

Getting epiphenomena to do real work  
What's right and what's wrong with reductionism

That's setting the expectation level pretty high.

# Emergence Explained

The Aerospace Corp.  
El Segundo, Ca.

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# Emergence the holy grail of complex systems

The father of genetic algorithms. One of the founders of the Santa Fe Institute.



It is unlikely that a topic as complicated as emergence will submit meekly to a concise definition, and I have no such definition to offer.

John Holland, *Emergence: From Chaos to Order*

# Cosma Shalizi

Physicist (& poet)

<http://cscs.umich.edu/~crshalizi/reviews/holland-on-emergence/>



Someplace ... where quantum field theory meets general relativity and atoms and void merge into one another, we may take “the rules of the game” to be given.

Call this  
*emergence*  
if you like.

It's a fine-sounding word, and brings to mind southwestern creation myths in an oddly apt way.

But the rest of the observable, exploitable order in the universe

benzene molecules,  $PV = nRT$ , snowflakes, cyclonic storms, kittens, cats, young love, middle-aged remorse, financial euphoria accompanied with acute gullibility, prevaricating candidates for public office, tapeworms, jet-lag, and unfolding cherry blossoms

Where do all these regularities come from?

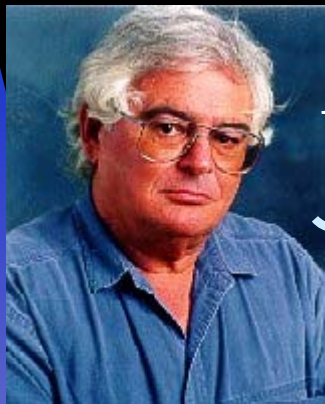
The ultimate  
reductionist.

# Steven Weinberg

[T]he reductionist view emphasizes that the weather behaves the way it does because of the general principles of aerodynamics, radiation flow, and so on (as well as historical accidents like the size and orbit of the earth), but in order to predict the weather tomorrow *it may be more useful to think about* cold fronts and thunderstorms. "Reductionism Redux," in Cornwell, J. (ed), *Nature's Imagination: The Frontiers of Scientific Vision*, Oxford University Press, 1995

Reductionism may or may not be a good guide for a program of weather forecasting, but it provides the necessary insight that *there are no autonomous laws of weather that are logically independent of the principles of physics.*

- There are no principles of chemistry that [do not need] to be explained ... from the properties of electrons and atomic nuclei,
- and ... there are no principles of psychology that ... do not need ultimately to be understood through the study of the human brain,
- which in turn must ... be understood on the basis of physics and chemistry.



# Jerry Fodor

An originator of and outspoken defender of Functionalism

"Special Sciences; Still Autonomous after All These Years," *Philosophical Perspectives*, 1998.

Mountains are made of all sorts of stuff. [Yet] generalizations about mountains-as-such ... continue to serve geology in good stead.

Autonomous laws of mountains?

Damn near everything we know about the world suggests that unimaginably complicated to-ings and fro-ings of bits and pieces at the extreme micro-level manage **somehow** to converge on stable macro-level properties.

Well, I admit that I don't know why. I don't even know how to think about why. I expect to figure out why there is anything except physics the day before I figure out why there is anything at all.

[T]he **somehow** really is entirely mysterious.

Why is there anything except physics?

# The question

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- Are there autonomous higher level laws of nature? (the functionalist claim)
- If so, how can that be if everything can be reduced to the fundamental laws of physics? (the reductionist position)

Early member of the Santa Fe Institute.

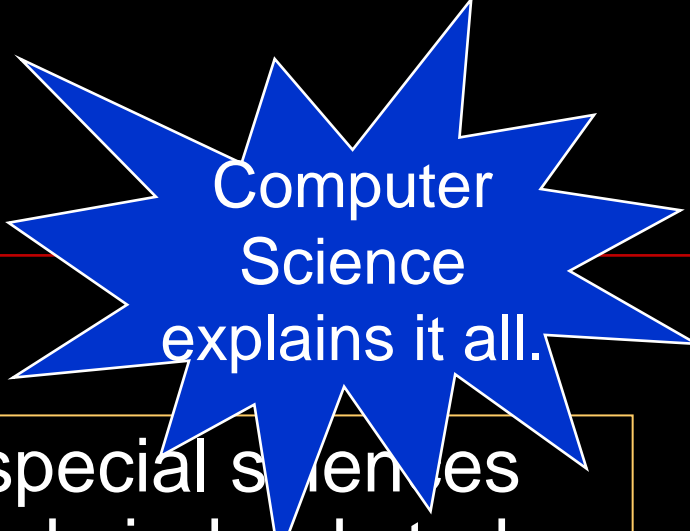
# Philip Anderson



- The ability to reduce everything to simple fundamental laws [does not imply] the ability to start from those laws and reconstruct the universe. “More is Different” (*Science*, 1972)
- [The hierarchy of the sciences] does not imply that science [n+1] is ‘just applied [science n].’ At each [level] entirely new laws, concepts, and generalization are necessary.

If so,  
why?

# Our answer (preview)



Computer  
Science  
explains it all.

- What functionalism calls the special sciences (sciences other than physics) do indeed study autonomous laws.
- Those laws pertain to *real higher level entities*.
- But *interaction* among such higher-level entities is epiphenomenal in that they can always be reduced to fundamental physical forces.
- In other words, epiphenomena — which we will identify with emergent phenomena — do the real work of relating real higher-level entities.

# Epiphenomena

From last year's conference.

```
temp := x;  
x := y;  
y := temp;
```

That this exchanges *x* and *y* is also epiphenomenal and emergent.

- **Epiphenomenon:** a secondary phenomenon that is a by-product of another phenomenon. <http://wordnet.princeton.edu/>
  - ◆ Before Einstein, Brownian motion was a mystery. How could inanimate matter move on its own?
  - ◆ We now know that Brownian motion is an *epiphenomenon* of collisions of particles with atoms or molecules.

It's not held in place by a long chain!

A satellite in a geosynchronous orbit is (epiphenomenally) motionless with respect to the earth as a reference frame.

It's "emergent" from the combination of the period and inclination of its orbit and the rate of rotation of the earth.

A two-body complex system.

# Emergence

- Epiphenomenon: a phenomenon that *can be described in terms that do not depend on its implementation*.
- In computer science (or systems engineering) these are called *specifications* (or *requirements*).
- But specifications only describe (and requirements only require). For there to be an epiphenomenon, it must exist.

Every epiphenomenon has an **implementation** — whose design can be described.

My wife says this makes me an Aristotelian.

It must be an epiphenomenon of something.

- A phenomenon is emergent  $\equiv$  it is epiphenomenal.

# Weinberg again

Macro from micro

- **Petty reductionism.** Things behave the way they do because of the properties of their constituents: for instance, a diamond is hard because the carbon atoms of which it is composed can fit together neatly.
  - ◆ Petty reductionism has probably run its course. It is not possible to give a precise meaning to statements about elementary particles being composed of other elementary particles.
- **Grand reductionism.** All of nature is the way it is because of simple universal laws [Weinberg's holy grail], to which *all other scientific laws may be reduced*.
  - ◆ The reductionist program of physics is the search for the **common source of all explanations** [from which all other scientific laws] can in principle be [derived] *as mathematical consequences*.

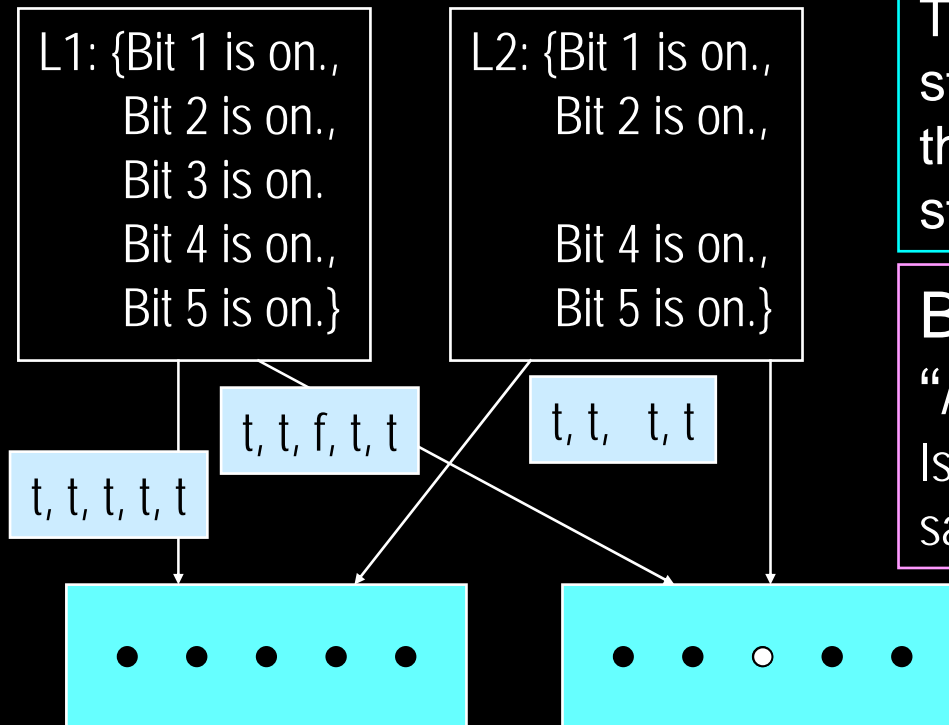
# Supervenience

Developed originally in philosophy of mind in an attempt to link mind and brain.

- A set of predicates H (for *higher-level*) about a world supervenes on a set of predicates L (for *higher-level*) if it is never the case that two states of affairs of that world will assign the same configuration of truth values to the elements of L but different configurations of truth values to the elements of H.
  - ◆ In other words, L fixes H.
- Think of L as statements in physics and H as statements in a (Higher-level) “special science.”

# Supervenience example

H: {An odd number of bits is on.,  
The bits that are on are the start of the Fibonacci sequence.,  
The bits that are on represent the value 10.,  
...}



**H supervenes over L1.**  
The truth value of a statement in H depends on the truth values of the statements in L1.

**But not over L2.**  
“An odd number of bits is on.”  
Is both true and false given the same truth values in L2.

The world in two different states

The  
interesting  
kind.

# Three types of emergence

- **Static:** (petty reductionism succeeds)
  - ◆ a house, cloth, hardness, e.g., of a diamond, pressure, temperature.
  - ◆ Supervenience works well.
- **Dynamic:** (grand reductionism fails): most agent-based models, market phenomena, (un)intended consequences.
  - ◆ Entity-environment interactions; stigmergic effects.
  - ◆ Supervenience does not work well.
- **Strong:** new forces of nature, e.g., vitalism: “life” from “lifeless” chemicals.
  - ◆ Magic; non-reductionist.
  - ◆ Supervenience isn’t even relevant.



# Reductionism vs. strong emergence

Weinberg: Darth Vader notwithstanding, there is no life force. This is [the] invaluable negative perspective that is provided by reductionism.

**Reductionism:** *the only forces* of nature are the  $n$  fundamental forces — for some *small* fixed  $n$ .

**Strong emergence:** *new forces* of nature may appear at many levels of emergence.

An absolutely stark choice.

What are the forces that make things happen?

What about dark energy?

# Epiphenomenal causation



Jaegwon Kim

- Any cause-like effect that results from a force-like phenomenon in the domain of any of the special sciences must be epiphenomenal.

David Hume

It just looks like that sword killed that man.

Why are there mathematical regularities — e.g., Lagrange's Theorem? (23)

The functionalist problem remains. Why are there higher order regularities — even if they are epiphenomenal?

Einstein, Wigner: Why does mathematics work in science?

# Historical accidents

A monster loophole!

- **Weinberg:** [A]part from historical accidents that by definition cannot be explained, the [human] nervous system [has] evolved to what [it is] entirely because of the principles of macroscopic physics and chemistry,
- which in turn are what they are entirely because of the principles of the standard model of elementary particles.

Uncontroversial?

It's not your father's historical accident.

# The environment

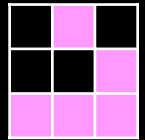
Stigmergic interactions

- The human nervous system (and human anatomy in general) evolved to what they are primarily because of the environment in which that evolution took place.
- You've heard of "net-centric?"
  - ◆ Anything may interact with, depend on, and make use of anything else over "the network."
- We live in an "environment-centric" universe.
  - ◆ Must look out as well as looking in.
- Because of the crucial role the environment plays in evolution, one *cannot* start with the principles of physics and chemistry and derive human anatomy.

Reality (a SOA) is the ultimate System of Systems

# The Game of Life

- Built on a rectangular grid.
  - ◆ A totalistic two-dimensional cellular automaton.
- A cell is either alive or dead. (Can't move.)
- Rules
  - ◆ The 8 surrounding cells are a cell's neighbors.
  - ◆ A live cell with two or three live neighbors stays alive; otherwise it dies.
  - ◆ A dead cell with exactly three live neighbors is (miraculously) (re)born and becomes alive.
    - ★ Article: <http://www.math.com/students/wonders/life/life.html> (bad applet?)
    - ★ Applet: <http://www.ibiblio.org/lifepatterns/>



The rules are the only “forces!”

# Epiphenomenal gliders

- Gliders (waves of births and deaths? epidemics?) are (amazing) **epiphenomena** of the Game of Life rules — whose **only(!)** consequences are to switch cells on and off.
- Gliders (and other epiphenomena) are **causally powerless**.
  - ◆ A glider does not change how the rules operate or which cells will be switched on and off. A glider doesn’t “go to an cell and turn it on.”
  - ◆ A Game of Life run will proceed in exactly the same way whether one notices the gliders or not. A very reductionist stance.
  - ◆ Cells don’t “notice” gliders — any more than gliders “notice” cells.
- Gliders exemplify stigmergy.
  - ◆ They result from the interaction of the rules with the environment,
  - ◆ which serves as a memory or past events.
- All software effects are stigmergically epiphenomenal over a computer’s instruction execution cycle,
  - ◆ which is stigmergically epiphenomenal over electron flows.



# Game of Life Programming Platform

Amazing as they are, gliders are also trivial.

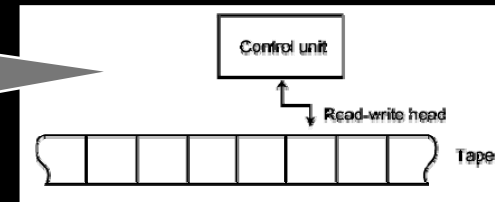
- ◆ Once we know how to produce a glider, it's simple to make them.

Can build a library of Game of Life patterns.

Do physicists think like this?

and their interaction APIs.

Also stigmergic.



By suitably arranging these patterns, one can simulate a Turing Machine.

Paul Rendell. <http://rendell.server.org.uk/gol/tmdetails.htm>

A second level of emergence. Epiphenomenal and stigmergic.

# It's the design that matters

What does it mean for epiphenomenal gliders and other epiphenomenal patterns to simulate a Turing Machine?

To prove that a Game-of-Life simulation of a Turing Machine works, must reason about *epiphenomenal interactions among epiphenomenal patterns*. Must show that *the design*:

1. Simulates a Turing Machine. (Reify the design; treat it as real.)
2. Can be implemented on a Game-of-Life platform.

**Free the design!**

**Functionalism:** it's (only!) the design that matters. Many possible implementations. Disengage the model from the implementation.

**Reductionism:** the patterns don't really interact. (But let's pretend that they do.)

# Recall Weinberg

- How about the “principles” of Turing Machines, e.g., the unsolvability of the Halting Problem?
- Does that need to be mathematically derived from the GoL rules?
- Clearly not.
  - ◆ A Turing Machine is an independent construct,
  - ◆ which may be *implemented* on a Game of Life platform,
  - ◆ not derived from it.

Grand  
reductionism  
fails.

- All of nature is the way it is because of simple universal laws, to which *all other scientific laws may be reduced.*

# Protectorate

A stable state of matter whose generic low-energy properties are determined by a higher organizing principle and nothing else.

*Physics from the Bottom Down*



Robert Laughlin

It's not as mysterious as he makes it sound.

- Nature **implements** solids by building lattices.
- No autonomous weather laws?
  - ◆ Why not think of the weather as being **implemented** on a **platform** of aerodynamics and radiation flows?

# Downward

Called  
“reductive”  
proofs.

# entailment

- The unsolvability of the TM halting problem entails the unsolvability of the GoL halting problem.
  - ◆ **How strange!** We can conclude something about the GoL because we know something about Turing Machines.
- Earlier, we dismissed the notion that a glider may be said to “go to a cell and turn it on.”
- Because of downward entailment, there is hope for talk of this sort.
  - ◆ One can build glider “velocity” laws and then use those laws to draw conclusions (make predictions?) about which cells will be turned on and when that will happen.
- Turing machines and gliders are not just conceptual conveniences for thinking about of the GoL. They are constructs which the GoL may implement
- and which then **constrain** the GoL.

# The reality of higher-level entities

- Is everything other than fundamental particles/strings/whatever (if there is anything fundamental) — you, me, puppy dogs, etc. — epiphenomenal?
  - ◆ Even though they may have properties, which we can describe, is it all an illusion?
  - ◆ Are the mystics (and the reductionists) right?
- Entities are real. An entity is either
  - ◆ atomic: fundamental, no components,
  - or
  - ◆ emergent: *a region of reduced entropy*
    - ★ persistent (static) or
    - ★ self-perpetuating (dynamic).

(Slightly) more than epiphenomenal.

# Entities at an energy equilibrium

## Static emergence

- Created in energy wells of various forces.
  - ◆ Atomic nuclei, atoms, molecules, crystal lattices, astronomical bodies and structures (planets, stars, solar systems, galaxies, etc.)
- (Negligibly) less mass than the sum of their parts.
- Supervenience works well.
  - ◆ Atomic nuclei, etc. are emergent from, epiphenomena of, and supervenient over their components.

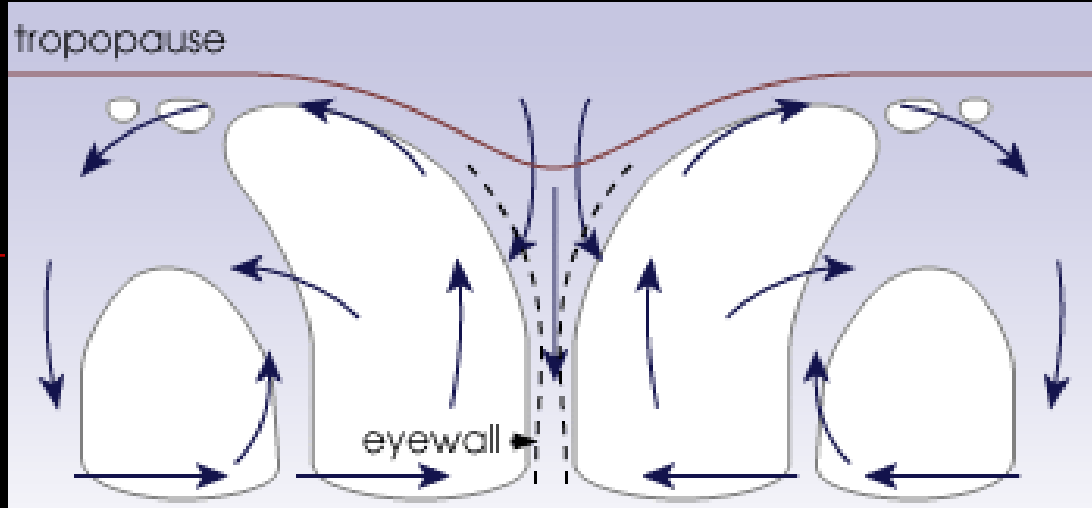
# Entities not at an energy equilibrium

“Far from equilibrium”

Dynamic emergence

- Self-perpetuating through their appropriation and use of energy from their environment.
  - ◆ Hurricanes, you, me, a corporation, a nation, Theseus' ship.
  - ◆ Many components are statically emergent, hence “solid.”
- Depend stigmergically on the environment for resources.
- (Negligibly) more mass than the sum of their parts.
  - ◆ Since they are “in operation,” they include the energy that is flowing through them. A warm body has (negligibly) more mass than “the same body” if allowed to cool.
- Supervenience does not work well. Most entities of interest supervene over “historical accidents.”

# A hurricane is a far-from-equilibrium non-biological dynamic entity



<http://earthobservatory.nasa.gov/Library/Hurricanes/>

No genetic code.  
Doesn't reproduce or evolve.

- Has a “metabolism.”
- Generates heat internally — by condensation rather than combustion.
  - ◆ “Eats” warm moist surface air; “excretes” cooler drier air.
  - ◆ Energy produced powers its self-perpetuating processes.
- **Design:** one can talk about how it works.
- **Fitness:** persists (is self-perpetuating) only so long as its environment provides adequate resources.

I'd look for a small version of this for the transition to life.

# Modeling problems: the difficulty of looking downward

Models of computer security or terrorism will always be incomplete.

Can only model unimaginative enemies.

- Strict reductionism implies that it is impossible to find a non-arbitrary base level for models.
  - ◆ What are we leaving out that might matter?
    - ★ Use Morse code to transmit messages on encrypted lines.
- No good models of biological arms races.
  - ◆ Combatants exploit and/or disrupt or otherwise foil each other's *epiphenomena*.
    - ★ Insects vs. plants: bark, bark boring, toxin, anti-toxin, ....
- Geckos use the Van der Waals "force" to climb.

epiphenomenal

Nature is not segmented into a strictly layered hierarchy.

# Modeling problems: the difficulty of looking upward

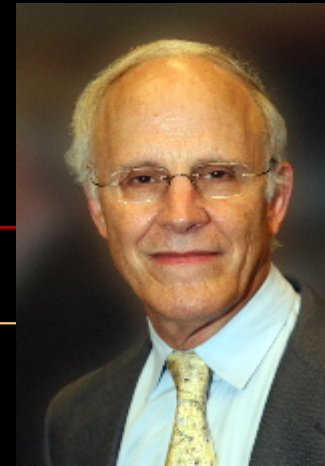
- Don't know how to build models that can **notice** emergent phenomena and **characterize** their interactions. We don't know what we aren't noticing.
  - ◆ We/they can use our commercial airline system to deliver mail/bombs.
- Model gravity as an agent-based system.
  - ◆ Ask system to find equation of earth's orbit.
  - ◆ Once told what to look for, system can find ellipse.
  - ◆ But it won't notice the yearly cycle of the seasons — even though it is similarly emergent.

Exploit an existing process.

Models of computer security or terrorism will always be incomplete.

Can only model unimaginative enemies.

# Summary



David Gross

- Higher level entities are real.
  - ◆ They have more structure than their surroundings.
    - ★ We exist only so long as we can hold it together.
  - ◆ They have more or less mass than their components.
- Interaction among entities is epiphenomenal.
  - ◆ A kiss is not really just a kiss.
  - ◆ The only real forces are elementary forces.
    - ★ Simultaneous multi-scalar interactions.
    - ★ We need new mathematics for multi-scalar systems.
- Hence: epiphenomena do real work.

Physicists want an equation for everything. It won't happen.

# Contact and paper

- [Russ.Abbott@GMail.com](mailto:Russ.Abbott@GMail.com)
- “Emergence Explained” is available at [arXiv.org](http://arXiv.org) and [cs.calstatela.edu](http://cs.calstatela.edu).
- Google: *Emergence Explained*

# The Aggregation of Complexity

- **Problem:** Too many snakes
- **Solution:** Pay people to kill them and turn them in.

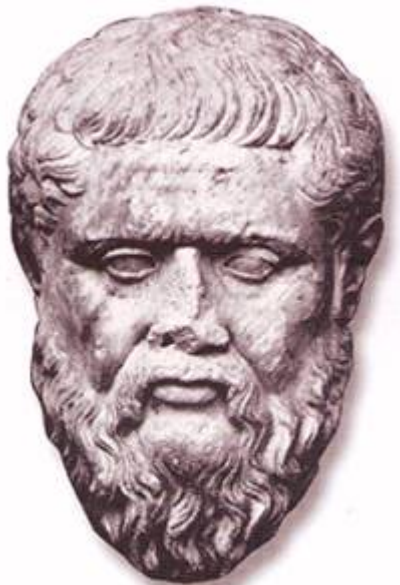
- **A mechanism/“service” is added to the environment.**
  - ◆ Turn in a dead snake → Receive money.
- **Unintended consequence:**
  - ◆ People create backyard snake farms.
- **Energy sources (mechanisms/services) will be exploited.**



If the rat population grew because the snake population declined, that would **not** be an example of exploiting a new mechanism.

# Emergence the holy grail of complex systems

How macroscopic behavior arises from microscopic behavior.



Emergent entities (properties or substances) ‘arise’ out of more fundamental entities and yet are ‘novel’ or ‘irreducible’ with respect to them.

Stanford Encyclopedia of Philosophy

<http://plato.stanford.edu/entries/properties-emergent/>

The ‘scare’ quotes identify problematic areas.

# Three ways to think about the GoL

- As an agent based model, e.g., of epidemics.
  - ◆ The cells are the (immobile) agents.
    - ★ Each is either alive or dead (infected or healthy, etc.)
- As a universe with a very simple physics.
  - ★ Fredkin & Zuse, Wolfram, [http://www.math.usf.edu/~eclark/ANKOS\\_zuse\\_fredkin\\_thesis.html](http://www.math.usf.edu/~eclark/ANKOS_zuse_fredkin_thesis.html)
  - ◆ The rules are the fundamental forces of nature.
    - ★ *Nothing* happens other than as a result of the rules.
  - ◆ The grid — and its state — is the environment.
    - ★ It is a consequence of how the rules interact with “historical accidents” — or connivances.
  - ◆ The reductionist agenda is to reduce any and all “higher level” phenomenon to the rules — and history.
- As a programming platform.
  - ◆ Let’s see what neat hacks we can build.

# When supervenience doesn't help

- A glider supervenes only over *the entire set of cells* that it traverses.
- A hurricane supervenes only over the air and water molecules *that make it up over its lifetime*.
- You and I supervene only over *the entire set of fundamental particles* that become part of our bodies over our lifetimes.
- Theseus' ship supervenes only over *all the stuff* that is ever used in its construction — plus the particles of the people who maintain it.

Most entities of interest supervene over historical accidents.