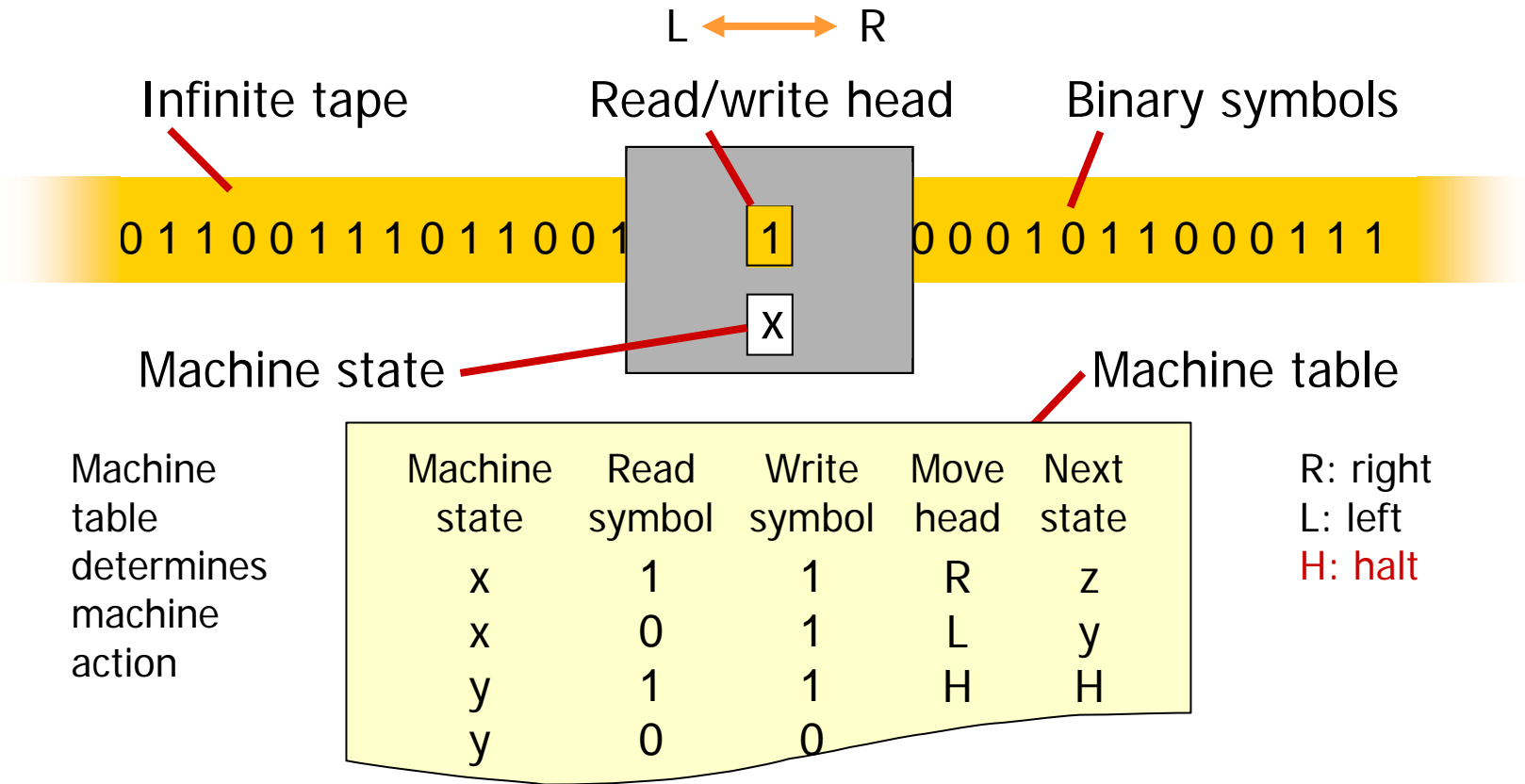
# A metatheoretic paradox

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- Let theory FA have metatheory MA
  - Code the structure S of FA into the model N of FA
    - Define numbers for names, predicates, variables, constants
    - Define arithmetic operations to generate numbers for sentences, inferences, proofs, axioms, theorems
  - Call the number n that codes an S-item s of FA the Gödel number G(s) of s:  $n = G(s)$
  - Define the open FA/MA sentence **g**:
    - For all s, G(s) is not the Gödel number of a proof in FA of x
  - An instance of **g** is FA/MA sentence **g\***:
    - For all s, G(s) is not the Gödel number of a proof in FA of g
    - **g\*** says **g** has no proof in FA, so **g\*** should be true in MA
- If FA is consistent, **g\*** is true but not provable in FA

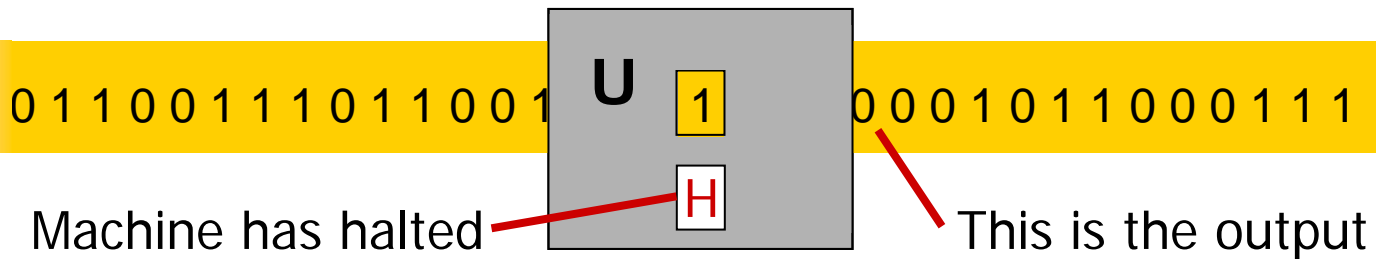
# Computation

- Turing machines are idealized computers



# Computable strings

- 1 Input: binary string on tape
- 2 Universal Turing machine **U** starts
- 3 **U** halts (maybe!)
- 4 Output: binary string on tape

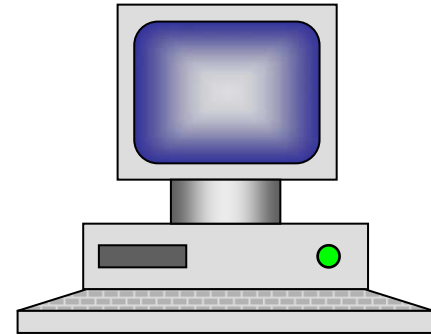


- Computable strings are **U** output from given input strings
- Turing built on Gödel's theorem for FA to prove:
  - **The halting problem**  
It is not decidable for which input strings **U** halts

# Are brains computers?

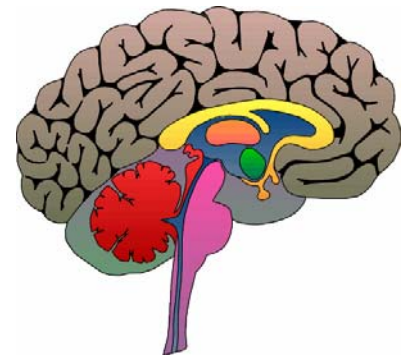
## ■ Computers

- Have digitized input and output
- Have a finite number of inner states
- Operate according to fixed rules



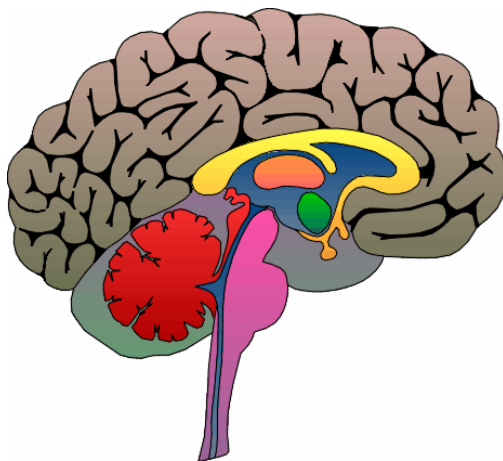
## ■ Human brains

- Have approximately digitized input and output (via sensory and motor nerves)
- Have a vast but probably finite number of inner states (if similar states are equivalent)
- Operate according to rules that are presumably fixed (but are complex and not well understood)

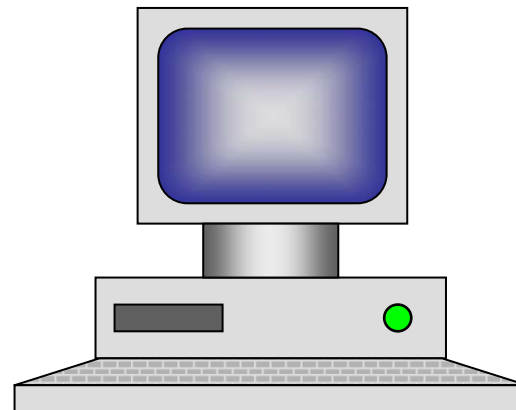


# Brains may not be computers

- Truth outruns provability in arithmetic
  - Not all truths in FA can be proved in FA – Gödel
- FA theorems are computable strings
  - The set of computable strings is not computable – Turing
- Not all truths are computable
  - So brains are not computers – Penrose

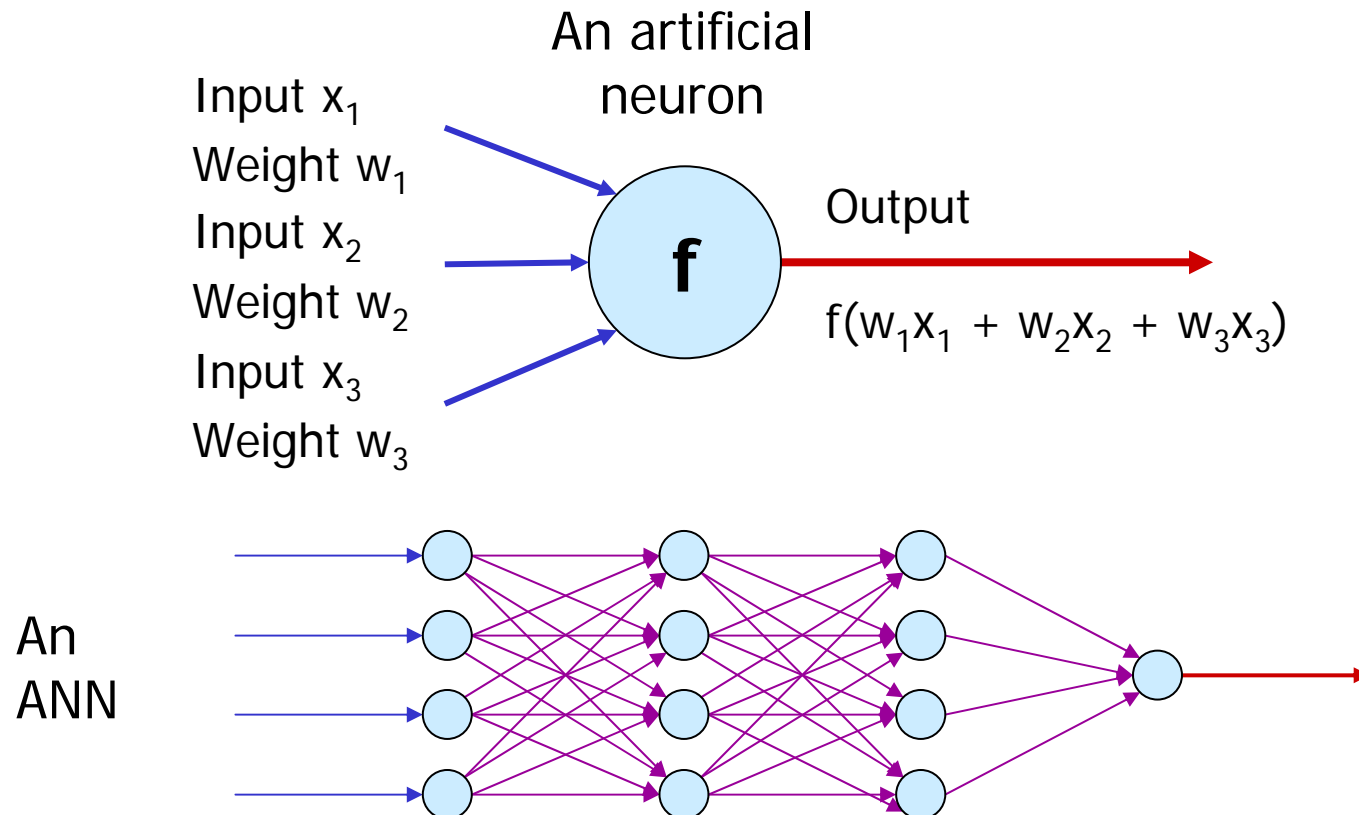


Says  
Penrose



# Artificial neuronets

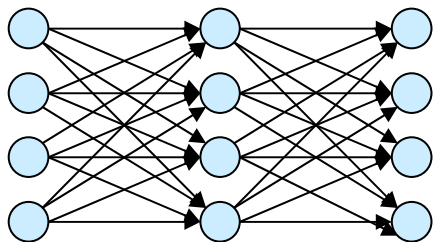
- Artificial neuronets (ANNs) reflect the gross architecture of natural cerebral neuronets



# Neuronets can be computers

- ANNs can compute any computable function
  - But how can they program themselves?
- ANNs with backpropagation can learn
  - Backpropagation is output fed back to reset weights
  - ANNs with backpropagation can use training input to reduce errors on pattern recognition tasks
- ANNs can emulate many brain functions

**But how well can ANNs emulate brains?**



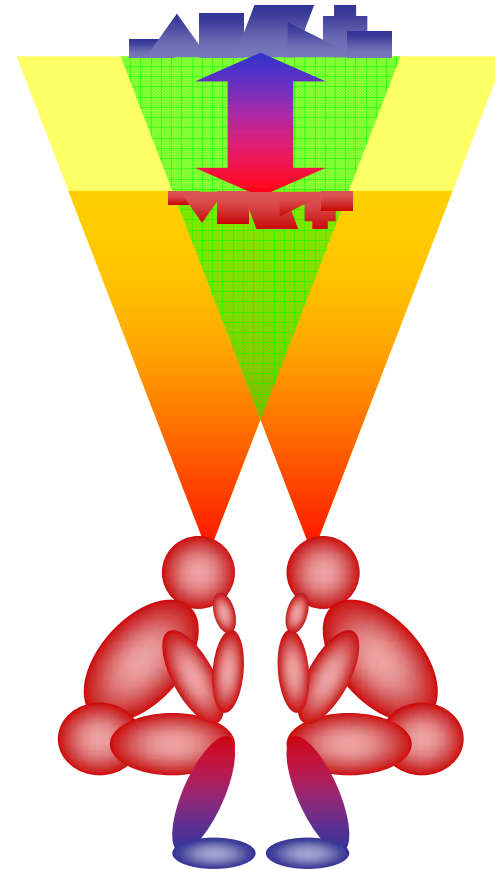
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# The miph of consciousness 4

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# From numbers to sets

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- Number theory is pure logic – Kant
- Numbers are sets of sets
- How to see numbers as sets:
  - Number  $n$  is the set of all sets that can be mapped 1-1 onto  $n$  – Frege
    - Problem: these sets are too big
  - Number 0 is the empty set  $\{ \}$   
Number  $n + 1$  is the singleton of  $n$ ,  $\{n\}$  – Zermelo
    - Problem: these sets are too small
  - Number 0 is the empty set  $\{ \}$   
Number  $n$  is the set of all  $m$  for  $m < n$  – von Neumann
    - ★ Bingo! These sets are just right



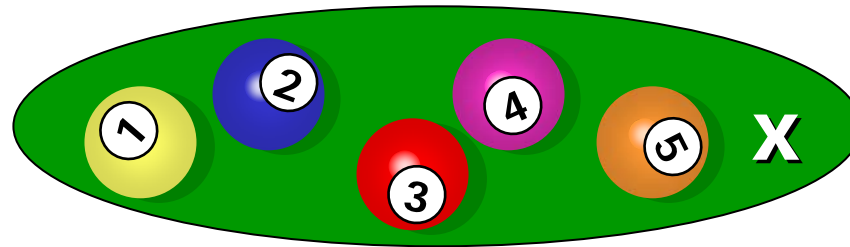
# Elements and classes

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- Sets are elements and/or classes
  - Elements  $a, b, c$  are members of class  $C$ :  
 $a, b, c \in C$  and  $C = \{a, b, c, \dots\}$
- In pure set theory, all elements are sets
  - The null set  $\{ \} = \emptyset$  and  $\emptyset \in \{\emptyset\} \in \{\emptyset, \{\emptyset\}\} \in \dots$
- Usually, classes are sets, but
  - **Russell's paradox**  
The class of all sets that are not members of themselves,  
 $R = \{x \mid x \notin x\}$ ,  
is a member of  $R$  iff it is not a member of itself:  
 $R \in R \leftrightarrow R \notin R$
  - So the **universe  $V$**  of all sets is a class but not a set

# Power sets

- The power set of  $x$  is the set of all subsets of  $x$ 
  - If  $x$  has  $n$  members,  $P(x)$  has  $2^n$  members



$x = \{1,2,3,4,5\} \rightarrow P(x) = \{\{\}, \{1\}, \{2\}, \{3\}, \{4\}, \{5\}, \{1,2\}, \{1,3\}, \{1,4\}, \{1,5\}, \{2,3\}, \{2,4\}, \{2,5\}, \{3,4\}, \{3,5\}, \{4,5\}, \{1,2,3\}, \{1,2,4\}, \{1,2,5\}, \{1,3,4\}, \{1,3,5\}, \{1,4,5\}, \{2,3,4\}, \{2,3,5\}, \{2,4,5\}, \{3,4,5\}, \{1,2,3,4\}, \{1,2,3,5\}, \{1,2,4,5\}, \{1,3,4,5\}, \{2,3,4,5\}, \{1,2,3,4,5\}\}$

- $P(N)$  cannot be mapped 1-1 onto  $N$  – Cantor
  - $N$  is a countably infinite set with cardinality  $\aleph_0$
  - $P(N)$  is uncountably infinite with cardinality  $\aleph_x$
  - Continuum hypothesis:  $P(N)$  has cardinality  $\aleph_1$



# Set theory

- Zermelo-Fraenkel set theory

## ZF axioms

For all  $x, y \in V$ ,

- Extensionality:  $x = y \leftrightarrow (\forall z)(z \in x \leftrightarrow z \in y)$
- Regularity:  $x \neq \emptyset \rightarrow (\exists z)(z \in x \wedge z \cap x = \emptyset)$
- Pairs:  $\{x, y\} \in V$
- Union: If  $U(x) = \{u \mid (\exists v)(u \in v \wedge v \in x)\}$  then  $U(x) \in V$
- Power set: If  $P(x) = \{u \mid u \subseteq x\}$  then  $P(x) \in V$
- Null set:  $\emptyset \in V$
- Infinity:  
If  $\omega = \{u \mid \emptyset \in u \wedge (\forall v)(v \in u \rightarrow v \cup \{v\} \in u)\}$  then  $\omega \in V$
- Replacement schema:  
For any ZF function  $f$  from  $D$  to  $C$ ,  $D \in V \rightarrow C \in V$



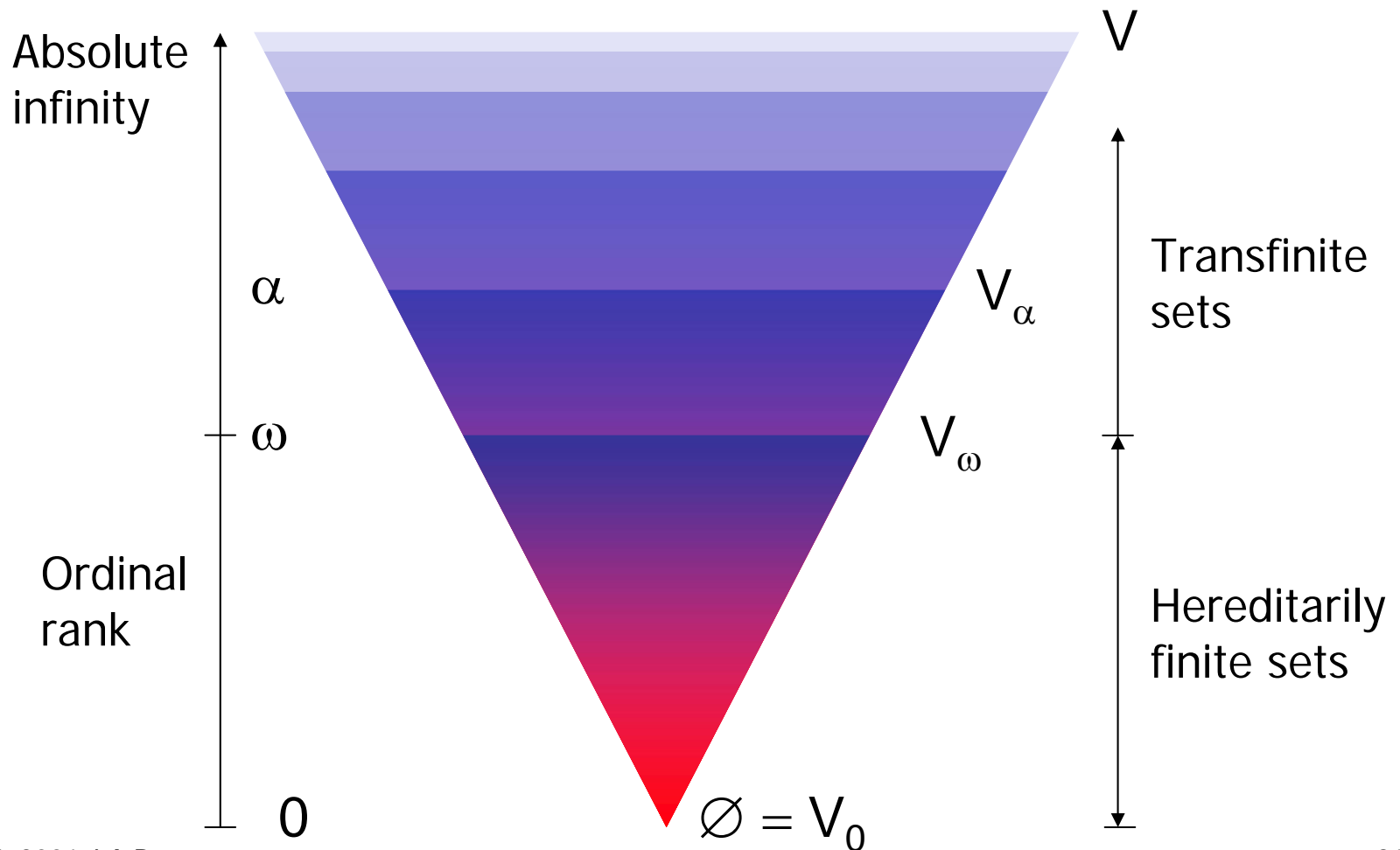
# Every set has a rank

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- Every ZF set  $x$  has an ordinal rank  $R(x)$ 
  - The von Neumann definition of ordinal numbers  $\alpha$ 
    - $0 = \emptyset = \{ \}$
    - $\alpha = \{ \beta \mid \beta < \alpha \}$   
(each ordinal is the set of all smaller ordinals)
  - The von Neumann transfinite V-set function  $V_\alpha$ 
    - $V_0 = 0$
    - $V_\alpha = P(V_{\alpha-1})$  for successor ordinals  $\alpha$   
(each successor V-set is the power set of its predecessor)
    - $V_\lambda = \bigcup \{ V_\alpha \mid \alpha < \lambda \}$  for limit ordinals  $\lambda$   
(each limit V-set is the union of all previous V-sets)
- $R(x) =$  the least ordinal  $\alpha$  such that  $x \subseteq V_\alpha$

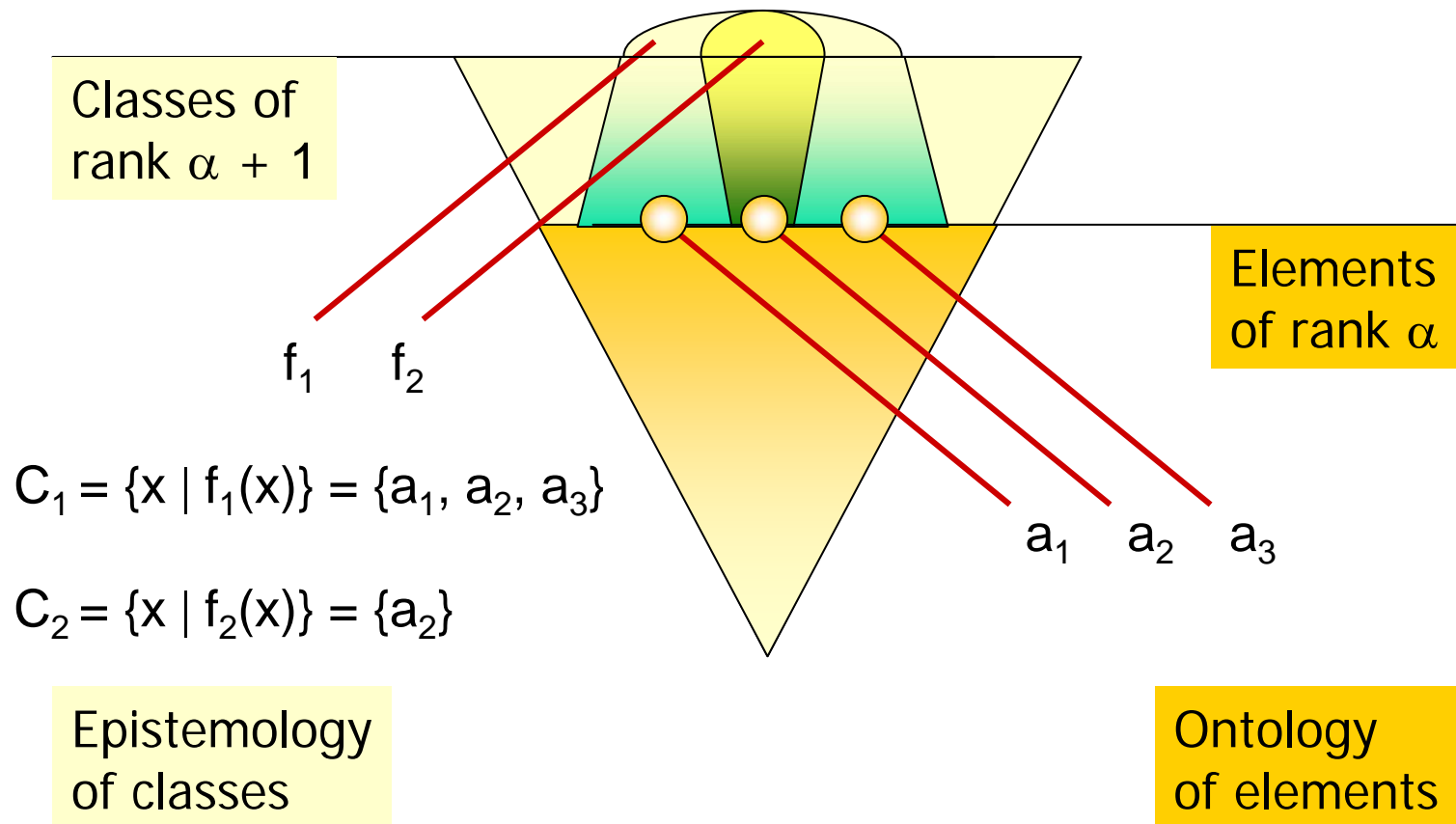
# The universe of sets

- The cumulative hierarchy of pure well-founded sets



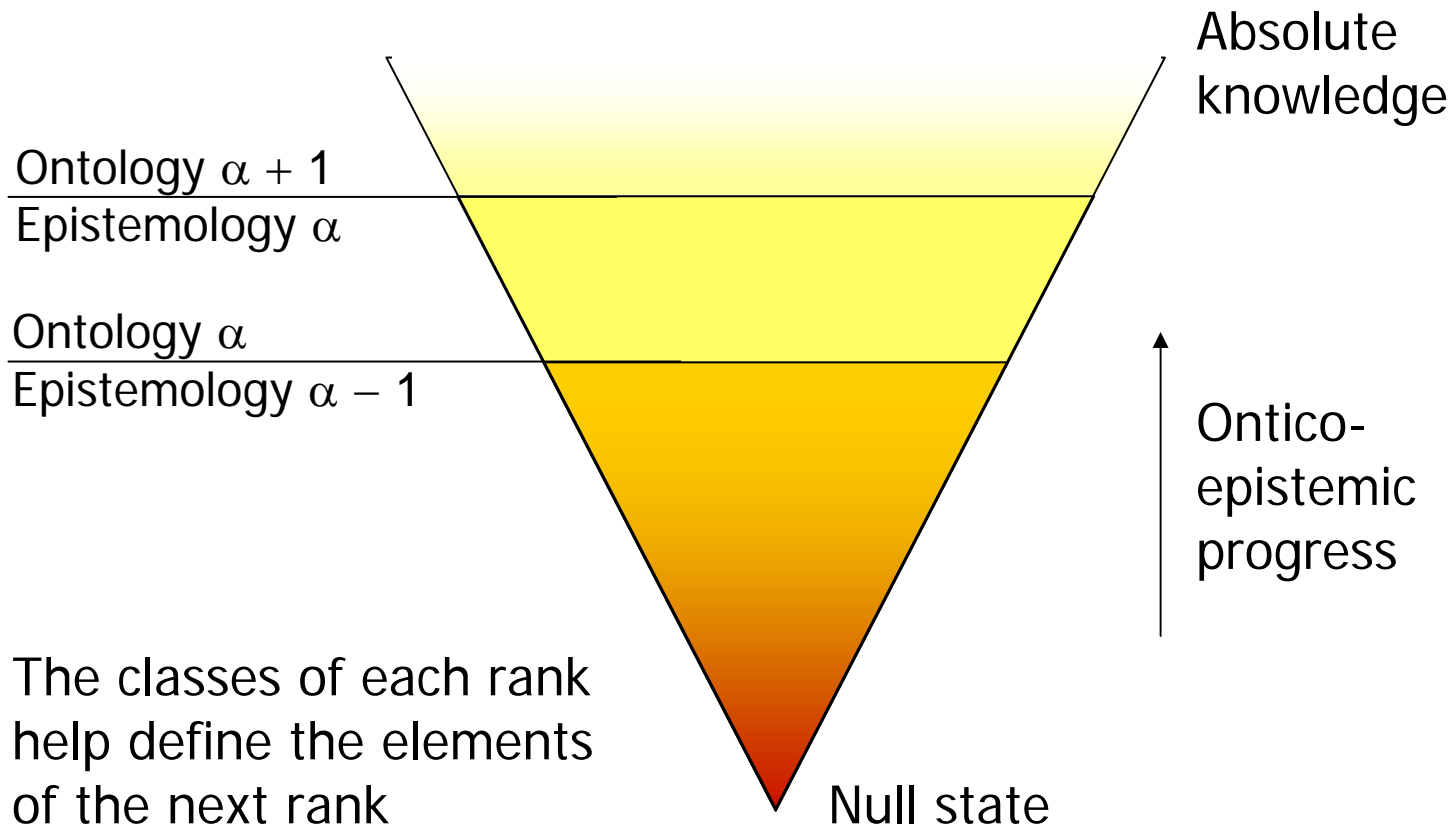
# Layers of logic

- First order theories have ranked models in  $V$



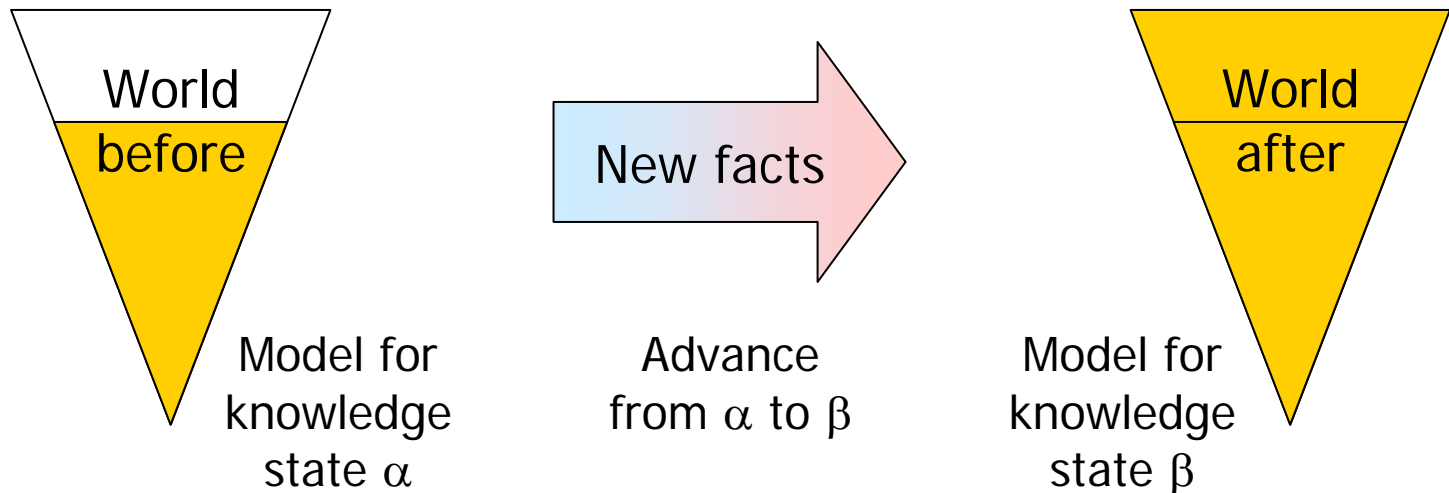
# Evolution of knowledge

- Epistemology and ontology form a dialectic in V



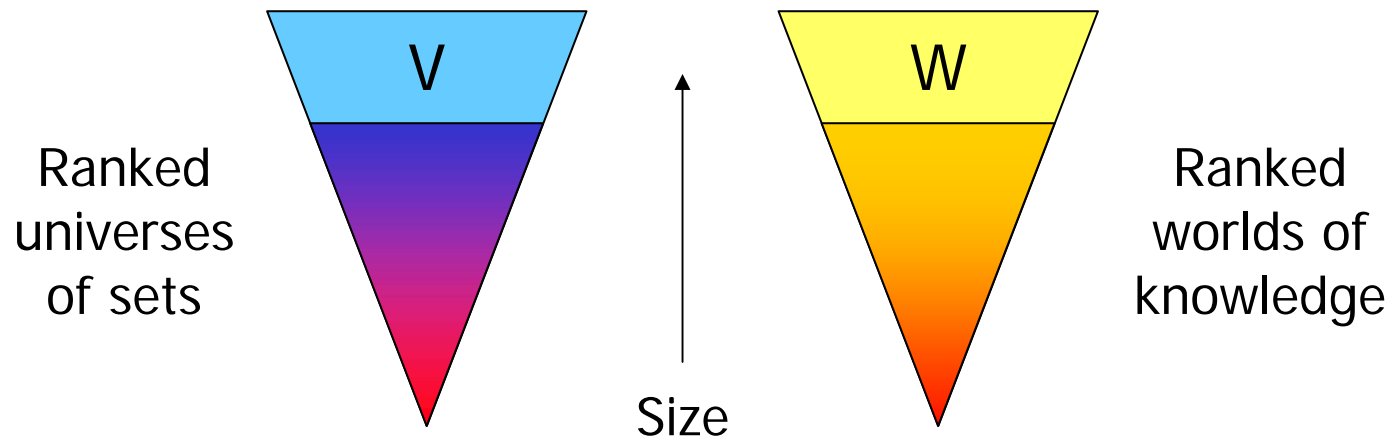
# Worlds of knowledge

- A knowledge state is satisfied in a world
  - A knowledge state is a set of true propositions
  - A knowledge state is closed under logical inference
  - True propositions state either tautologies or facts
  - A world of knowledge is a totality of facts
- New facts are informative



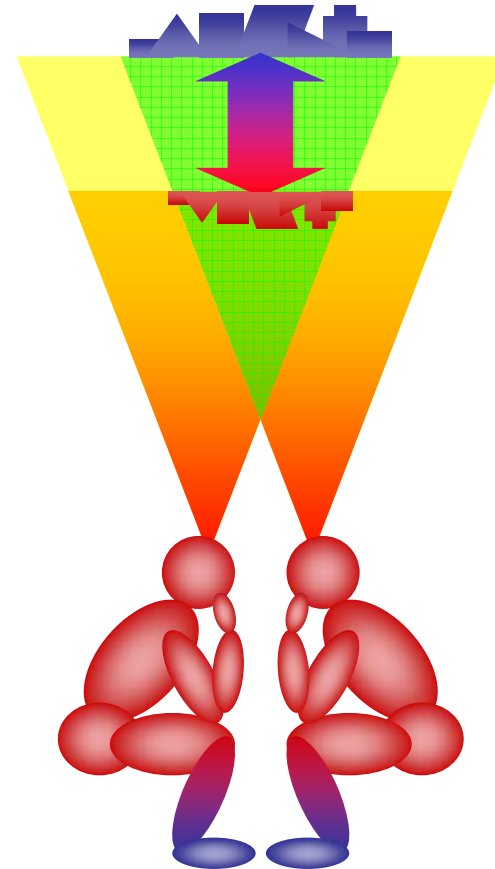
# Worlds as universal sets

- Universal sets can represent worlds
  - Let set  $V_\alpha$  be the natural model for set theory  $T_\alpha$
  - If knowledge state  $K_\alpha$  is logically isomorphic to  $T_\alpha$ , then  $V_\alpha$  is a formal model for  $K_\alpha$
  - If world  $W_\alpha$  satisfies knowledge state  $K_\alpha$ , then  $V_\alpha$  formally represents  $W_\alpha$



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# Worlds as realities

- Worlds

- Reflect states of

- **Information**

- Made of bits  
= logical atoms

- **Knowledge**

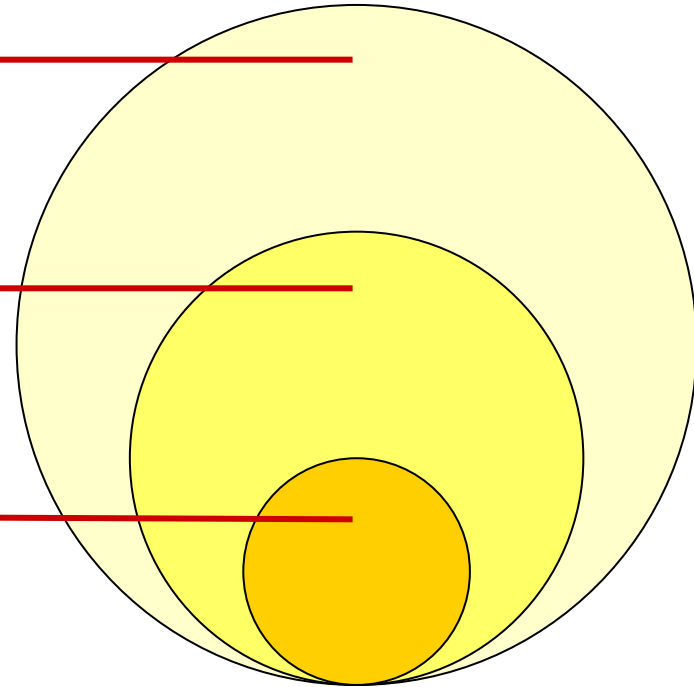
- Made of facts  
= cognitive atoms

- **Consciousness**

- Made of qualia  
= sensory atoms

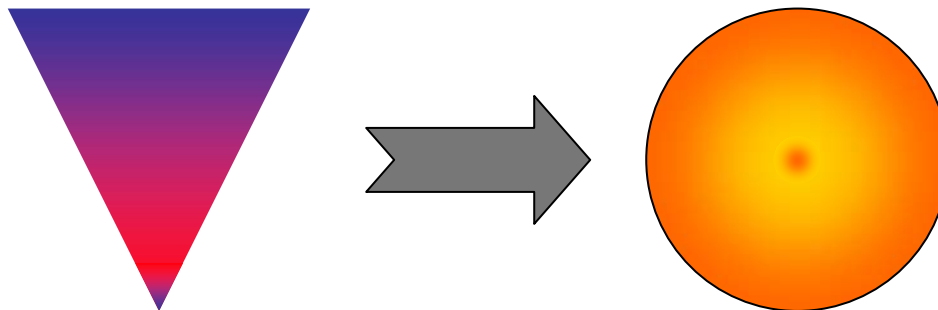
- **Closure**

- Made round



# Worlds as closed loops

- Closure
  - In set theory, looping  $V$  to  $0$  effects closure
    - But the loop is a paradox
  - For a **world**  $W$  represented as a  $V$ -set,
    - Its universe  $V$  is not an element, but  $V$  can be nonuniversal **outside**  $W$
    - Its urelement  $0$  has no members, but  $0$  can be nonempty **outside**  $W$
    - Closure makes  $W$  a totality



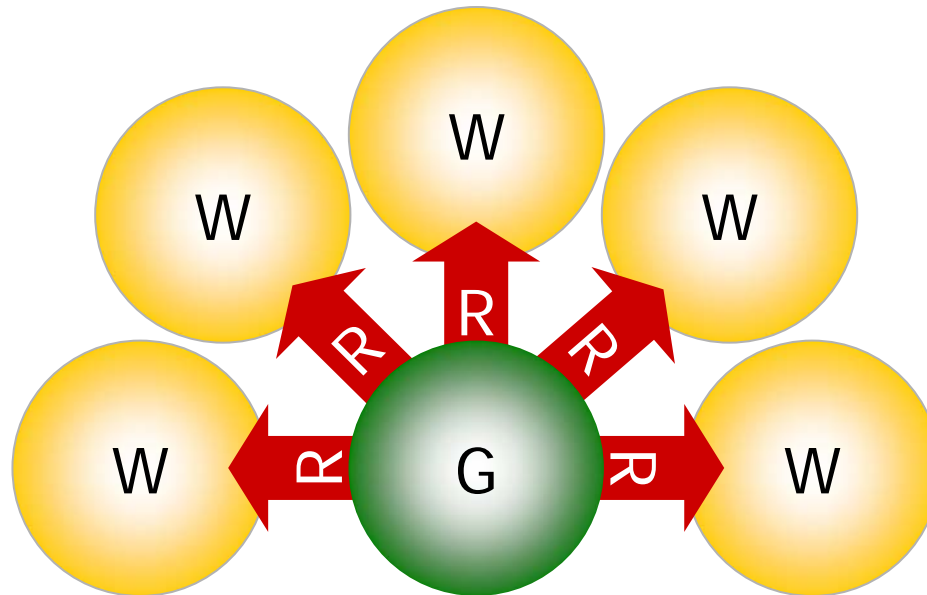
# Virtual realities

- A world embeds a subject
  - The world is reality for the embedded subject
- A world may be actual or possible
  - An actual world is an existing state of
    - Information (bits)
    - Knowledge (facts)
    - Consciousness (qualia)
  - A possible world is a **virtual reality**
    - The VR is defined by computable rules from atomic bits to resemble the actual world relative to which it is possible



# Possible worlds

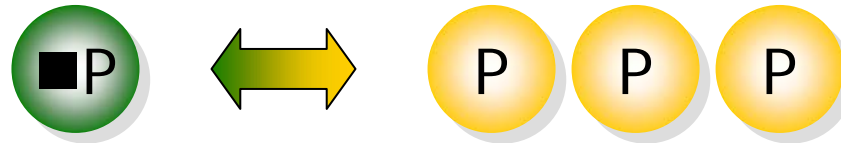
- Worlds can be actual and/or possible
  - The actual world **G** is the world as it **is now**
    - G may be a state of knowledge or consciousness
  - Possible worlds **W** are worlds as they **may be**
    - Worlds W may be possible futures relative to G
  - An accessibility relation **R** links pairs of worlds



# Modal logic

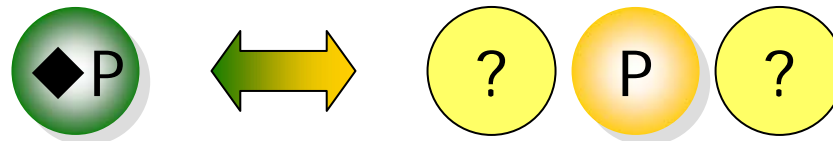
- Modal logic is the logic of possible worlds

There are two main modal operators



## Necessarily P

■P is true in G iff, for **all** worlds W such that W is R-accessible from G, P is true in W



## Possibly P

◆P is true in G iff, for **some** world W such that W is R-accessible from G, P is true in W



# Possible world semantics

---

- Possible worlds form model structures – Kripke
  - A model structure  $A = \langle G, K, R \rangle$  contains
    - Actual world  $G$
    - Set  $K$  of possible worlds  $W$  (including  $G$ )
    - Relation  $R(W, G)$  saying world  $W$  is accessible from  $G$
- Satisfaction
  - Truth conditions for sentences  $s$  of modal language  $L$  are defined relative to all  $R$ -accessible worlds  $W$  in  $K$
  - If language  $L$  defines modal theory  $T$ , a suitable model structure  $A$  satisfies  $T$ :  $A \models T$
- Completeness
  - For suitable modal theories  $T$  and all sentences  $s$  of  $L$ ,  $T \models s$  iff  $A \models s$



# Epistemic and ontic modalities

---

- Axioms for modal logic define
  - Necessarily P: ■P
  - Possibly P: ◆P
- Different axioms are true in model structures A with different relations R
- In a modal theory, modalities may be
  - Epistemic / psychological
    - P if P is implied by what is known / believed
    - ◆P if P does not contradict what is known / believed
  - Ontic / physical
    - P if the probability of P = 1
    - ◆P if the probability of P > 0

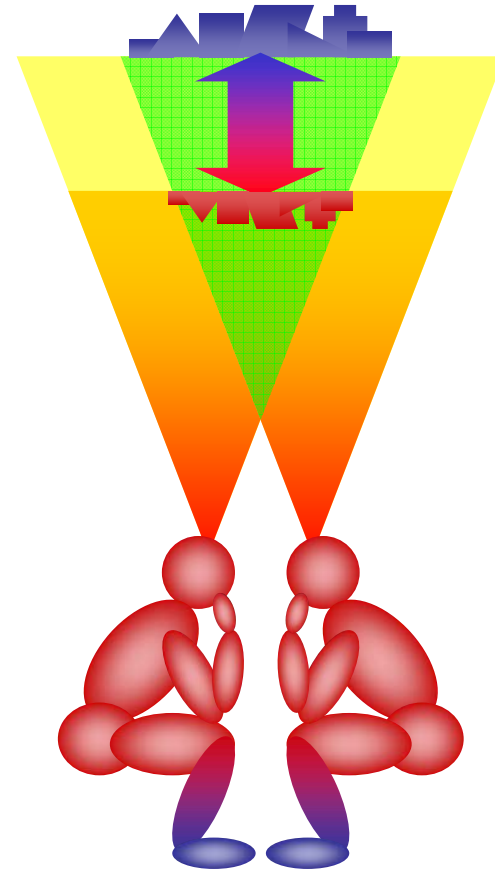
# Probabilities

- Probabilities are numerical weights attached to possible worlds such that
  - The probability of world  $W$ , relative to world  $G$  in a model structure  $A$ , is a real number  $p(W)$  between 0 and 1
  - The combined probability of two or more distinct worlds is the sum of their separate probabilities
  - Each world  $W$  such that  $R(W, G)$  is possible from  $G$ 
    - Each  $p(W) > 0$
  - The worlds  $W$  such that  $R(W, G)$  cover all cases
    - Sum  $\sum p(W) = 1$



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# Quantum theory

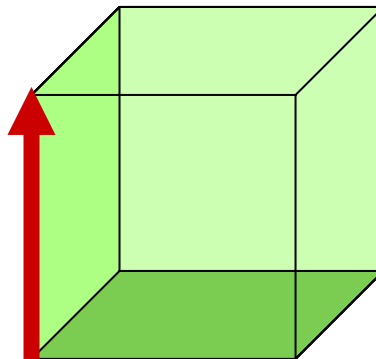
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- In classical physics, the world is eternal
  - Reality evolves rigidly along a fixed timeline
  - Exact laws determine the past and future
  - Statistical approximations generate probabilities
    - ➔ Classical probabilities are **epistemic**
- In quantum physics, the world is changing
  - Reality comes into focus along a growing timeline
  - The past is fixed but the future is fuzzy
  - The probability of possible futures is intrinsic
    - ➔ Quantum probabilities are **ontic**
- We live in a quantum world
  - Classical physics is out of date

# Physical systems

- A world is a state of a physical system
  - An actual world  $G$  is a **real** state of the system
    - The complexity of  $G$  reflects the theory  $T$  defining it
  - A possible world  $W$  is a **virtual** state of the system
    - The complexity of  $W$  is related to that of  $G$
- All the possible states of a physical system coexist in an  $n$ -dimensional space
  - The number of dimensions may be infinite

**State vector**  
specifies the  
real state of  
the system



**State space**  
includes all  
the states of  
the system

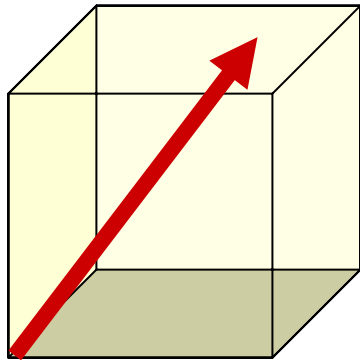
# State space

- Each state of a physical system is a spatiotemporal configuration of **fields**
- In each state, each field appears as a distribution of real and/or virtual **particles**
- In each state, each elementary particle has some momentum and energy
- The fields are **quantized**
  - Quantization generates uncertainty – Heisenberg
  - The **quantum of action**  $h$  (about  $6 \cdot 10^{-34}$  joule-second) is a *tiny* fuzzball of uncertainty in momenergy-spacetime

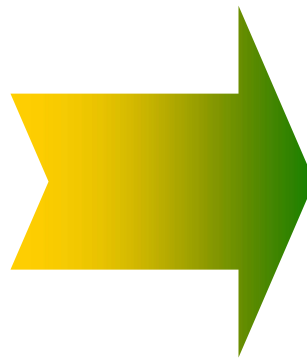
$$\begin{array}{ccc} \Delta p \text{ or } \Delta E & \begin{array}{c} \updownarrow \\ \bullet \\ \updownarrow \end{array} & \Delta p \Delta x \sim h \\ \Delta x \text{ or } \Delta t & \begin{array}{c} \leftarrow \rightleftarrows \rightarrow \\ \leftarrow \rightleftarrows \rightarrow \end{array} & \Delta E \Delta t \sim h \end{array}$$

# Superposed states

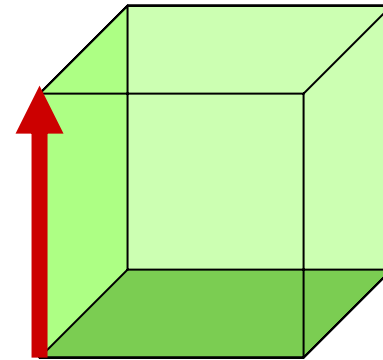
- A system can be in several states at once
  - Generally, the system is in a superposition or **mixed** state of the possible observational values for an observable  $Q$
  - Each dimension of the state space is a **pure** state of  $Q$
- Measurement nudges a mixed state to a pure state



Mixed state in  
n-dimensional  
state space



Measurement  
Interaction  
Decoherence

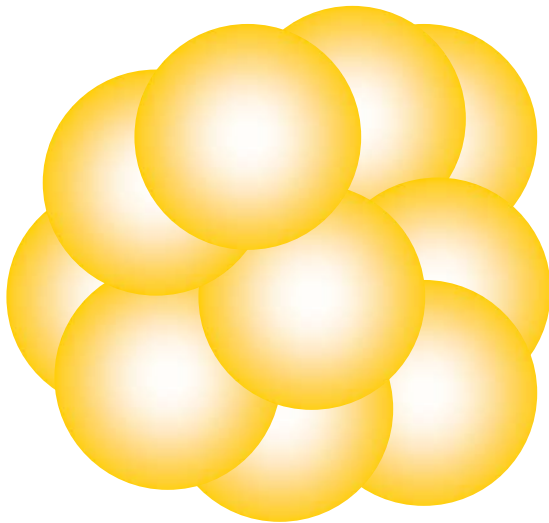


Pure state in  
n-dimensional  
state space

# Quantum worlds

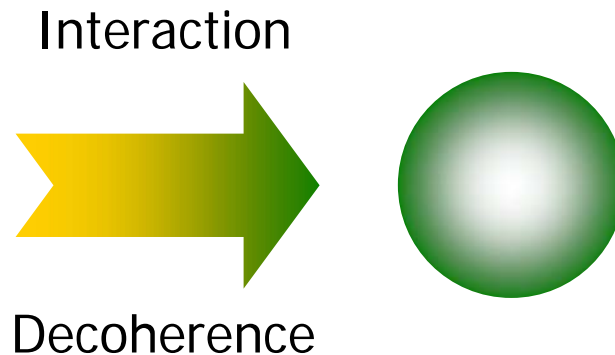
- As time passes, a quantum world focuses stepwise on ever more fully defined states

Old world: time  $t_1$



Superposition of states  
For each state,  
old probability  $< 1$

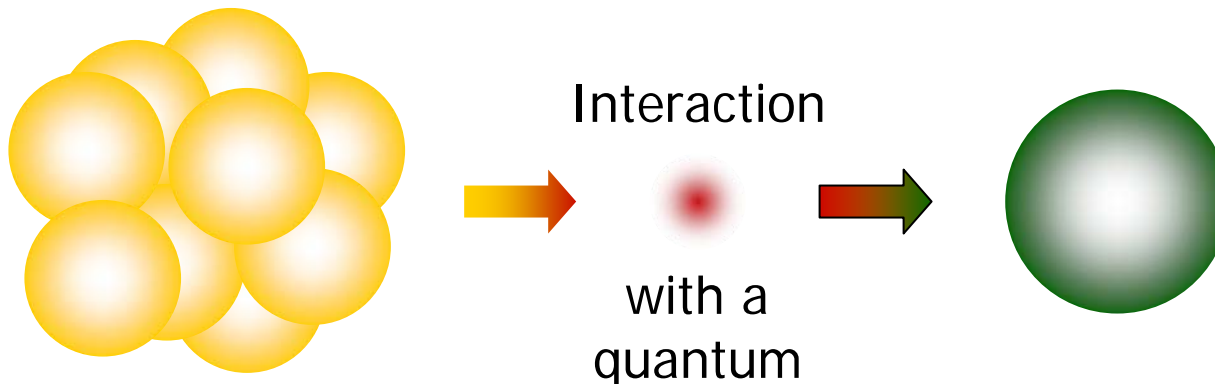
New world:  $t_2 > t_1$



Measured state  
For this state,  
new probability = 1

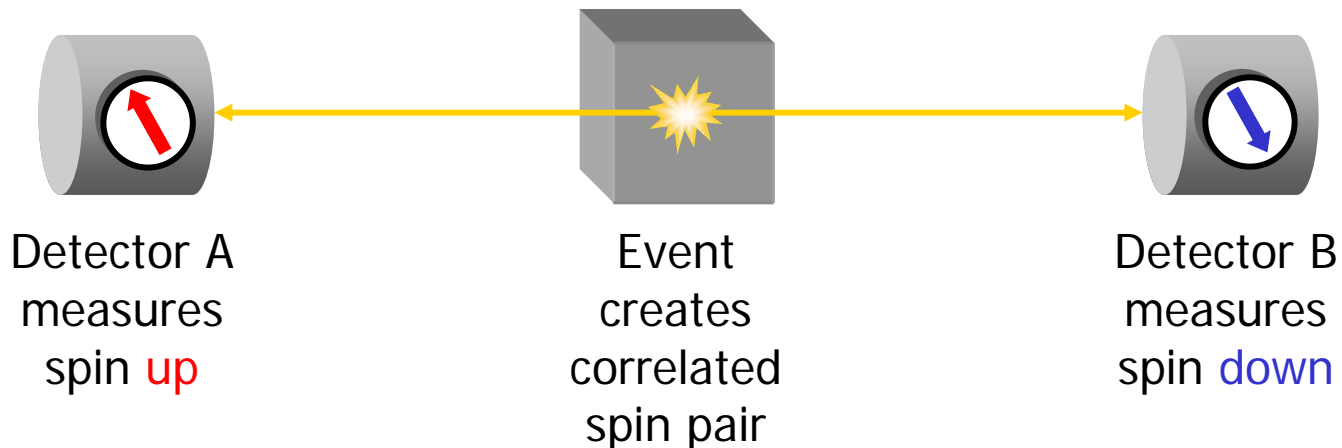
# Decoherence

- When a mixed state evolves to a pure state, a symmetry of possible states is broken
  - Actualization of one state breaks the symmetry
- Systems in mixed states decohere spontaneously during interaction with their environment
  - The interaction couples the system and its environment
- Coherent systems usually decohere *very* quickly
  - A system can decohere by coupling with a single quantum



# Nonlocal correlations

- Multiparticle mixed states can be
  - Spatiotemporally extended
  - Distributed or scattered
- Nonlocal mixed states decohere
  - Simultaneously
  - To correlated pure states
    - ★ Even if detector choices are made **after** creation





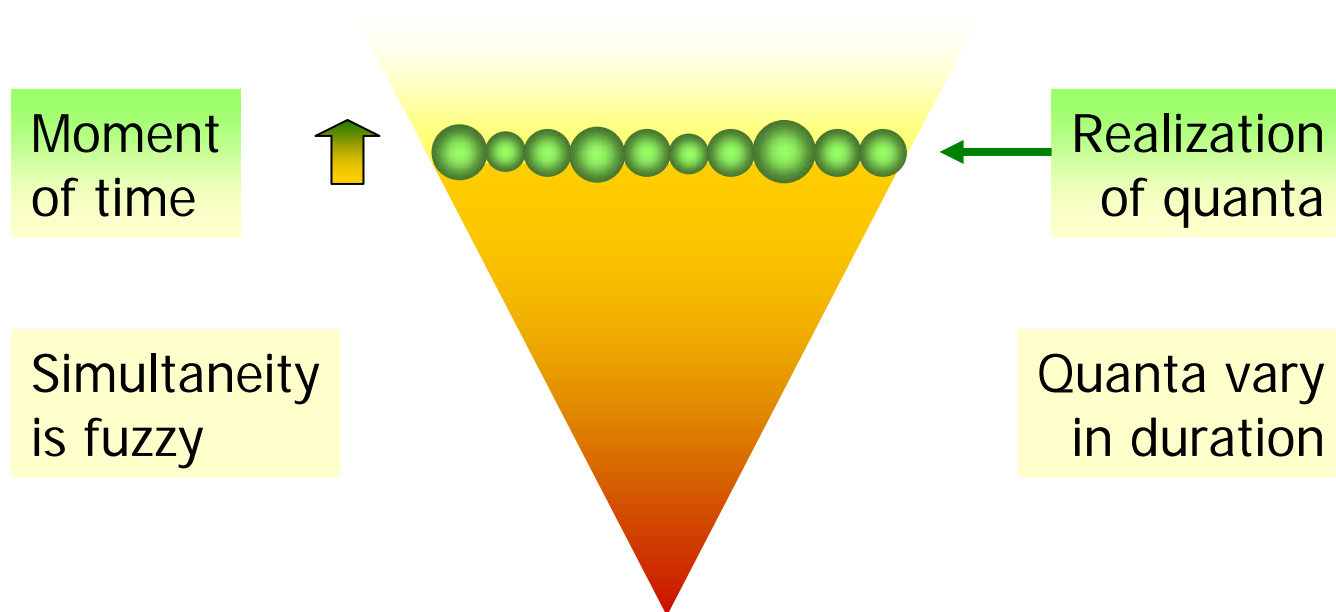
# Quasi-classical worlds

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- In the series of worlds leading up to the actual world, each new world is consistent with its predecessors
- Each new world has a history of symmetry breaking that leads back consistently to the primal moment
  - The consistent history approach based on decoherence is the clearest interpretation to date of quantum theory
  - For objects of mass  $> 1$  fg decoherence times are  $< 1$  as
    - Macroscopic worlds appear overwhelmingly classical
  - Quantum superpositions studied so far are mostly
    - very **small** or
    - very **cold** or
    - very **fragile**

# Time and realization

- Symmetries of a world relative to its superposed states break in **time**
  - Superpositions decohere to pure states in time
  - Moments of time are realized by approximately simultaneous devirtualization of fuzzy quanta

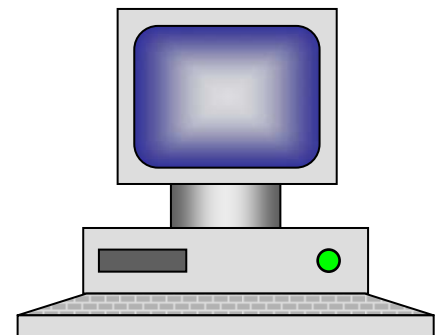




# Physical computation

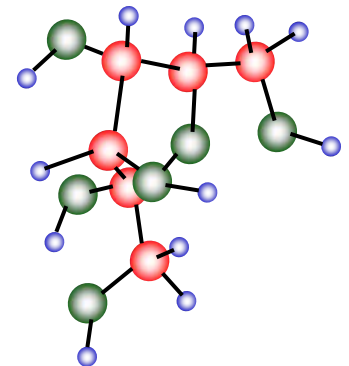
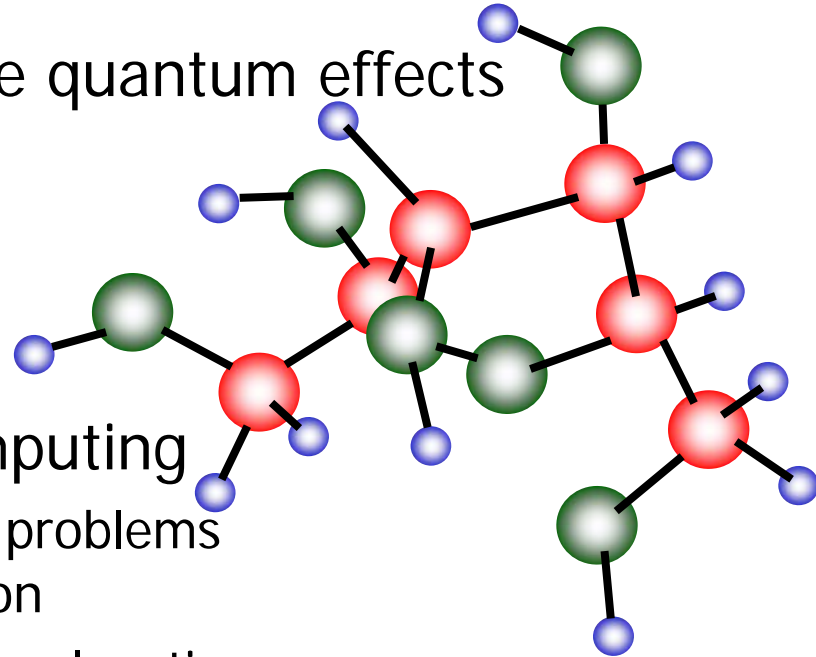
- Computation is a physical process
  - Information processing is **thermodynamic**
    - Information is negentropy
    - Losing information raises entropy
    - Reversible computation conserves entropy
    - Reversible computation conserves superpositions
- Commercial computers are physical machines
  - Their operation is more or less **deterministic**
    - They are made to perform classical computation
    - Only their components use quantum effects
    - Their computations are often irreversible
    - They create entropy like heat engines

– Deutsch



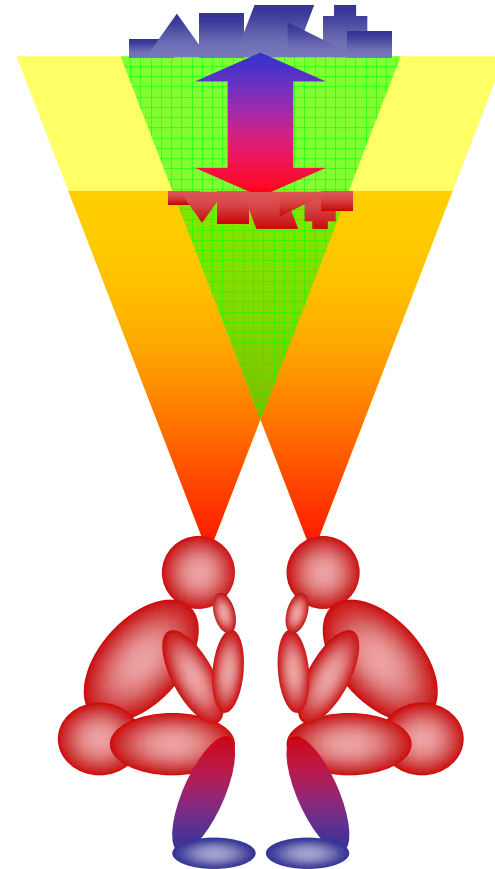
# Biological computation

- Biological processes may use quantum effects
  - Biological processes occur at molecular scales
  - At molecular scales quantum effects can dominate
- Neuronets can do fuzzy computing
  - ANNs can solve combinatorial problems by trial and error approximation
  - ANNs learn by thermodynamic relaxation
  - This is a classical stochastic process
  - In the brain, this is an *extremely* delicate analog process
  - ➔ Thinking may involve quantum effects



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# Worlds of consciousness

## ■ Worlds

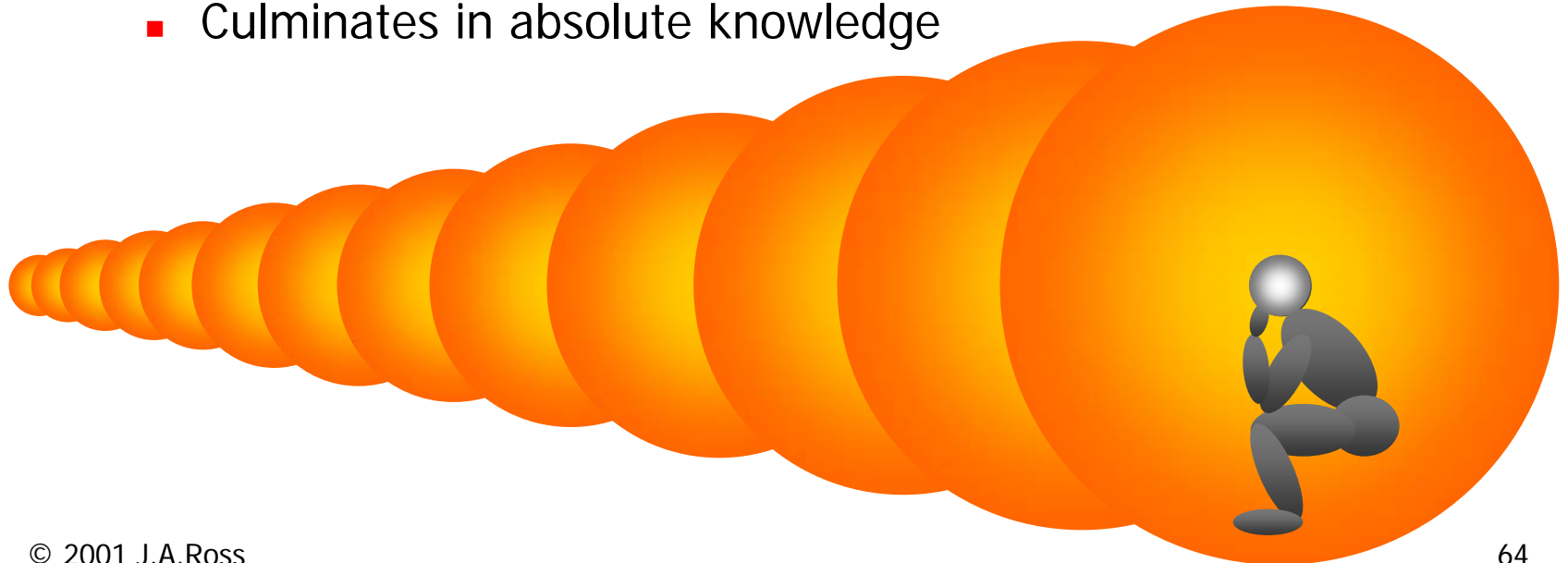
– Kant

- Embody the categorial structure of consciousness
- Reflect the synthetic unity of consciousness

## ■ Consciousness

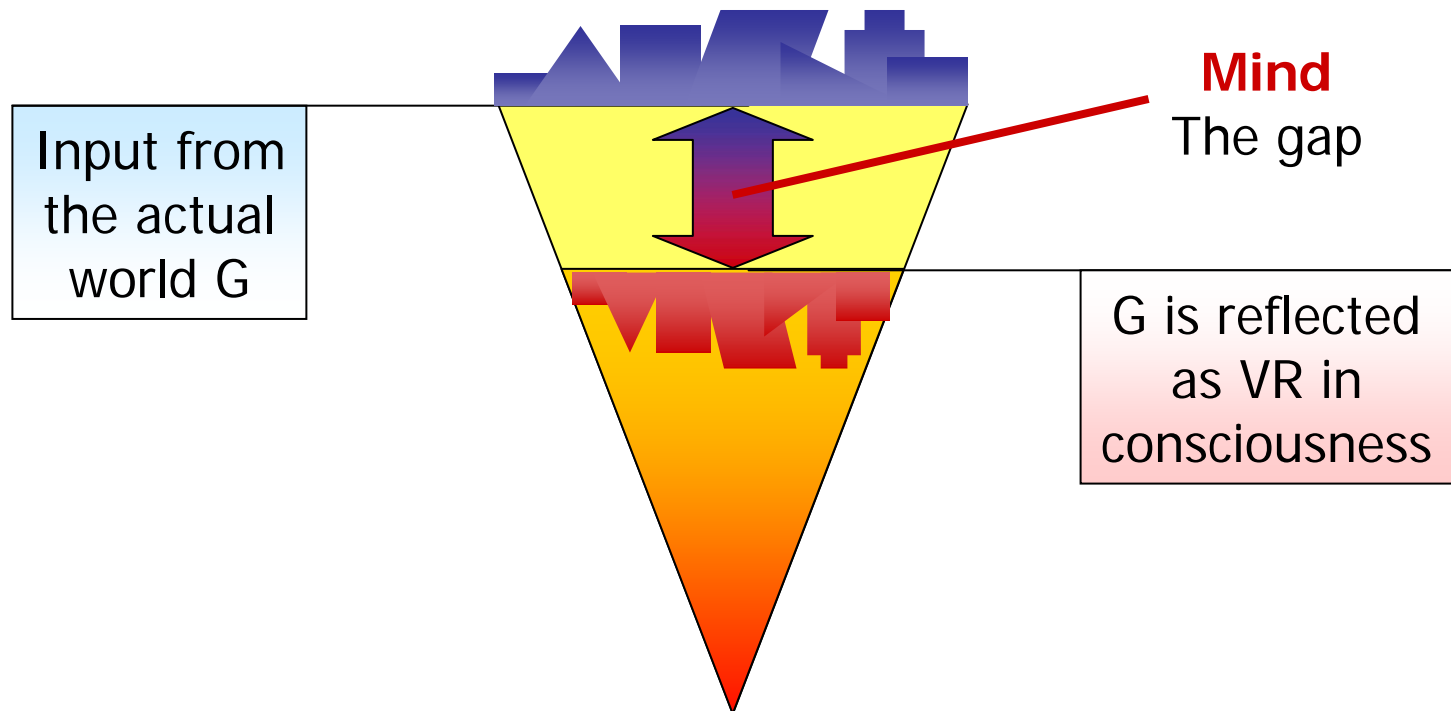
– Hegel

- Begins in sensory immediacy
- Grows in an epistemo-ontic dialectic
- Culminates in absolute knowledge



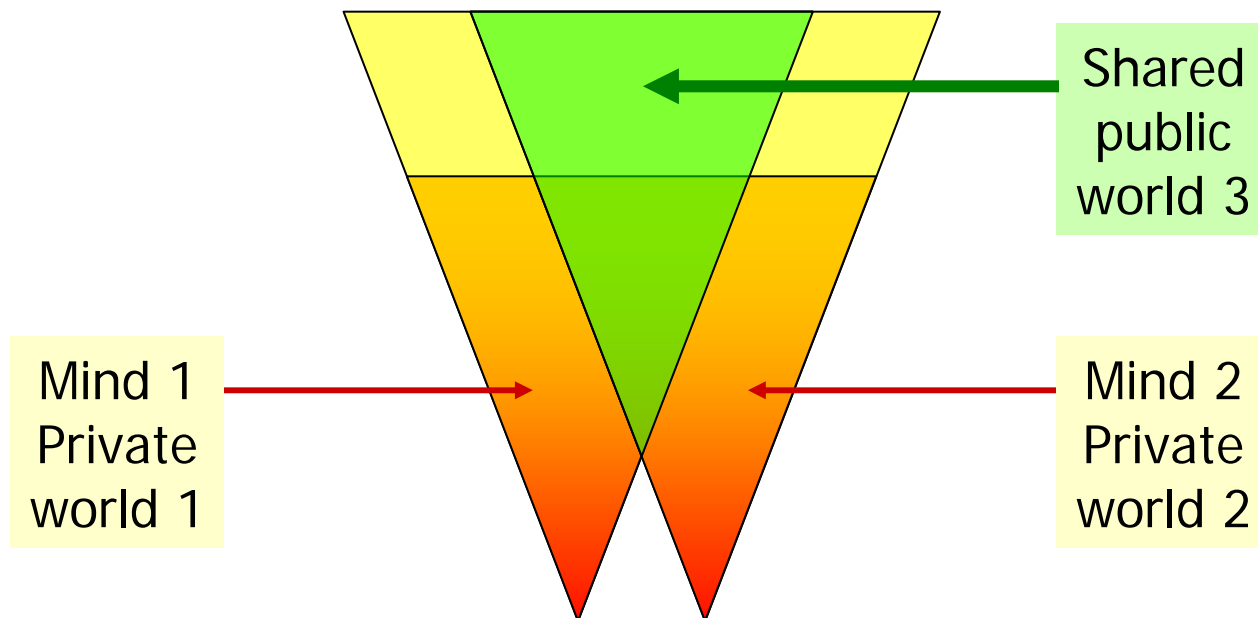
# Consciousness as process

- Human consciousness forms a VR in the brain
- The VR is identified with the actual world
  - The VR is adjusted in an ongoing evolutionary process to optimize its consistency with new sensory input



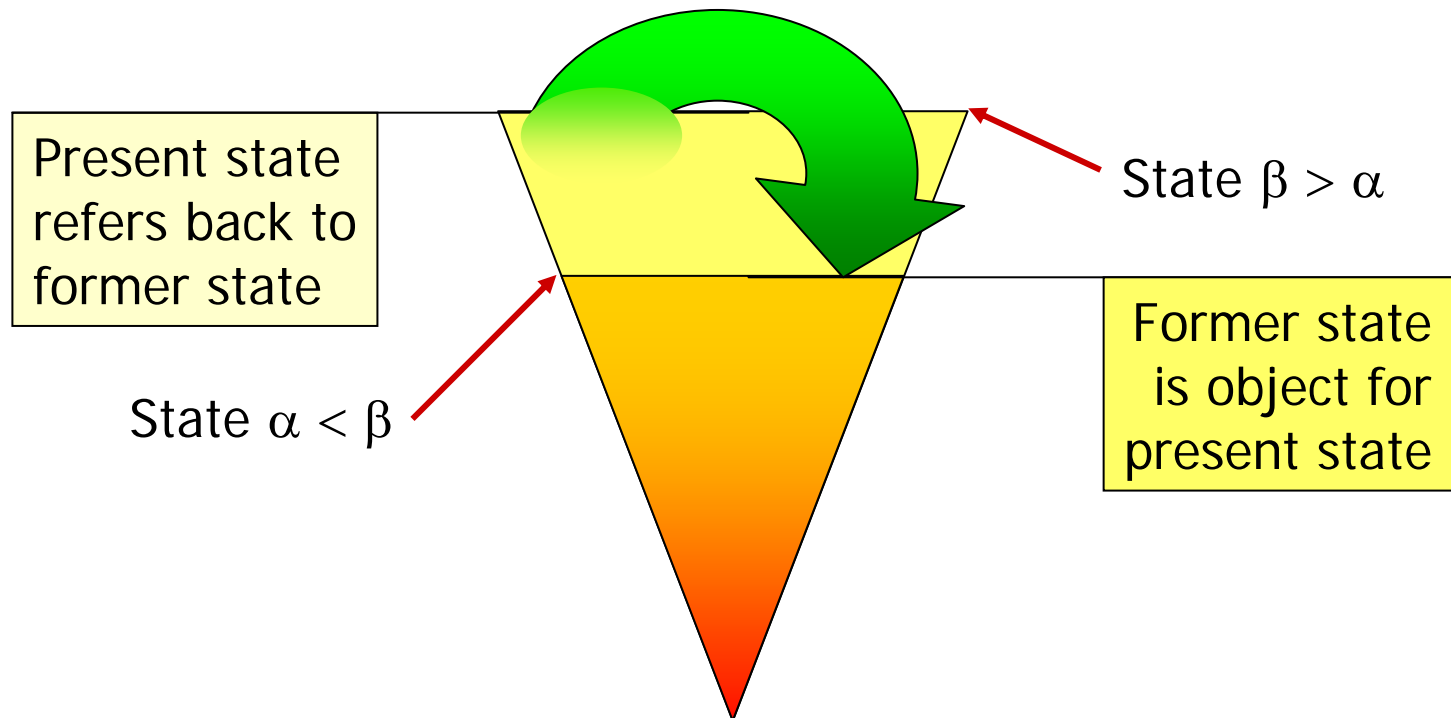
# Other minds

- Each consciousness inhabits a different world
- The private worlds of different minds overlap
- Their intersection forms a shared public world
  - A public world of information can grow independently of the minds that help define it



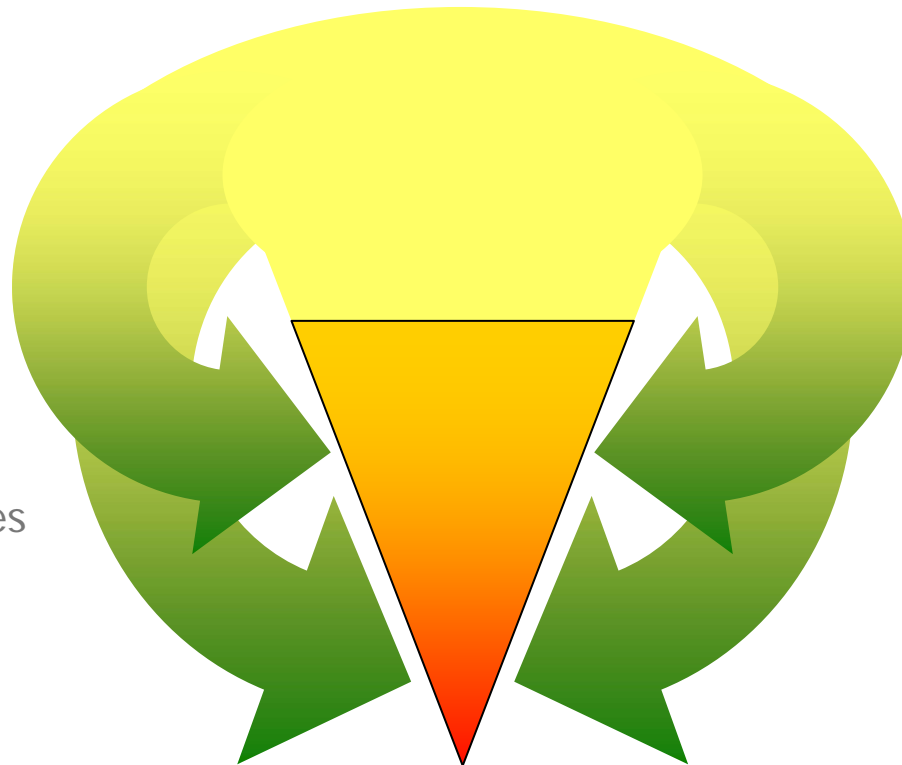
# Self-consciousness

- Self-consciousness is a self-referential loop
- Consciousness forms a VR of its (former) self
  - Like universal sets in set theory, for consistency, the inner self must be a **former** conscious state



# Self-knowledge

- Self-knowledge is a self-referential loop that forms a series of inner models of its former states
  - Knowledge of a series of former states that form a meaningful evolution can be self-corroborating



Aus dem Kelche  
dieses Geisterreiches  
schäumt ihm seine  
Unendlichkeit  
*Schiller*

The chalice of this  
realm of spirits  
foams forth to God,  
His own infinitude  
*Schiller*

# I am conscious

- I create an evolving VR that helps me survive in a natural world  
*Therefore*
- I am conscious

*Cogito*

*Ergo*

*Sum*

Descartes

My  
world

Our  
world

Your  
world

# Me, myself, I

- Consciousness implies an **I**
  - The **I** is the 0 and V of the phenomenal world
- I become an object as me
  - I see **you** as object – You see **me** as object
- I try to see me as myself
  - I see an inner representation as myself
  - I can intend the representation to be perfect
    - But it cannot be perfect

My self  
image is an  
imperfect  
reflection

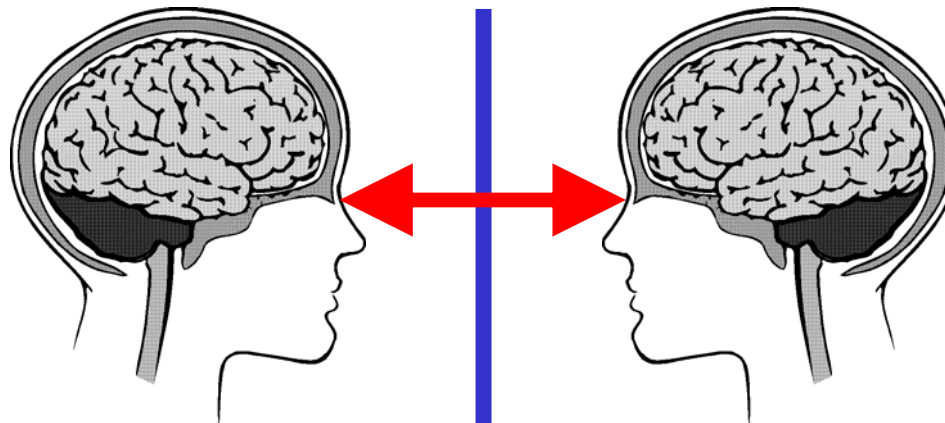
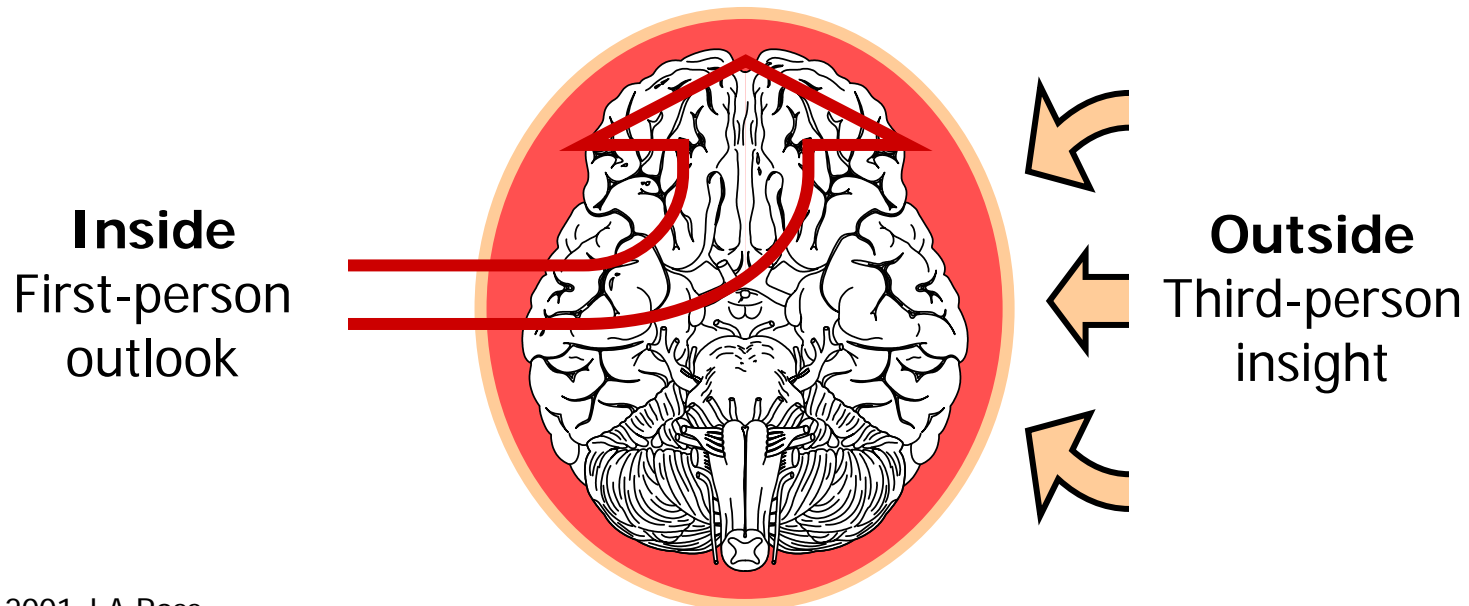


Image  
quality is  
reduced in  
reflection

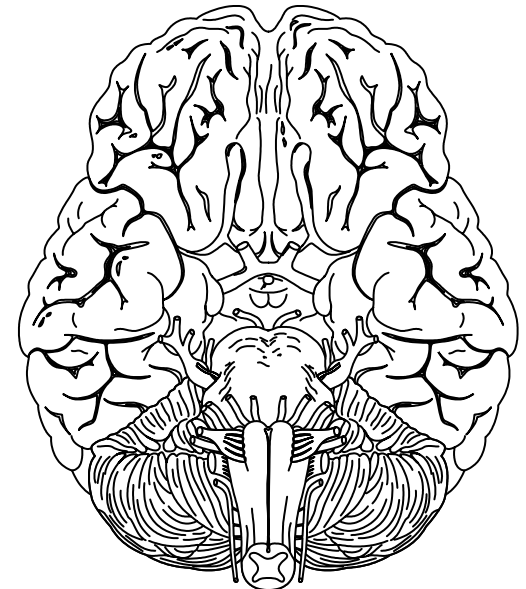
# The conscious brain

- The conscious brain seems radically different from the inside and from the outside
  - From **inside**, it seems like a phenomenal world of qualia
  - From **outside**, it seems like a wet lump of cells sustaining an intricate electrochemical dance with decahertz rhythms
- The complementarity is *amazing* but not *absurd*



# Quantum consciousness

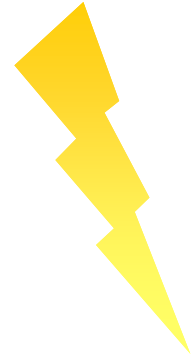
- Conscious states evolve in time like physical states
  - As time passes, superposed possible future states cohere or condense into unique actual present states
  - Possible states remain balanced in symmetry until the environment triggers realization of a unique state
  - States cohere at intrinsically fuzzy moments of time
    - Not **past** (states already fixed)
    - Or **future** (states still only possible)
    - But **now** (in the specious present)
- ➔ Is thinking quantum computation?
- Consciousness is unified
  - Like a Bose–Einstein (BE) condensate
    - Example: photons in a laser beam





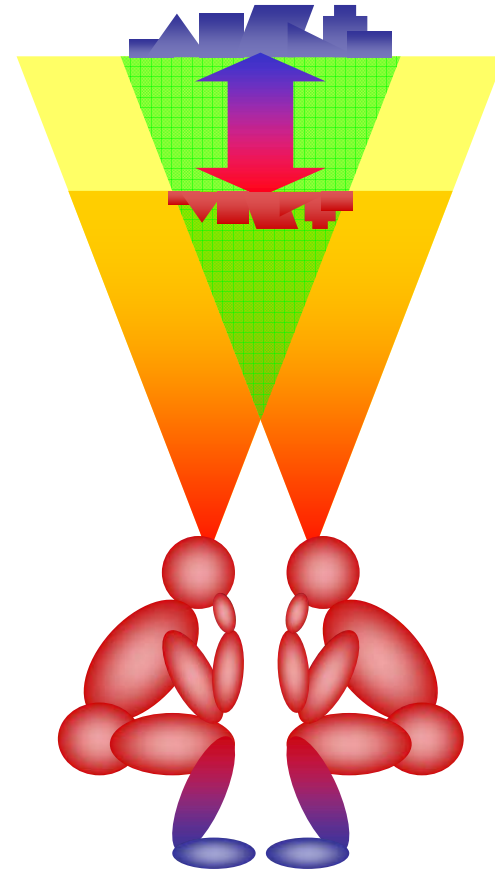
# Is consciousness photonic?

---

- Human consciousness is closely correlated with electrical activity in the brain
    - The cerebral electromagnetic (EM) field generates macroscopic waves over a range of frequencies
    - Synchronized neural firings produce coherent EM fields over regions  $\sim 1$  cm with frequencies  $\sim 40$  Hz
      - **Hypothesis:** these synchronized firings generate neural binding and unified percepts in consciousness – Singer
      - **Hypothesis:** neurons bound in groups support the functional architecture of consciousness – Edelman
      - **Hypothesis:** photons with frequency  $\sim 40$  Hz form BE states that in the environment of the living brain have decoherence times  $\sim 100$  ms (duration of the specious present) and are the **quantum correlates of consciousness** – Ross
- 

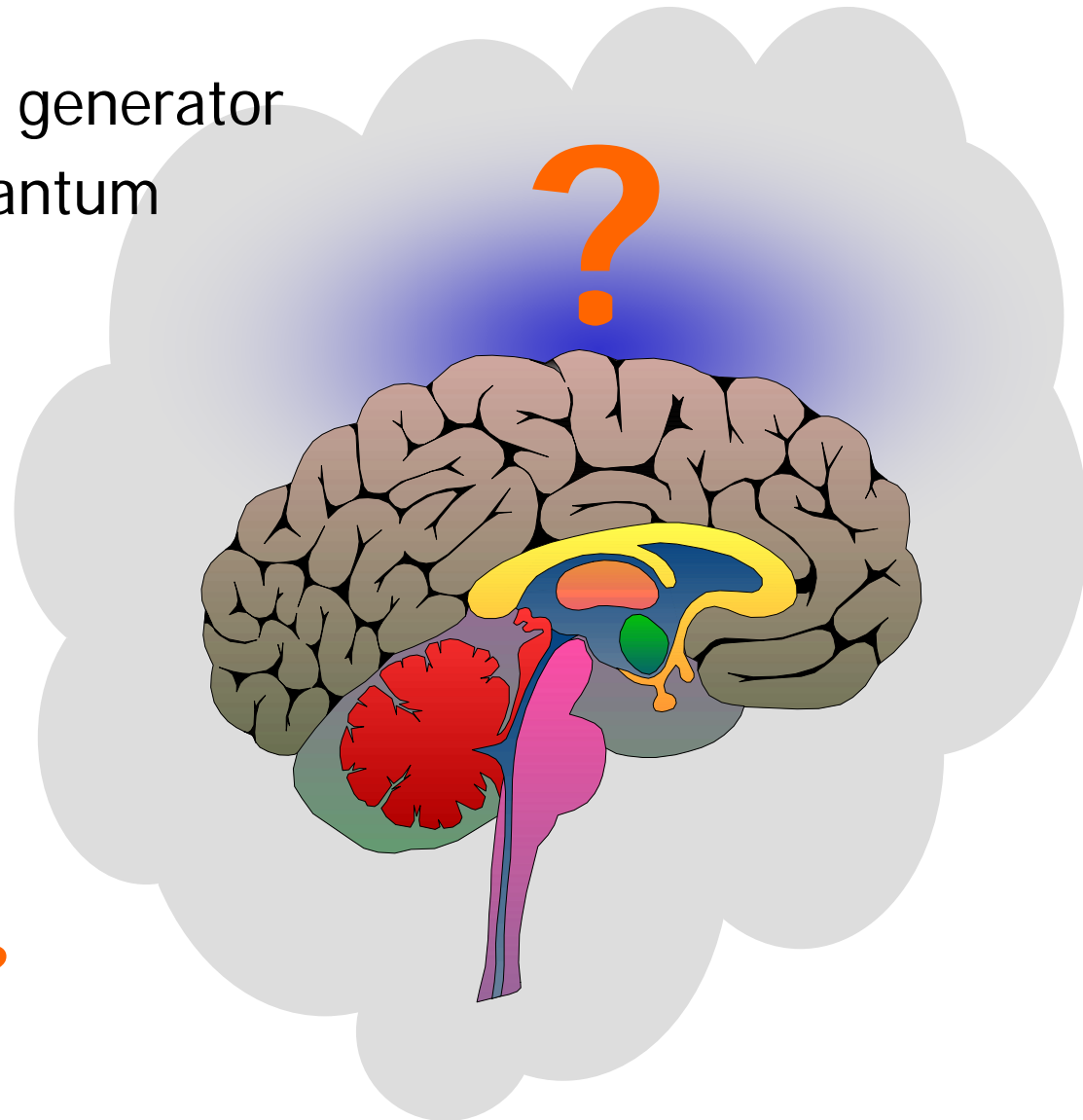
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# Brain states

- The brain is a VR generator
- Is the brain a quantum computer?
- Do its coherent 40 Hz EM fields evolve into superposed BE states?
- Are these the **quantum correlates of consciousness?**



# Consciousness in context

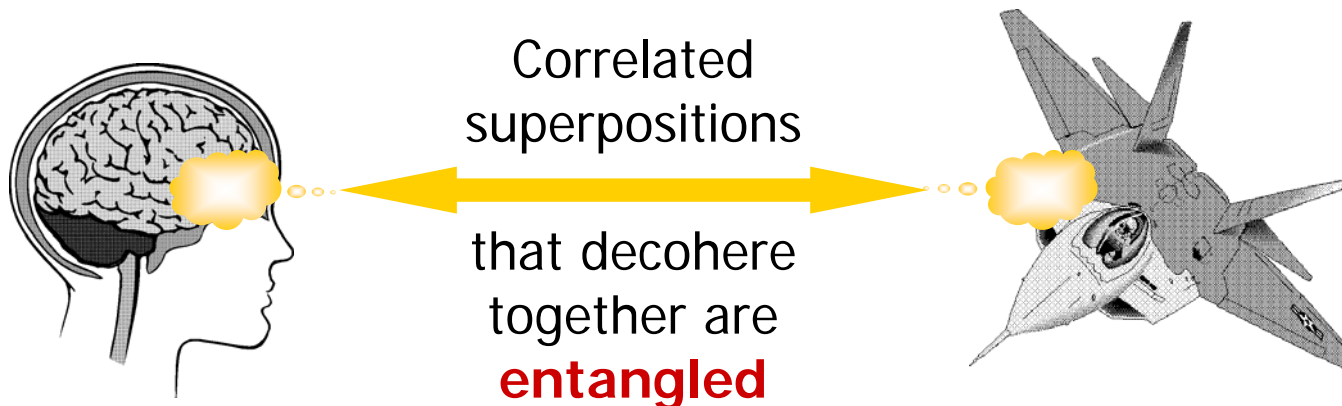
- Our inner representation of the natural world is inseparable from that world itself
- We unite our representations in a shared public world
  - ➔ We must make regular updates of our inner worlds
  - ➔ We must accept public epistemological correction
- Private phenomenology is enslaved to public ontology
  - Biological evolution enslaves our minds to **nature**
  - The evolution of knowledge emerges from biology



The mind  
is a tool  
for survival

# Intentional entanglement

- The identity of inner and outer worlds is **intentional**
  - Intentional identification is unconscious projection
  - The intentional medium is taken as transparent
  - Any structure imposed by the medium is taken as real
- Its quantum correlate may be **entanglement**
  - Inner states may be entangled with the natural world
  - Entangled states involve nonlocal correlations





# Experimental research

---

- A new scientific hypothesis must be **experimentally testable** – Popper
  - It must make definite predictions
  - The predictions must be falsifiable
- A new paradigm must support a **fertile research program** – Kuhn
  - It must support a family of scientific hypotheses
  - It must motivate a program of detailed experiments
  - The experimental results should be interesting and illuminating even if they overthrow the hypotheses
- A quantum theory of consciousness
  - Looks promising



# Experimental suggestions

---

- The miphic view of consciousness suggests that a **quantum** theory may be fruitful
- Experiments needed to test it:
  - Detailed brain-scan studies of phase locking and coherence in cerebral decahertz EM fields
  - Neurophysiological studies of how the cerebral interneural environment can support BE states
  - New techniques for *in vivo* measurement of decoherence times of interneural BE states
  - Statistical studies of correlations of localized BE states with subjective reports of conscious states
  - Measurements of perturbation thresholds for coherent interneural EM fields from extracerebral events



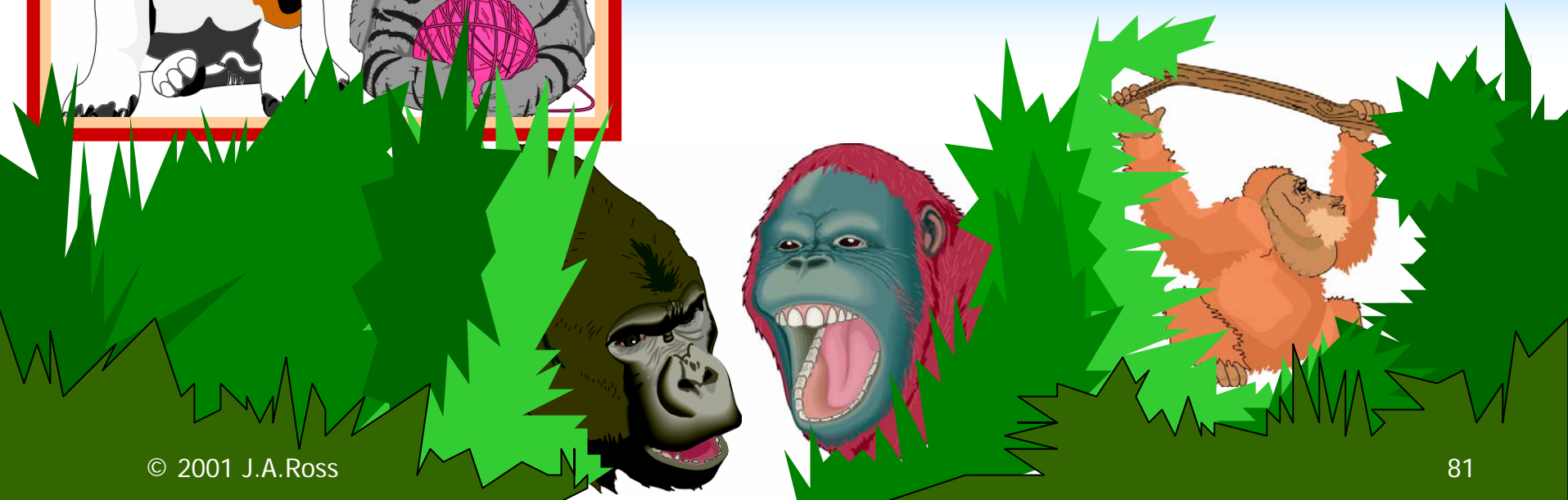
# Can machines be conscious?

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- If consciousness arises in BE states in EM fields,
  - Artificial consciousness (AC) should be possible
    - **Prediction:** AC will appear soon after quantum computation becomes a mature technology
- Present-day computers are classical
  - Their circuitry exploits quantum effects in semiconductors but their logical architecture is classical
    - **Prediction:** AC machines will exploit quantum effects in their logical architecture
- How will we know we have an AC?
  - Maybe a *zombie* can pass the Turing test!
    - **Prediction:** We will never build classical machines with the full range of human abilities

# Consciousness in nature

- Which DNA based organisms enjoy consciousness?



# Consciousness in the universe

- Is Gaia conscious?
- If so, where?
- And how?

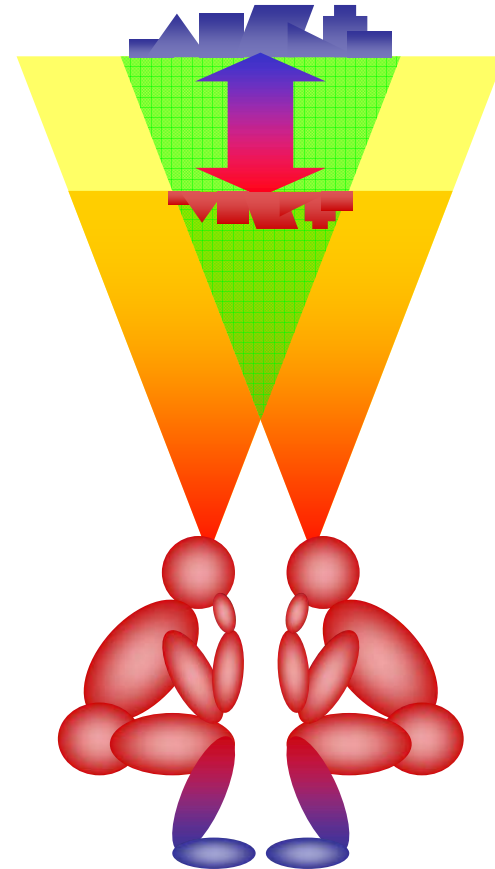


- Are we part of a global self?

Are we  
alone?

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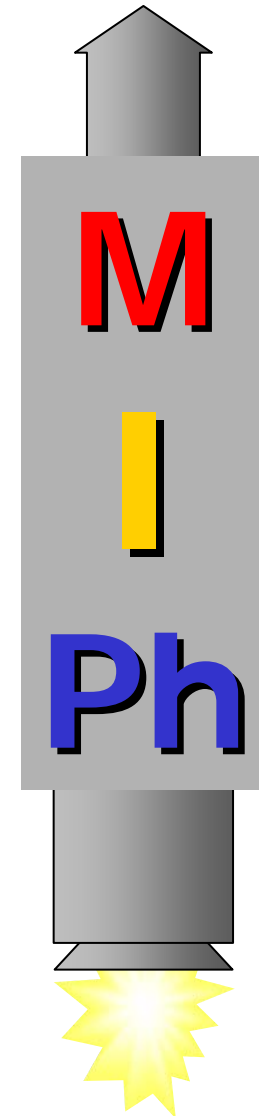
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# Conclusion

To launch a science of consciousness  
we need a 3-stage booster

- **Mathematics** of consciousness  
The universe of sets gives a model
- **Informatics** of consciousness  
Information states evolve over time  
Virtual worlds surround the subject
- **Physics** of consciousness  
Quantum states grow and decohere





# Countdown

---

- ③ The science of consciousness today is like the science of electromagnetism at the time of Faraday  
– Vilayanur Ramachandran
- ② It's possible that in the next hundred years something really surprising will happen that will make us look at the whole mind-brain problem in a new way. More likely, we'll have a bunch of theories but still no consensus  
– David Chalmers
- ① In a hundred years, we'll know the causal mechanisms that produce consciousness  
– John Searle

