GRANULAR MATERIAL AND SELF ASSEMBLY

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What are granular materials?

A granular material is a collection of distinct macroscopic particles, such as sand in an hourglass or peanuts in a container. The evolution of the particles follows Newton's equations, with repulsive forces between particles that are non-zero only when there is a contact between particles. Although granular materials are very simple to describe they exhibit a tremendous amount of complex behaviour, much of which has not yet been satisfactorily explained. They behave differently than solids, liquids, and gases which has led many to characterize granular materials as a new form of matter.

Granular Material

- Conglomeration (aggregate) of discrete solid, macroscopic particles characterized by a loss of energy whenever the particles interact (Example: friction when grains collide).
- the lower size limit for grains in granular material is about 1 μm.
- On the upper size limit, the physics of granular materials may be applied to ice floes where the individual grains are icebergs and to asteroid belts of the Solar System with individual grains being asteroids.
- According to material scientist Patrick Richard, "Granular materials are ubiquitous in nature and are the second-most manipulated material in industry (the first one is water)".


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Patter forming behaviour of granular material

- un-mixing or segregation of unlike grains under vibration and flow (Brazil nut effect – Granular convection or granular separation).
- formation of surface patterns (stripes, squares and hexagons) in vibrated granular layers. These patterns are thought to be composed of fundamental excitations of the surface known as oscillons.
- formation of sand ripples, dunes, and sandsheets.
- Granular materials discharged from silos produce loud acoustic emissions in a process known as silo honking.

Static and driven granular systems behave in many ways like thermal glassy systems. However, they also show **phenomena like arching and force chains as well as shear thickening and avalanches which demonstrates that their properties are also affected by unique many-particle effects**.

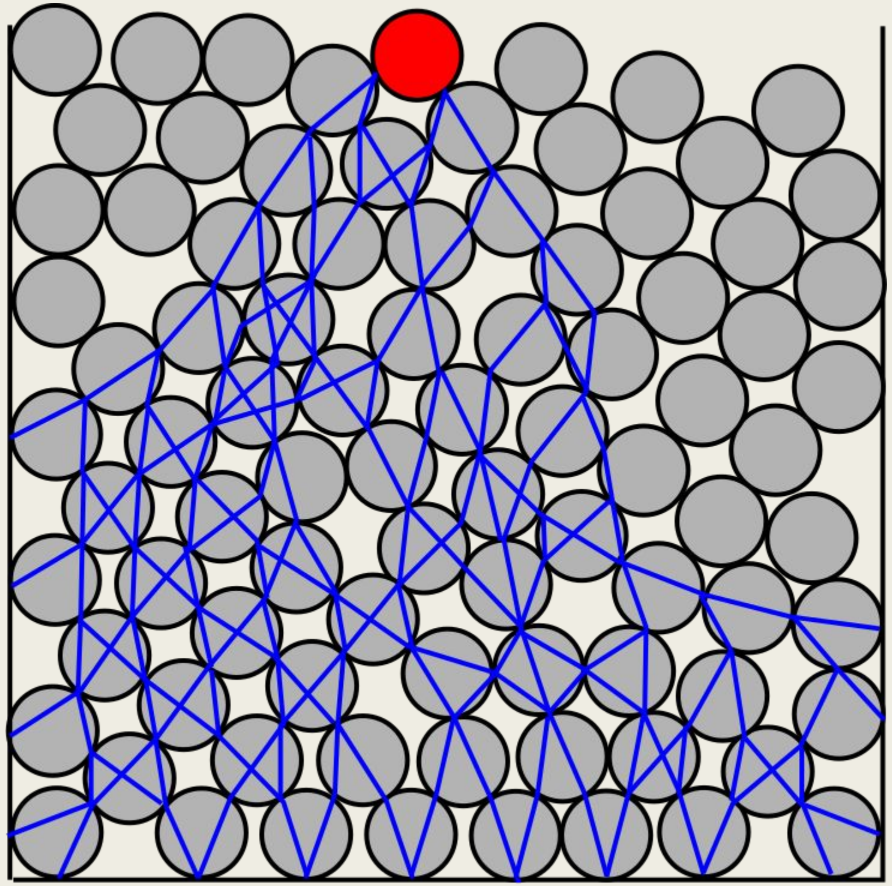
Although there are a multitude of studies on the macroscopic properties of granular systems, only few investigations have probed in three dimensions (3D) their structure and dynamics on the level of the particles because of the experimental difficulty to determine the position and orientation of the particles.

In some sense, granular materials do not constitute a single phase of matter but have characteristics reminiscent of solids, liquids, or gases depending on the average energy per grain. However, in each of these states granular materials also exhibit properties which are unique.

Pour sand from a bucket, and it flows like a liquid—but stand on it, and it supports weight like a solid.

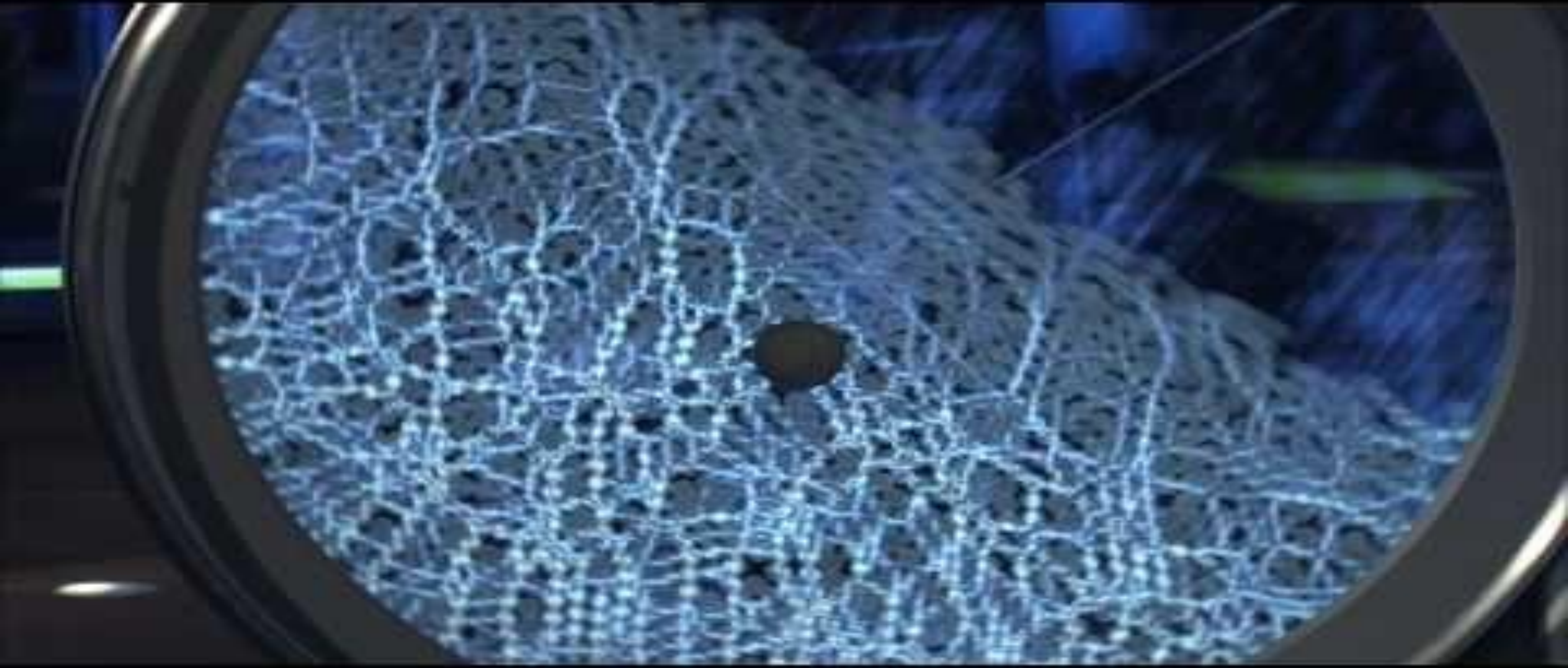
Granular solids

- average energy of the individual grains is low and the grains are fairly stationary relative to each other.
- The fact that particles within the strong force network are usually correlated in a line–line mode over distances of several particle diameters leads to the so-called “force chains” - linear paths of contacting grains which carry stress.



Force Chains and Stress in Granular Materials

- “force chains” are linear paths of contacting grains which carry stress.
- The propagation of stress in granular materials remains a challenge to scientists, particularly in the limit of very hard grains.
- When a load is applied to a dense granular material, the stress is largely transmitted by relatively rigid, heavily stressed chains of particles forming a sparse network of larger contact forces.
- Force chains act as the key determinant of mechanical properties such as **stability, elasticity and flowability.**



Granular gases

- If the granular material is driven harder such that contacts between the grains become highly infrequent, the material enters a gaseous state.
- Granular gases can be kept in a statistically stationary state by means of an external forcing. In experiments, this forcing is realized with shear strains, shaking, air fluidization, and so on.
- **Unlike conventional gases, granular materials will tend to cluster and clump due to the [dissipative] nature of the collisions between grains.**
- For example, if a partially partitioned box of granular materials is vigorously shaken then grains will over time tend to collect in one of the partitions rather than spread evenly into both partitions as would happen in a conventional gas.
- **This effect does not violate any thermodynamics principles since energy is constantly being lost from the system in the process.**

Emergent Properties

- An **emergent property** is a **property** which a collection or complex system has, but which the individual members do not have.
- Example: The taste of saltiness is a property of salt, but that does not mean that it is also a property of sodium and chlorine, the two elements which make up salt. Thus, saltiness is an emergent or a supervenient property of salt. Claiming that chlorine must be salty because salt is salty would be an example of the fallacy of division.
- Example: Heart is made of heart cells, heart cells on their own don't have the property of pumping blood. You will need the whole heart to be able to pump blood. Thus, the pumping property of the heart is an emergent or a supervenient property of the heart. Claiming that an individual heart cell can pump blood because the heart can would be an example of fallacy of division.

Emergent Property

Different neurons work together to function as a brain. These neurons, on their own, are incapable of doing so.

Emergent properties of a granular pack

- **void size distribution and connectivity correlate well with permeability to flow**, which is relevant to underground water, pollutant dispersion and oil extraction.
- catalysis and heat exchange between the grains and a fluid in the void space are more sensitive to the solid-void surface distribution.
- **The mechanics of granular solids is governed by an interplay between the structure and the force transmission through the intergranular contacts.**

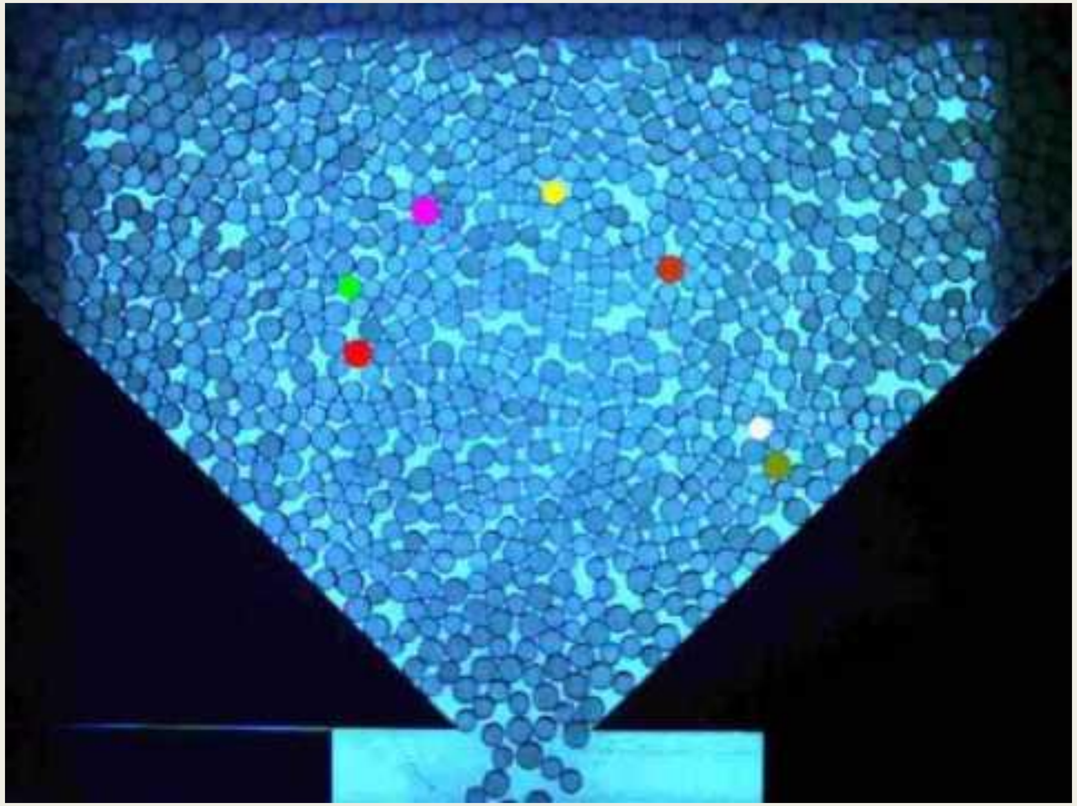
Granular flow concerns the collective motion of macroscopic particles. These flows are of interest for nonequilibrium physics and have many engineering applications. Continuum models describe average flows of granular materials but cannot describe particle-scale details. However, these microscopic details are often important to the unique nature of granular flow.

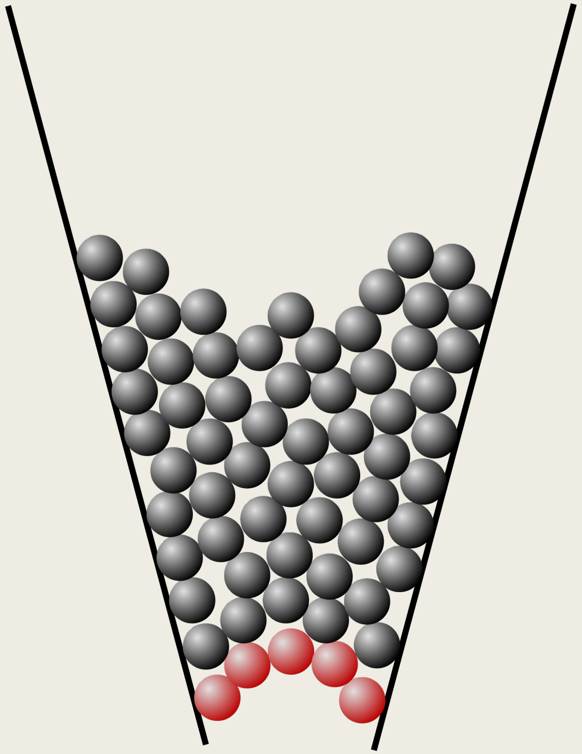
For example the particle-scale effects result in “jamming” of hopper flow in case of grains which are granular material.

How granular materials jam in a hopper?

(J. Tang and R. P. Behringer Department of Physics and Center for Nonlinear and Complex Systems, Duke University, Durham, North Carolina 27708, USA)

- We study 2D hopper flow by high-speed video of gravity driven flow for roughly 5000 photo elastic particles (bidisperse, average d¼ 5.3 mm) confined between a pair of Plexiglas sheets, with slanted aluminium walls on the sides to form the 2D hopper geometry.
- When jamming occurs, **there is always a stable arch across the outlet**. Particle tracking allows us to see which particles form the jamming arch.
- The **occurrence of the arch is random**, in as much as it is impossible to predict which set of particles will form the arch.
- The jamming particles come from roughly **the same radial initial positions**, but from a range of **different angular positions**.





Why granular material are important?

- Granular materials are special because they are non-equilibrium materials—unlike crystalline materials, they will never be able to reach their optimal state of packing.
- Granular materials have been used as a model system to help scientists study materials that behave similarly, like glass, which is structurally like a liquid, but behaves like a solid.
- There exists a property called “jamming,” which describes the transition from liquid- to solid-like behaviour in granular material. A traffic jam is one familiar example of this phenomenon—cars will flow smoothly until a phase transition occurs, and gridlock descends.

Let’s talk about integrating the property of jamming in robots - Robots are typically made of rigid structures, **but jamming robots can become soft, reshape themselves, and become hard again**. One application the group has worked on is a **robotic gripper**. Instead of stiff fingers, which may have trouble grasping complex shapes, a soft gripper can be used to mould around an object, and jamming can then be induced to tighten its grip.

Fascinating, isn’t it?

(Heinrich Jaeger, the William J. and Alicia Townsend Friedman Professor in Physics, has chosen to focus on these types of materials in his research)

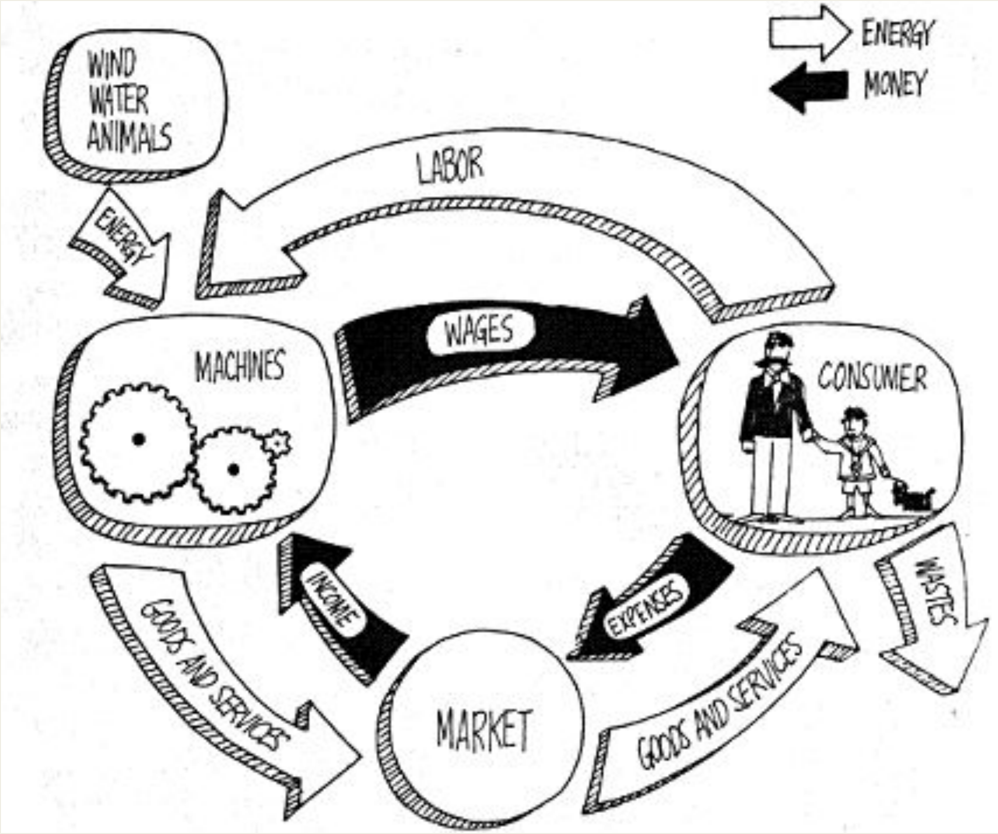
Granular material exhibit pattern forming behaviour when excited and under such an excitation granular material can be thought of as an COMPLEX SYSTEM.

COMPLEX SYSTEM

The most famous quote about Complex Systems comes from Aristotle who said that "**The whole is more than the sum of its parts**".

Complex systems are systems where the collective behaviour of their parts entails emergence of properties that can hardly, if not at all, be inferred from properties of the parts.

Examples of complex systems include ant-hills, ants themselves, human economies, climate, nervous systems, cells and living things, including human beings, as well as modern energy or telecommunication infrastructures, Weather, living organisms, ecological systems, social systems, organizations, human health care system.



A complex system is any system featuring a large number of interacting components (agents, processes, etc.) whose aggregate activity is nonlinear (not derivable from the summations of the activity of individual components) and typically exhibits hierarchical self-organization under selective pressures.

Complexity
Theory
1

Self Assembly

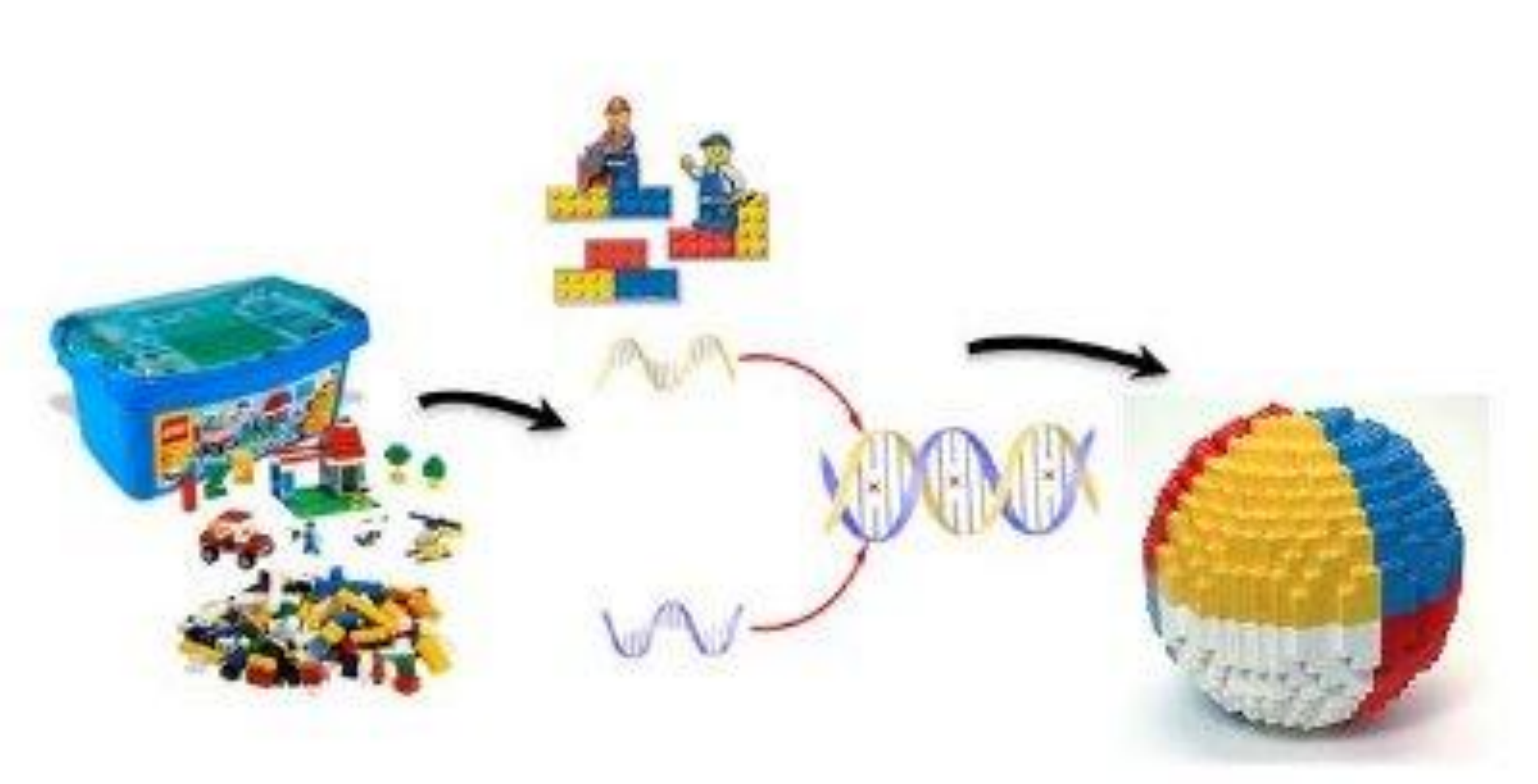
- **Self-assembly** is a process in which a disordered system of pre-existing components forms an organized structure or pattern as a consequence of specific, local interactions among the components themselves, without external direction.
- When the constitutive components are molecules, the process is termed molecular self-assembly.
- Self-assembly is the autonomous organization of components into patterns or structures without human intervention.
- Self-assembling processes are common throughout nature and technology. They involve components from the molecular (crystals) to the planetary (weather systems) scale and many different kinds of interactions. The concept of self-assembly is used increasingly in many disciplines, with a different flavour and emphasis in each.

There are several reasons for interest in self-assembly:

- Humans are attracted by the appearance of order from disorder.
- Living cells self-assemble, and understanding life will therefore require understanding self-assembly. The cell also offers countless examples of functional self-assembly that stimulate the design of non-living systems.
- It is one of the few practical strategies for making ensembles of nanostructures. It will therefore be an essential part of nanotechnology.
- Manufacturing and robotics will benefit from applications of self-assembly.
- It is common to many dynamic, multicomponent systems, from smart materials and self-healing structures to netted sensors and computer networks.

- The focus on spontaneous development of patterns bridges the study of distinct components and the study of systems with many interacting components. It thereby connects reductionism to complexity and emergence.

- The most famous example of self-assembly phenomenon is the occurrence of the life on Earth. It is plausible to hypothesize that it happens because the sun generates a strong temperate gradient in its environment. This general idea has been confirmed in the experiment of self-assembly of carbon nanotubes.



“Self-assembly” is not a formalized subject, and definitions of the term “self-assembly” seem to be limitlessly elastic. As a result, the term has been overused to the point of cliché. Processes ranging from the non-covalent association of organic molecules in solution to the growth of semiconductor quantum dots on solid substrates have been called self-assembly.

Types of self assembly

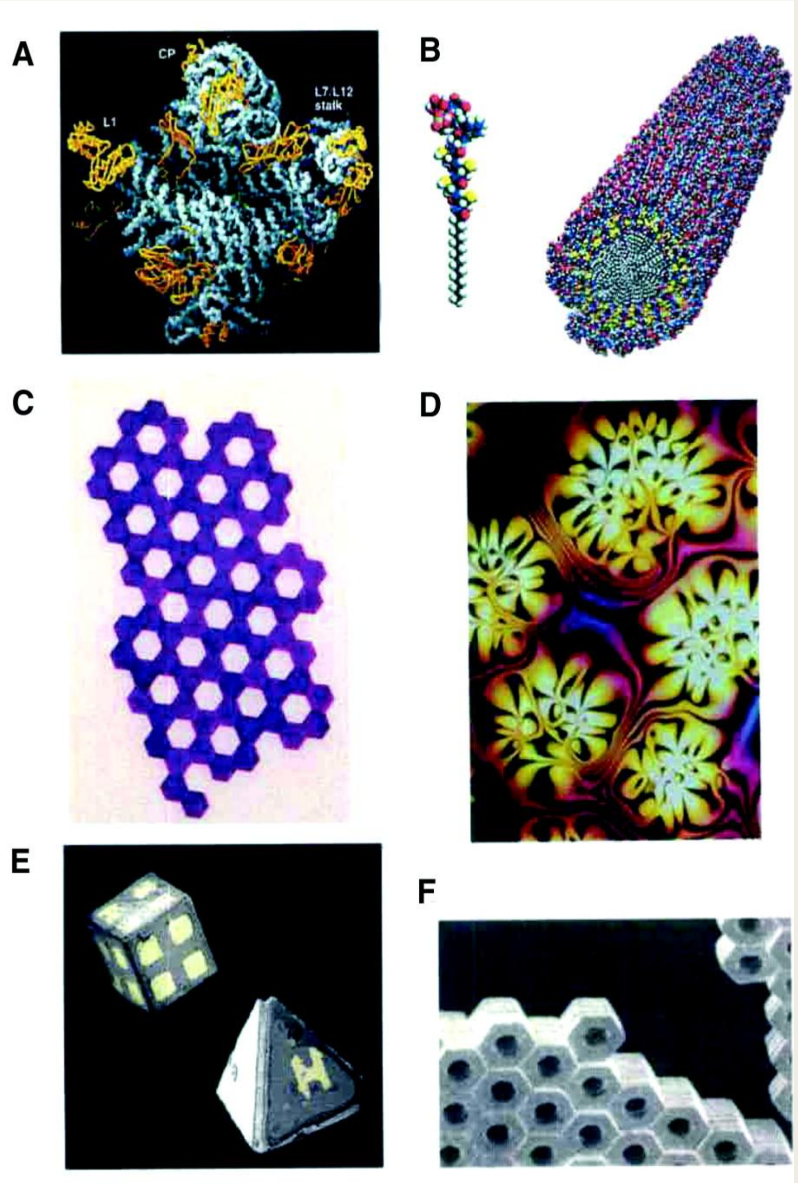
There are two types of self assembly :

Static self assembly and **Dynamic self assembly**

Static self assembly

- In *static* self-assembly, the ordered state forms as a system approaches equilibrium, reducing its free energy.
- Static self-assembly involves systems that are at global or local equilibrium and do not dissipate energy.
- For example, molecular crystals are formed by static self-assembly; so are most folded, globular proteins. In static self-assembly, formation of the ordered structure may require energy (for example in the form of stirring), but once it is formed, it is stable.
- Most research in self-assembly has focused on this static type.

EXAMPLES OF STATIC SELF ASSEMBLY



(A) Crystal structure of a ribosome.

(B) Self-assembled peptide-amphiphile nanofibers.

(C) An array of millimetre-sized polymeric plates assembled at a water/perfluoro decalin interface by capillary interactions.

(D) Thin film of a nematic liquid crystal on an isotropic substrate.

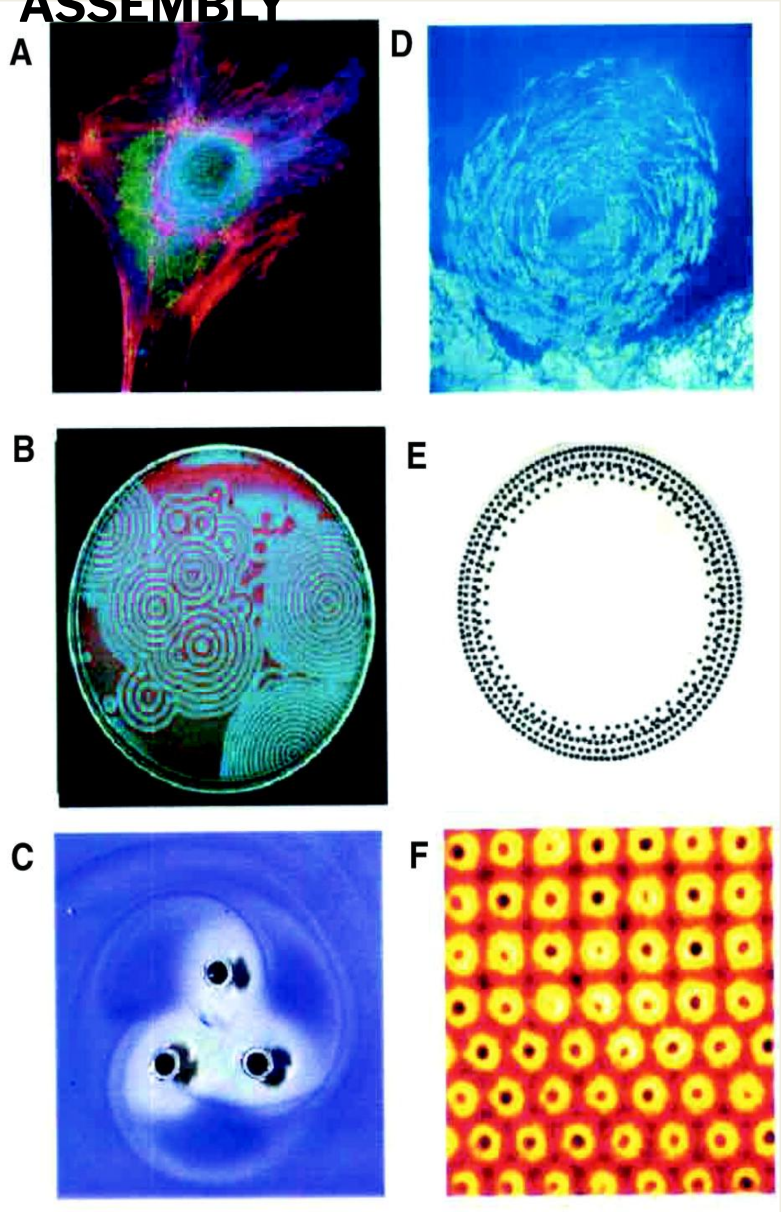
(E) Micro meter-sized metallic polyhedra folded from planar substrates.

(F) A three-dimensional aggregate of micro meter plates assembled by capillary forces.

Dynamic self assembly

- patterns of pre-existing components organized by specific local interactions are not commonly described as "self-assembled" by scientists in the associated disciplines. These structures are better described as "self-organized", although these terms are often used interchangeably.
- In dynamic self-assembly the interactions responsible for the formation of structures or patterns between components only occur if the system is dissipating energy.
- The patterns formed by competition between reaction and diffusion in oscillating chemical reactions are simple examples; biological cells are much more complex ones. The study of dynamic self-assembly is in its infancy.

EXAMPLE OF DYNAMIC SELF ASSEMBLY



(A) An optical micrograph of a cell with fluorescently labeled cytoskeleton and nucleus; microtubules (~24 nm in diameter) are colored red.

(B) Reaction-diffusion waves in a Belousov-Zabatinski reaction in a 3.5-inch Petri dish.

(C) A simple aggregate of three millimeter-sized, rotating, magnetized disks interacting with one another via vortex-vortex interactions.

(D) A school of fish.

(E) Concentric rings formed by charged metallic beads 1 mm in diameter rolling in circular paths on a dielectric support.

(F) Convection cells formed above a micropatterned metallic support.

Self Assembly Vs Self Organization

- People regularly use the terms "self-organization" and "self-assembly" interchangeably. As complex system science becomes more popular though, there is a higher need to clearly distinguish the differences between the two mechanisms to understand their significance in physical and biological systems.
- Both processes explain how collective order develops from "dynamic small-scale interactions", according to an article in a November/December 2008 issue of the journal *Complexity*. Self-organization is a non-equilibrium process where self-assembly is a spontaneous process that leads toward equilibrium.
- Self-assembly requires components to remain essentially unchanged throughout the process.
- Besides the thermodynamic difference between the two, there is also a difference in formation. The first difference is what "encodes the global order of the whole" in self-assembly whereas in self-organization these initial encodings are not necessary.

- Another slight contrast refers to the minimum number of units needed to make an order. Self-organization appears to have a minimum number of units whereas self-assembly does not. The concepts may have particular application in connection with natural selection.
- Eventually, these patterns may form one theory of pattern formation in nature.
- Self-assembly is pretty well understood, and it’s clear that at small length scales it is important in biology. Protein folding, for example, is a very sophisticated self-assembly process, and viable viruses can be made in the test-tube simply by mixing up the component proteins and nucleic acid.
- Self-organisation is much less well understood; it isn’t entirely clear that there are universal principles that underly the many different examples observed, and the relevance of the idea in biology is still under debate.

Other types of self assembly

- We define two further variants of self-assembly.

- In templated self-assembly (T), interactions between the components and regular features in their environment determine the structures that form.

- Crystallization on surfaces that determine the morphology of the crystal is one example, crystallization of colloids in three-dimensional optical fields is another. The characteristic of biological self-assembly (B) is the variety and complexity of the functions that it produces.

Common Features of Self-Assembly

- Self-assembly reflects information coded (as shape, surface properties, charge, polarizability, magnetic dipole, mass, etc.) in individual components; these characteristics determine the interactions among them.
- The design of components that organize themselves into desired patterns and functions is the key to applications of self-assembly.
- The components must be able to move with respect to one another. Their steady-state positions balance attractions and repulsions.
- Molecular self-assembly involves noncovalent or weak covalent interactions (van der Waals, electrostatic, and hydrophobic interactions, hydrogen and coordination bonds).

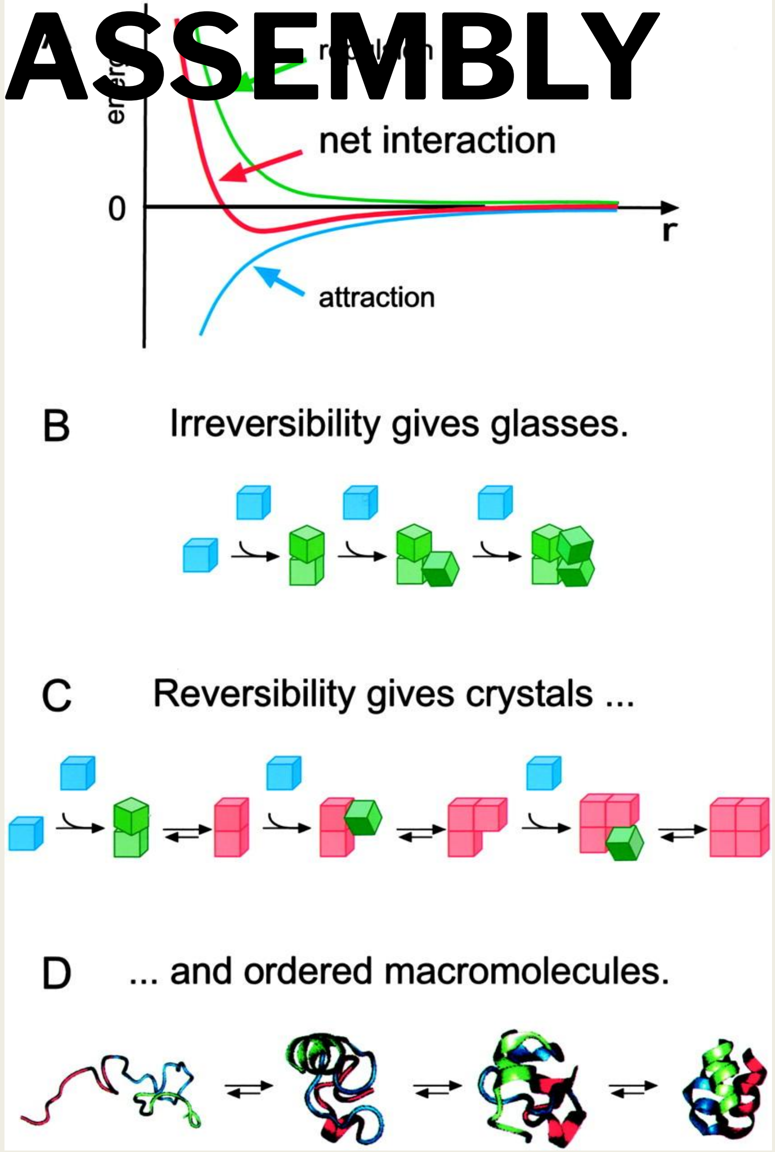
- In the self-assembly of larger components—meso- or macroscopic objects—interactions can often be selected and tailored, and can include interactions such as gravitational attraction, external electromagnetic fields, and magnetic, capillary, and entropic interactions, which are not important in the case of molecules.
- Because self-assembly requires that the components be mobile, it usually takes place in fluid phases or on smooth surfaces.
- The environment can modify the interactions between the components; the use of boundaries and other templates in self-assembly is particularly important, because templates can reduce defects and control structures.
- Equilibration is usually required to reach ordered structures. If components stick together irreversibly when they collide, they form a glass rather than a crystal or other regular structure.
- Self-assembly requires that the components either equilibrate between aggregated and non-aggregated states, or adjust their positions relative to one another once in an aggregate.

What makes self assembly a distinct concept?

- **Order:** First, the self-assembled structure must have a higher order than the isolated components, be it a shape or a particular task that the self-assembled entity may perform. This is generally not true in chemical reactions, where an ordered state may proceed towards a disordered state depending on thermodynamic parameters.
- **Interaction:** The second important aspect of SA is the key role of slack interactions (e.g. Van der Waals, capillary, hydrogen bonds) with respect to more "traditional" covalent, ionic, or metallic bonds. It can be instructive to note how slack interactions hold a prominent place in materials, especially in biological systems, For instance, they determine the physical properties of liquids, the solubility of solids, and the organization of molecules in biological membranes.

- **Building blocks**: The third distinctive feature of SA is that the building blocks are not only atoms and molecules, but span a wide range of nano- and mesoscopic structures, with different chemical compositions, shapes and functionalities. Research into possible three-dimensional shapes of self-assembling micrites examines Platonic solids (regular polyhedral). The term ‘micrite’ was created by DARPA to refer to sub-millimeter sized microrobots, whose self-organizing abilities may be compared with those of slime mold. Recent examples of novel building blocks include polyhedra and patchy particles. Examples also included microparticles with complex geometries, such as hemispherical, dimer,discs,rods, molecules, as well as multimers. These nanoscale building blocks (NBBs) can in turn be synthesised through conventional chemical routes or by other SA strategies such as Directional Entropic Forces.

PRINCIPLES OF SELF ASSEMBLY



(A) Aggregation occurs when there is a net attraction and an equilibrium separation between the components. The equilibrium separation normally represents a balance between attraction and repulsion. These two interactions are fixed in molecular self-assembly but can be engineered independently in macroscopic self-assembly.

(*B* and *C*) Schematic illustration of the essential differences between irreversible aggregation and ordered self-assembly.

(*B*) Components (shown in blue) that interact with one another irreversibly form disordered glasses (shown in green).

(*C*) Components that can equilibrate, or adjust their positions once in contact, can form ordered crystals if the ordered form is the lowest-energy form (shown in red).

(*D*) Biology provides many examples of self-assembly (here, the formation of a protein, an asymmetric, catalytically

Self-assembly (SA) in the classic sense can be defined as *the spontaneous and reversible organization of molecular units into ordered structures by non-covalent interactions*. The first property of a self-assembled system that this definition suggests is the spontaneity of the self-assembly process: the interactions responsible for the formation of the self-assembled system act on a strictly local level—in other words, *the nanostructure builds itself*.

For self-assembly to generate structures more complex than simple crystals, different components in a mixture must come together in an ordered way. The selective recognition of different molecular components in a mixture is the basis for much of molecular biology and medicinal chemistry. The parameters that control molecular recognition (complementary shapes, complementary forces, and appropriate levels of plasticity) will also be broadly useful in the self-assembly of larger systems.

Present and Future Applications of self assembly

(1) Robotics and Manufacturing: Robots are indispensable to current systems for manufacturing. As components become smaller, following the trend in miniaturization through microfabrication to nanofabrication, conventional robotic methods will fail because of the difficulty in building robots that can economically manipulate components only micrometers in size. **Self-assembly offers a new approach to the assembly of parts with nano- and micrometer dimensions**.

(2) Crystallization at All Scales: The formation of regular, crystalline lattices is a fundamental process in self-assembly, and is **a method to convert ~100-nm particles into photonic materials**; using micrometer-scale components may lead to new routes to microelectronic devices.

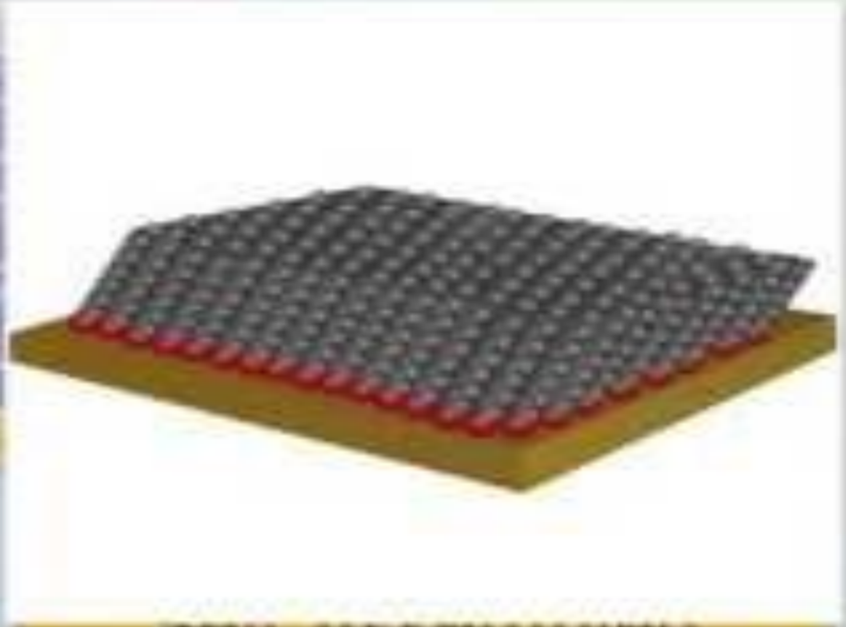
(3) Microelectronics: The fabrication of microelectronic devices is based almost entirely on photolithography, an intrinsically two-dimensional technology. Another computer of great interest—the brain—is three-dimensional. There are no clear strategic paths from two-dimensional to three-dimensional technology (and, of course, no absolute certainty that three-dimensional microelectronic devices will be useful, although the brain is certainly a three-dimensional system, and three dimensionality offers, in principle, the advantages of short interconnects and efficient use of volume**). Self-assembly offers a possible route to three-dimensional microsystems**.

(4) Nanoscience and Technology: There are two approaches to the fabrication of nanosystems: bottom-up and top-down. Chemical synthesis is developing a range of methods for making nanostructures—colloids, nanotubes, and wires—to use in bottom-up approaches. Self-assembly offers a route for assembling these components into larger, functional ensembles.

(5) Netted Systems: At the outer limits of self-assembly, at least as it is currently defined in the physical and biological sciences, are **netted systems: computers, sensors, and controllers that interact with one another only through the flow of bits and configure (or self-assemble) themselves based on that flow into functional systems. These netted information systems will be entirely different in their realization from self-assembled aggregates of material components**, but will share underlying concepts of design and architecture.

Explain what is **Self Assembly.**

Common examples of self assembled chemical structures



Self Assembled
Mono Layers

Keywords

- *Small*
- *Chemical Units*
- *Natural*
- *Spontaneous*
- *Mechanisms*
- *Stable*
- *Complex*
- *Larger Structures*

SELF ASSEMBLY refers to the phenomena whereby *Small Chemical Units* undergo *Natural* and *Spontaneous Mechanisms* to form *Stable, Complex* and much *Larger Structures,* under some **Defined Conditions.**

THERMODYNAMICS OF SELF ASSEMBLY: AN EMPIRICAL EXAMPLE RELATING ENTROPY AND EVOLUTION

- There was a study by John R. Jungck Department of Biology, Merrimack College North Andover, Massachusetts 01845.
- In **the absence of theoretical thermodynamic constructs to base an empirical view of the relationship of entropy and evolution, available calorimetric data on biochemical systems was examined** to gain some insight into how experimental evidence may allow us to proceed to anew, workable paradigm on how apparent order is evolved.
- According to the study, this **examination of the nature of self assembly phenomena** can be carried out on two fronts, both of which are resolved by the same mechanism. First, how is it that a highly ordered structure forms spontaneously; i. e., does not that violate the second law? Secondly, what is the energetic parameter which drives self-assembly reactions of proteinaceous polymers?

- In 1952, Dobry and Sturtevant (10) **measured the heat of reaction between the enzyme trypsin and the polypeptide, soybean trypsin inhibitor, by calorimetry. The surprising result was that the heat of reaction was very small and the equilibrium appeared to be independent of temperature.**
- If the only process occurring was an association of the two polymers, a large drop in entropy would be expected; however, the data indicated just the opposite, i. e. , this spontaneous reaction was being driven by a large increase in entropy. Two alternatives were conjured up to explain these data.
- Either the reaction was liberating a substantial number of ions or water bound to the polymers, or the polymers were unfolding so that they were becoming configurationally less ordered.

Chemical and entropic controls are ultimately related to **the thermodynamics of self-assembly process** and are best characterized *via* theoretical studies. However, several **problems** are encountered when applying atomistic computational approaches to molecular self-assembly phenomena. Molecular self-assembly takes place over enormous, often **microsecond-exceeding, time scales**, making the prediction of thermodynamically stable molecular assemblies with atomistic models prohibitive. While some remarkable progress has been made in this area, there is little consensus in the literature on how molecular self-assembly should be simulated. The lack of molecule-surface force fields for the important case of molecular self-assembly on metal surfaces further **limits the feasibility of atomistic simulation**, although promising progress is being made here as well. An arguably more serious issue is that atomic simulations do not directly address the effects of chemical and entropic controls on the molecular self-assembly process. Instead, they yield large volumes of data that require **lengthy post-simulation analysis**, and it is not clear what kind of analysis is needed for the study of chemical and entropic controls. In order to surmount these difficulties, it is necessary to develop novel computational techniques that unambiguously separate the effects of chemical and entropic controls on molecular self-assembly without difficult post-simulation analysis.

Self Assembly of Granular Material

- It is very interesting to see **How Self-Assembling Granular Materials Are Changing the Future of Architecture.**
- Architects are toying with exotic new materials that can be poured into place and yet form complex structures.

- But some designers are toying with another idea—that **there's a different way to build that exploits randomness rather than avoids it**. This kind of building will rely on new kinds of **granular materials that when tipped into place, bind together in ways that provide structural stability**. In this way, walls, columns and even domes could be poured into place, forming complex but stable structures.
- **Sean Keller at the Illinois Institute of Technology in Chicago and Heinrich Jaeger at the University of Chicago** explain how this kind of "**aleatory architecture**" is finally becoming possible. These guys say that the first aleatory structures are already being built and that the approach is introducing new ways to think about architecture and design in general.
- **Human have used granular materials such as stones, sand, or earth to build structures for thousands of years. Even today, the technique is common for constructing dams, harbour breakwaters, and gravel beds for railways.**

- These structures benefit from the **special properties of granular materials—their porous nature that allows quick drainag**e and the fact that they can be poured into place quickly and at **low cost**.
- Conventional structures require specially designed columns or arches. But **granular materials rely on force chains between adjacent particles inside the materials that are set up when the material becomes jammed**. At the same time, the material can flow when the jam is released.
- There is downside though. The shape of these structures is severely limited by the material's natural angle of repose. And that also limits the applications.
- Much of the properties of granular materials are determined by the shape of the particles from which they are made. This is roughly spherical in many cases.
- But in recent years, materials scientists have begun to experiment with particles with more exotic shapes, **such as 3-D star shapes, X shapes, hook shapes, and others. When poured, these more easily jam and form stable structures**.

- One approach is to pour the material into an air-tight fabric container that can be vacuum packed. This generates the pressure that causes the material to jam into more or less any desired shape. A few years ago, engineers at the Technical University of Delft constructed a bridge using this “deflateable” idea.
- A more ambitious goal is to come up with the overall structure and then work backward to determine the shape of the particles that would produce it when poured. These granules could then be 3-D printed and poured into place, where they would self-assemble or be assembled using a robot.

Self Assembly and nanostructured materials

- "Nanostructured materials" are those having properties defined by features smaller than 100 nm.
- This class of materials is interesting for the reasons: i) They include most materials, since a broad range of properties-from fracture strength to electrical conductivitydepend on nanometer-scale features. ii) They may offer new properties: The conductivity and stiffness of buckytubes, and the broad range of fluorescent emission of CdSe quantum dots are examples. iii) They can mix classical and quantum behaviors. iv) They offer a bridge between classical and biological branches of materials science. v) They suggest approaches to "materials-by-design".

- Nanomaterials can, in principle, be made using both top-down and bottom-up techniques.
- Self-assembly bridges these two techniques and allows materials to be designed with hierarchical order and complexity that mimics those seen in biological systems. Self-assembly of nanostructured materials holds promise as a low-cost, high-yield technique with a wide range of scientific and technological applications.
- This bridging strategy is 'bself-assembly7-9": that is, to allow structures (in principle, structures of any size, but especially nanostructures) synthesized bottom-up to organize themselves into regular patterns or structures by using local forces to find the lowest-energy configuration, and to guide this self assembly using templates fabricated top-down.
- Fundamentals of nanoparticle self-assembly lead to a better understanding of how nanomaterials organize and assemble themselves, how they are constructed, and how they operate in complex nanostructured systems. The theory behind the main approach that organize and assemble nanoscale particles or molecules is the self-assembly of nanostructured molecular materials and devices. Self-assembly allows predefined components to organize into ordered superstructures

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