Emergence and Discovery

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Slides in part based on:
“Types and Forms of Emergence”, J. Fromm, Universität Kassel.

Outline

- Emergence
- Types of emergence
- Scientific Discovery
- Examples

Emergence

Definition

Emergence is the observation of an effect without an apparent cause

A property of a system is emergent if it is not a property of any fundamental element of the system. Emergence is the appearance of emergent properties on higher levels of organization or complexity.

Properties

Emergent properties are:

- Irreducible (i.e., not properties of the constituents)
- Nonlinear (i.e., “more is different”)
- undeducible (from the system constituents)
- causal

Examples

Classes of complex systems capable of emergence:

- cellular automata
- interacting particle systems
- many-agent systems

Classes of Emergence

- Type 1: **Simple/nominal emergence** (only feedforward interactions, no feedbacks; fixed roles)

- Type 2: **Weak emergence** (simple positive or negative feedbacks; dynamic roles)

- Type 3: **Multiple emergence** (learning and adaptation; randomly fluctuating roles)

- Type 4: **Strong emergence** (state explosion, not even in principle predictable; entirely new role system)

Type 1

- Type 1a: Simple intentional emergence
- Type 1b: Simple unintentional emergence

Only feedforward (i.e., top-down) interactions.

Fixed roles (i.e., behavior of every part is independent of the other parts' states and of the environment)

Type 1a - Examples

- Intended function of a designed machine
- Function of a software system emergent from its source codes
- Meaning of a sentence emergent from the words and letters
- Planned command economy
- Clocks, steam engines, computer networks, …

Type 1b - Examples

- Statistical properties of a large collection of particles **that do not make sense for a single particle**

- Thermodynamic properties (pressure, temperature, entropy, …) emergent from gas molecules

- Shortest path lengths and node clustering emergent from network architecture

- Wave front speed of an avalanche

- Turing patterns

Type 2

- Type 2a: Stable weak emergence
- Type 2b: Unstable weak emergence

Simple feedback (i.e., bi-directional) interactions. No unique direction of causality.

Dynamic roles (i.e., behavior of a part may depend deterministically on the states of other parts)

Type 2a

- Multi-Agent Systems

- Weakly emergent properties can only be derived by simulating the system from its parts.

- Stable = balance between exploration (diversity) and exploitation (unity)

- Exploration (creativity): bottom-up from autonomous components.

- Exploitation (constraints): top-down feedback from the collective

Type 2a - Examples

- Open-Source projects like Linux, Mozilla, etc.
- The World Wide Web, Wikipedia, …
- Prices of goods in a free-market economy driven by supply and demand
- Shoal of fish, flock of birds, swarms of insects, … (the “flocking trick” — direct multilateral interaction)
- ant colonies, bee hives, … (the “pheromone trick” — interactions through environment)

Type 2b

- No balance between exploration and exploitation, but vicious circles

- Positive feedbacks (high wages lead to high prices, which in turn lead to higher wages)

- Imitation (leading to fashion/trends)

- Distributed decision making in small-world networks (doing what the neighbors do)

- Economy of increasing returns (emergence of lock-in states. e.g., PC keyboard layout, Microsoft Windows)

Type 2b - Examples

- Market crashes, bubbles, and inflation in free-market economies
- Sudden outburst of social unrest (changes in previously stable social norms)
- “celebrity effect” (famous for being well known)
- Socioeconomic cluster formation (slums, gentrification)
- (Drug) addiction

Type 3

- Type 3a: Stripes, Spots, and Bubbling
- Type 3b: Tunneling, Adaptation

Learning and adaptation (“intelligent agents”).

Fluctuating roles (i.e., behavior of a part may depend stochastically on the states of other parts or on the environment)

Type 3a

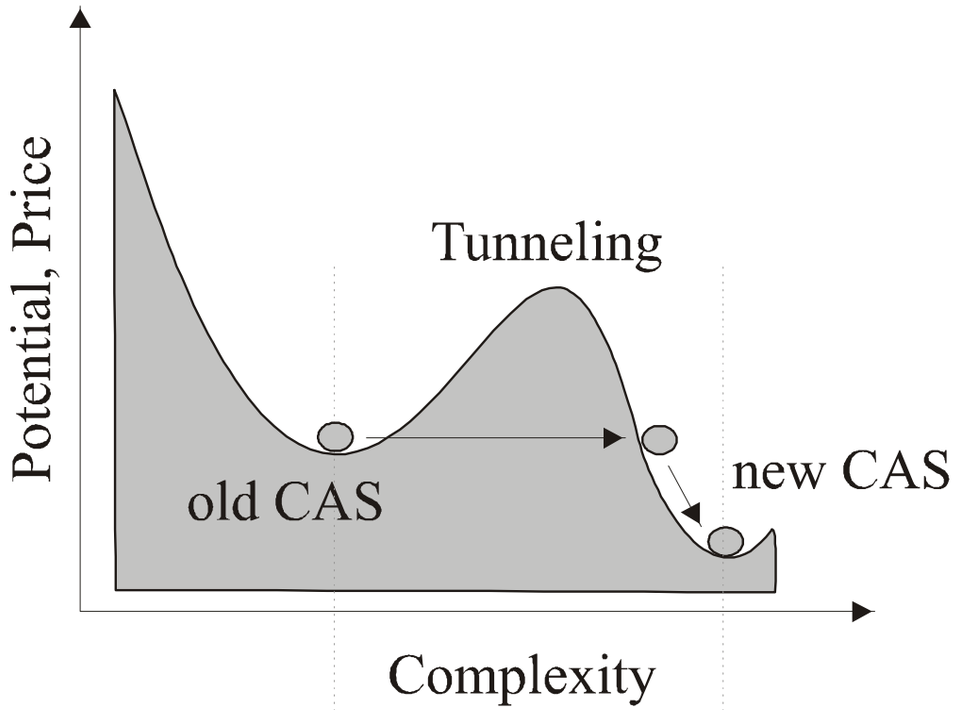
- Adaptive, intelligent agents behaving in a non-deterministic way
- Often combination of short-term positive feedback (immediate imitation) and long-term negative feedback (desire to be different/unique)
- Unpredictable runs of successive wins and losses
- Cooperation with occasional cheaters

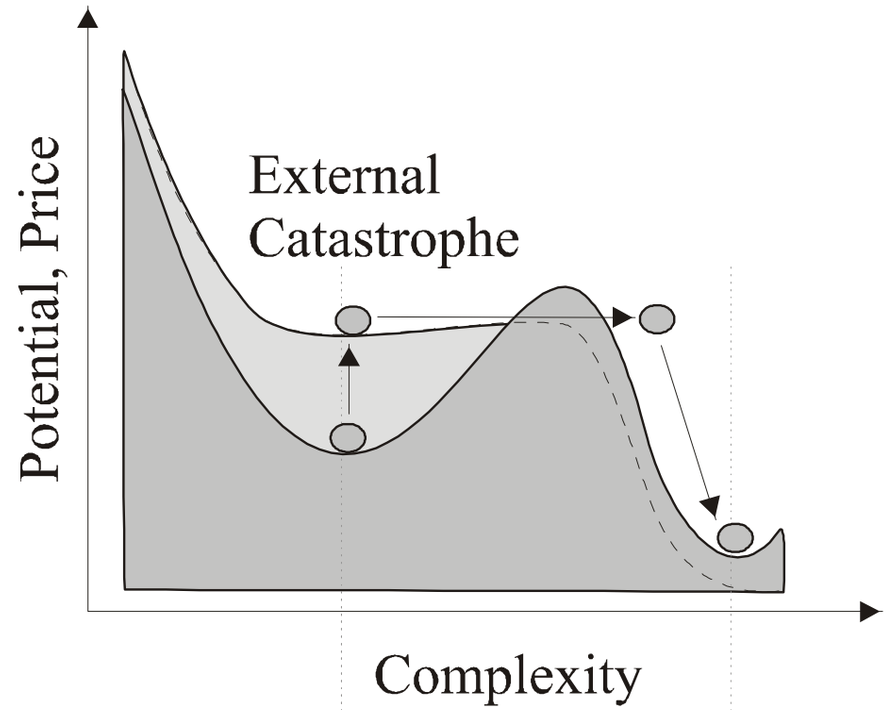
Type 3a - Examples

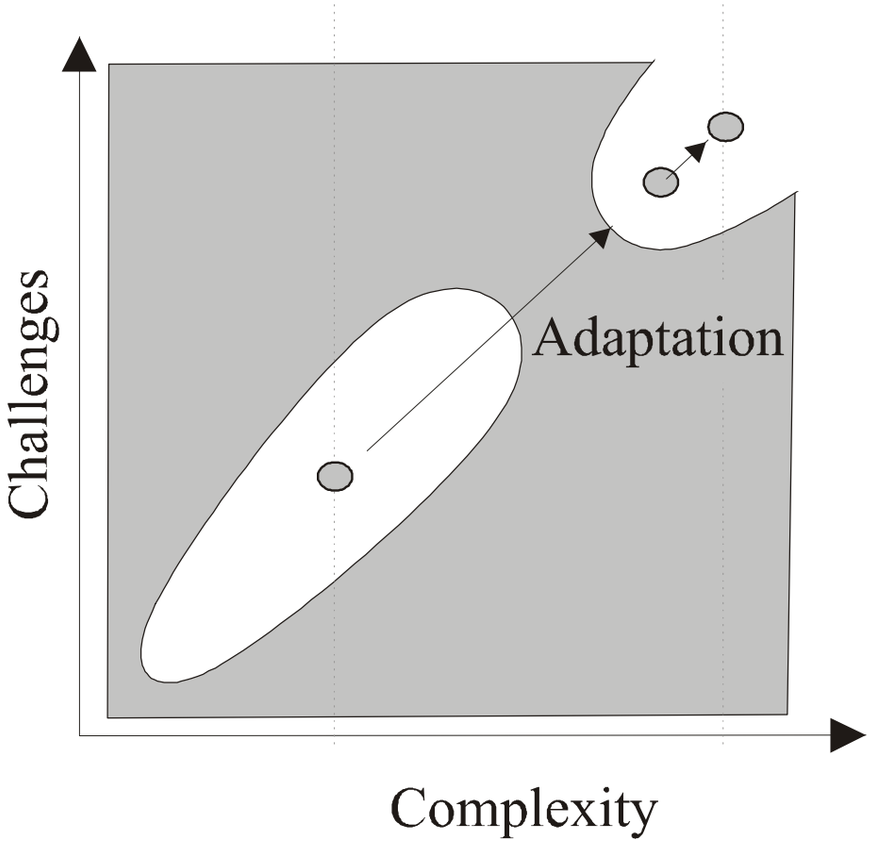
- Stochastic cellular automata (e.g., Conway's Game of Life) leading to the emergence of patterns ("space ships") that move stereotypically.
- Stock markets: fractal and multi-fractal structures
- Chaos
- Behavior of groups of people

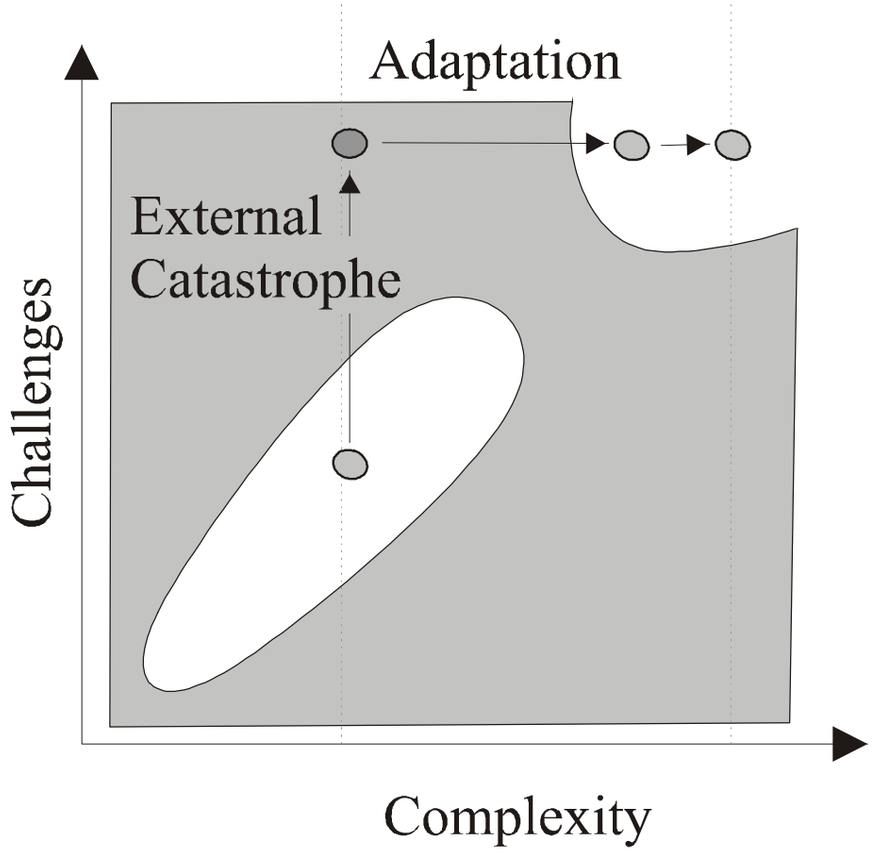
Type 3b

- Complex adaptive systems with multiple nested feedbacks
- An emergent behavior that has been suppressed suddenly breaks through (tunneling)
- External catastrophe (large impact from environment) catapults the system to a new state funnel
- The system adapts and develops new roles









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Type 3b - Examples

- Mass extinction in evolution (evolutionary transitions)
- Natural disasters (volcanoes, earthquakes)
- scientific / mental revolutions (“enlightenment”, quantum physics)
- political revolutions (triggered by catastrophe, mental revolutions, or tunneling)
- jokes (laughter emergent as brain overcomes cognitive dissonance)

Type 4

Combinatorial explosion in the number of possible system behaviors.

Roles theoretically unpredictable.

“Supervenience”

Type 4

- Emergence of truly novel properties, which cannot, even in principle, be deduced from the system description.

- Does not violate the laws of physics (i.e., it no magic)

- Often characterized by the appearance of new replicators (e.g., new genes, new languages), new forms of evolutions (cultural evolution, medical evolution), and enormous numbers of combinations

- Breaking Bremermann's Limit (computing 10^{120} bits would require the age of the universe and the energy of all mass in the universe)

Type 4 - Examples

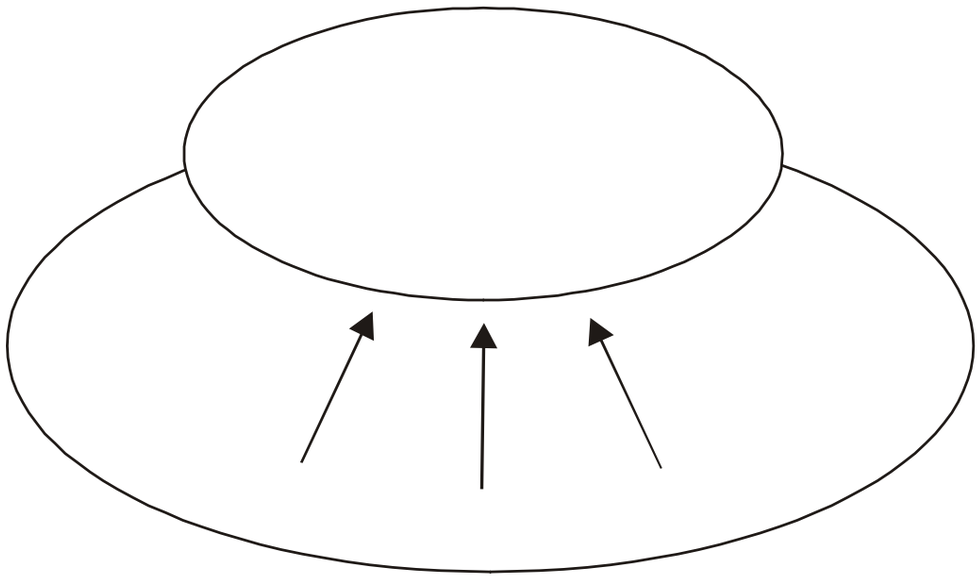
- Life (emerging from genes, biomolecules, etc.). A protein of length 100aa has 20^{100} sequences

- Culture (any text with more than 25 words breaks the Bremermann Limit)

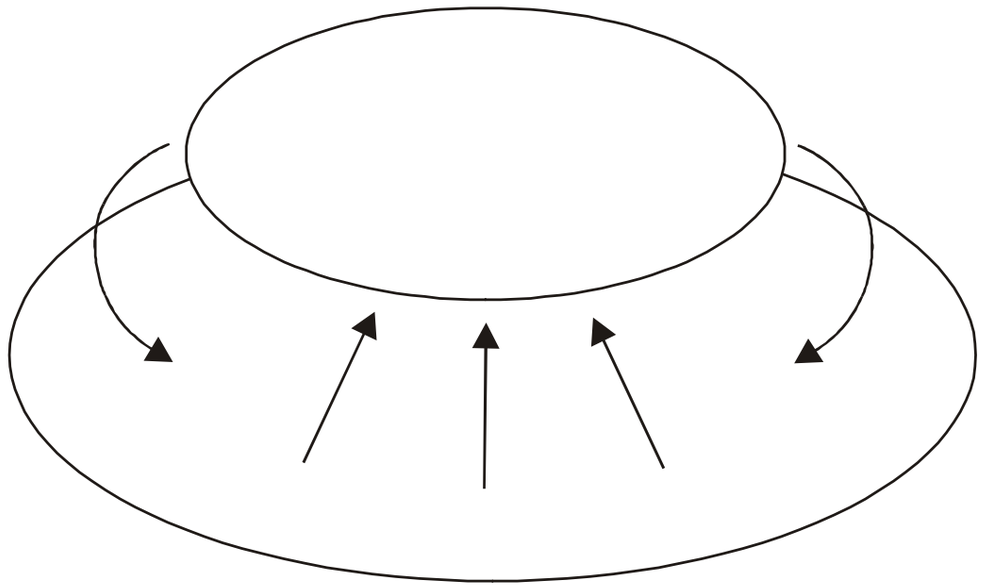
- Intelligence (emerging from the neurons of the brain)

- Creativity (emerging from what??)

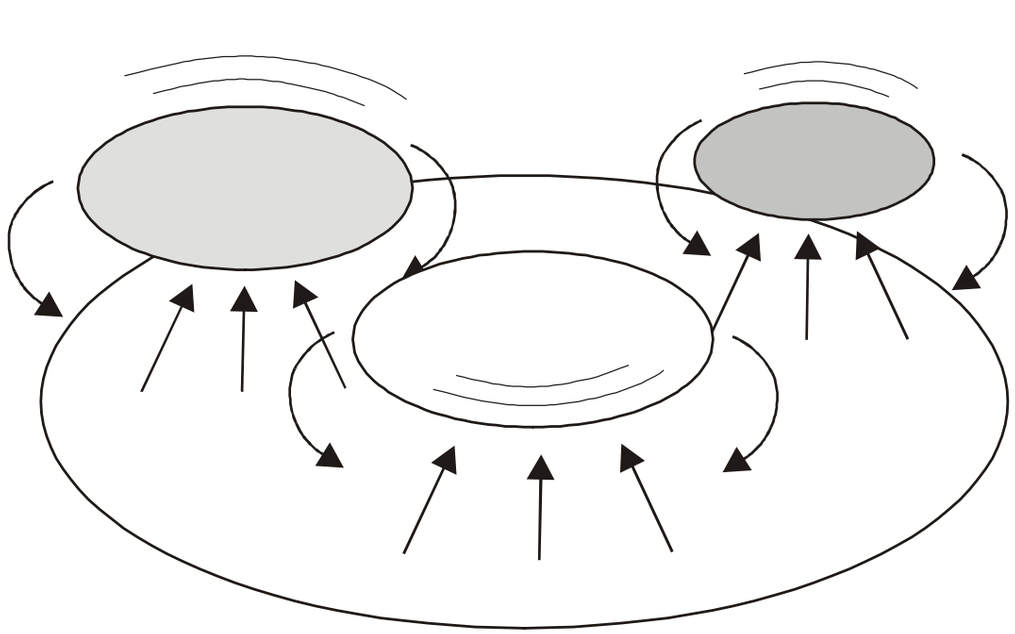
- Universal Turing Machines



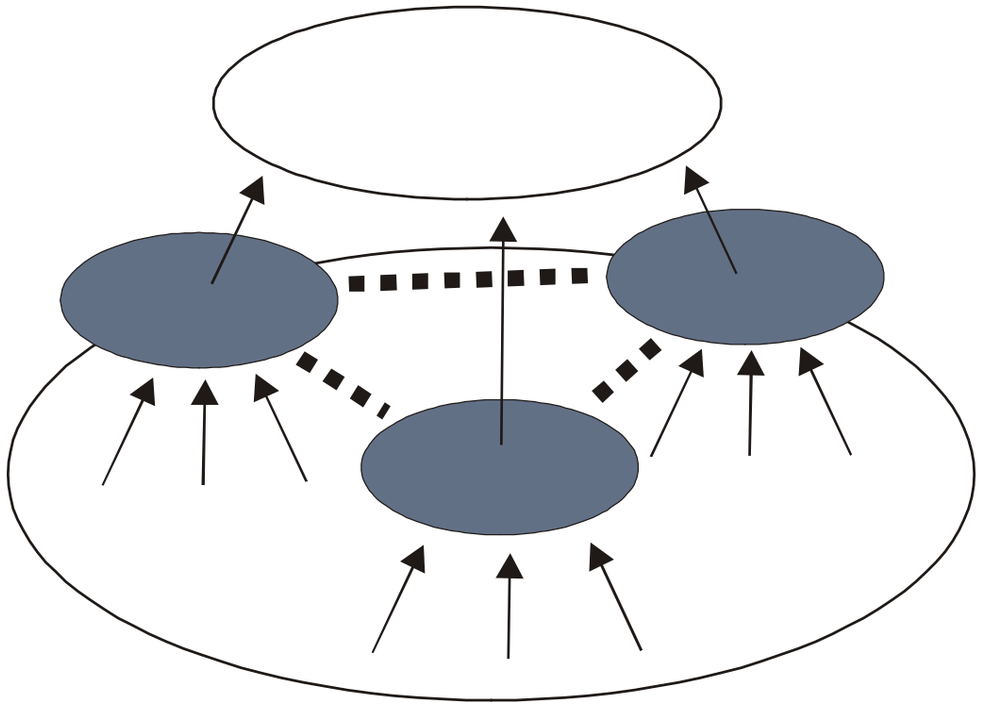
TYPE I
Simple Emergence



TYPE II
Weak Emergence



TYPE III
Multiple Emergence



TYPE IV
Strong Emergence

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Discovery

Definition

Discovery is the realization, design, or explanation (i.e., reduction) of emergence.

Discovery of a new design of (typically type 1a) emergence: Invention.

Discovery of an explanation of emergence (how, from what, when?): mechanistic insight.

Discovery of a new realization of emergence: new idea or new observation.

Types of discovery

- **new idea**: a non-rational leap of insight
    - Founding a new theory (e.g., relativity, quantum, topology, evolution, …)
    - Inventing a new kind of machine (steam engine, semiconductors, …)
    - First observation of something (Brownian motion, exoplanets, atoms, …)

- **justification**: systematic application of criteria to knowledge
    - Identifying the function of a gene
    - Finding a new molecular structure
    - Proving a theorem
    - Optimizing a design

Elements of discovery

- **Insight (“Eureka! moment”)”** Often accidental, but chance favors the prepared mind

- **Development:** collecting the facts under a common formulation, putting into context

- **Testing:** proving, falsifying, supporting, demonstrating

- **Articulation:** formulating, publishing, communicating

Processes of discovery

- **Creativity:** formulating a new idea or hypothesis *de novo*
- **Analogy:** explanation by similarity/dissimilarity to a known phenomenon
- **Deduction:** formulation of novel facts in a closed logical system (e.g., probability theory)
- **Accident:** happening to be the first to observe something or realize an observation is surprising/unexplained

Questions

- Is applying a known concept to a new system a discovery?

- Is an invention a discovery or an application? (Newcomen & Watt invented the steam engine, but did not discover the laws of thermodynamics)

- Are there disciplinary differences in what constitutes an invention?

- Which parts of discovery can be automated using data mining or machine intelligence?

Expl.: design

- The microprocessor
- Calculus
- The page-rank algorithm
- Convolutional deep neural nets
- TCP/IP
- the Conjugate Gradient method

Expl.: explanation

- Statistical learning theory
- A biochemical signaling pathway
- semiconductor physics
- molecular dynamics simulations
- thermodynamics
- the geometric interpretation of conjugate gradients

Expl.: realization

- the Turing machine
- von-Neumann architecture
- quantum physics (observation of the photo-effect)
- invention of probability theory
- our solar system
- the concept of Conjugate directions

Interrelations

- New designs often enable new realization or explanations (the telescope enabled the realization of planets, calculus enabled the explanation of thermodynamics)

- New designs are often inspired by new explanations (semiconductor physics —> microprocessor) or motivated by new realizations (Turing machine —> Algorithms)

- The three are often different faces of the same (conjugate gradients — the concept, the algorithm, the explanation)

- The three often form a hierarchy from “fundamental” to “useful” (probability theory —> statistical learning —> deep neural nets)