The Limits of Reductionism

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Outline

- Preface for this talk
- Introduction and perspective
- An influential astronomical success of reductionism
- What is water?
- Central role in fundamental physics
- Philosophical & scientific implications of reductionism
- Current frontiers of reductionism in neuroscience
- Practical limitations
- The L-Ant/Vant cellular automata: Reductionist Heaven (or Hell)
  - Behavior - short & long term
  - Cohen-Kong Theorem
  - Generalized L-Ants
  - Undecidable questions
  - Memory and emergence
- Conclusions and a speculation

Preface

- Not related to my research activities or expertise
- Not a talk about astrophysics (or only marginally so)
- A talk about the intersection of computation and philosophy with fundamental (meta-)physics/science
- Probably some novel material for most of you
- Theorems & ***Animations***!
- Based on a guest lecture in a Princeton course on "Human Identity in the Age of Neuroscience and Information Technology" (PSY 214)…with thanks to Daniel Osherson* for the opportunity and prodding

Henry R. Luce Professor of Information Technology, Consciousness and Culture

Introduction and Perspective

- Reductionism: "the idea that developing an understanding of a complex system's constituent parts and their interactions is sufficient for an understanding of the system as a whole", closely allied with the philosophy's of materialism and rationalism
- Rene Descartes (*Discourses* 1637) argued the world is like a machine, its pieces like clockwork mechanisms, and that the machine can be understood by taking its pieces apart, studying them, and then putting them back together to see the larger picture.
- Proven profoundly powerful in the physical sciences, reductionism has become nearly indistinguishable from scientific understanding/theory at present.
- Computational "worlds" can be *perfectly* reductionist…

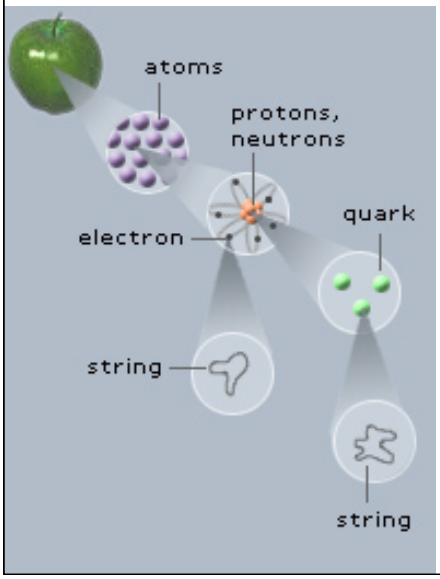
Tycho, Kepler & Newton

- A very powerful and persuasive early demonstration of reductionism's power occurred in astronomy.
- Tycho Brahe (1546-1601) collected a huge volume of precision astrometric data on the positions of the planets relative to the "fixed stars" over a period of many years.
- Johannes Kepler (1571-1630) ***reduced*** Tycho's vast bulk of numerical/observational data to his three simple, phenomenological laws of planetary motion
- Issac Newton (1642-1727) ***reduced*** Kepler's laws to basic, universal laws of motion and gravitation

The Definition of Water

- Leonardo da Vinci (1513, *Il Codice Arundel.*) attempted to define the essential properties of water and encountered great difficulties and ambiguities ("colorless, odorless, tasteless liquid" etc)
- The problem received substantial attention and generated controversy among medieval alchemists:
  - Physical properties
  - Biological properties
  - (Al)chemical properties (*phases, ability to dissolve solids*)
- Sea water versus sulfuric acid ??
- All issues later conclusively resolved by ***reductionist*** atomic and molecular theory $\Rightarrow H_2O$

Modern Fundamental Physics ≈ Reductionist Description of Reality



- Molecular theory
- Atomic theory
- Quantum theory
- Nuclear Theory
- QED
- Quark models
- Standard Model
- String Theory
- …

Philosophical & Scientific Implications of Reductionism

- "understanding of a complex system's constituent parts (and their interactions) is sufficient for an understanding of the system as a whole"
- In principle, it is possible to know everything about the world in terms of an objective, impersonal underlying microscopic reality, *i.e.*, Descartes' clockwork universe
- Apparently incompatible with "free will"
- Apparently incompatible with "meaning" or "purpose"
- Apparently incompatible with normative values
- *But also the key to scientific understanding*

Four proprietary slides on fMRI and neuroscience removed here.

Practical limitations of Reductionism

- Analytic solutions too difficult
- Numerical computation too demanding
- Excessive data requirements/volumes
- Quantum effects produce inherent randomness
- Chaos - exponential sensitivity to initial conditions

However, none of these practical issues much affect the philosophical implications of reductionism or its effectiveness as an approach to science.

Are there any other limitations of a more fundamental or philosophical import?

Langton's Ant

- A cellular automata (C. Langton, 1980s)
- Rules/definition of Langton's Ant:
  - Moves in an infinite cartesian grid of cells
  - Each cell can be in 2 states (white or black)
  - Ant enters a cell & turns left by 90° if cell is white
  - Ant enters a cell & turns right by 90° if cell is black
  - Ant then advances one cell
  - State (color) of cell switches when the Ant exits it
- It is a *perfectly reductionist* world: simple & known "law", no chaos or QM, precisely determined by its initial conditions, time reversible, easy to compute, …

http://mathworld.wolfram.com/LangtonsAnt.html

Ant Animations

But first, your predictions please!

Keep it simple to make it easier.

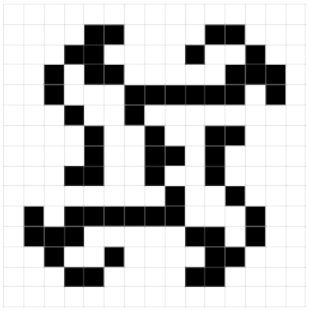
Start with a pure (all white) initial state:

http://www.math.ubc.ca/~cass/www/ant/ant.html

Let's go a bit faster:

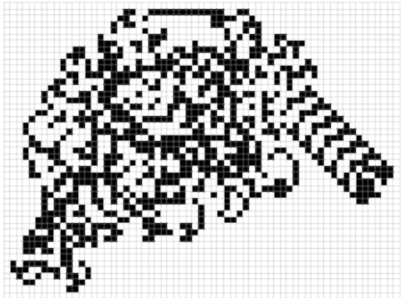
http://www.tiac.net/~sw/LangtonsAnt/LangtonsAnt.html

A Nearly Perfect Four-fold Symmetric State (Step Number 386)



Symmetry soon disappears; short term behavior is complex, asymmetric, and shows no apparent patterns but is not stochastic in any sense (perfectly deterministic).

A Highway to Nowhere (Step Number 10,647)

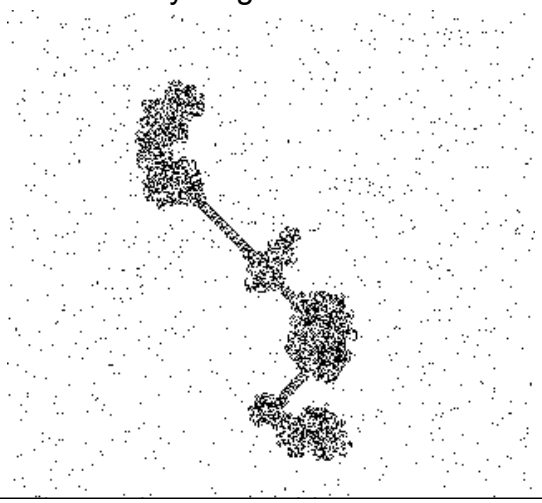


Long term behavior (after ~10^4 steps) is precisely regular and repetitive. The ant builds an infinite "highway" by repeating the same 104-step pattern with a diagonal shift recursively. But the same simple reductionist "law" produces both behaviors!

Addition of “dirt” (scattered black cells)

- Believed to always build a “highway” eventually
- Sometimes only after an extremely long interval
- But an open question

A 1% random dirt case.



Reductionism Strikes Back!

The Cohen-Kong Theorem: The Ant’s trajectory is unbounded.

C-K proven by assuming a bound trajectory exists and showing that this leads to a logical contradiction.

Illuminates the nature of explanation and understanding

However, C-K does not explain, predict or guarantee “highways” although highways appear to be the way The Ant satisfies C-K in nearly all, perhaps every, case.

Generalized Langton's Ants
(Gants or Glants)

Multi-state ants (colors), arbitrary number

Rule specified by a binary string

C-K applies if the rule contains both 1's and 0's

http://wphooper.com/visual/langtons_ant/ant/applet.html

Turing Limits on Reductionism

Langton's Ant is a 2-D 4-State Turing Machine

"Dirt" is the program and the data

Proven to contain undecidable questions

Turing "Halting problem" is a concrete example

Many others are known

Uncountably many exist

Why Is The Ant's Behavior So Complex Despite It's Simple Reductionist "Law"?

- Best reductionist answer: It just is; nothing at all is going on except The Ant is following its "law"…*true by construction!* Thus, nothing more may/need be said.
- A non-reductionist answer: Complex behavior *emerges* generically in systems for which past states affect current changes of state, *i.e.*, in systems with "memory".

Conclusions

- *Emergence* can make a reductionist hell out of even its most perfect and pristine heavens.
  - Understanding a system perfectly at its ultimate ***reduced*** level can leave interesting questions unanswered.
  - Some questions may be impossibly difficult to answer in practice or even impossible to answer in principle.
  - Computation is a powerful tool for exploring complex systems but, by itself, not for explaining or understanding them.
- Real world fundamental laws and systems, in which "memory" of previous states is a generic feature, are likely to be far less accessible to reductionism than simple constructed/computational ones.

Speculation:

The long term future of science will eventually see reductionism's usefulness saturate (dwindle) at its research frontiers in an ever increasing number of disciplines.