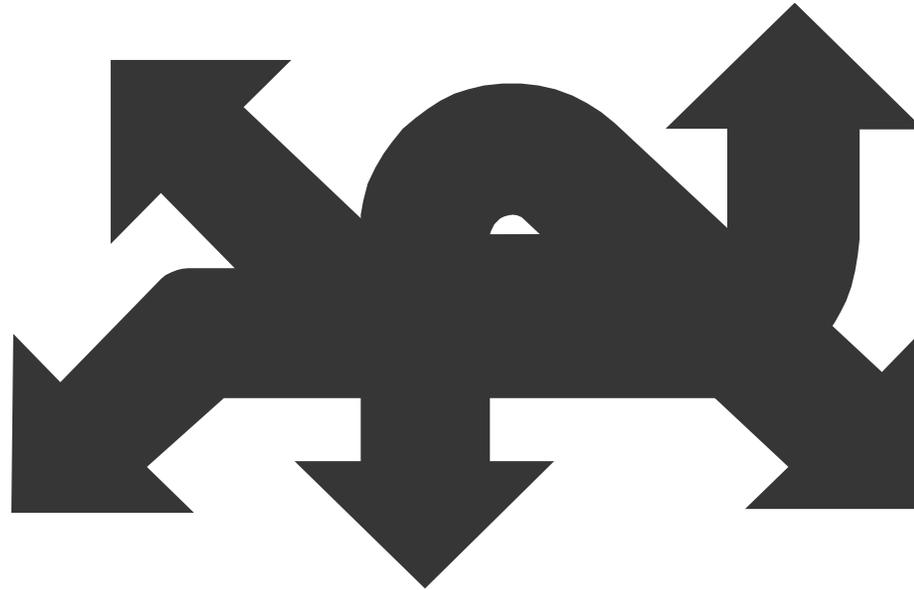


# **Entangled Behavior and Bizarre Systems**

(Ideas Stolen Fair and Square from Authors in Bizarre Systems Track)



**ANNIE '99 Plenary Presentation**

**Stephen W. Kercel**

**Oak Ridge National Laboratory**

**November 9, 1999**

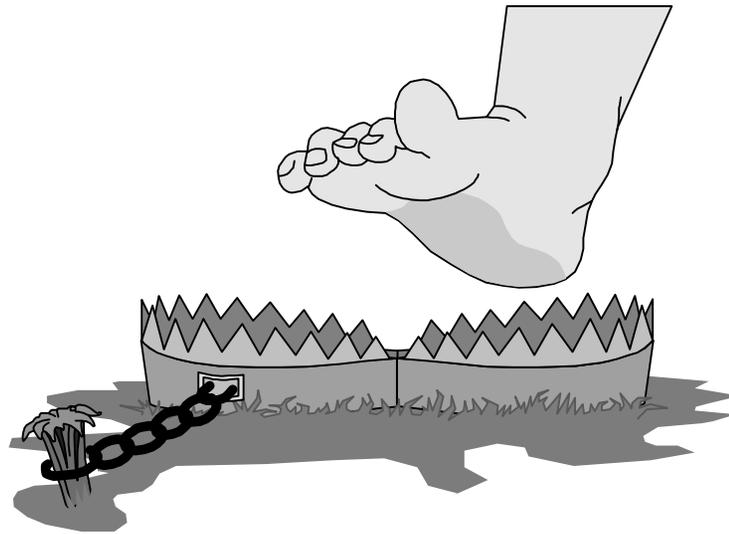
# **Embedded Intelligence: Bizarre Systems for the Steel Industry**



**Prepared for  
AISE - Sensors Meeting  
Dr. Stephen W. Kerchel  
ORNL - Instrumentation and Controls Division  
November 16, 1999**

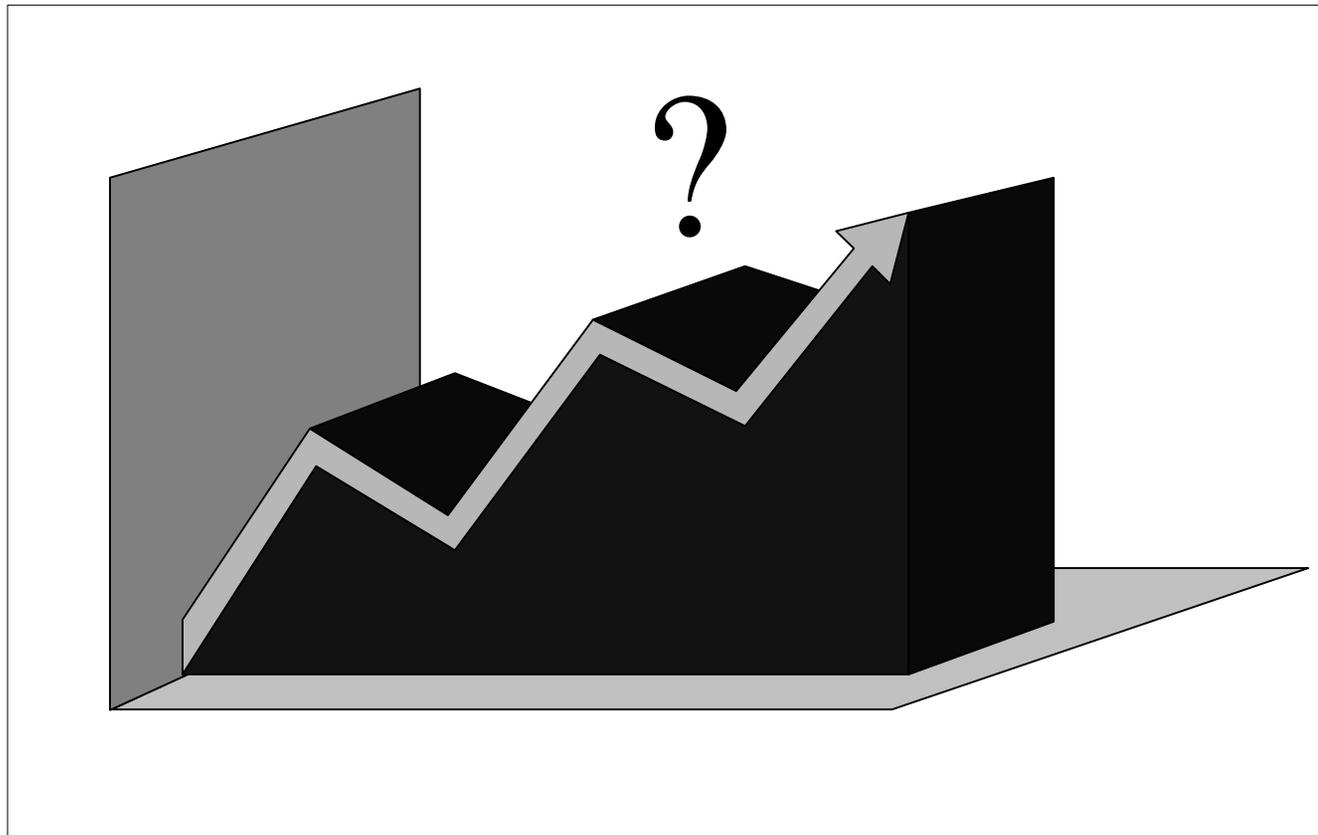
***Why* should engineers be concerned  
with bizarre systems?**

**Given:  
bad outcomes for bad *guessing* ...**



**how do I make a good decision?**

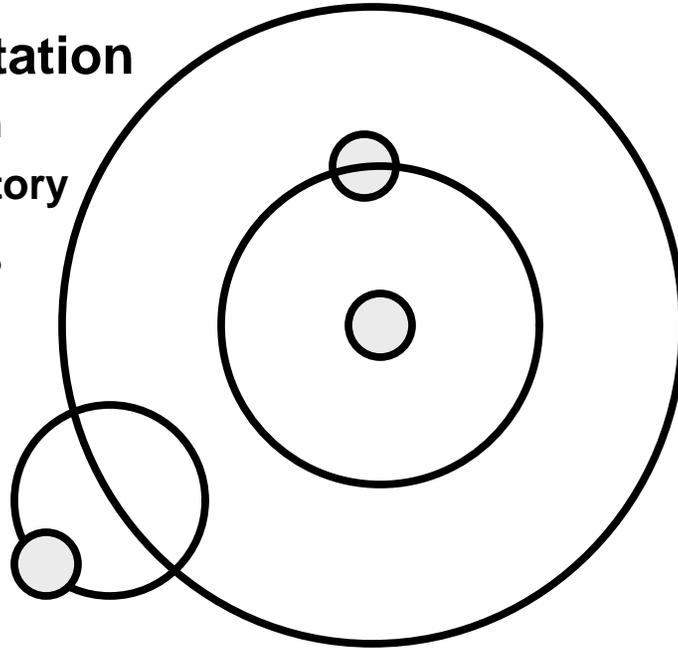
**We make a prediction about the future  
based on some kind of expectation**



**Unfamiliar situation    =>     
bizarre (counterintuitive) behavior / prediction**

# Epicycle simulations provided the basis for decision making that endured for centuries

- Input for casting horoscopes
- More “scientific” than computation
  - Computation led to contradiction
  - Underlying reality non-contradictory
- *Reduces everything to circles*
- Self-correcting
- It works
- “Better” than Kepler’s laws
- Gives right answer
  - If you ask right question

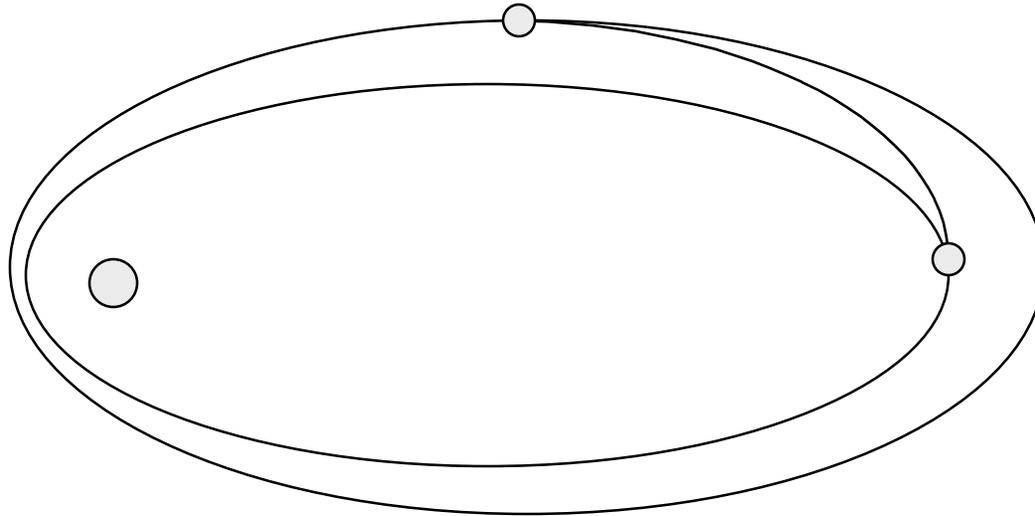


# What about questions that epicycles could not answer?



- **Bizarre questions led to bizarre answers**
- **Simple solution: kill people who ask them**
- **Such questions threatened funding**

# Finally, somebody asked a bizarre question, found a bizarre answer, and survived



- **Kepler: Must we *reduce* data to circles?**
  - Ellipses are bizarre; fit better than circles
- **Newton: “Why ellipses?”**
- **Got much more ... Modern science/technology**
- **Is there a question Newton can't answer?**

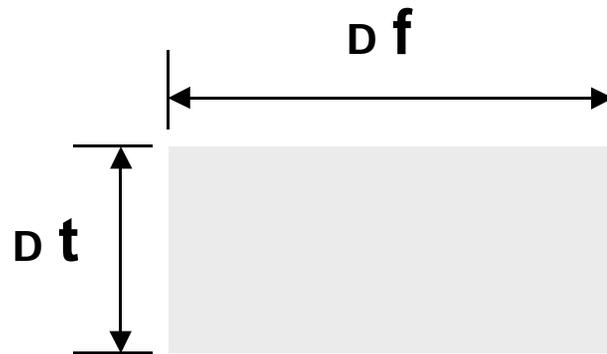
# Is the behavior of any system *bizarre*, if it ...



- is consistent with classical physics?
- is routinely observable in the *macro* world?
- is routinely used for engineering decisions?

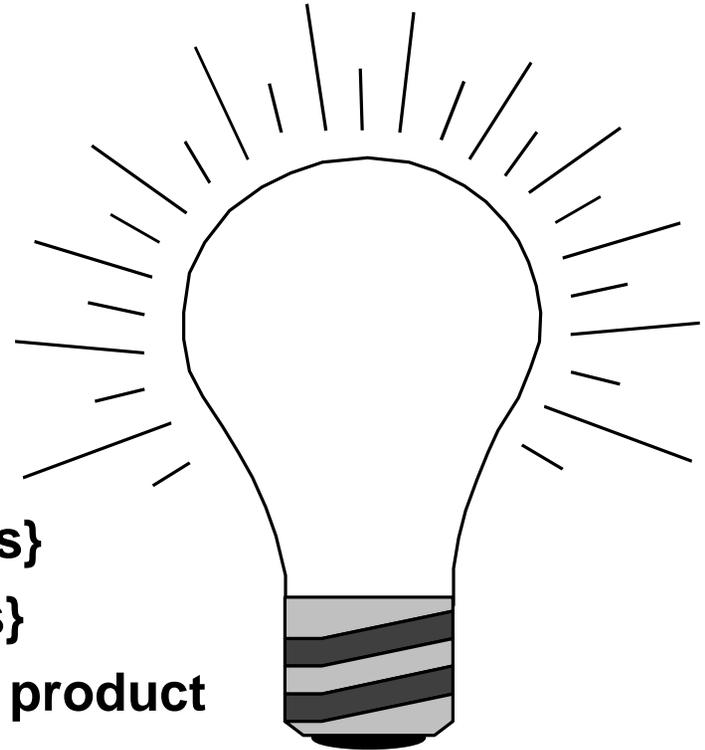
**... then, even some of the most notorious behaviors widely attributed to quantum mechanics are *not bizarre***

- **Direct consequences of Maxwell's Equations:**
  - Confinement of states to discrete modes (quantization)
  - Evanescence (tunneling)
- **Direct consequence of classical concept of energy**
  - The Heisenberg tradeoff
  - Routinely occurs in signal processing



**The common idea:  
descriptions of non-bizarre behaviors  
are *reducible*  
to lists of real numbers**

- $f: P \rightarrow R^n$
- $P = \{\text{process states}\}$
- $R = \{\text{Real numbers}\}$
- $R^n = \text{nth Cartesian product}$



**Given that bizarre *does not* mean absurd, what logical conclusion can we draw about bizarre systems?**

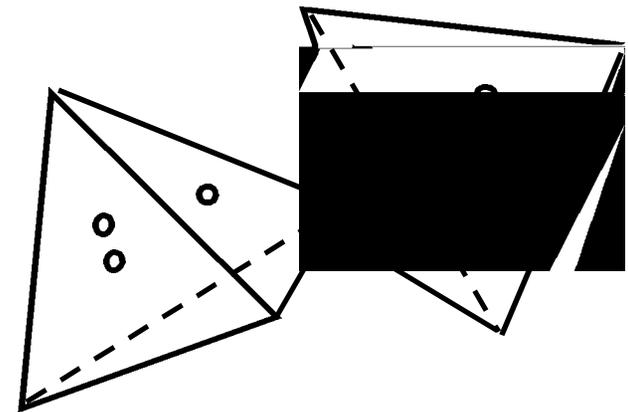
**((not bizarre) => reducible)**

**<=>**

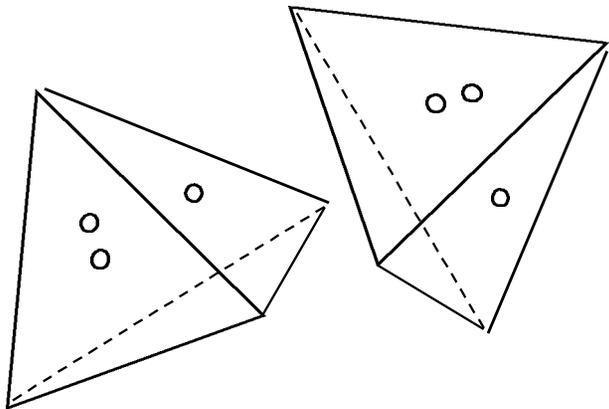
**((not reducible) => bizarre)**

# To appreciate what a truly bizarre behavior might look like in the macro world, imagine a pair of “magic dice”

- Each die is fair
  - Four outcomes per die
  - $p = 0.25$
  - for any toss of either die
- The pair is rigged
  - Toss both at once
  - $a = 1 \text{ or } 4 \iff b = 2 \text{ or } 3$
- If I know “a,” I can tell “b”
- Behavior is *entangled*



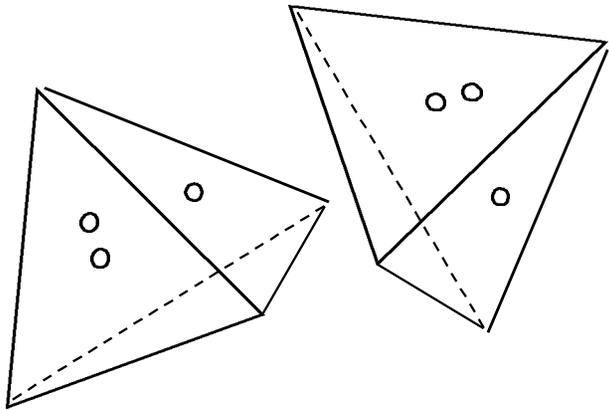
# To keep the math simple, we consider 4-sided dice



		DIE 2				
		1	2	3	4	S
DIE 1	1	1/16	1/16	1/16	1/16	1/4
	2	1/16	1/16	1/16	1/16	1/4
	3	1/16	1/16	1/16	1/16	1/4
	4	1/16	1/16	1/16	1/16	1/4
	S	1/4	1/4	1/4	1/4	

- “Fair” behavior is unentangled
- All rows or all columns proportional  $\Leftrightarrow$  unentangled
- Fair  $\Rightarrow$  Reducible (examine each die individually)

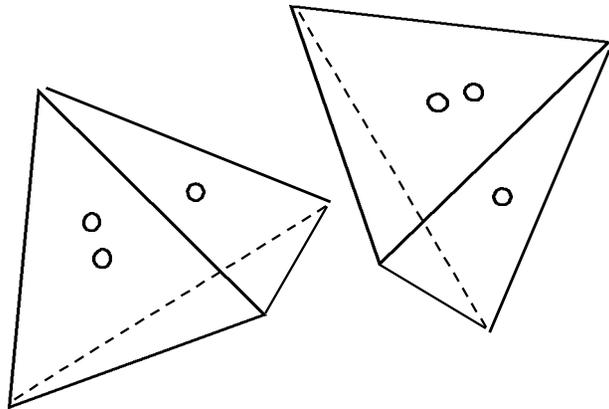
**$A^2+B^2=1 \Rightarrow$  superficially fair:  
 $p(\text{any face of either die}) = 1/4$**



		DIE 2				
		1	2	3	4	S
DIE 1	1	$A^2/4$	0	0	$B^2/4$	$1/4$
	2	0	$A^2/4$	$B^2/4$	0	$1/4$
	3	0	$B^2/4$	$A^2/4$	0	$1/4$
	4	$B^2/4$	0	0	$A^2/4$	$1/4$
	S	$1/4$	$1/4$	$1/4$	$1/4$	

- “Magic” is in the entanglement
- No rows or columns proportional  $\Leftrightarrow$  completely entangled
- Reduction (Examine each die)  $\Rightarrow$  entanglement not revealed
- “Something is not right!”

# Partially entangled behavior $\Leftrightarrow$ some rows or columns proportional



		DIE 2				
		1	2	3	4	S
DIE 1	1	1/16	1/16	1/16	1/16	1/4
	2	1/16	0	1/8	1/16	1/4
	3	1/16	1/8	0	1/16	1/4
	4	1/16	1/16	1/16	1/16	1/4
	S	1/4	1/4	1/4	1/4	

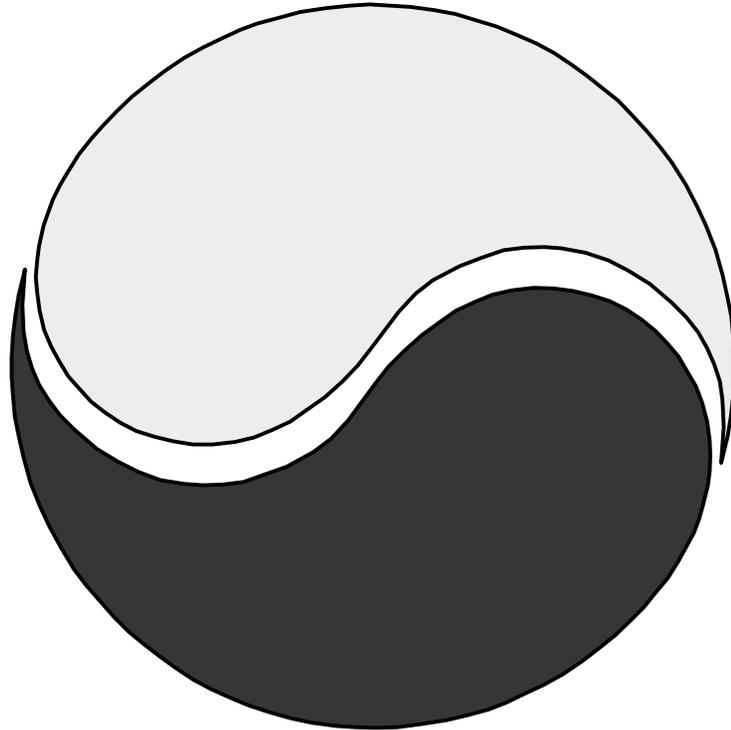
- “Something’s still not right”
- Much harder to detect
- Still irreducible

# The “magic” is inherent in the relationship between the parts



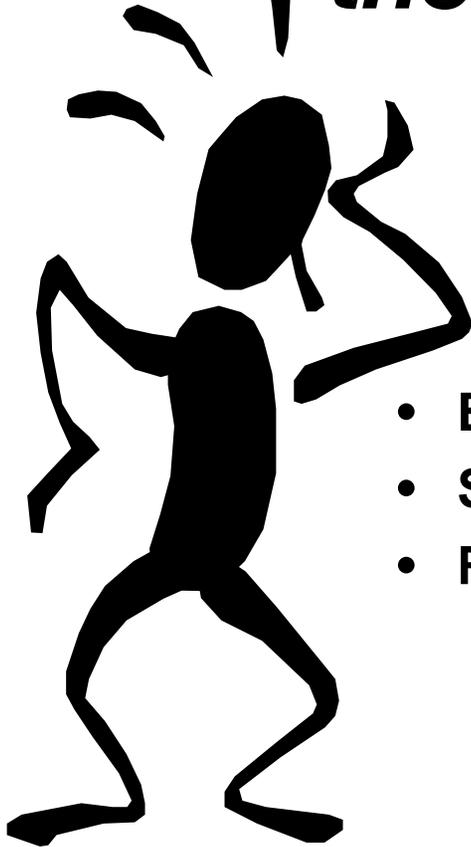
- If I know “a,”
- I can tell “b”
- Must observe pair (no entangling part)
- *Reduction* to individual dice ignores entanglement
- Ignoring it won’t make it vanish
  - it is no less real
  - because it is irreducible

# Entanglement is bizarre behavior



- **Predicted by quantum mechanics**
- **No classical analog**
- **Not intuitively expected**
- ***Is observed in reality***

**We can infer properties for one element  
by observing another remotely, and  
*there is no connecting part!***



- Each part behaves as intuitively expected
- System behaves counterintuitively
- Reduction ignores something crucial in reality

**Now, that's bizarre!**

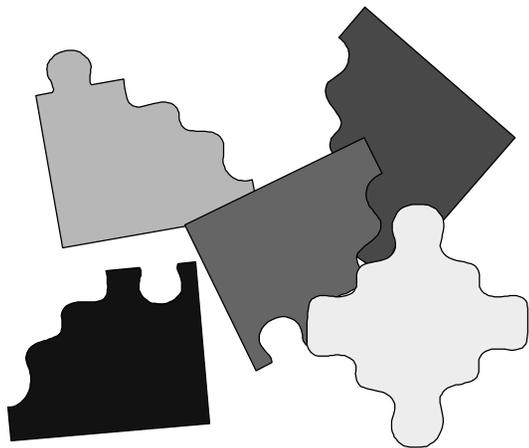
# Is this a misguided appeal to quantum mechanics? No!



- **Entangled behavior is bizarre but causal**
  - Not revealed by conventional thinking
  - Predicted by quantum mechanics
  - Observed (in some contexts) where predicted
- **Quantum mechanics is *misused* when**
  - Attempting to deny causality
  - Describing the absurd, not the bizarre

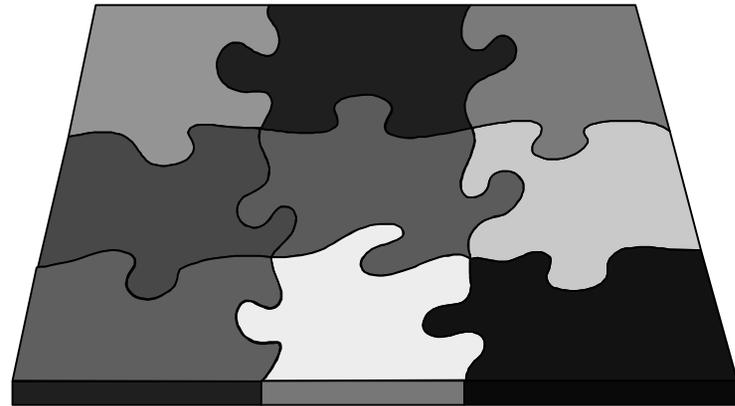
# Entanglement is bizarre, not because it contradicts reality, but because it violates intuition

We see this...



**Our model of reality**

... instead of this



**Underlying reality**

- Our inability to perceive directly or intuitively
- Does not eliminate a causal connection

# **Causality is the proposition that effects or events in reality have causes**



## **Why this effect?**

- **Material cause (input)**
- **Efficient cause (transforming relationship / transfer function)**
- **Formal cause (algorithm)**
- **Final cause (purpose)**

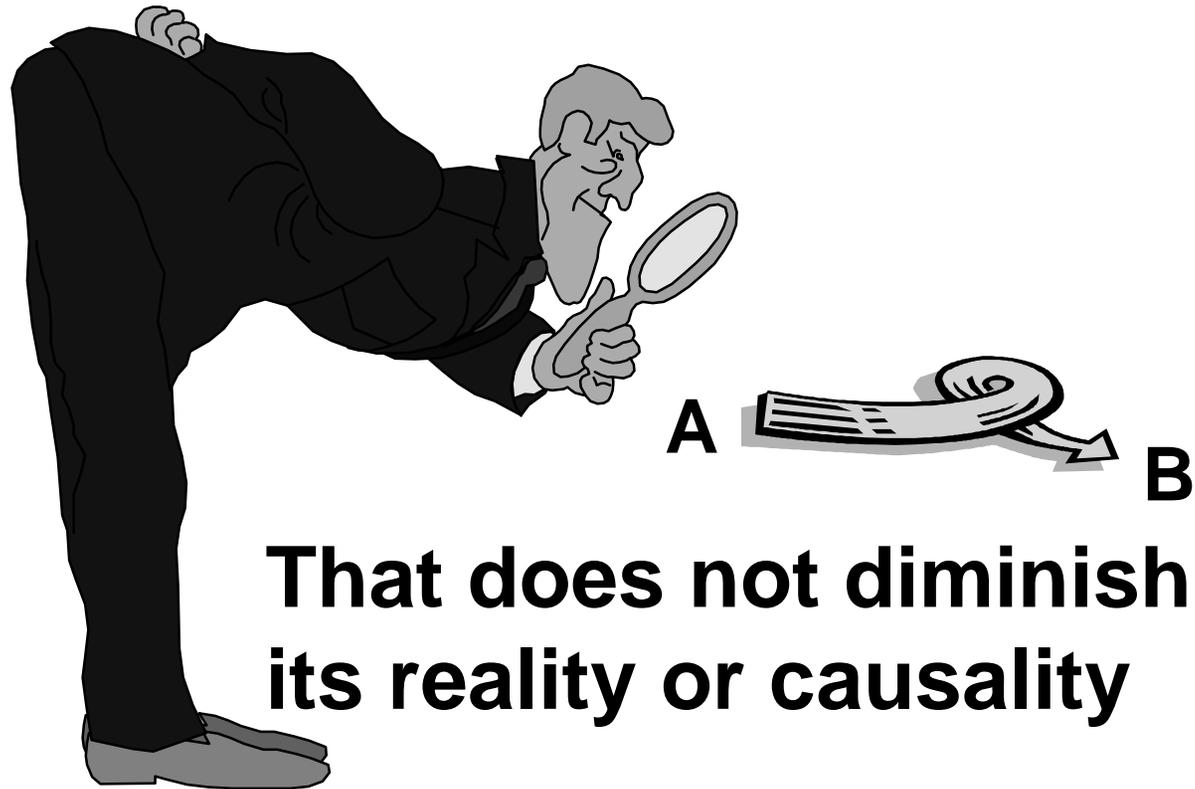
# **In a simple (reducible or mechanistic) system ( $P \rightarrow R^n$ ) causes are distinct and unentangled**



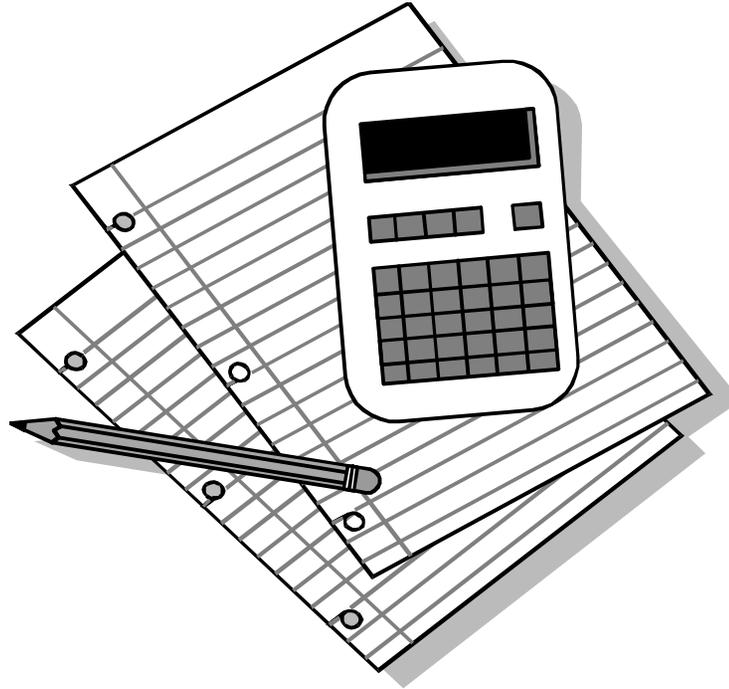
## **Why this effect?**

- **Material cause (initial conditions)**
- **Efficient cause (constraining dynamical law)**
- **Formal cause (operation of system under law)**
- **Final cause (there isn't any)**

**Can the behavior of a pair of magic dice  
be enumerated (reduced to  $P \rightarrow R^n$ )  
No!**



# Reduction of processes to lists of real numbers: an arbitrary choice



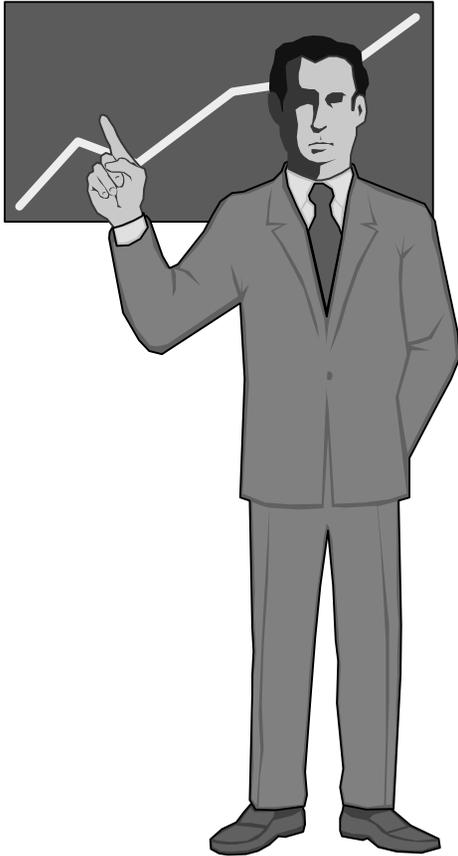
- **Reduction has delivered when it counted**
  - Vectors of real numbers -> Modern technology
  - Epicycles -> Horoscopes
- **Fundamental element: a pure abstraction**
  - Cartesian reduction: irrational number
  - Epicycles: perfect circle

# **“Real” numbers are actually a figment of human imagination**



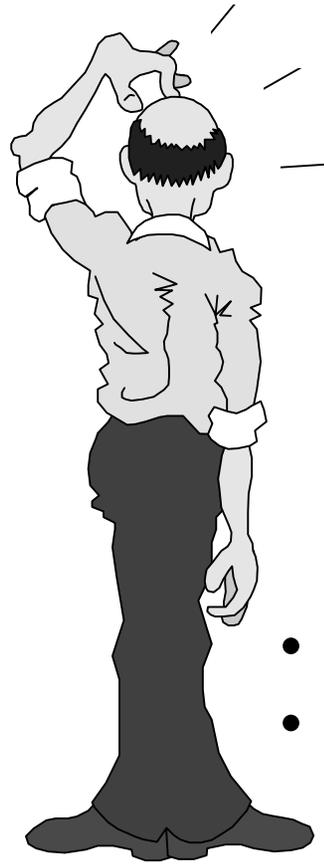
- **“Real” numbers:**
  - abstract construct
  - resolve paradoxes in geometry
- **For comparing counts of objects in reality**
  - Ratios of integers probably suffice

# Quantification is insufficient; it allows only a restricted range of correct inferences



- $f: (\text{process state}) \rightarrow \mathbb{R}^n$
- Ignores unquantifiable relationships
- Can lead to disappointing or deceptive results
  - Scientific management: The Edsel
  - College grading
  - Bowl Championship Series
- Never predicted anything important in biology

# Ignoring an aspect of reality does not make it vanish



- **Epicycles ignored force/energy**
- **Cartesian reduction ignores relationships**

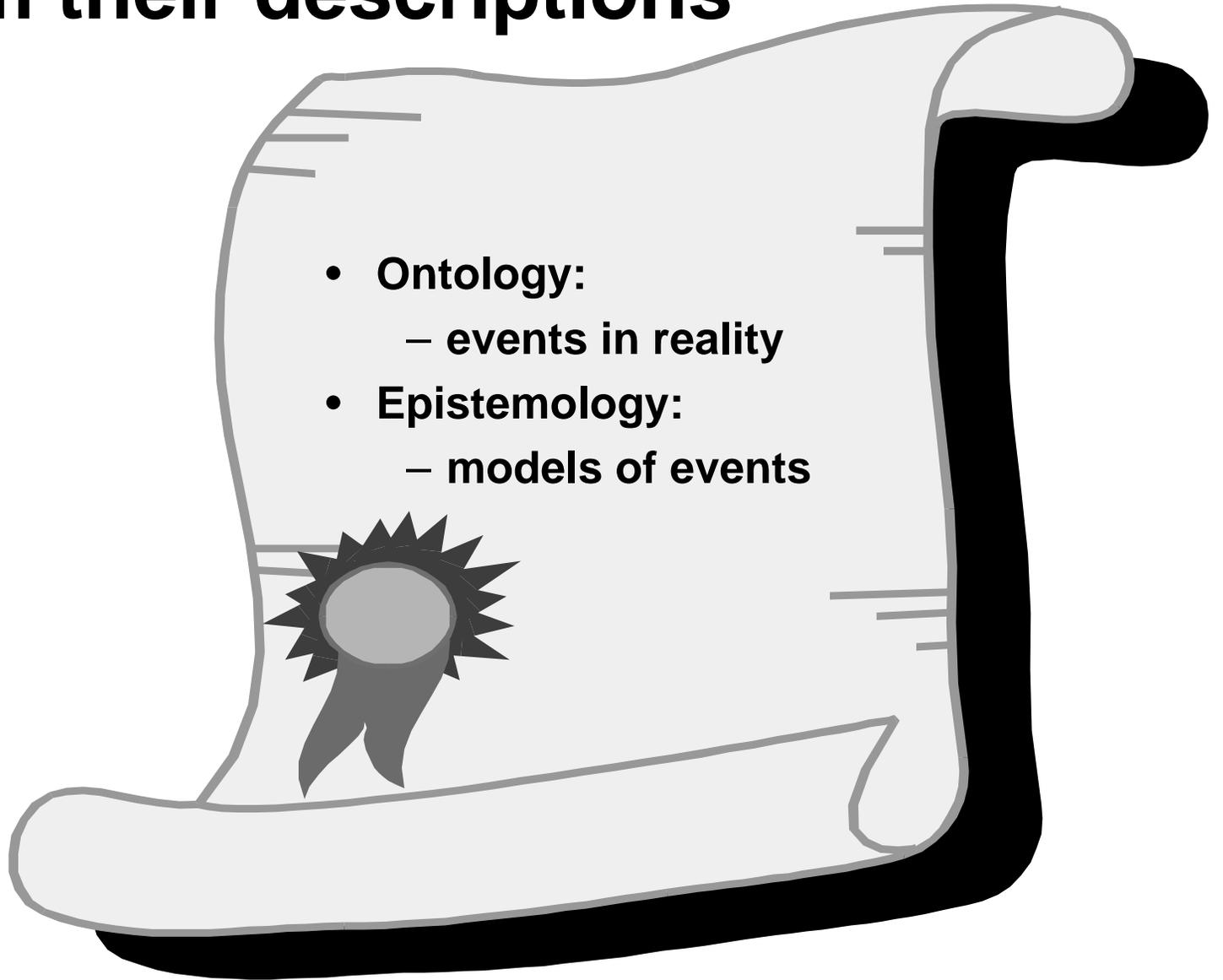
# Can we rationally describe the relational aspect of reality?



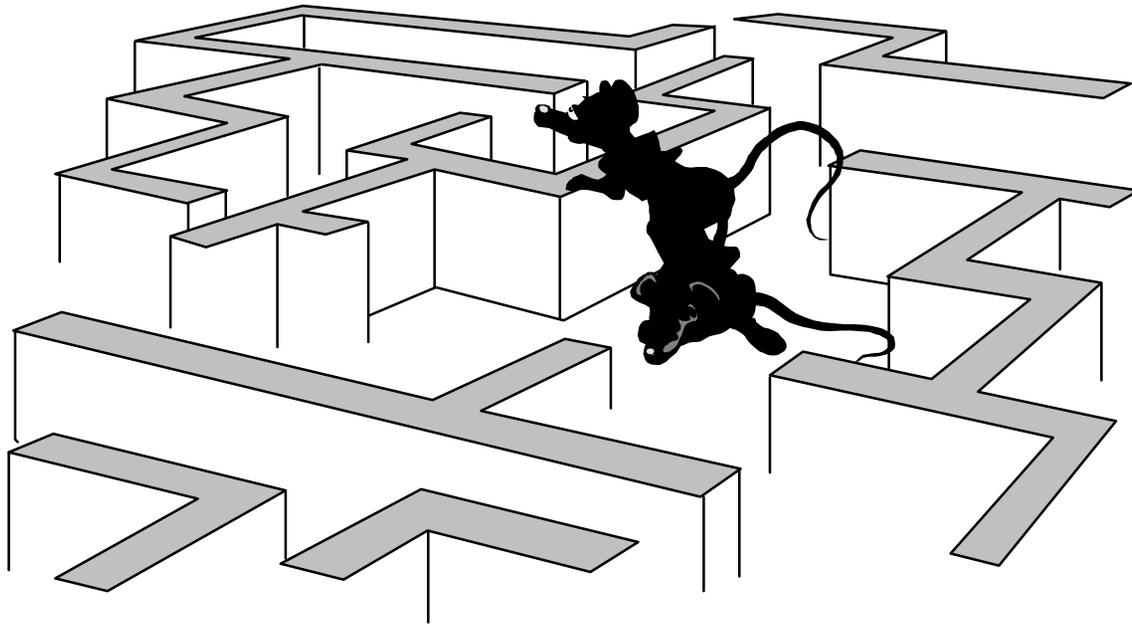
- **Mathematical models**
  - Traditionally used only to count pieces
  - However, they can encompass relationships

# We must distinguish events from their descriptions

- **Ontology:**
  - events in reality
- **Epistemology:**
  - models of events

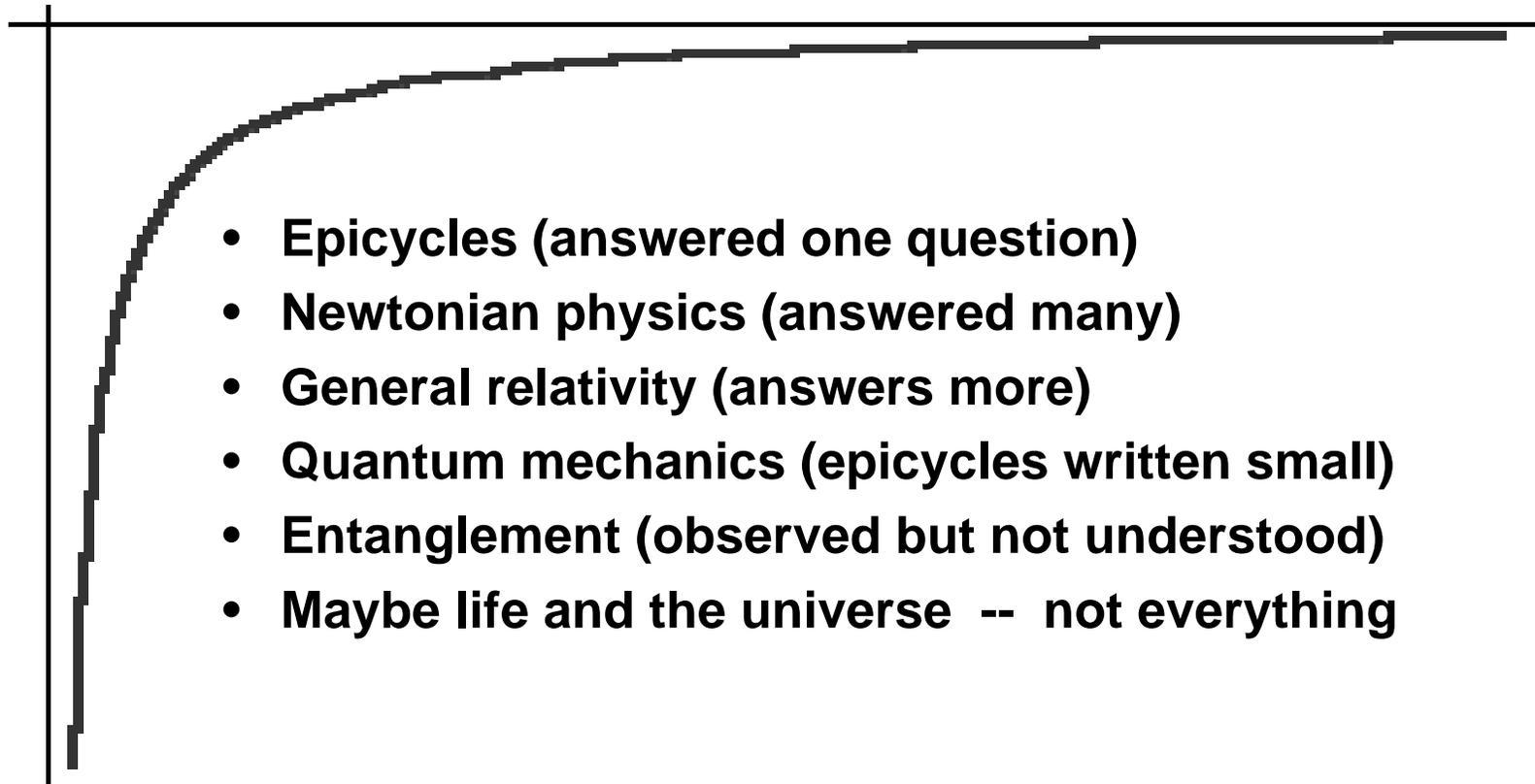


# Consider some of the confusion surrounding quantum mechanics

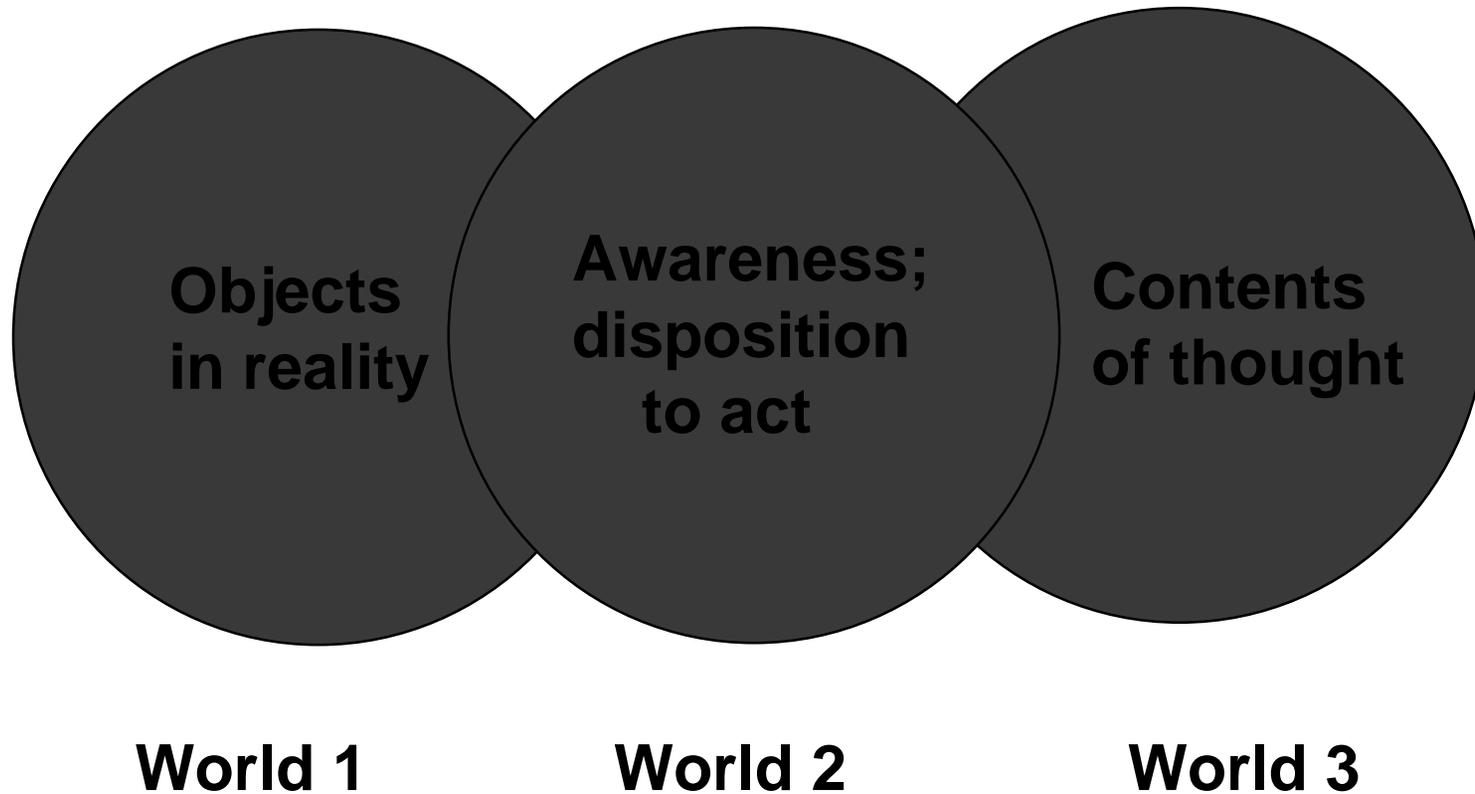


- **When a mouse observes the universe**
- **Does a wave function collapse in reality?**
- **Isn't the mouse's ignorance all that collapses?**

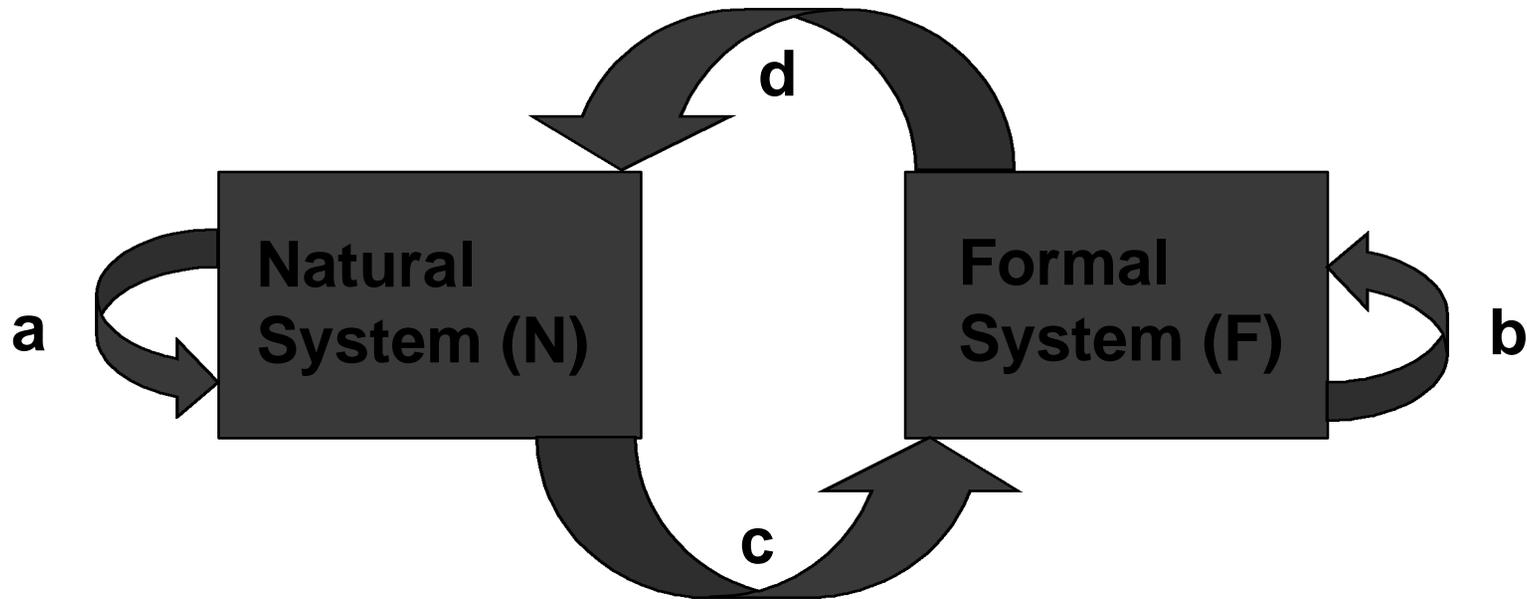
**When reality differs from expectation we call it *bizarre*; we can make the difference smaller but only asymptotically**



**In trying to validate knowledge,  
Popper suggests that we consider  
the distinctions between 3 worlds**

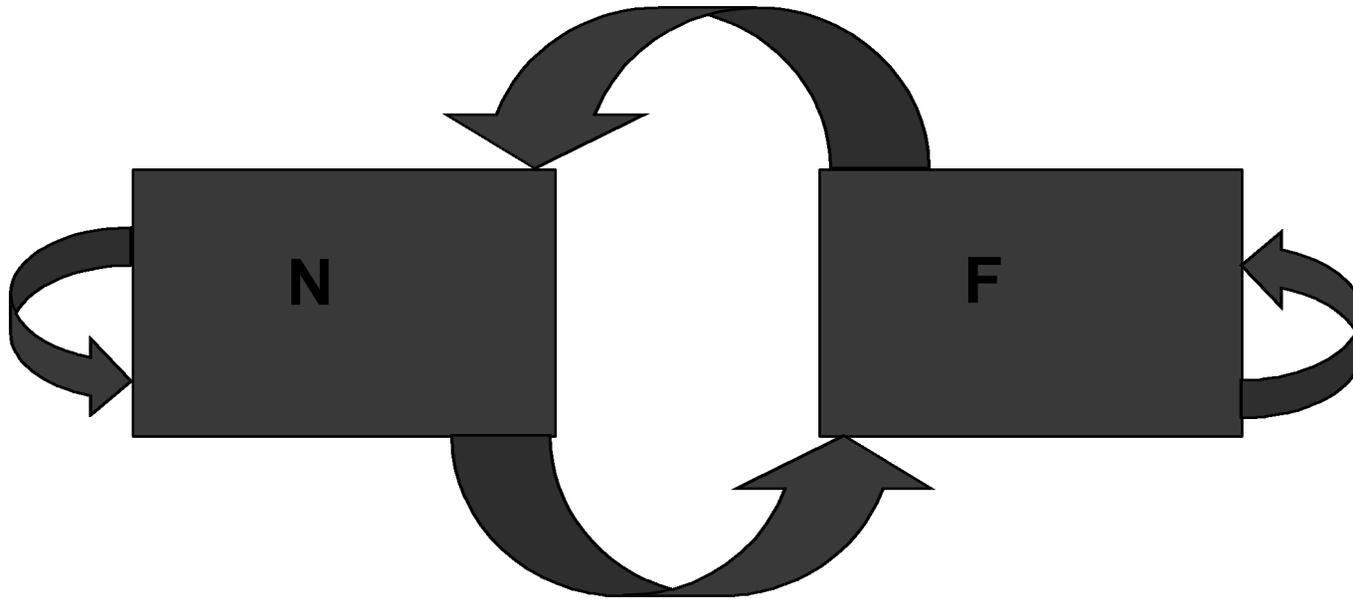


**Rosen's modeling relation is a mathematical formalism that describes this distinction**



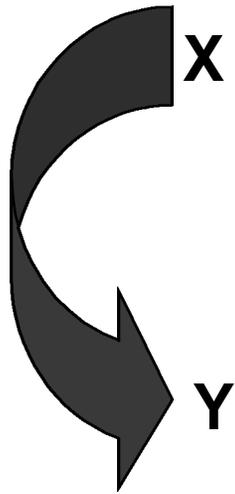
$$\text{MR} = \{ (a, b) \mid a = c + b + d \}$$

# MR is a general in a sense and restrictive in another sense



- **General**
  - N need not be reality
  - F need not be ideas
- **Restrictive**
  - Entailments are required
  - They must commute

# Entailment? What's an entailment?



- **An entailment is a consequence**
  - N = Natural world => a = causal link
  - F = Formalism => b = inference
  - c = measurement
  - d = prediction
- **MR requires  $a = c+b+d$** 
  - Concatenation
  - Mapping of entailments
  - More general than mapping of numbers

# A mapping between entailments is more general than a mapping between lists of numbers

**Function:**

$$y = f(x)$$

$$y \in Y$$

$$x \in X$$

$$f: X \rightarrow Y$$

**Category:**

$$z = g(y), y = f(x)$$

$$z \in Z, y \in Y, x \in X$$

$$h: X \rightarrow Z$$

$$h = F(g, f)$$

- Inferences can be drawn from either mapping
- One just as logical as the other
- Categories can address unquantifiable relationships

**It follows from MR that what distinguishes complexity is its irreducibility**



- **A system of magic dice is irreducible**
- **Considering either die alone ignores relationship**
- **Relationship inherent in structure of reality**
- **Ignoring it does not make it vanish**
- **Relationship not captured as a number**
- **Mathematically described in the modeling relation**

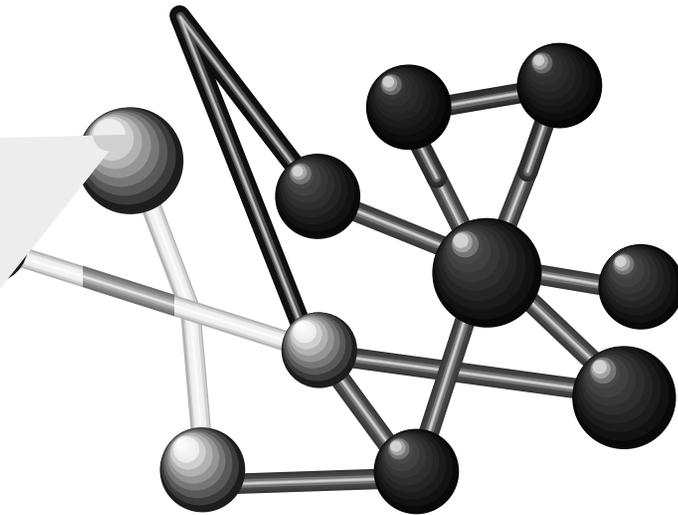
**In an entangled or complex system,  
the whole is greater than the product  
of its parts**

**Complex System:  $A > a_1 \ddot{a} a_2 \ddot{a} a_3 \ddot{a} \dots \ddot{a} a_n$**

**Complicated System:  $A > a_1 \mathring{a} a_2 \mathring{a} a_3 \mathring{a} \dots \mathring{a} a_n$**

**The Gestalt is an understatement**

# The Modeling Relation explains other bizarre behaviors



# Doesn't emergent complexity violate the Law of Entropy?



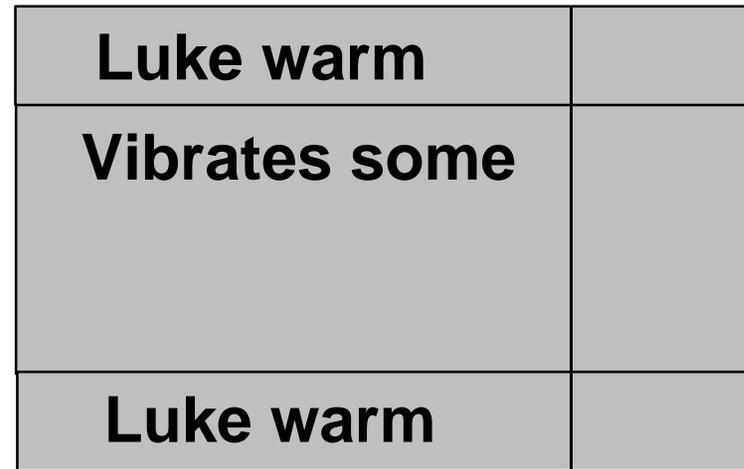
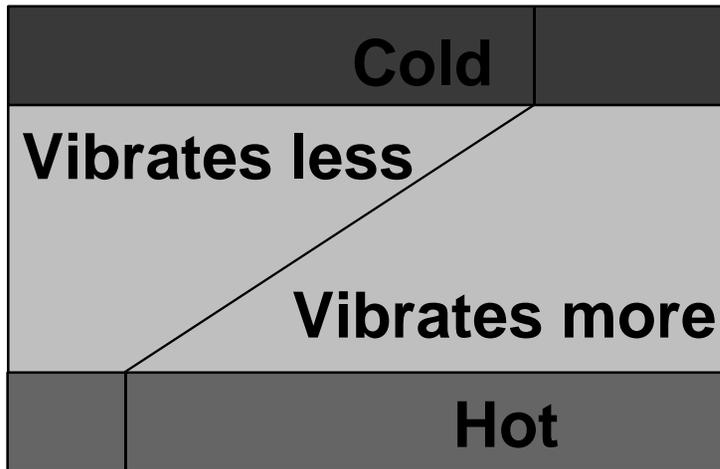
- It does not
- No such law exists

# Entropy is an “average” measure of a global effect



- **Assume:**
- **State inside the pot everywhere the same**
- **Result:**
- **Accurate prediction of work**

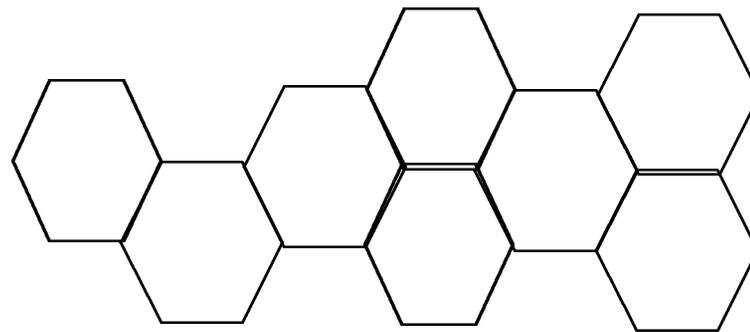
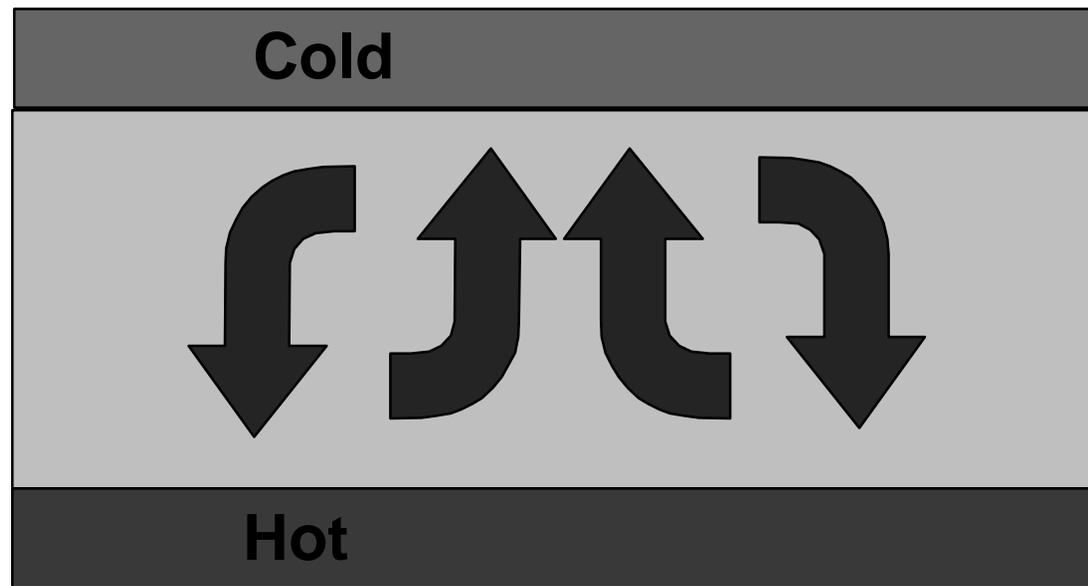
# A thermal gradient imposed on a medium causes local variations in behavior



**Near thermal equilibrium:**

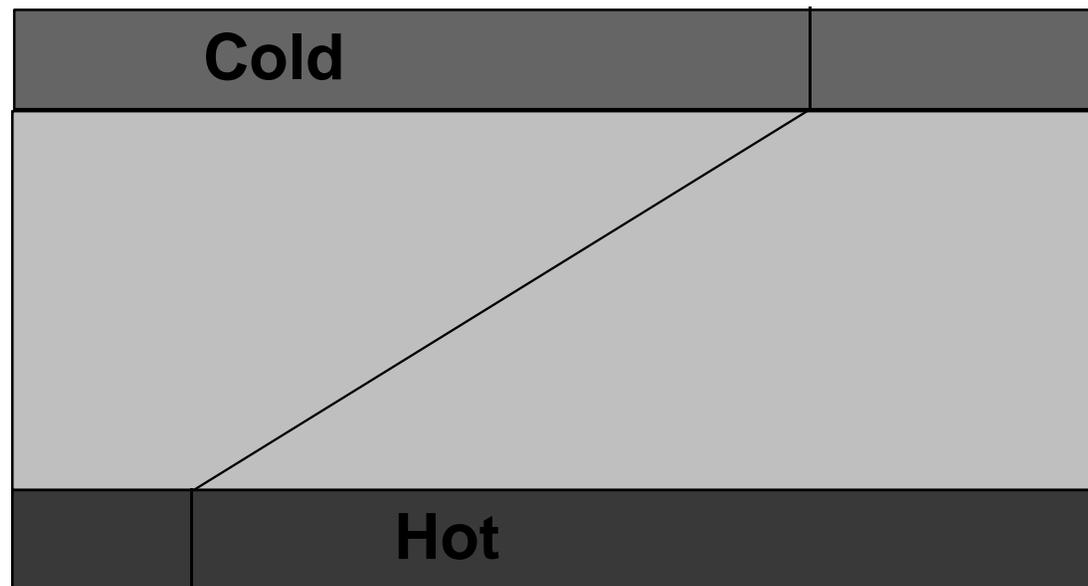
**Imposed gradient tends to be averaged out over time**

**Given a severe gradient,  
*dissipative structures* like  
convection cells will emerge**



***Dissipative  
structures:  
use up energy  
to preserve  
their integrity***

# A generalized Second Law of Thermodynamics addresses gradients, not entropy



**“As thermodynamic systems are moved away from equilibrium, they will use all available avenues to counter the applied gradient.”** Schneider and Kay

# **Entropy *does not describe* dissipative structures; this *does not preclude* their occurrence**

- **Ontological (objects in reality)**

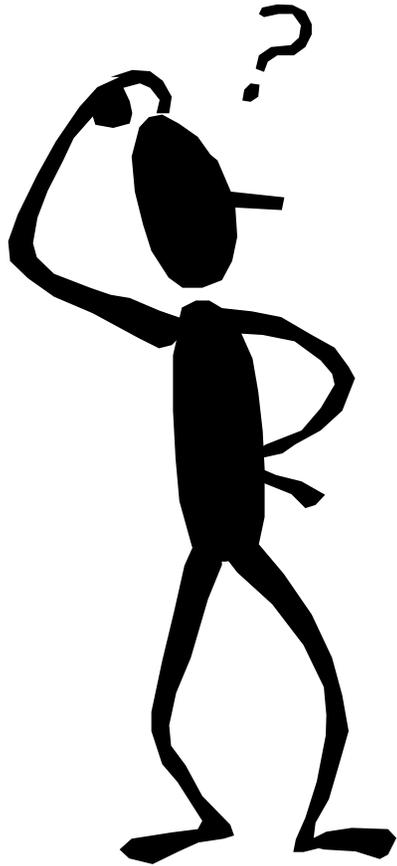
- Convection cells
- Tornadoes
- Hurricanes
- Organisms
- Ecosystems

- **Epistemological (conceptual abstractions)**

- Irrational numbers
- Entropy



# The point of this digression into entropy is that emergent complexity is bizarre, but not absurd



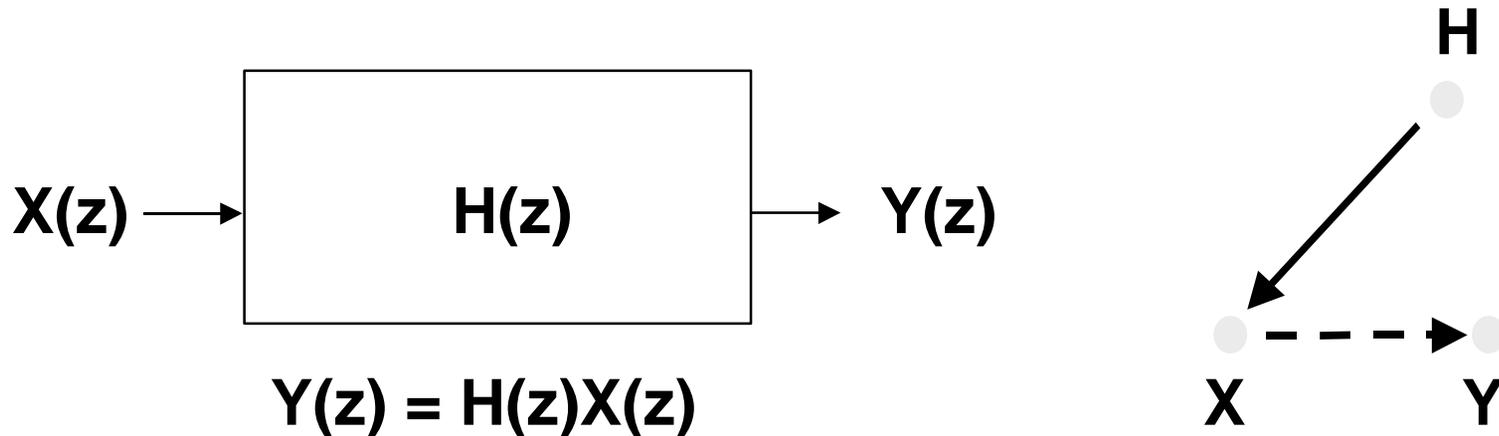
- **Absurd**
  - Limiting the model limits reality
  - Contradicts causality
- **Bizarre**
  - Counterintuitive
  - Popular model doesn't fit reality
  - Causality still holds
  - We may not like how it holds

# A bizarre consequence of causal entailment in complex systems is anticipatory behavior



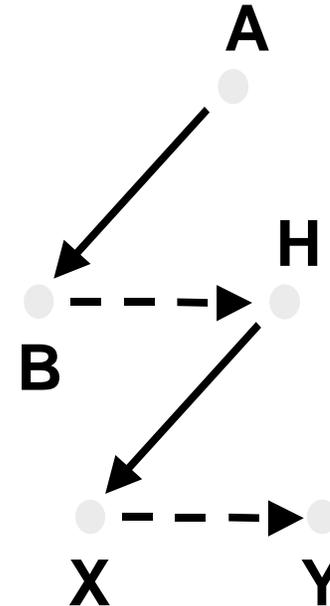
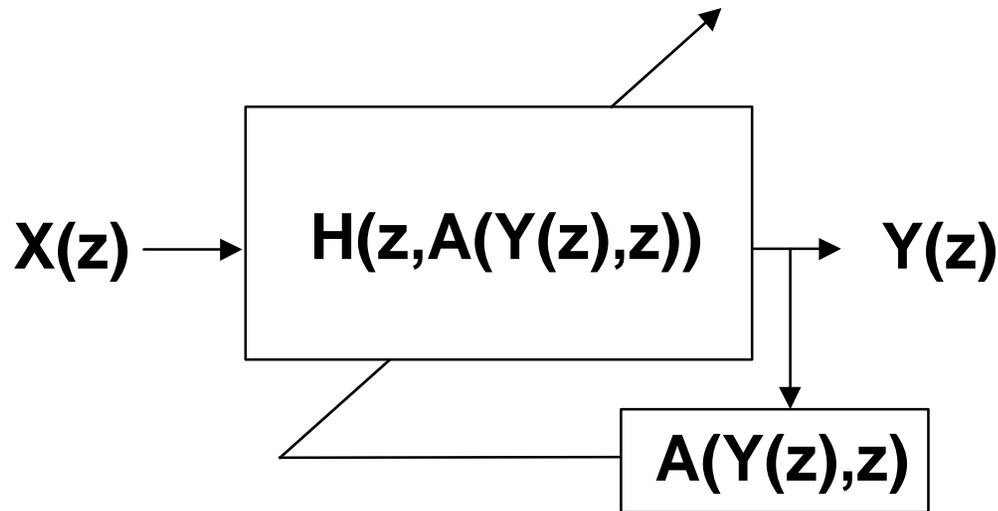
- Record of past is a model
- Prediction of future is a model
- Both are epistemological models with inferential entailments
- Ontological reality has causal entailments
- Prediction validates congruency of entailments
- Anticipatory behavior: act motivated by prediction

# To appreciate causal entailment, consider a LTI digital filter

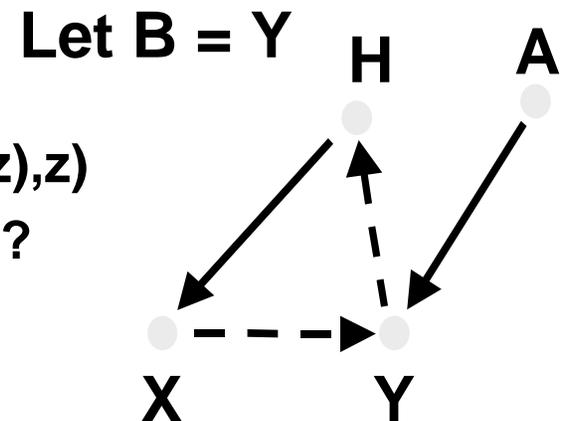


- $H$  entails X-Y relation
- What causes the output (effect),  $Y(z)$ ?
  - Input data (material cause),  $X(z)$
  - System transfer function (efficient cause),  $H(z)$
- But, what causes  $H(z)$ ; why this function?
  - The Hand of Man
  - Unentailed from within the system

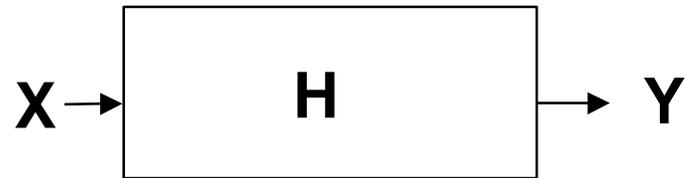
# We can design an adaptive filter, one that updates its own transfer function



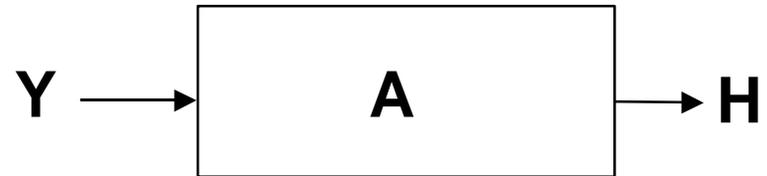
- Entailment, H, is itself entailed
- What causes H(z), (effect)?
  - Material cause, Y(z)
  - Adaption algorithm (efficient cause), A(Y(z),z)
- But, what causes A(Y(z),z); why this function?
  - The Hand of Man
  - Unentailed from within the system



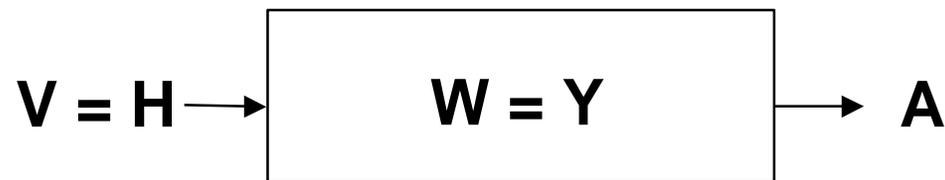
# Can we appeal to biology to find a constraint to stop the infinite regress?



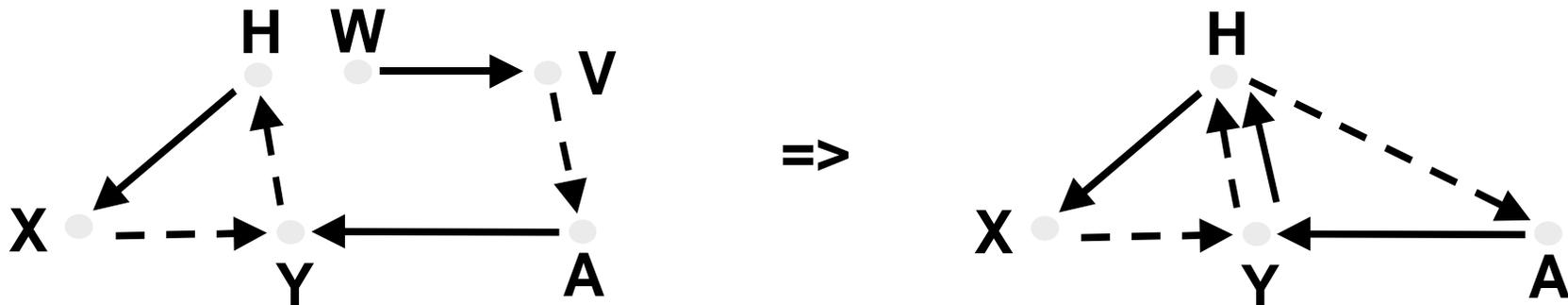
I/O process (metabolism)



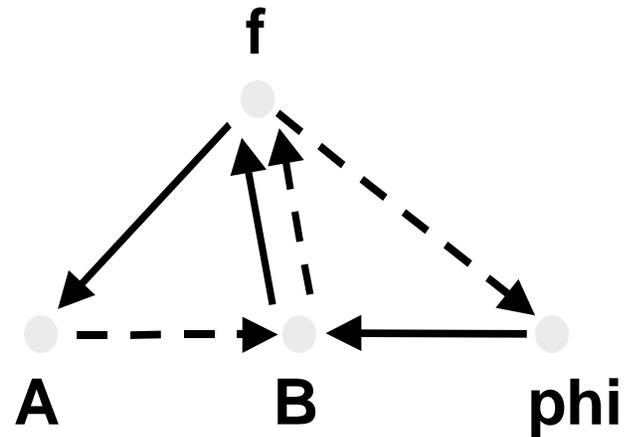
Adaption process (repair)



Entailment of adaption (replication)



# Organisms can be distinguished as a category of bizarre systems closed to efficient cause



- Simplest organism: repair subsumes replication
- Everything internally caused, except input, A
- Every entailment is entailed within the system
- Life is self-referential
- Infinite regress of causal entailments not required
- Causalities are entangled and inseparable

# What distinguishes a conscious organism from non-conscious? Another category



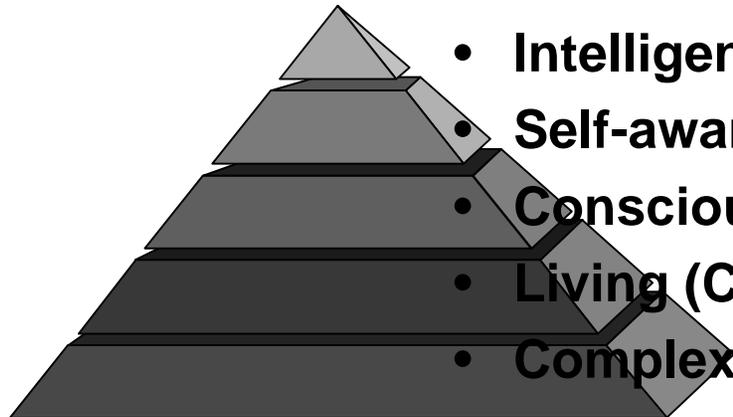
- **Awareness of reality**
  - Reinforced by perceptual stream
  - Depends on relationship between percepts and structures
  - Relationship more important than specific content
  - Semantics more important than syntax
- **Dynamic pattern of psychological structures**
- **Psychophysiological models: windows into reality**
- **Dissipative structure (“maintained by loading with stimuli”)**

# What distinguishes self-awareness from consciousness? Yet another category



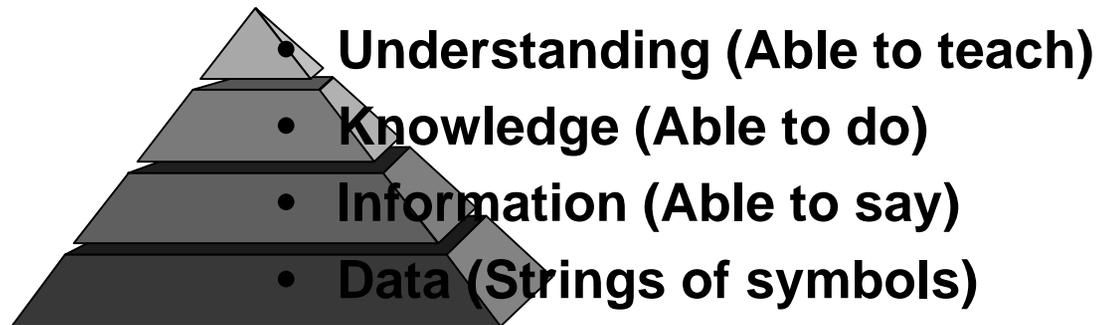
- A particular awareness of reality
- **Semantics (meaning) completely eclipses syntax (structure)**
  - My distinct and separate self
  - Everything and everybody else

# A hierarchy of categories *suggests* a hierarchy of bizarre systems



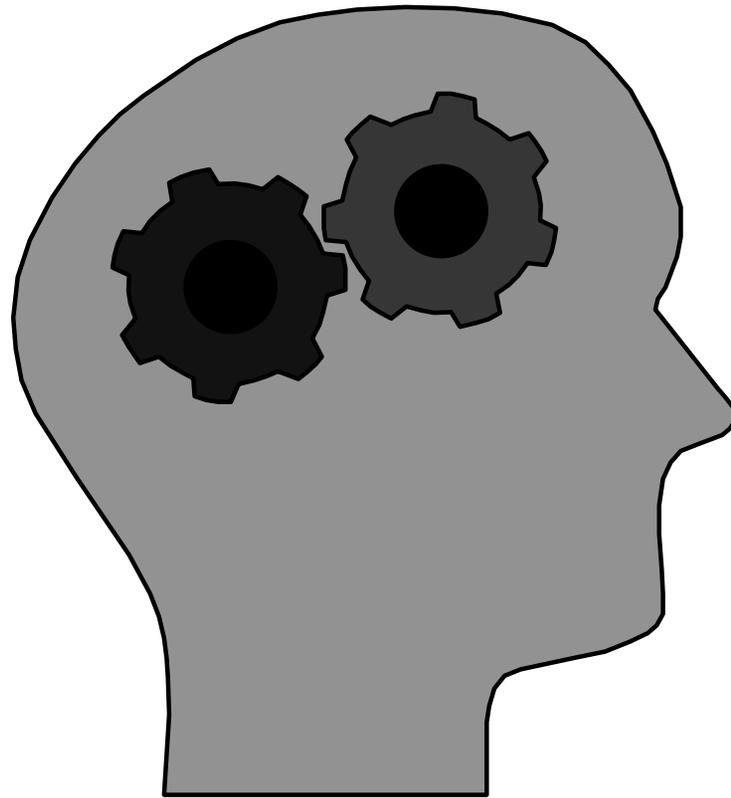
- Intelligent (Not defined in this discussion)
- Self-aware (Distinguishes self from ambience)
- Conscious (Awareness / intentionality?)
- Living (Closed to Efficient Cause)
- Complex (irreducible/entangled) => anticipatory

# **Notice the similarity of the hierarchy of complexity and Landauer's hierarchy of meaning:**



**Higher levels of meaning  
abstracted from lower level details**

**A hierarchy of meaning suggests a  
hierarchy of systems for  
abstracting meaning from symbols**



# Have we made an artifact that abstracts meaning? Probably not

**Turing Computable:**  
(Finite algorithm of finite instructions)

=>

**Purely syntactical**  
**Finally reducible**  
(life and consciousness not reducible)



**Life/consciousness:**  
(self referential)  
**inherently**  
**vulnerable to**  
**incomputability**

**Could the Hand of Man make a  
semantic (extracts meaning)  
artifact? Yes... ,**



... ***if*** we can make a

**complex,**

**living,**

**conscious artifact**

**(much more than a  
reduced, or syntactic, simulation)**

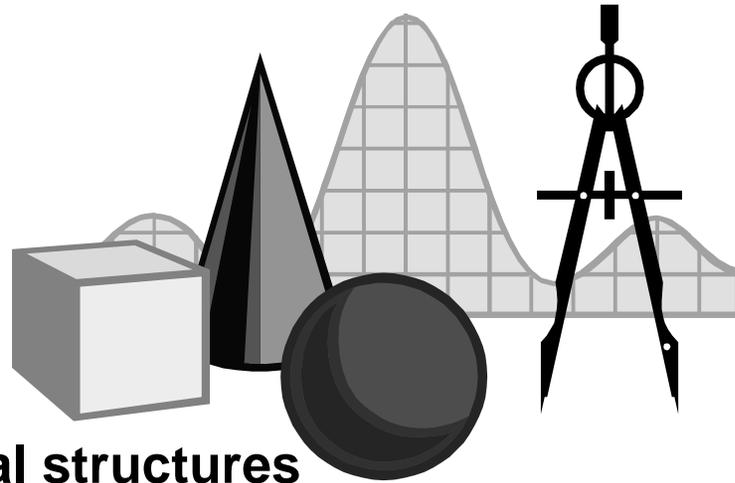
# What's holding us back is technology --- not fundamental or theoretical limits

- A bizarre artifact must behave bizarrely
  - Irreducible => Functional components, instead of parts
  - Might need to grow rather than build



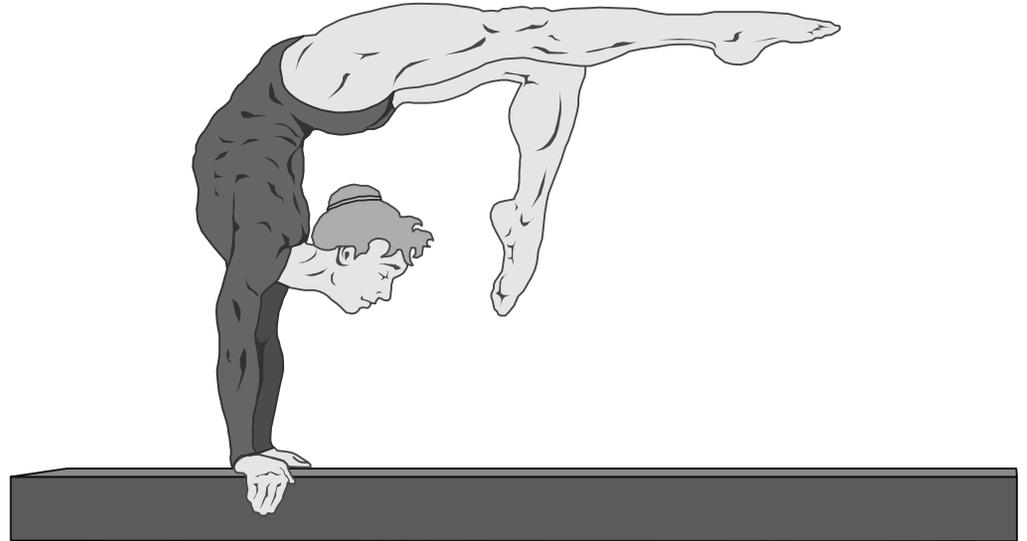
Entanglement *might* serve  
as a material cause

# Enough math? Bellman's conceptual categories, Rosen's categories, and Goldfarb's ETS equivalent?



- **Non-rigid mathematical structures**
- **Map current structures to new foundations**
- **Model-based**
- **Hierarchical (categories of categories)**
- **More general than sets or “things”**
  - Inferential entailments congruent with causal links
  - Multiple descriptions from multiple perspectives

# Bizarre behavior is counterintuitive, completely real and probably engineerable



- **Consistent with reality**
  - Causal behavior
- **Non-contradictory**
  - Formally entailable and encodable
- **Several (possibly equivalent) descriptions**
  - Irreducible to  $R^n$
  - Entangled
  - Analogous to thermal non-equilibrium