V MADHURIMA

A Playful Introduction To Soft Matter

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A Playful Introduction to Soft Matter

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To all my students from the last quarter-century (and then some)—you kept me on my toes, tested my patience, and taught me things I never expected.

Like how to edit a large group project.

"Soft matter is matter that is soft to touch, soft to study, and soft to the understanding of the scientist. It is a field where physics meets complexity."

– Pierre-Gilles de Gennes, Nobel laureate in Physics (1991)

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துணை வேந்தர்
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Prof. M. Krishnan
Vice Chancellor

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तमिलनाडु केन्द्रीय विश्वविद्यालय
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FOREWORD

For centuries, humankind has explored metals, transforming ancient ores into useful tools and structures through processes such as rolling and forging. The age of iron and steel gave us strength and durability, while also providing a platform to understand the molecular dynamics of materials and engineer them into new forms.

In more recent decades, polymers, particularly plastics, have emerged as another cornerstone of modern life, finding countless applications across industries. Alongside them, the development of semiconductors marked a technological revolution, reshaping communication, computation and society itself.

Today, we stand at the threshold of another transformative field: soft matter physics. Unlike the "hard" materials of traditional metallurgy or semiconductors, soft materials such as gels, colloids, foams, polymers and biological tissues are still only partially explored. Though central to products like detergents, plastics, gels and even biological processes, soft matter often receives limited attention in conventional textbooks.

This book is unique in how it addresses that gap. By weaving together playful, toy-based examples with rigorous yet accessible explanations, it transforms what might seem like an abstract subject into something tangible, relatable and deeply engaging. This work is both educational and delightful, appealing equally to curious students, teachers seeking creative approaches and anyone fascinated by the physics of the everyday world.

Equally remarkable is the book's interdisciplinary reach. Soft matter, by its very nature, sits at the crossroads of physics, chemistry, biology and engineering. The chapters in this work reflect that breadth: explaining the fluidity of colloids, the resilience of polymers, the self-assembly of biological tissues and the technological applications of foams and gels. In doing so, it broadens scientific horizons and demonstrates how interconnected our understanding of the natural and technological world truly is.

The author deserves admiration for the vision and dedication required to bring this project to life. By blending the roles of teacher, editor and writer, the author has distilled decades of classroom experience into a work that is approachable without being simplistic. By choosing toys as the entry point, the book reaffirms the joy of learning, reminding us that science is not merely to be studied, but to be played with, questioned and experienced.

In a broader sense, the reflections within these pages hold special meaning for society today. We live in an age where materials science shapes our future, whether in sustainable packaging, biomedical innovations, or responsive technologies. Understanding soft matter is not just an academic pursuit but also a social necessity, for it underpins industries that touch our health, environment and daily lives.

By inspiring curiosity and scientific literacy, this book contributes to a culture that values both knowledge and creativity, traits that are indispensable for solving tomorrow's challenges.

I am confident that this text will make the journey into soft matter engaging and accessible, softening the entry into the fascinating world of physics through the study of "soft things."

With Best Wishes,

(Prof. M. Krishnan)
Vice-Chancellor

பேராசிரியர். மு. கிருஷ்ணன்
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Preface

It was a hot afternoon in April 2023. We had just completed the official syllabus for a course on Soft Condensed Matter Physics. I knew this would be among the last groups of students to take the course, as it was being removed in an upcoming curriculum overhaul.

The combination of stifling heat, the end of the formal course content, and the knowledge that this was the penultimate iteration of this syllabus created a certain inertia—but also opened up space for creativity. To make the most of the remaining weeks, I invited the students to revise what they had learned—not through conventional review sessions, but by selecting a toy made of soft matter and explaining how it works.

The contents of this book are a direct outcome of that exercise. Once I received all the material, it was evident to me that a collation of the essays would be a good read, especially as an introductory text to soft matter, albeit in a semi-formal to informal manner.

In the process of curating the essays, I have a new found respect for editors. Bringing together and editing this compilation was a herculean task, given the wide range of writing styles and grammatical variations across the contributions. Also, many diagrams needed to be redone, for one reason or the other. Moreover, the collection needed an introduction to the topic. The task kept swinging from the front burner to the back since I wanted cohesion in the reading style, but was constrained by that of the student who wrote the original essay.

This is where I turned to artificial intelligence (AI) for help. AI was used in this document to clean up the text and generate many images. The original writing came from the students, was heavily edited by me, and then passed through AI tools to give it a consistent style. The core content—and the prompts for the images—remained entirely human-driven.

Given the scale of the task, I'm not quite sure what to call myself. I'm more than just the editor, since large portions of the book—especially the entire first section and several parts of the later chapters—were written entirely by me. I'm not the sole author either, as the original ideas and the text for all the toys came from my students (whose names are listed in the document), although very little of it is retained in the original form.

Call me what you like. My only motivation in putting this together was to share with you the joy of physics.

Physics often gets a reputation for being tough—and honestly, that's not entirely unfair. Imagine a person from a time long before tools or instruments. Curious about the world, they might've wondered: *What's the shortest bit of time I can really notice passing?* Probably something like a blink of an eye—about a tenth of a second, as we know today.

And what about the longest stretch of time they could comprehend? Maybe the span of a human life—say, around 100 years. That's a whopping 3.15 billion seconds, or roughly a 1 followed by 9 zeros. Pretty big!

Now, if you asked a physicist today about the *shortest* time we know of, they'd tell you it's what's called *Planck time*: 5.39×10^{-44} seconds. That's one divided by a 1 followed by 44 zeros. Wild, right? And the *longest* time we talk about? That would be the estimated lifetime of the Universe—about 13.8 billion years, or a 1 followed by 17 zeros in seconds. Mass and length come with similarly mind-bending extremes.

What does this tell us? The human body, with all its senses, is really only tuned into a small slice of what's out there. That's not surprising—we evolved to survive, not to measure nanoseconds or light-years. But the human *mind*? Now that's the real powerhouse. It can reach across all these scales and make sense of them.

Few subjects cover such a vast range as physics. That's both the challenge and the charm. What's true at the microscopic level might not hold at cosmic scales. Some physical laws stretch across the board; others only show up in specific zones. Even if you grasp this intuitively, there's still the issue of *how* we talk about it. Natural languages—English, Hindi, Swahili, you name it—evolved to describe everyday life, not quantum fields. That's where mathematics comes in; the only "language" that works across all of physics. Unfortunately, like stage fright, math anxiety can sneak in and trip us up.

This book aims to soften that entry into the world of physics. It introduces the world of *soft matter*—yes, literally soft stuff—through the lens of soft toys. The first section rounds up the necessary introduction, terminology and math. Chapter 3 is a little technical and can be omitted by those who don't want even this level of maths. A small glossary is provided at the end for such readers. The second explores the ideas behind some well-known toys. Each one has been picked to illustrate a concept from the world of soft matter. The third section summarizes and gives the additional data.

This isn't a textbook, and it's not written for the seasoned scientist. It's here to spark your curiosity, give you a glimpse into the fascinating world of soft matter, and maybe—just maybe—make you see physics a little differently.

Date: 18-8-2025
Station: Thiruvarur V Madhurima

The Book at a Glance

This book is divided into three sections. It is suggested that you go through the first section first. The rest of the book can be read in a non-linear fashion. Here are a few suggestions.

- The first section is an introduction to soft matter. It would be helpful to go through chapters 1 and 2, in that order. Chapter 3 is slightly more rigorous, and meant for those who have studied physics at class 12 level. The 3rd chapter, and in fact the entire first section can be skipped if you so wish.
- Section 2 is about the toys. This section can be navigated in a non-linear fashion. You can choose any toy at random and read about it. It might be helpful to read the introductory comments to the sub-section to get a feel for that particular type of material of toy.
- Section 3 provides a comprehensive summary, along with a simple glossary and additional activities that you can perform either by yourself or with students/children. The section also provides a nominal bibliography for each toy, just in case you want to learn a little more.

Note on images:

All images are taken from open access sources, or those with creative commons licences. All images of cats (*since the internet tells me that books with cat images have a higher probability of being read*) were made using Meta.ai. No specific captions are given for the cat pictures, since cats need no explanation! All of the others have been credited duly, as a part of the caption, to the possible extent.

Note on Table of Contents and List of Figures:

You can click on the text in the table of contents and the list of figures to go to the selection in the book. [Use *Control+Click,* if needed].

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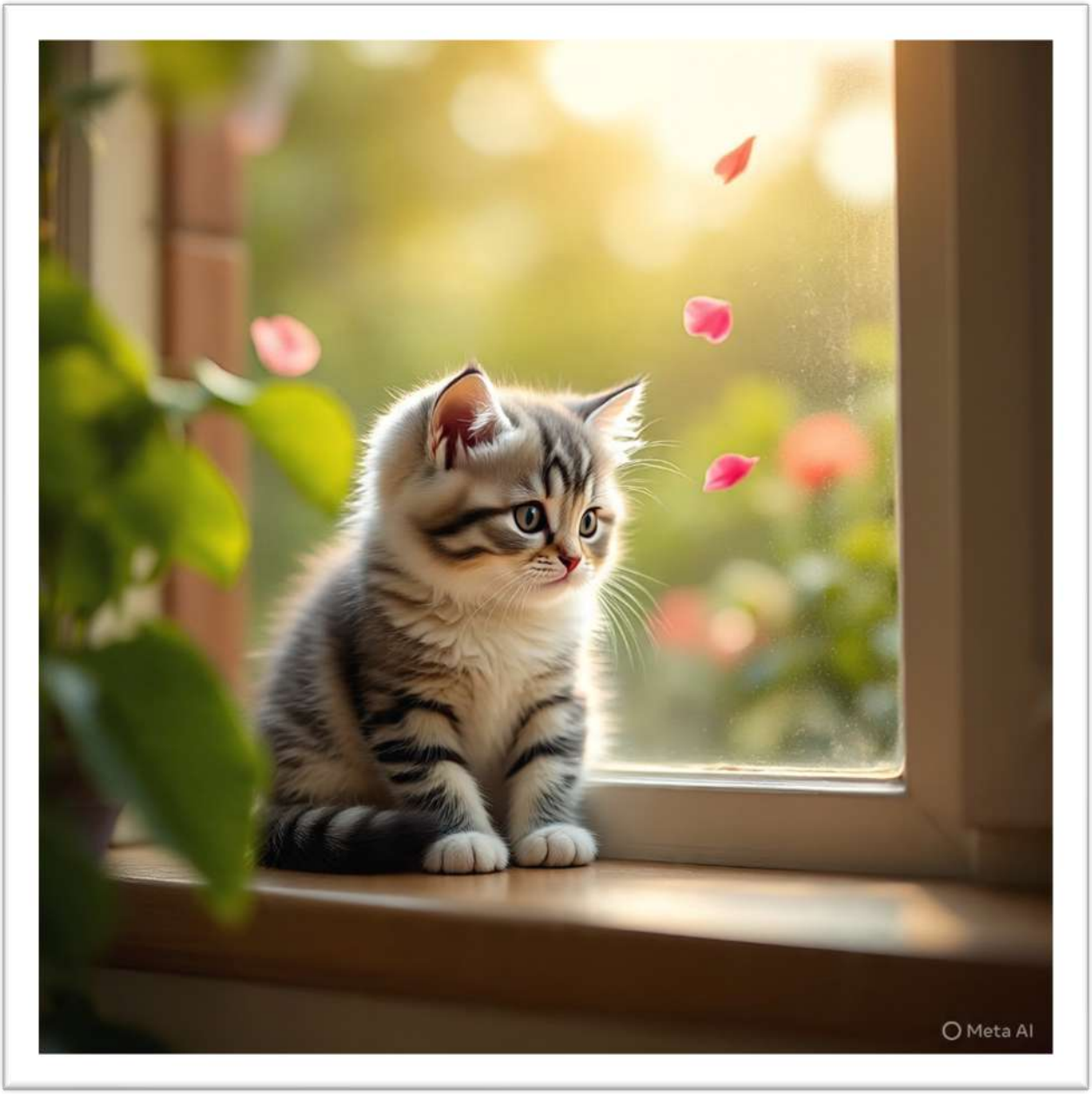

Meta AI

A collection of soft matter

Section 1: Understanding Soft Matter

1.1: Between Solid and Liquid: The Landscape of Soft Matter Physics

Most of us grow up learning that matter exists in three basic states—solid, liquid, and gas. Ice, water, and steam are often used as textbook examples, clearly showing the transition from one phase to another. We learn these categories early on, and they help us make sense of the physical world. But is that really all there is?

As it turns out, nature doesn't always follow simple rules. The moment we start paying closer attention, we begin to notice materials that don't fit so cleanly into these three states. Consider the things around you right now. Perhaps you have a glass of milk on the table, a tube of toothpaste in the bathroom, or a bowl of jelly in the fridge. Try to categorize each of these. Is milk a liquid? Maybe. But it's not just water; it has fat globules suspended in it. Toothpaste holds its shape like a solid, but flows like a liquid when squeezed. Jelly wobbles somewhere in between, resisting motion like a solid, yet shifting like a liquid under enough force.

Clearly, the solid-liquid-gas classification has limits. These real-world examples challenge the simplicity of the three-phase model and point us toward a richer, more complex area of science known as soft matter. But before we can fully appreciate what makes soft matter so unusual—and so important—it helps to build a foundation in how all matter is structured, right down to its tiniest components.

Figure 1:Some examples of soft matter

(Source: https://pxhere.com/)

From Atoms to Matter: The Hidden Architecture of the Universe

At the most fundamental level, everything we see, touch, smell, and taste is made up of atoms—tiny units of matter that combine in specific ways to form the materials around us. Whether we're talking about a glass of water, the air we breathe, or the fabric of your shirt, all of it is constructed from different combinations of atoms.

Take water as a starting point. Each molecule of water is composed of three atoms: two hydrogen atoms and one oxygen atom, chemically written as H_2O. Simple enough—but even this simple molecule illustrates some deeply important ideas.

Scientists often use what's called a ball-and-stick model to represent molecules. In these models, coloured spheres represent atoms—red for oxygen, white for hydrogen—and the "sticks" between them represent the bonds, or the connections, that hold the atoms together. These bonds aren't literal sticks, of course. They are invisible forces of attraction, the result of shared or exchanged electrons that keep atoms linked in stable arrangements.

One key concept here is that a single molecule—like one molecule of water—doesn't have a state of matter on its own. It's not a solid, liquid, or gas in isolation. Those categories emerge only when large numbers of molecules interact with each other in coordinated ways.

So what determines the state of a substance? The answer lies in how tightly the molecules are packed and how freely they move.

In a solid, molecules are packed closely together in fixed positions, forming a rigid structure. In a liquid, they're still close but free to slide past one another. And in a gas, they are far apart, moving independently and quickly. The degree of interaction between molecules—how strongly they attract or repel—dictates which of these behaviours emerges.

Figure 2: Ripples created by drops of water

(Source: pixabay.com)

Why Atoms Bond: The Drive for Stability

To understand why molecules form in the first place, we need to look at how atoms behave when they encounter each other.

Each atom has a nucleus at its center, which contains positively charged protons (and usually neutral neutrons), and is surrounded by negatively charged electrons. These electrons occupy regions around the nucleus called shells or orbitals. The outermost shell is especially important because it determines how the atom interacts with others.

Atoms often follow what's known as the octet rule—a tendency to form bonds in ways that give them eight electrons in their outer shell. This configuration is especially stable, and atoms will gain, lose, or share electrons to achieve it. Some atoms, like

those of the noble gases (helium, neon, argon), already have full outer shells and are so stable that they rarely react with anything.

But most atoms are not so content. When they come near one another, several forces come into play. On one hand, opposites attract: the negative electrons of one atom are drawn to the positive nucleus of another. On the other hand, if atoms get too close, their electrons start to repel each other. This repulsion is a consequence of the Pauli exclusion principle, a quantum rule that prevents electrons from occupying the exact same state.

Think of electrons—the tiny, negatively charged particles that move around the nucleus of an atom—like people looking for seats. The “seats,” in this case, are specific energy levels or “states” where electrons are allowed to exist inside the atom.

Pauli’s Exclusion Principle, discovered by Austrian physicist Wolfgang Pauli in 1925, says something very similar to the concert rule:

No two electrons in the same atom can have exactly the same set of properties, or be in the same "quantum state" at the same time.

The result is a kind of balancing act. At a certain distance—just right, not too close, not too far—the attractive and repulsive forces cancel out. This point of balance is where a stable chemical bond forms, and a molecule is born. The distance between the bonded atoms is known as the bond length, and the strength of the connection is described by the bond energy—how much energy is needed to break the bond apart.

Understanding these forces is crucial, not only to chemistry, but to how we understand the behaviour of matter at larger scales, especially when we enter the domain of soft matter.

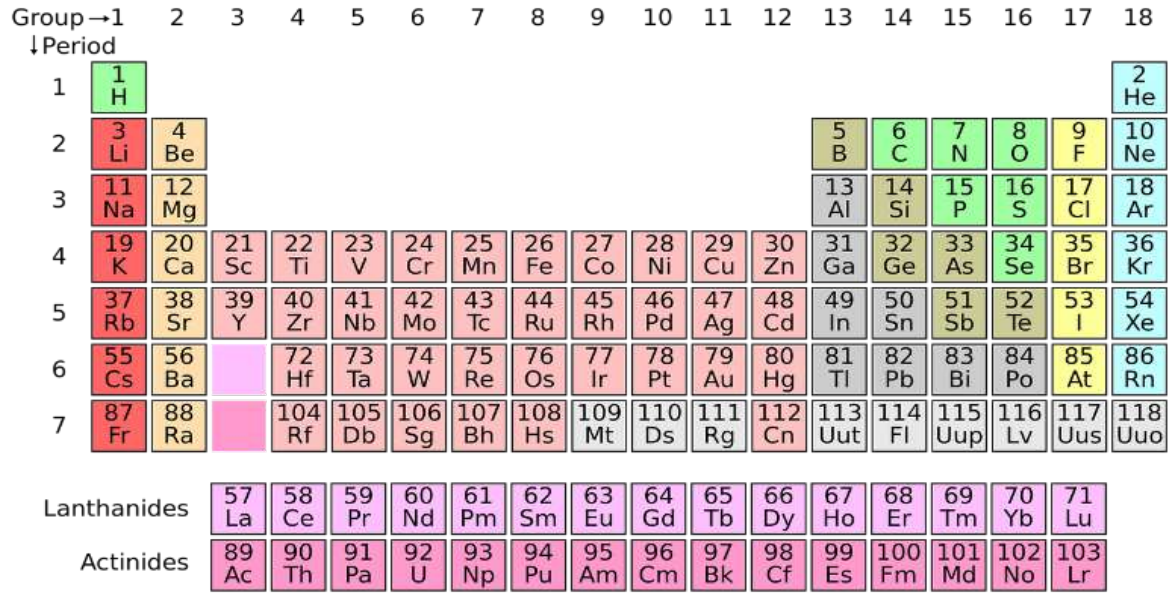


Figure 3: The periodic Table.

(Source: Geralt on Pixabay)

Between Solid and Liquid: The Curious World of Soft Matter

Let's return to those ambiguous substances like toothpaste, cream, jelly, or shaving foam. These are all examples of soft matter—materials that don't fit neatly into the categories of solid, liquid, or gas.

Soft matter is a broad class of materials that includes gels, colloids, foams, pastes, emulsions, liquid crystals, and even biological tissues. What makes them special is not just their texture or feel, but their intermediate nature—the way they exhibit characteristics of multiple phases at once. A soft material may flow like a liquid under gentle force but hold its shape like a solid when left undisturbed.

Why does this happen? The key lies in how molecular interactions are balanced within the material. In hard solids, strong bonds fix atoms or molecules into place. In soft matter, there are still bonds, but they are often mixed with weaker, non-bonding interactions, such as van der Waals forces or hydrogen bonds. These weaker interactions allow for flexibility, rearrangement, and sensitivity to external conditions like temperature, pressure, or electric fields.

Try this at home: press your finger into a wooden table and then into a bowl of yogurt. The table resists—your finger leaves no mark. The yogurt, on the other hand, yields under even light pressure. That yielding behaviour is the hallmark of soft matter.

This malleability makes soft matter especially versatile and useful. Consider everyday products like lotions, cosmetics, sauces, inks, and glues. They must flow when used but remain stable otherwise. Many food products are emulsions or foams—stable mixtures of fat and water, or air and liquid, that only soft matter physics can explain.

But the significance of soft matter goes far beyond the kitchen or bathroom. Biological tissues, for example, are soft materials. The cell membrane—an essential boundary around all living cells—is made of a soft, flexible bilayer of molecules that self-assemble and adapt to their environment. Understanding soft matter helps us understand how life itself functions at the molecular level.

A Matter of Scale: Why Numbers Matter

It's important to remember that many of the exotic behaviours of soft matter emerge only when large numbers of molecules are involved. A single molecule of water doesn't "know" whether it should be a liquid or a gas. But when billions of them come together, their interactions—how tightly they stick, how freely they move—define the overall behaviour.

The same principle holds for soft matter. Its unique properties come not just from the building blocks, but from how those blocks collectively organize and respond to their surroundings. These collective behaviours—sometimes called emergent properties—are why soft matter is such an active area of scientific research.

Soft matter often exists in what scientists call metastable states—structures that are temporarily stable but can easily change given a small push. This sensitivity makes soft matter ideal for smart materials, like self-healing gels or shape-changing polymers that can respond to heat, light, or chemical signals. In modern science and engineering, soft matter sits at the frontier of discovery. It bridges the microscopic world of atoms with the macroscopic world of materials we can hold and use. It spans physics, chemistry, biology, and materials science. And despite its softness, it is a powerful force—quietly shaping our world in ways we are only beginning to understand.

"The Persistence of Memory" is a well-known surrealist painting by Salvador Dalí, made in 1931. It features melting clocks and reflects Dalí's interest in dreams and the subconscious mind. It also captures the essence of soft matter – where everything is soft and gooey.

Figure 4: "Dali Style Soft Matter" as imagined by AI

(Source: Deep AI)

Solid, liquid, gas and plasma (collection of charged particles) are considered to be the four fundamental states of matter. Certain other states like Bose-Einstein condensates are made under laboratory conditions. Soft-matter are found naturally, but have small to finite lifetime due to their numerous metastable states. Polymers, gels, surfactants, colloids, liquid crystals, foam, sponge etc., all fall into the broad classification of soft matter. We experience these in our everyday lives in numerous forms: toothpaste, soap, shaving foam, milk, ice-cream and jelly to sponges, ocean froth and many more. Major industries that rely on soft matter are display devices (computers, TV screens etc.,) cosmetics (perfumes, make-up materials, soaps and detergents) and toys.

1.2: A Comprehensive Introduction to Soft Matter

"Colloidal systems have a unique beauty. They straddle the boundary between the microscopic world of individual particles and the macroscopic world of bulk materials."
– David G. Grier

Soft matter, being mostly in metastable states, can manifest in various forms. While they generally share traits like being easily deformed under stress, each type also exhibits distinct characteristics. For instance, liquid crystals get their special properties from the asymmetric molecular shapes of their molecules. Colloids and surfactants tend to self-assemble, and polymers are composed of long, repeating molecular chains. The following provides a closer examination at the main types of soft matter and what sets each apart.

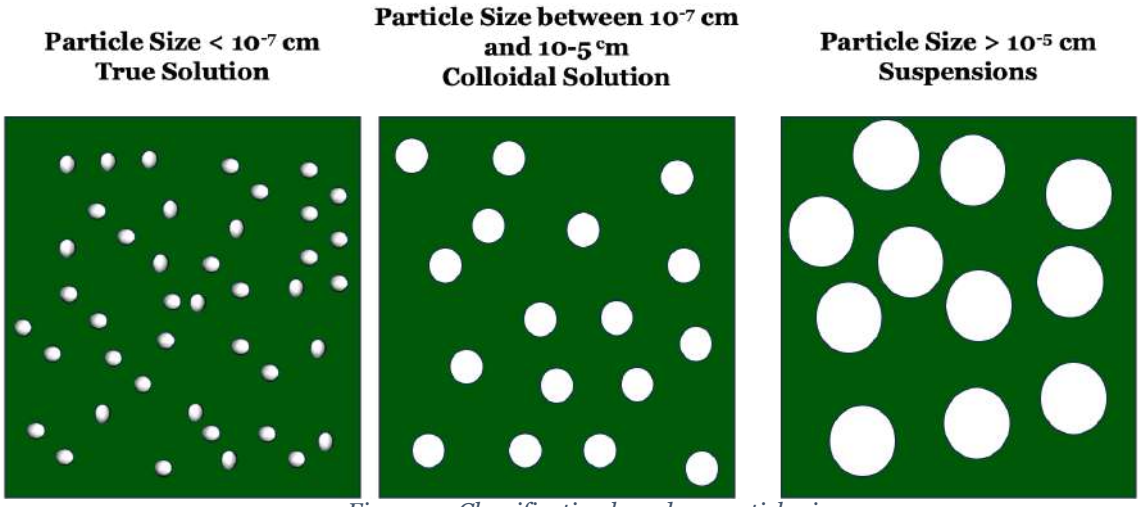


Figure 5: Classification based on particle size

(Source: Author)

A large part of this chapter may feel like we are name dropping. The idea is to impress upon you the fact that what is broadly known as soft-matter is in fact a complex regime. No attempt is being made to be rigorous in explaining them.

Liquid Crystals

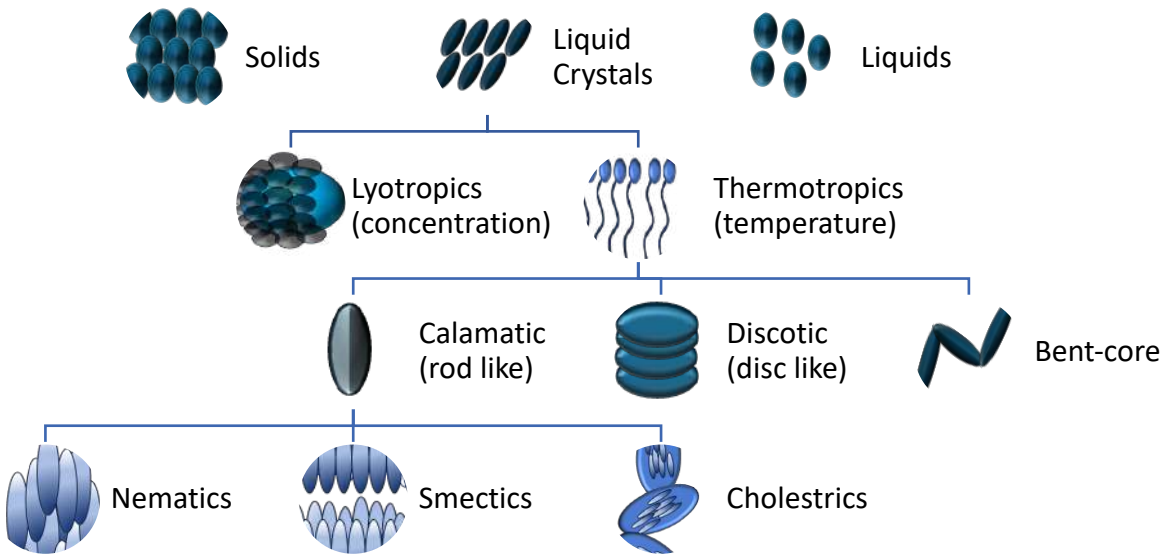


Figure 6: Classification of Liquid Crystals

(Source: Author)

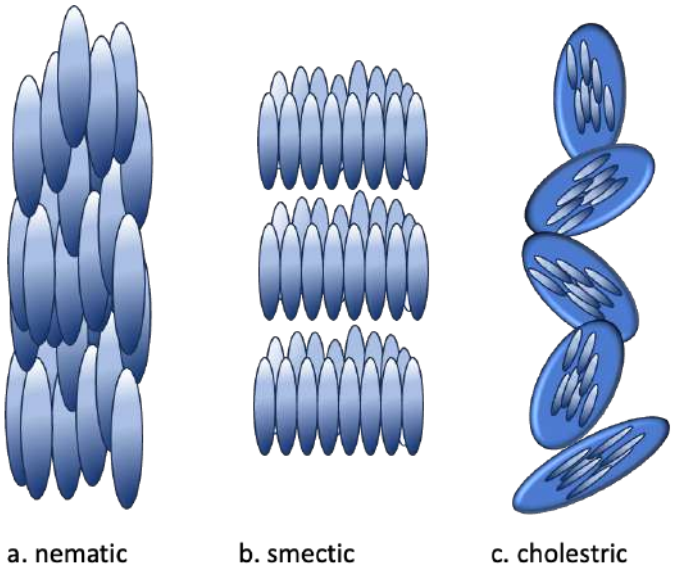


Figure 7: Representation of types of thermotropic Liquid Crystals

(Source: Author)

You've likely heard of liquid crystals (LCs)—they're the "LC" in LCD, or Liquid Crystal Displays, used in everything from thermometers and calculators to TV

screens. Liquid crystals are a unique state of matter that exhibit properties intermediate between those of conventional liquids and solid crystals. Like solids, they feature a degree of molecular order, but like liquids, their molecules retain some mobility.

This unusual behaviour arises from the asymmetric shape of LC molecules—most are elongated, rod-like structures rather than spherical. Their shape leads to directional interactions and ordered arrangements that respond sensitively to external stimuli such as temperature, electric fields, and pressure. When these rod-like molecules interact and seek low-energy configurations, they form distinct phases with characteristic packing arrangements and physical properties.

Based on how the molecules are arranged, liquid crystals are broadly classified into several types.

Classification of Liquid Crystals:

Liquid crystals are categorized based on how their molecules are arranged and how they react to external influences. The average direction of the length of the molecules is called a director, and it defines the direction for the molecular arrangement. Here are the primary classifications:

Nematic Liquid Crystals:

Molecules in nematic liquid crystals have long axes aligned in a common direction but with no positional order. The orientation of the molecules is more ordered than in an isotropic liquid but lacks the positional order found in crystalline solids. Nematic liquid crystals are sensitive to external fields and can align their long axes parallel to the field.

Smectic Liquid Crystals:

Smectic liquid crystals have molecules arranged in layers, with each layer having a positional order. Within each layer, the molecules exhibit either nematic or smectic order. Smectic liquid crystals are more ordered than nematic and often have higher viscosity (drag, like castor oil).

Cholesteric (Chiral Nematic) Liquid Crystals:

Cholesteric liquid crystals have a twisted molecular structure, resulting in a helical arrangement of molecules. This helical structure reflects light selectively, leading to colourful patterns. Cholesteric liquid crystals are responsive to temperature changes and external fields.

Discotic Liquid Crystals:

In discotic liquid crystals, the molecules are disc-shaped and form columnar structures. These columnar stacks can exhibit liquid crystal properties. Discotic liquid crystals are often used in electronic applications.

Smectic Phases (SmA, SmC, SmF, etc.):

Smectic phases further categorize smectic liquid crystals based on the specific molecular arrangements within the layers. Smectic A (SmA) involves parallel alignment of molecules with positional order, whereas Smectic C (SmC) involves tilted molecules.

Isotropic Liquid (IL) Phase:

At higher temperatures, liquid crystals lose their ordered structure and transition into the isotropic liquid phase, where molecules have no long-range order.

Colloids

Milk, mayonnaise, blood, whipped cream, fog, paints and inks are all everyday examples of colloids. Colloids are heterogeneous mixtures where one or more substances are dispersed as finely divided particles (dispersed phase) within another substance (dispersion medium). The particles in a colloid are larger than individual molecules but smaller than what can be seen with the naked eye. Colloidal systems exhibit unique properties arising from the extensive surface area and the interactions between the dispersed phase and the dispersion medium.

Classification of Colloids:
Colloids are variously classified with some of the more common ones listed here.

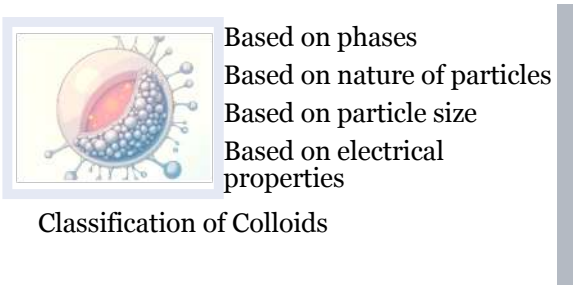


Figure 8: Classification of Colloids

(Source: Author)

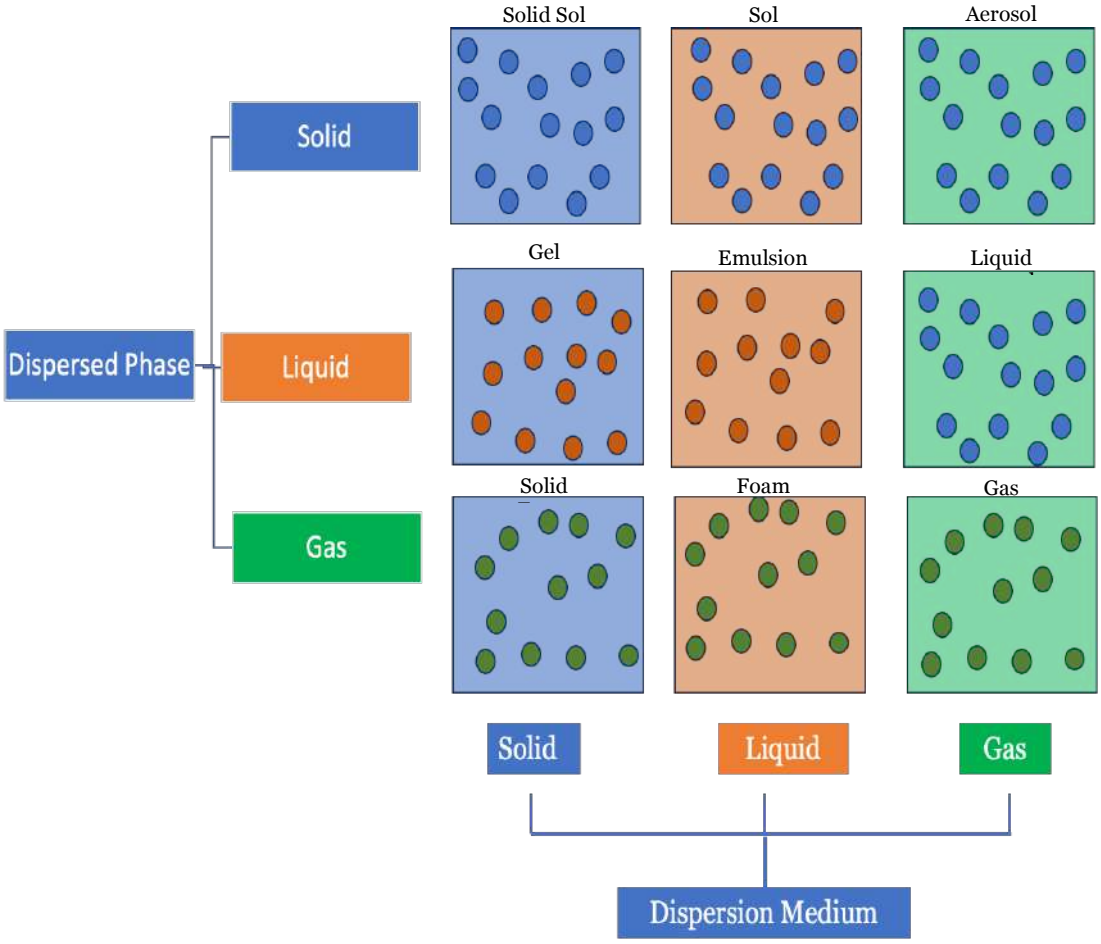


Figure 9: Classification of matter based on dispersed and dispersion media

(Source: Author)

Based on Phases:

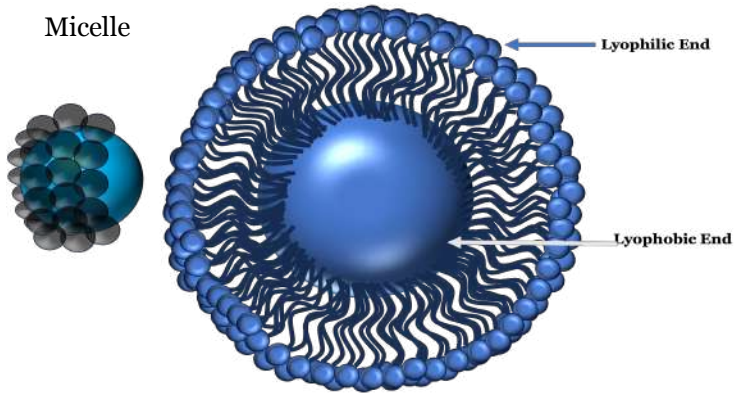


Figure 10: Representation of formation of micelles and colloids through self-assembly

(Source: Author)

Sol: Colloidal particles dispersed in a liquid medium. For example, starch dispersed in water.

Gel: Colloidal particles dispersed in a solid medium. For example, Gelatine in water.

Emulsion: Colloidal particles dispersed in another liquid medium. For example, oil droplets in water.

Based on Nature of Particles:

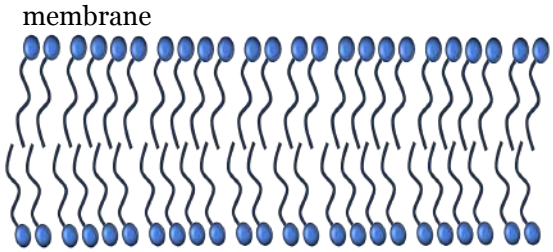


Figure 11: Formation of membrane-like structures through the self-assembly of molecules

(Source: Author)

Lyophilic Colloids: Also known as "solvent-loving," these colloids have an affinity for the dispersion medium. The particles are usually finely divided and readily form stable colloidal solutions. Examples include proteins and starch.

Lyophobic Colloids: Also known as "solvent-hating," these colloids have little or no affinity for the dispersion medium. The particles are less stable and may require the addition of stabilizing agents. Examples include metal sulphides.

Based on Particle Size:

Macromolecular Colloids: Colloids with large molecules as the dispersed phase, such as proteins and synthetic polymers.

Associated Colloids: Colloids formed by the association of molecules in the dispersion medium. Micelles in soap solutions are an example.

Based on Electrical Properties:

Electrolytic Colloids: Colloids in which the dispersed particles carry an electric charge. Examples include colloidal solutions of metals like silver or gold.

Non-Electrolytic Colloids: Colloids in which the dispersed particles are uncharged. Examples include starch or cellulose in water.

Understanding the classification of colloids is crucial for studying their behaviour, stability, and applications in various fields, including chemistry, biology, and materials science.

Gels

Gels are yet another class of materials we encounter every day, starting from the toothpaste to hand sanitizers, hair and cosmetic gels, to fruit jellies and jams. Gels represent a state of matter that combines properties of both liquids and solids. They are characterized by a three-dimensional network of interconnected structures, often formed by a liquid dispersed in a solid matrix or vice versa. The resulting material has a semi-solid, jelly-like consistency with unique physical and mechanical properties.

Figure 12: Aloe vera gel – a classic example of a natural gel

(Source: RosinaS on Pixabay)

Classification of Gels: Gels can be classified based on various factors, including their composition, structure, and formation. Here are some common classifications:

Based on Composition:
Hydrogels: Gels where the liquid component is primarily water. These gels are often used in medical applications, such as drug delivery systems or wound dressings.

Organogels: Gels where an organic liquid is dispersed in a solid matrix. Organogels find applications in areas like cosmetics and pharmaceuticals.

Based on Structure:
Chemical Gels: Formed by covalent bonds between polymer chains, resulting in a stable and permanent gel structure. Examples include epoxy gels.

Physical Gels: Formed by non-covalent interactions, such as hydrogen bonding, van der Waals forces, or electrostatic interactions. Physical gels are reversible and can undergo changes in response to external stimuli.

Based on Origin:
Biological Gels: Gels that occur naturally in living organisms, such as mucus or extracellular matrices.

Synthetic Gels: Gels created in a laboratory or industrial setting for specific applications, such as in the production of consumer products, pharmaceuticals, or materials.

Based on Use and Application:
Cosmetic Gels: Gels used in cosmetics and personal care products, such as hair gels, skincare gels, or toothpaste gels.

Food Gels: Gels used in the food industry for various purposes, including thickeners, stabilizers, or texture modifiers.

Pharmaceutical Gels: Gels designed for drug delivery, topical applications, or as carriers for therapeutic agents.

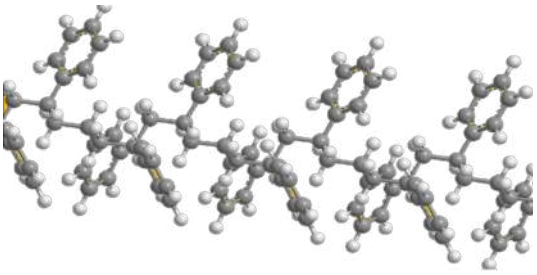
Based on Rheological Properties:
Elastic Gels: Gels that exhibit predominantly elastic behaviour, returning to their original shape after deformation.

Viscoelastic Gels: Gels with a combination of viscous and elastic properties, displaying both flow and elastic recovery.

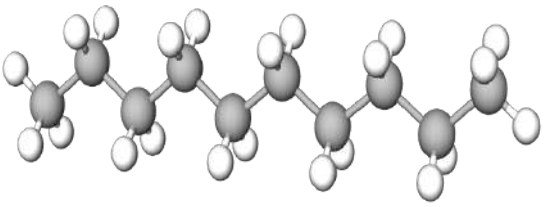
Polymers

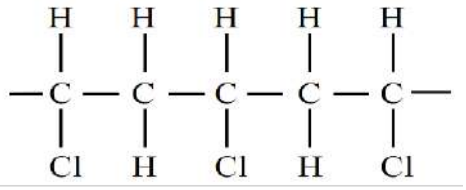
Plastics are polymers. Many of them are crucial for our everyday living (not including bio-polymers such as proteins, sugars etc., that we are made of). The rubber of the tyres of our vehicles are polymers as are silicone baking accessories, nylon clothes and stockings to rubber bands. Polymers are large molecules composed of repeating structural units called monomers. These macromolecules can have a linear, branched, or network structure. The process of linking monomers together to form a polymer is known as polymerization. Polymers exhibit a wide range of properties and find applications in various industries, including plastics, textiles, adhesives, and biomaterials.

(a) polysulphide rubber

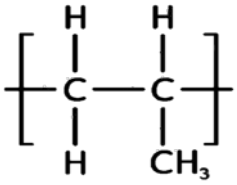


(b) polyisobutylene (synthetic rubber)





(c) polyvinylchloride (PVC)



(d) polypropylene

Figure 13: Representations of some polymers.

Figures (a) polysulphide rubber and (b) polyisobutylene (a synthetic rubber) are shown using the ball and stick model. (c) Polyvinylchloride (PVC) and (d) polypropylene are represented using the molecular formulae. The square brackets represent the repetition of the basic unit (monomer). (Source: Author)

Classification of Polymers:
Polymers can be classified based on different criteria, including their source, structure, and properties. Here are some common classifications:

Based on Source:
Natural Polymers: Derived from natural sources. Examples include proteins (e.g., silk, wool) and polysaccharides (e.g., cellulose, starch).

Synthetic Polymers: Man-made polymers produced through chemical processes. Examples include polyethylene, polyvinyl chloride (PVC), and nylon.

Based on Structure:
Linear Polymers: Polymers with a straight or slightly branched chain structure. Examples include polyethylene and polypropylene.

Branched Polymers: Polymers with side chains branching off from the main chain. Examples include low-density polyethylene (LDPE).

Crosslinked or Network Polymers: Polymers with a highly interconnected three-dimensional structure. Examples include rubber and epoxy resins.

Based on Polymerization Mechanism:
Addition (Chain-Growth) Polymers: Formed by the repeated addition of monomers. Examples include polyethylene, polypropylene, and polyvinyl chloride.

Condensation (Step-Growth) Polymers: Formed by the stepwise reaction between functional groups in monomers, with the elimination of a small molecule (e.g., water or alcohol). Examples include polyester and nylon.

Based on Thermal Behaviour:
Thermoplastics: Polymers that can be melted and reshaped multiple times without undergoing chemical degradation. Examples include polyethylene, polypropylene, and polystyrene.

Thermosetting Polymers: Polymers that undergo irreversible curing (crosslinking) upon heating and cannot be remoulded. Examples include epoxy resins and phenolic resins.

Based on Chemical Composition:
Homopolymers: Polymers formed from a single type of monomer. Examples include polyethylene and polypropylene.

Copolymers: Polymers formed from two or more different types of monomers. Examples include styrene-butadiene copolymer (SBR) and acrylonitrile-butadiene-styrene (ABS) copolymer.

Based on Use:
Engineering Polymers: Polymers with high mechanical strength and thermal resistance, suitable for engineering applications. Examples include polyamide (nylon) and polyethylene terephthalate (PET).

Biopolymers: Polymers derived from renewable biological sources. Examples include polylactic acid (PLA) and cellulose derivatives.

Granular materials

"Granular materials are the most perplexing. They neither behave as solids nor liquids. They exhibit a complex range of behaviours that reflect a unique form of matter."
– *R. P. Behringer*, physicist specializing in granular materials

Granular materials consist of discrete, macroscopic particles and are known for their unique properties. They exhibit unique properties due to their particle-based nature and the forces between them. Sand, coffee grounds, a heap of rice grains, laundry detergent powder to powdered spices are all common examples of granular materials. Some essential features of the physics of granular materials include:

Inelastic collisions: Granular materials are characterized by inelastic collisions between particles, which can lead to energy loss and the formation of metastable structures

Size-dependent properties: The properties of granular materials can be size-dependent, with smaller particles exhibiting different behaviour than larger particles

Density-dependent properties: The mechanical properties of granular materials are often described as density-dependent, with denser packings being stronger and more resistant to deformation

Granular temperature: In driven systems, granular materials can exhibit a granular temperature, which is equal to the root mean square of grain velocity fluctuations and is analogous to thermodynamic temperature

Clustering and aggregation: Granular materials can tend to cluster and clump due to the dissipative nature of particle interactions, leading to interesting consequences such as enhanced friction and percolation

Complex behaviour under excitation: Granular materials can exhibit a wide range of pattern-forming behaviours when excited, such as vibrated or allowed to flow. They can also display fluid-based instabilities and phenomena like the Magnus effect

Unmixing behaviour: Granular materials can exhibit unique mixing and size-separation behaviour, particularly in vibrated or flowing states

Jamming: Jamming in granular materials refers to the transition where a collection of particles like sand, sugar, or grains changes from behaving like a fluid (able to flow) to behaving like a solid (unable to flow) when certain conditions are met. Jamming happens when granular materials are loosely packed, the grains can move past each other easily, so the material flows like a liquid. As you squeeze or compress the grains together (increasing their density), or apply certain stresses, they become so tightly packed that they can no longer move freely. At this point, the material becomes rigid and resists further deformation, behaving more like a solid. This is called the jammed state. Pouring sand into a pile: It flows easily at first, but if you press down, it can become solid and hold its shape. Trying to pour sugar from a narrow container: Sometimes it gets stuck and won't flow out—this is jamming.

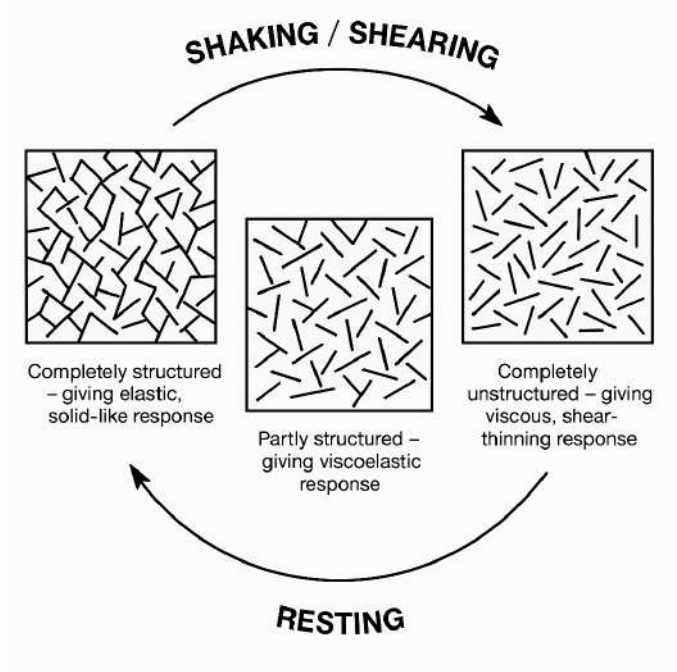


Figure 14: Jamming in granular materials

Note: This image is recreated from recreations of the original image from a text book called "A handbook of rheology" by Howard A Barnes, (2000) The University of Wales Institute of Non-Newtonian Fluid Mechanics, Department of Mathematics. (Source: Author)

Let us try and understand what the above diagram means. When the material has a well-organized internal structure, it is resting and its behaviour is elastic with a solid-like response. In the partially structured state (shaking/shearing), the material, such as a gel, is at rest, yet holding its shape. If an external stress is added to the material, the structure begins to break down due to applied stress. The material now exhibits viscoelastic response (partly solid, partly liquid). This would broadly correspond to stirring or mildly shaking the gel. With continued shaking/shearing, the structure becomes completely unstructured, and the material becomes "thin" and can flow easily. Once the stress is removed, the material slowly rebuilds its structure over time, returning to the original elastic state.

Other Interesting Soft Materials

Ferro-Fluids: Ferrofluids are special liquids that contain tiny magnetic particles suspended evenly throughout a carrier fluid, such as oil or water. These nanoparticles, usually about 10 nanometres in size and made of iron-containing compounds like magnetite, are coated with materials called surfactants to prevent them from clumping together. When exposed to a magnetic field, the particles align and cause the whole fluid to become strongly attracted to magnets, often forming unique spike-like patterns along the magnetic field line. Because the particles are so small, ferrofluids behave like liquids but can respond to magnetic forces, making them useful for applications such as sealing computer hard drives, cooling

loudspeakers, and potentially delivering medicine inside the body. Without a magnetic field, the fluid acts like a normal liquid with no magnetization, but when a magnetic field is applied, its properties change dramatically due to the alignment of the magnetic nanoparticles. In short, ferrofluids are liquids that become magnetic and change shape when near magnets, combining properties of both liquids and magnets in a fascinating way.

Soap Bubbles: A soap bubble is a thin, spherical film made of soapy water that traps air inside. The bubble's surface is actually a sandwich: a very thin layer of water is held between two layers of soap molecules. This structure is possible because soap molecules have two ends—one that likes water and one that avoids it—so they arrange themselves to keep the water layer stable. Soap bubbles appear colourful because light waves reflect and interfere off their thin surfaces, creating shifting rainbow patterns called iridescence. Bubbles always try to form perfect spheres because this shape uses the least amount of surface area to contain a given volume of air, which is a principle known as the minimal surface. Bubbles pop easily if the water in the film evaporates or if the surface is disturbed, breaking the delicate balance that holds them together. In summary, soap bubbles are fun, fragile spheres that beautifully demonstrate the science of surface tension, light, and geometry.

Table 1: Various forms of soft matter and their properties

Type of Soft Matter	Structure	Properties	Applications
Liquid Crystals	Molecules with partial order, either in layers or aligned along axes	Sensitivity to external stimuli (temperature, electric fields)	Display technology (LCDs)
		Intermediate state between solid and liquid	Optical devices
		Birefringence (light interaction)	Tuneable lenses
			Sensors
Colloids	Particles (nanometre to micrometre scale) dispersed in a medium (liquid, solid, or gas)	Exhibit Brownian motion (random movement)	Food industry (mayonnaise, ice cream)
		Stability depends on surface area and interactions	Pharmaceuticals (drug delivery)
		Can be lyophilic (solvent-loving) or lyophobic (solvent-hating)	Cosmetics (creams, lotions)
			Paints and inks
Polymers	Long chains of repeating monomers, can be linear, branched, or crosslinked	High molecular weight	Plastics (polyethylene, PVC)
		Can be flexible or rigid	Textiles (nylon, polyester)
		Thermoplastic or thermosetting	Medical devices (implants, stents)
		Can undergo polymerization reactions	Adhesives and coatings
Gels	Three-dimensional network of polymers, with a liquid phase dispersed inside	Semi-solid consistency	Medical applications (wound dressings, drug delivery)
		Reversible (physical gels) or irreversible (chemical gels)	Food industry (Gelatine, thickeners)
		Viscoelastic properties (both solid-like and liquid-like behaviour)	Cosmetics (hair gels, skin moisturizers)
			Personal care (toothpaste, lotions)

1.3: Properties of Soft Matter

Introduction

Physics explores the extremes – from what is inside of the particles that are inside the nucleus of an atom, all the way to what happens at the scale of the Universe itself. The human body on the other hand, having evolved for survival on earth, can perceive only a tiny fraction of this. Of course, the limitation is to the bodily senses and not to the instruments (sensors) or the mind that understands them. Just as human experiences are expressed through human languages, what happens from the smallest of small to the largest of large in the Physical world is expressed through mathematics. Maths and Physics are inseparable twins like Castor and Pollack, or the Aswini brothers, to take an astronomical metaphor.

In this chapter a very rudimentary mathematical background is given to the most essential parameters that are needed to understand the physics of the toys to be discussed in later chapters. It is written for a reader with little to no background in mathematics. However, if you choose to skip this, please proceed to the next chapter.

Chemical Bonding

Now that we have a basic idea of how atoms come together to form molecules, let's explore the different types of bonds that hold them together. These chemical bonds are the forces that keep atoms connected, and they are broadly grouped into two main categories: strong bonds and weak bonds.

Strong bonds—also known as bonding or intra-molecular bonds—occur within a molecule and are responsible for actually forming the molecule. The three most important types of strong bonds are:

- Covalent bonds, where atoms share electrons.
- Ionic bonds, where one atom gives up electrons to another, creating charged particles (ions) that attract each other.

These types of bonds play a major role in forming the solid, liquid, and gaseous substances that make up the material world.

On the other hand, weak bonds—also called non-bonding or intermolecular bonds—are usually found between different molecules rather than within a single one. Although weaker than the strong bonds mentioned above, they are still very important, especially in biological and soft materials. Two key types of weak bonds we'll focus on are:

- Hydrogen bonds, which often occur between water molecules and help give water its unique properties.
- van der Waals forces, which are weak attractions between molecules due to temporary shifts in their electric charges.

In some special cases, these weak bonds can also appear within a single large molecule, not just between separate ones. We'll explore those situations a bit later.

Understanding both strong and weak bonds is essential for grasping how everything from metals to liquids to living cells hold together and behave the way they do.

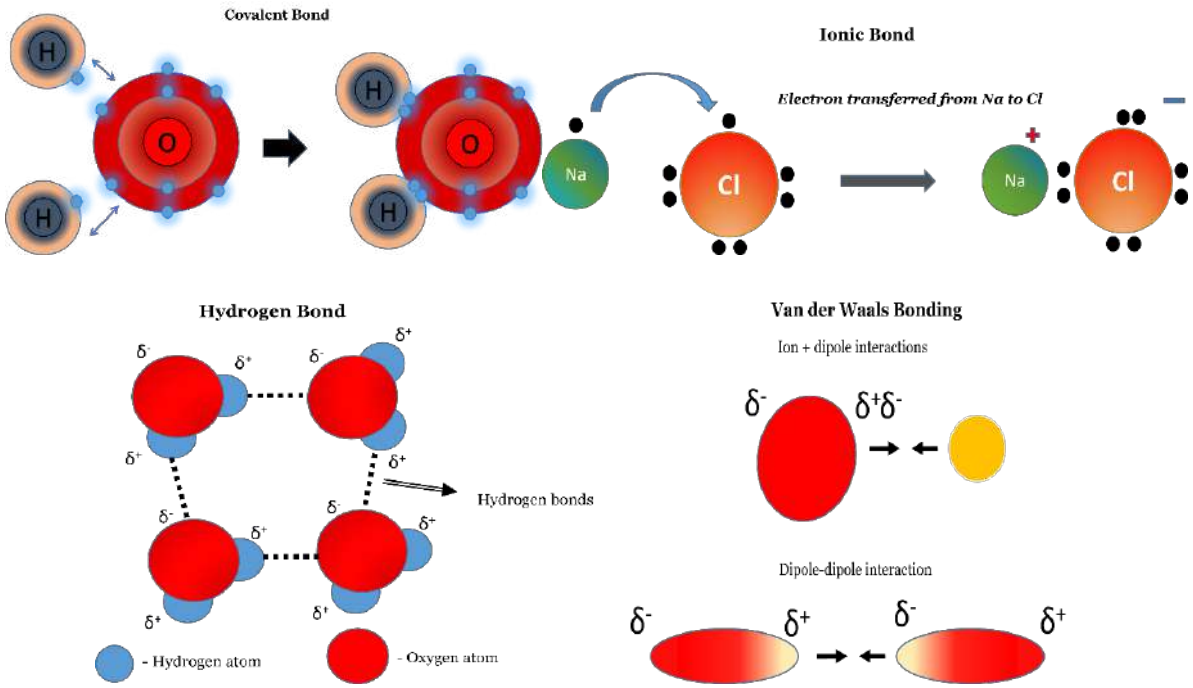


Figure 15: Different types of chemical bonding

(Source: Abdulkareem U)

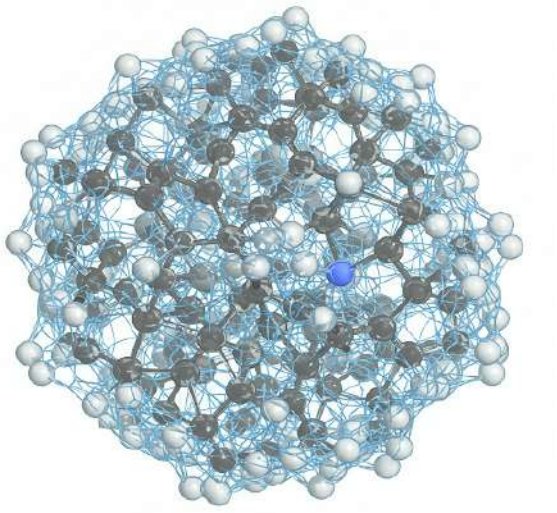


Figure 16: Hydrogen bond network in water molecules.

The hydrogen bonds give a more complex structure to water leading to its unique properties such as high boiling point

(Source: Gemini AI)

One of the many equations that is often used to describe the balance between the attractive and repulsive forces between atoms, that enables the formation of molecules is the Lennard-Jones equation.

$$V(r) = 4\varepsilon\left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6}\right] \qquad \textit{Equation 1}$$

- **r:** Distance between particles.
- **ε** : Depth of the potential well — measures how strongly the two particles attract.
- **σ:** Distance at which the potential is zero — roughly the size of the particles.

The variation in the form of the potential when ε and σ are varied.

The form of the equations for some specific values of ε and σ are shown in the figure below. When the depth of the potential is small, such as in a and b, lesser amount of energy is required to break the atoms apart. One can imagine it as lesser energy being required to crawl out of the trench, as compared to the deeper ones.

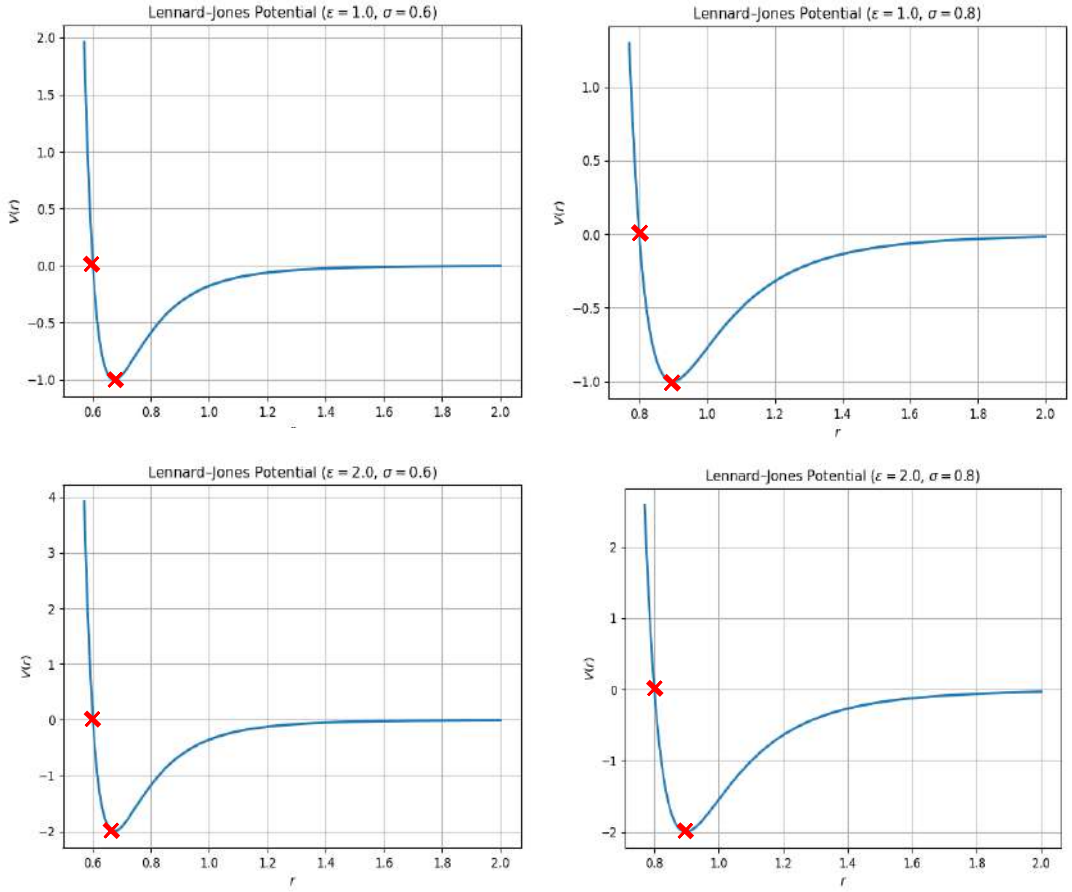


Figure 17: Plots of the Lennard-Jones potential for various values of σ and ε

(a) σ =0.6, ε =1 (b) σ = 0.8, ε = 1 (c) σ=0.6, ε =2 (d) σ =0.8, ε=2. [Source: Sampurn Anand, plotted using Python code. The source code and the steps to simulate these using Google Colab are provided towardsthe end of the document].

What makes non-bonding interactions—like hydrogen bonds—especially interesting is that they are weak enough to be broken at room temperature. This is because the natural energy that molecules have at room temperature is often just enough to break these bonds. That's why these interactions are so important in living systems, where reactions and changes need to happen without extreme heat or pressure.

For example, hydrogen bonds play a crucial role in many biological processes. They help give water its unique properties, like surface tension and its ability to dissolve many substances. They also help hold together the DNA double helix, the structure that carries our genetic information. In DNA, the two strands are connected by hydrogen bonds between matching base pairs—strong enough to hold the strands together, but weak enough that they can be separated when needed, like during cell division.

These weak bonds are also behind some other fascinating behaviours. One is self-assembly, where molecules come together on their own to form organized

structures—like puzzle pieces snapping into place—without anyone forcing them to. This happens because the molecules naturally move from a disordered state to an ordered one when they reach a balanced, or equilibrium, condition. These structures don't last forever, though. They are often in what scientists call metastable states, meaning they seem stable but can break apart after a short or long time, depending on the situation.

Another phenomenon driven by weak bonds is molecular folding, especially in very large molecules like proteins or polymers (long chains of repeating units). These weak interactions help different parts of a large molecule interact with each other, allowing it to fold into a compact shape. This folding is essential for the molecule to work properly, especially in biology where shape often determines function.

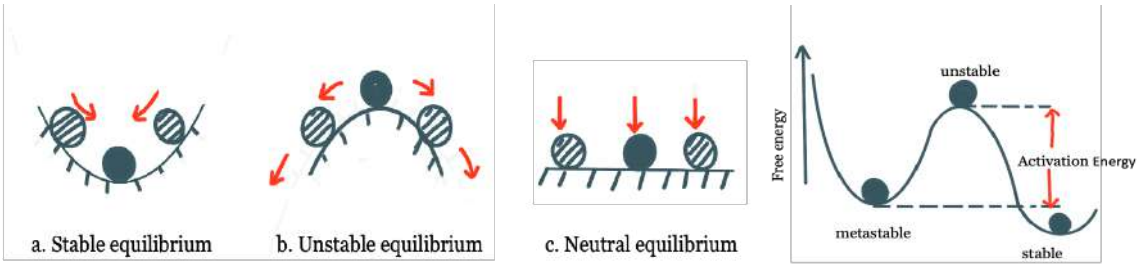


Figure 18: Equilibrium and stability

(Source: Author)

To really understand how these weak interactions guide the behaviour of molecules, scientists often think in terms of energy landscapes—a kind of map that shows how molecules move and settle into different shapes and states based on their energy levels. We'll take a closer look at this next.

Balance is the key

In nature, systems tend to settle into states of *minimum energy*. This idea shows up again and again across all areas of science. To help picture it, imagine a ball rolling down a hillside. Naturally, it will move downward until it comes to rest at the *lowest point*—that's the place where its energy is the least. Similarly, molecules and other physical systems will move or change in ways that reduce their energy.

This principle applies to all kinds of energy—*mechanical*, *chemical*, *thermal*, and more. Whether it's a falling object, a chemical reaction, or a folding protein, everything tries to reach a stable, low-energy state.

Now, imagine that instead of a smooth hill, the ball is rolling over a rugged landscape—like a view from above a range of hills and valleys. This uneven terrain represents what scientists call a potential energy surface. In real systems, this "landscape" can be very complex. It has:

- Peaks, where the energy is high,
- Valleys, where the energy is low,
- Special points called saddle points, which are high in one direction and low in another—like a mountain pass.

Some valleys are deeper than others. The deepest valley is called the global minimum, and that's the most stable state the system can reach. Shallower valleys are called local minima—these are still low-energy spots, but not the lowest possible.

If you placed a ball on this kind of landscape and let it roll, it might come to rest in any of these valleys—points like *a, b, or c* in Figure 19. Each point represents a possible stable or semi-stable state the system can reach. Which one it ends up in depends on where it starts and how much energy it has along the way. This idea of energy landscapes helps us understand how molecules behave—how they move, fold, change shape, or even react with each other.

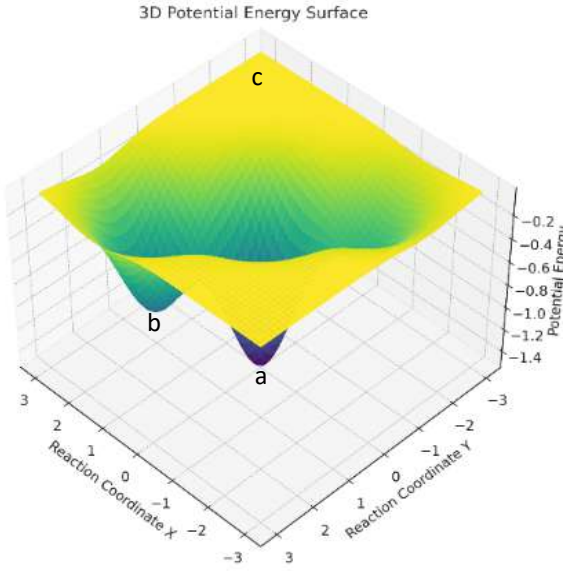


Figure 19: A representative view of potential energy surface

(Source: ChatGPT)

If the ball reaches point *a*—the global minimum on the energy landscape—it has found the lowest possible energy. This is the most stable state the system can be in, and the ball will stay there forever, unless something from the outside disturbs it with a large enough force.

If the ball ends up at *b*, which are local minima, it will also stay put—but only temporarily. These are stable spots, but not the most stable. If the ball gets just enough energy (like a small push), it can roll over the nearby peak and drop into a deeper valley, possibly reaching the global minimum.

Now, imagine the ball at point *c*, which lies on a flat surface—neither a hill nor a valley. This is a neutral equilibrium point. The ball won't move on its own, but if it's

nudged slightly, it may shift around and stay wherever it stops. However, if it reaches the edge of that flat surface, gravity takes over, and it starts to roll down again. This shows that it was not in a completely stable state to begin with.

All of this brings us to an important concept: equilibrium. A system is said to be in equilibrium when all the different forces acting on it balance out. For example, a ball at rest on a slope will roll down because the forces are unbalanced. But a ball in a valley—or even on a flat surface—has balanced forces, meaning it's in some form of equilibrium.

There are different types of equilibrium, and the way a system responds when disturbed tells us what kind it is:

- Stable equilibrium: The system returns to its original state (like a ball in a deep valley).
- Unstable equilibrium: A small disturbance sends the system away from its position (like a ball on top of a hill).
- Neutral equilibrium: The system stays in its new position after being moved (like a ball on a flat surface).

In nature, systems tend to move toward equilibrium because that's where energy is minimized. Reaching equilibrium is nature's way of settling into a more stable, lower-energy condition.

Material Density

There is that famous question one asks a child, which is heavier? One kilogram of cotton or one kilogram of iron. An innocent child would perhaps respond it is one Kg of cotton that weighs more, while a more astute child would claim that both weigh the same. The confusion arises since one Kg cotton occupies far more volume than one Kg iron. This is in turn because both have different material densities.

The density of a material (ρ) is defined as its mass per unit volume. In the context of soft matter, density plays a key role in determining material behaviour under gravitational, thermal, or mechanical influences. Density can be expressed by the equation:

$$\rho = m / V \qquad \textit{Equation 2}$$

Where:

- ρ is the density
- m is the mass of the material
- V is the volume occupied by the material

The above equation gets modified if there is a solute such as particles or polymers dissolved in a solvent.

Then material density is then given as:

$$\rho = \phi\rho_p + (1 - \phi)\rho_s \qquad \textit{Equation 3}$$

where ϕ= porosity, i.e., the fraction of the total volume occupied by pores, ρ_p = particle/polymer density and ρ_s= solvent density.

Critical Packing Density

Have we all not tried to add the last bit of sugar to a jar by tapping it on the counter-top? The act of tapping packs the existing sugar particles more tightly, making space for some more. However, there comes a point when no matter what you do, you cannot pack more sugar, even if you feel there is more space. This is even more evident if you take a glass jar and try to fill it with marbles of two different sizes. What determines the maximum packing?

Consider a different scenario. Suppose you were watering a flower-pot, how much water will you need to wet the floor of the pot? Will this quantity necessarily wet the entire soil? Both of these phenomena are controlled by the critical density fraction.

Critical density fraction is defined as the point at which a granular system undergoes a transition — such as percolation, mechanical stability, or jamming. There are many of these critical densities, two of which are percolation threshold and jamming threshold.

Jamming threshold: this is the critical volume fraction where particles can't be packed any denser, in a random manner. This is given by $\phi_c \approx 0.64$. This is to say, randomly poured sugar particles will initially occupy at best 64% of volume. When you tap the bottle, the arrangement goes from random to regular, and the volume occupied can go to as much as 74%.

Surface Tension

Ever seen those insects that happily walk on water? One of them is called a water-strider since, obviously, it strides over water. Ever wondered how do they manage to do that? The insects are able to walk on water due to a phenomenon called the surface tension. Surface tension is the tension in the top-most layer of a liquid, that occurs since the molecules on the surface have a different behaviour that those in the bulk of the liquid. A molecule in the bulk would see molecules on all sides – thus experiencing forces in all directions. A molecule on the surface, however, does not feel the force on the top side (assuming that its interaction with air molecules in much weaker than its interaction with its own type). This causes a tension that makes the top layer of the liquid feel like a very thin stretched rubber sheet. Since the insects are light-weight, they are able to walk over this “rubber sheet”. We, on the other hand, are too heavy for this thin sheet to support.

Surface tension is a fascinating physical phenomenon that arises due to the cohesive forces between liquid molecules, particularly prominent at the boundary between a liquid and a gas. In the case of soap bubbles, surface tension plays a crucial role in determining the bubble's shape, stability, and the vivid colours we observe. To understand this better, we delve into the behaviour of soap bubbles and films, guided by the principles known as Plateau's Laws, and explore the optical phenomena responsible for their vibrant appearance.

Surface Tension and the Shape of Soap Bubbles

At its core, surface tension can be thought of as the liquid's tendency to minimize its surface area because molecules at the surface experience an unbalanced inward force. This leads to a contracting effect on the surface, making the liquid behave as though it were covered by an elastic skin.

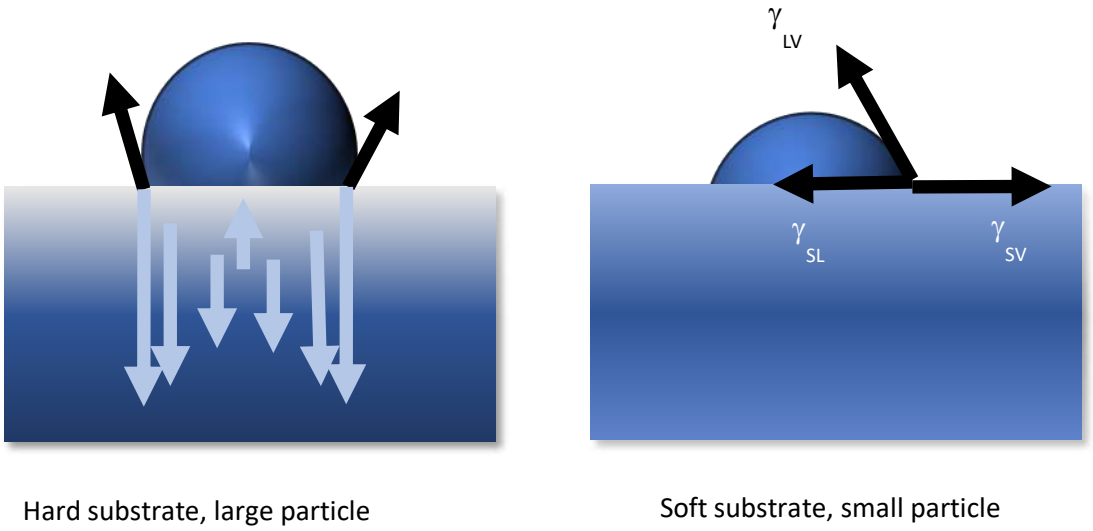


Figure 20: Forces on a drop due to surface tension

(Source: author)

Soap bubbles, which are essentially thin layers of soapy water enclosing air, naturally adopt spherical shapes. The reason behind this lies in the principle of minimizing surface area. Among all three-dimensional shapes, a sphere encloses the largest possible volume for the smallest possible surface area. This minimizes the free energy of the system, rendering the spherical shape the most stable configuration for a solitary soap bubble.

Mathematically, the surface area AA and volume VV of a sphere of radius rr are given by:

$$A = 4\pi r^2, V = \frac{4}{3}\pi r^3 \qquad \textit{Equation 4}$$

The ratio of surface area to volume decreases as the sphere enlarges, explaining why bubbles tend to coalesce into larger spheres, reducing overall surface energy.

Plateau's Laws: Geometry and Stability of Soap Films

Plateau's Laws, formulated in the 19th century by Joseph Plateau, provide a detailed description of how soap films and bubbles arrange themselves when multiple films or bubbles come into contact. These observations are grounded in the universal tendency of systems to minimize their total energy, and they reveal intricate geometrical patterns in soap structures.

First, soap films always try to minimize their total surface area. This fundamental tendency dictates that the films settle into configurations known as *minimal surfaces*. A minimal surface is defined mathematically as a surface whose mean curvature is zero at every point, which means that the surface bends equally in opposite directions, balancing itself perfectly.

Second, Plateau discovered that when three soap films meet along a line (called a Plateau border), they always meet at equal angles of 120°. This can be understood by considering the forces exerted by surface tension along the films. At equilibrium, these forces must balance, and the only configuration where three equal forces balance in a plane is when they are separated by 120°. This is essentially a result of the vector sum of forces equating to zero.

$$\sum \vec{F}_{surface\ tension} = 0 \qquad \textit{Equation 5}$$

Graphically, if you draw three lines at 120° to each other and represent them as force vectors, they sum to zero, ensuring stability.

Third**,** when bubbles cluster together, the soap films adjust to form the most energy-efficient arrangements. For instance, four bubbles can come together in a *tetrahedral arrangement*. Here, four films meet at a single point with angles approximately equal to 109.5°, the tetrahedral angle, as dictated by geometry in three-dimensional space. This minimizes the total surface area while maintaining mechanical equilibrium.

Fourth, when two bubbles touch, a flat film forms between them, and the interface curves slightly depending on the relative sizes of the bubbles. The pressure inside a bubble is related to its curvature, described by the Young-Laplace equation:

$$\Delta P = \gamma \left(\frac{1}{R_1} + \frac{1}{R_2}\right) \qquad \textit{Equation 6}$$

where ΔP is the pressure difference across the film, γ is the surface tension, and R_1, R_2 are the principal radii of curvature. Smaller bubbles, having higher curvature, exhibit higher internal pressure and thus tend to merge with larger bubbles to reduce overall surface energy.

Coalescence: Merging to Minimize Energy

When bubbles come into contact, the thin film separating them may collapse, leading to the merging or *coalescence* of the bubbles. The result of coalescence is a new, larger bubble with a lower total surface area compared to the sum of the original smaller bubbles. This process continues until the system reaches a state of minimal total surface area, exemplifying a universal principle in nature—systems tend to evolve toward configurations with the lowest possible energy.

Thin Film Interference and Bubble Colours

One of the most visually striking aspects of soap bubbles is their vivid, swirling colours. These colours are not due to pigments but arise from a phenomenon called *thin film interference*. As light encounters the thin soap film, part of it is reflected from the outer surface and part from the inner surface. The two reflected waves can interfere constructively or destructively depending on the thickness of the film and the wavelength of the light.

The condition for constructive interference (bright bands) is approximately given by:

$$2nd = m\lambda \qquad \textit{Equation 7}$$

while for destructive interference (dark bands):

$$2nd = \left(m+\frac{1}{2}\right)\lambda \qquad \textit{Equation 8}$$

where n is the refractive index of the soap film, d is the film thickness, λ is the wavelength of light, and mm is an integer representing the order of interference.

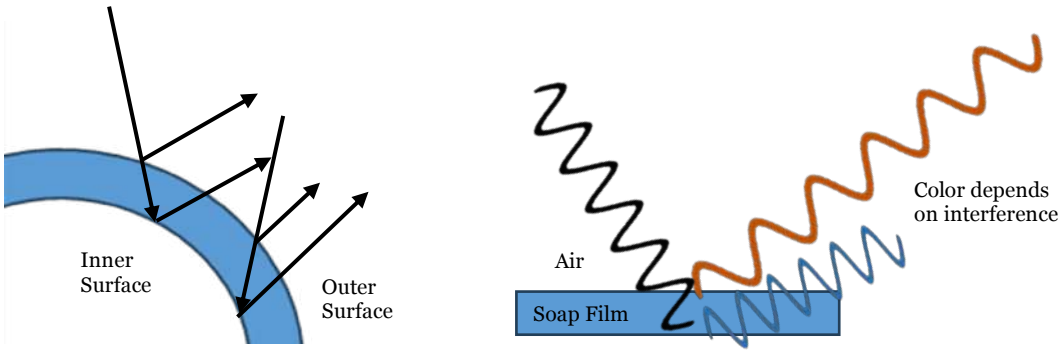


Figure 21: Schematic of interference in thin films and soap bubbles

(Source: author)

As the soap film drains under gravity and becomes thinner over time, different wavelengths interfere constructively or destructively at different positions on the bubble's surface. This creates the dynamic and colourful patterns we see, which shift and change as the thickness of the film evolves.

The study of soap bubbles elegantly combines principles of physics, geometry, and optics. From the minimization of surface area governed by surface tension to the precise geometric patterns described by Plateau's Laws, to the colourful displays created by thin film interference, soap bubbles serve as a beautiful and accessible example of how simple physical principles manifest in nature. These principles not only explain everyday observations but also have important applications in materials science, biology, and fluid mechanics.

Ferrofluids

Certain soft materials blur the line between fluids and responsive solids, exhibiting unusual behaviour when placed near magnets. Unlike ordinary liquids, they can stretch, spike, or even climb walls under the influence of a magnetic field. What makes them remarkable is not just their ability to flow, but their capacity to do so while carrying and responding to magnetic forces. At rest, they behave like typical viscous fluids or pliable gels. But when exposed to a magnetic field, their internal structure reconfigures, resulting in dramatic changes in shape, stiffness, or movement.

This magneto-responsive behaviour arises from the presence of magnetic particles dispersed throughout a flexible or fluid matrix. In one case, the particles are nanoscale and finely suspended, giving rise to stable magnetic fluids. In another, they are embedded in a deformable solid-like medium, leading to materials that deform and stiffen under field gradients. Both systems highlight the unique intersection of soft matter physics and magnetism, where simple-looking substances reveal highly complex, tunable interactions driven by external fields.

Synthesis of Magnetic Nanoparticles

The most widely adopted method for synthesizing iron oxide magnetic nanoparticles, particularly magnetite (Fe_3O_4), is the chemical co-precipitation route. This method offers a scalable and controllable synthesis pathway, producing monodisperse nanoparticles under relatively mild reaction conditions.

In the co-precipitation process, ferrous (Fe^{2+}) and ferric (Fe^{3+}) salts are dissolved in an aqueous solution at a stoichiometric molar ratio of 1:2. Common salts include $FeCl_2 \cdot 4H_2O$ and $FeCl_3 \cdot 6H_2O$. The precipitation of Fe_3O_4 occurs upon the introduction of a strong base such as sodium hydroxide (NaOH) or ammonium hydroxide (NH_4OH), leading to the nucleation and growth of magnetite nanoparticles. The general reaction proceeds as follows:

$$Fe^{2+} + 2Fe^{3+} + 8OH^- \rightarrow Fe_3O_4(s) + 4H_2O \qquad \textit{Equation 9}$$

This reaction is typically carried out under an inert atmosphere (e.g., nitrogen or argon) to avoid the partial oxidation of Fe^{2+} to Fe^{3+}, which would result in the formation of maghemite (γ-Fe_2O_3) or hematite (α-Fe_2O_3). The solution temperature is usually maintained between 70–90 °C to ensure uniform nucleation and adequate particle crystallinity.

The pH is a critical parameter; it must be kept in the alkaline regime (pH > 9) to favor complete precipitation and avoid formation of iron hydroxide intermediates. After precipitation, the nanoparticles are washed repeatedly with deionized water and ethanol to remove ionic byproducts and unreacted precursors, then isolated via magnetic separation or centrifugation.

Control over nanoparticle size and polydispersity is achieved by tuning synthesis parameters such as ionic strength, base addition rate, temperature, and the use of capping agents or surfactants.

Surface Functionalization and Stabilization
Bare Fe_3O_4 nanoparticles tend to aggregate due to van der Waals and magnetic dipole interactions. Therefore, surface functionalization is critical to impart colloidal stability and prevent irreversible agglomeration, particularly for applications in ferrofluids or biomedical systems.

Surface coating may be achieved in situ during synthesis or ex situ post-synthetically. Hydrophobic surfactants like oleic acid are used for dispersion in nonpolar solvents, while hydrophilic stabilizers such as citric acid, polyethylene glycol (PEG), dextran, or polyvinyl alcohol (PVA) are preferred for aqueous systems.

The stabilization mechanism can be steric, electrostatic, or electrosteric in nature. For example, citric acid imparts negative surface charge to the particles through carboxylate groups, enabling electrostatic repulsion in aqueous suspension. The coating also provides reactive groups for further functionalization in biomedical or sensor applications.

Preparation of Ferrofluids
A ferrofluid is defined as a stable colloidal dispersion of single-domain magnetic nanoparticles (typically < 15 nm in diameter) suspended in a carrier liquid. The fluid responds to external magnetic fields while retaining fluidic behaviour, owing to the Brownian motion that counteracts magnetic dipole-dipole attractions.

The process of ferrofluid preparation involves dispersing the previously synthesized and surface-stabilized Fe_3O_4 nanoparticles into a suitable carrier medium such as water (for hydrophilic coatings) or mineral oil, kerosene, or synthetic hydrocarbons (for hydrophobic coatings).

High-intensity ultrasonication or high-shear mixing is typically used to break up agglomerates and ensure homogeneous distribution. Additional surfactants or dispersants are sometimes added during this phase to further reduce interparticle interactions.

The colloidal stability of the resulting ferrofluid is assessed via zeta potential measurements, dynamic light scattering (DLS) for particle size distribution, and sedimentation tests under static conditions.

Preparation of Magnetic Slime and Magneto-Rheological Gels
Magnetic slimes or magneto-rheological (MR) gels are viscoelastic polymeric matrices embedded with magnetic particles. Unlike ferrofluids, which are purely liquid, MR gels exhibit semi-solid behaviour with field-dependent viscosity and elasticity.

From a materials science perspective, these are composite systems consisting of:

- A polymeric network or cross-linked gel (such as PVA, polyacrylamide, or gelatin),
- A dispersion of magnetic nanoparticles or larger magnetic microparticles,
- A plasticizer or solvent system to tune viscoelastic properties.

The synthesis typically involves dispersing stabilized Fe_3O_4 nanoparticles in a pre-polymer or monomer solution. The cross-linking process is then initiated chemically (e.g., with glutaraldehyde for PVA), thermally, or by UV exposure, depending on the polymer chemistry. In-situ gelation traps the magnetic particles in the matrix, creating a soft, magnetically responsive composite.

The rheological properties can be tuned by varying particle loading (typically 10–40 wt%), polymer concentration, cross-linking density, and temperature. In the presence of a magnetic field, the particles align into chain-like structures along the field lines, inducing anisotropic stiffness and viscoelastic behaviour.
These materials are used in applications ranging from soft actuators and vibration dampers to educational tools and responsive drug delivery matrices. The synthesis of magnetic nanoparticles via co-precipitation remains the most practical and scalable method for generating Fe_3O_4 with tunable size and superparamagnetic properties. These nanoparticles, once properly stabilized, can be formulated into ferrofluids by colloidal dispersion into appropriate solvents, or into magneto-rheological gels by embedding in cross-linked polymer matrices. The physicochemical characteristics of these materials can be finely tuned through control of synthetic parameters, enabling their application across fields such as soft robotics, biomedical engineering, and advanced materials science.

Magnetic Properties

Magnetic susceptibility (χ) is given by

$$\chi = \frac{M}{H} \qquad \textit{Equation 10}$$

Where

- M = magnetization,
- H = applied magnetic field.

The Langevin function describes how the magnetization of superparamagnetic particles aligns with an external magnetic field in thermal equilibrium and is given by

$$L(x) = coth\,(x) - \frac{1}{x} \qquad \textit{Equation 11}$$

Where:

$$x = \frac{\mu BH}{kT} \qquad \textit{Equation 12}$$

- μ = magnetic moment of the particle,
- B = Bohr magneton,
- H = applied magnetic field,
- k = Boltzmann constant,
- T = temperature.

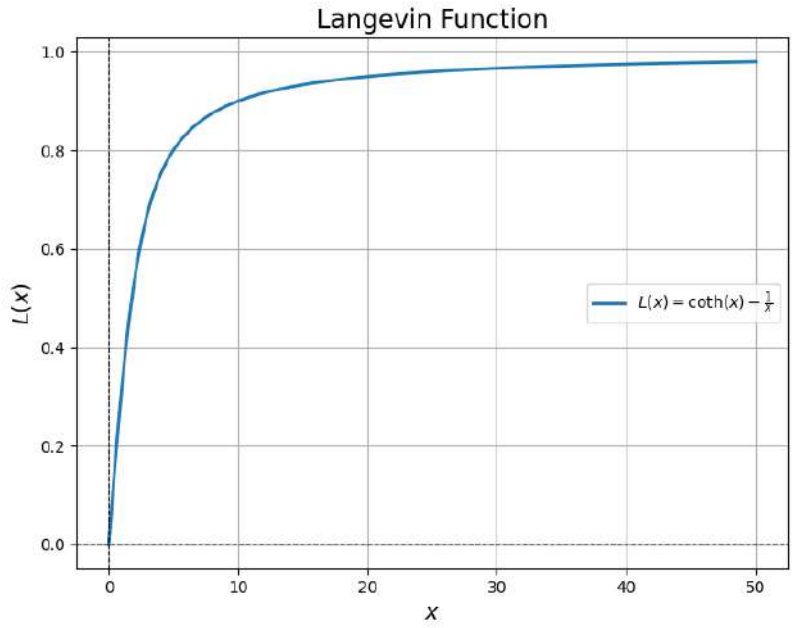


Figure 22: Plot of Langevin function (L(x) vs. x)

[Source: Sampurn Anand, plotted using Python code. The source code and the steps to simulate these using Google Colab are provided towards the end of the document].

From the graph it can be seen that when there's no magnetic field, the magnetic moments (tiny magnets) point in random directions, so the total magnetization is zero. As the filed increases, the graph rises smoothly and bends upward, but it never

becomes a straight line. The magnetic moments begin to align with the field, and the magnetization increases. A t high fields, the graph gets closer and closer to 1 (but never actually reaches it). This shows that almost all magnetic moments are aligned — the material is nearly fully magnetized. This condition is called saturation.

Viscosity and Magnetic Force:

Viscosity is a measure of fluids' resistance to flow. The viscosity influences the speed at which bubbles move through the liquid (η). The relationship between the force required to move an object through a viscous fluid and its velocity is described by Stoke's Law:

$$F = 6\pi\eta r v \qquad \textit{Equation 13}$$

Where:

- F is the drag force.
- η is the dynamic viscosity of the fluid.
- r is the radius of the bubble/particle.
- v is the velocity of the bubble/particle

In the case of materials whose fluid viscosity changes with applied magnetic field, the field-dependent viscosity is given by:

$$\eta = \eta_0(H^2) \qquad \textit{Equation 14}$$

Where:

- η = viscosity,
- η_0 = zero-field viscosity,
- ξ = material-dependent constant,
- H = applied magnetic field.

This equation tells us that the viscosity increases when a magnetic field is applied. Specifically, that the viscosity grows proportional to the square of the magnetic field. Which means that if you double the magnetic field, the viscosity becomes four times greater.

Ferrofluids are stable colloidal suspensions of magnetic nanoparticles, stabilized through a combination of steric and electrostatic repulsions to prevent aggregation. In non-polar media like oil, a single layer of surfactant coats each nanoparticle.

The polar head of the surfactant binds to the magnetic particle surface, while the non-polar tail aligns with the carrier fluid.

In citrated ferrofluids, small chain molecules such as COOH–CH_2–COH–COOH–CH_2–COOH coat the particles and ionize in water, leading to electrostatic repulsion in addition to steric effects.

Porosity and Sponges

Some soft materials, like sponges, are defined not by their composition alone but by their internal structure—specifically, by the voids they contain. These materials are porous, meaning they are riddled with interconnected cavities or channels that can hold, transport, or exchange fluids. The mechanical softness of such materials is often paired with high absorbency, making them effective at soaking up and retaining liquids.

Porosity plays a central role in how these materials behave. The size, shape, and distribution of pores influence everything from how fast a liquid can be drawn in to how the material responds to compression. In biological and synthetic systems alike, porosity allows for capillary action, filtration, selective permeability, and tunable mechanical properties. A sponge, whether natural or engineered, isn't just soft—it's a dynamic network of empty space within a soft solid, enabling a range of functions far beyond simple flexibility.

Research has shown that sponges with aligned channels absorb liquid faster than those with random pores. Additionally, decreasing the width of the channels results in slower absorption. Therefore, porosity—the ratio of void volume (empty spaces) to the total volume of the sponge—is a critical factor in determining the absorption capacity and speed of sponges. This property is typically expressed as a percentage and is essential in understanding the material's structure and performance

$$\boldsymbol{Porosity}(\%) = \left(\frac{\boldsymbol{Void\ Volume}}{\boldsymbol{Total\ Volume}}\right) * \mathbf{100} \qquad \textit{Equation 15}$$

MECHANICAL PROPERTIES:

When compressed under load, porous soft materials such as foams, sponges, and other cellular solids exhibit a distinct mechanical response that differs significantly from that of dense solids like metals or plastics. This response typically unfolds in three phases. Initially, in the elastic region, deformation is uniform and reversible—much like gently compressing a sponge. The internal cell walls bend slightly, and the material can return to its original shape upon unloading.

As compression continues, the material enters the plateau collapse region. Here, the internal porous structure begins to buckle and collapse, absorbing energy with relatively little increase in stress. This plateau stage is especially important in energy-damping applications, as it allows for substantial deformation while maintaining consistent mechanical resistance. In this region, the compressive response becomes more spatially heterogeneous, and the deformation progresses through localized collapse events. This behaviour is reminiscent of metallic foams and other cellular solids, where energy absorption is gradual and distributed.

Eventually, the densification region is reached. At this stage, the pores have mostly closed, and the solid matrix begins to dominate the mechanical response. Any further

deformation requires significantly more force, causing a steep rise in the stress-displacement curve. This marks the material's transition into a much stiffer state, where it can no longer compress easily.

The strength and stiffness of such porous materials are known to scale predictably with their density. The relationship between compressive strength (σ_o) and density (ρ_o) can be described using a power law:

$$\sigma_0 = A\,\rho_0^B \qquad \textit{Equation 16}$$

where A and B are empirical constants determined by the structure and failure modes of the material. A similar relation holds for Young's modulus, which characterizes stiffness:

$$E \propto \rho^n \qquad \textit{Equation 17}$$

with E in pascals and ρ in kilograms per cubic meter. These relations highlight how even subtle changes in density can lead to significant shifts in mechanical performance, making density a key design parameter.

Upon unloading, these materials typically recover only a small portion of the energy stored during compression. This is evident in their stress–strain behaviour, where unloading curves are steep and do not intersect with reloading paths. The resulting hysteresis loop—representing energy dissipation—is relatively small compared to the total area under the stress–strain curve. The steep slope of the unloading curve and its nonlinearity at the start suggest minimal recoverable elastic strain. In contrast, the reloading path tends to be more linear. This mechanical signature implies that while these materials can deform substantially, they are better suited for one-time energy absorption rather than repeated mechanical cycling.

In short, the compressive mechanics of porous soft materials are governed by their internal structure and density, with well-defined regimes of elastic response, structural collapse, and densification. Their capacity for predictable energy dissipation and structural adaptability makes them crucial components in damping, cushioning, and absorptive technologies.

Capillary Effects:

In porous soft materials like sponges or foams, liquid can spontaneously rise through narrow spaces without any external force—this is known as capillary action. It happens because the liquid is more attracted to the solid walls of the pores than to itself, pulling it upward against gravity. The height to which the liquid rises, denoted h, depends on several factors, including the surface tension of the liquid (γ), the density of the liquid (ρ), gravity (g), and the radius of the pores (r). Mathematically, it scales as:

$$h \propto \frac{\gamma}{\rho g r} E \qquad \textit{Equation 18}$$

This means that a liquid with higher surface tension (like water) and smaller pore sizes will rise higher. So in a sponge with very fine pores, water can climb up significantly, while in a coarser sponge, the rise will be much smaller. This principle

helps explain how plants draw water up through tiny vessels in their stems, and why soft, porous materials can absorb and retain liquids so effectively.

Gravity and Buoyancy

Until now, we have not considered the effects of gravity, since the size of the particles was too small to be significantly influenced by it. However, in certain cases (when the size of the particle is large, it mass heavy, or a toy like the liquid bubbler), gravity plays an important role.

Gravity is the force of attraction that acts on all bodies having mass. The force of gravity directs all objects towards the centre of the Earth. The formula for gravity is:

$$F = mg \qquad \textit{Equation 19}$$

Where:

- F represents the force of gravity.
- m is the mass of the object.
- g is the acceleration due to gravity

According to Archimedes' Principle, a buoyant force acts on an object submerged in a fluid. The upward force (buoyant force) equals the weight of the fluid displaced by the object. In the case of a liquid motion bubbler, the rising bubbles experience this upward force.

Buoyant Force: The formula for buoyant force is given by:

$$F = \rho V g \qquad \textit{Equation 20}$$

Where:

- F is the buoyant force.
- ρ is the density of the liquid.
- V is the volume of the displaced liquid
- g is the acceleration due to gravity.

Viscoelasticity

Viscoelasticity is a key mechanical property of elastomers, describing their ability to exhibit both elastic and viscous behaviour under applied stress. Elasticity refers to the capacity of a material to deform when subjected to a force and to return to its original shape once the force is removed. Viscosity, on the other hand, is the tendency of a material to resist flow, causing it to deform continuously under a sustained force. Elastomers, being viscoelastic, do not

behave like purely elastic solids or purely viscous liquids; rather, they display a combination of both properties depending on the duration and rate of applied stress.

Viscoelastic materials exhibit both viscous and elastic behaviour when subjected to deformation. Unlike purely elastic materials, which instantly return to their original shape after stress is removed, viscoelastic materials show time-dependent strain. They may deform gradually under a constant load (creep) and recover slowly after the load is removed (recovery).

Key Mechanical Properties

- Elasticity: Immediate deformation proportional to applied stress, typically modelled by *Hooke's Law*.
- Viscosity: Time-dependent deformation, typically modelled by *Newton's Law of Viscosity*.
- Viscoelasticity: A combination of elasticity and viscosity, where materials exhibit both delayed elastic response and flow behaviour.

Material Responses to External Forces

Materials typically respond to external forces in three ways:

1. Atomic or Molecular Bond Deformation – as seen in crystalline solids.
2. Large-Scale Shape Changes – common in crystalline polymers.
3. Flow and Deformation – reversible in viscoelastic materials, and permanent in plastic materials.

In crystalline polymers, strong intermolecular bonds resist deformation unless subjected to significant force.

<u>Stress–Strain Behaviour</u>

When an external load is applied to a material, its deformation increases with the load. This behaviour is typically divided into three regions (see Figure XX):

- Elastic Region: The material deforms but returns to its original shape when the load is removed.
- Plastic Region: Permanent deformation occurs.
- Fracture Point: The material breaks.

Stress is defined as the force per unit area (Pa), representing internal resistance to deformation. Strain is the relative change in shape or size in the direction of the applied force. The Young's modulus is the ratio of stress to strain and quantifies material stiffness.

<u>Viscoelastic Behaviour in Soft Materials</u>

Soft matter, such as polymers and biological tissues, often exhibits viscoelasticity—deformation that depends on both the magnitude and rate of applied stress. At low

stress, these materials behave elastically, returning to their original shape. At higher stress levels, they behave more like viscous fluids, with irreversible deformation even after the stress is removed.

A hallmark of viscoelastic materials is hysteresis—a lag between applied stress and resulting strain. This results in energy dissipation, represented by the area enclosed in the hysteresis loop during loading and unloading cycles.

- **Newtonian**: Flows the same no matter how fast you stir.
- **Pseudoplastic**: Stir faster = thinner.
- **Dilatant**: Stir faster = thicker.
- **Bingham Plastic**: Won't flow unless you squeeze or press.
- **Thixotropic**: Becomes thinner the longer you stir.
- **Rheopectic**: Becomes thicker the longer you stir.

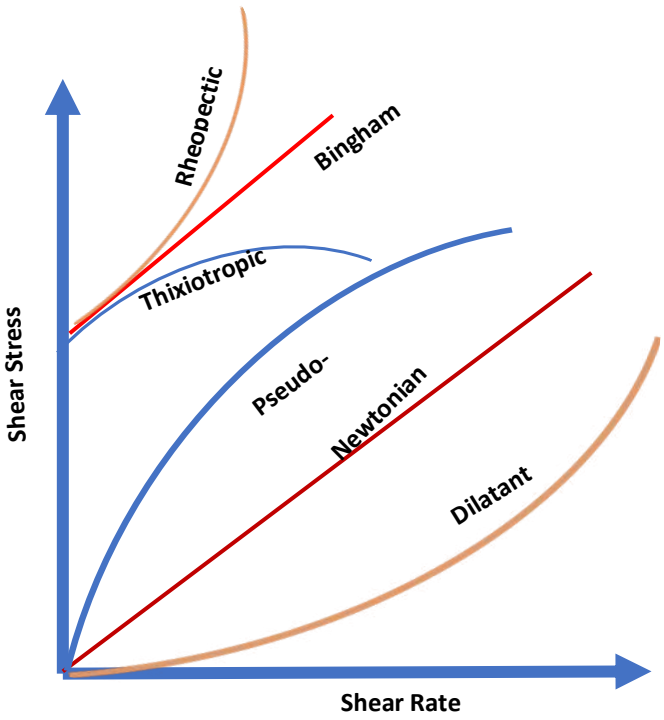


Figure 23: Classification of fluids

Classification based on the relationship between shear stress (force required to slide one layer of fluid over the other) and shear rate (how fast the layers are sliding over each other) (Source: Author)

Table 2: Comparison of fluid types

Fluid Type	Definition	Viscosity Behaviour	Example
Newtonian	Fluids with constant viscosity regardless of applied shear rate.	Viscosity stays constant as shear rate increases.	Water, air, alcohol, mineral oil
Pseudoplastic	Fluids whose viscosity decreases with increasing shear rate.	Shear-thinning	Paint, blood, ketchup
Dilatant	Fluids whose viscosity increases with increasing shear rate.	Shear-thickening	Cornstarch in water ("oobleck"), wet sand
Bingham Plastic	Behaves as a solid until a minimum shear stress is applied, then flows.	Requires yield stress to flow	Toothpaste, mayonnaise, mud
Thixotropic	Viscosity decreases over time under constant shear.	Time-dependent shear-thinning	Yogurt, some gels, printer ink
Rheopectic	Viscosity increases over time under constant shear.	Time-dependent shear-thickening	Gypsum paste, cream being whipped, printer inks (some types)

Newtonian vs. Non-Newtonian liquids

- Fluids are commonly classified based on how their viscosity responds to shear stress:
- Newtonian Fluids: These fluids maintain a constant viscosity regardless of the applied shear rate. Examples include water, air, and most common oils.
- Non-Newtonian Fluids: These exhibit a viscosity that changes with shear rate. A well-known example is oobleck (a cornstarch-water suspension), which becomes more solid-like when subjected to rapid force.

Creep in Plastic Materials (Cold Flow)

- Creep, often referred to as cold flow in plastics, is the tendency of a material to deform permanently under a sustained load over time. This phenomenon is particularly significant in polymers, which can continue to deform even at room temperature when subjected to constant stress.
- Example: The slow sagging or failure of plastic chair legs that have supported weight for extended periods is a common real-world illustration of creep.

- Factors influencing creep: Load duration, temperature, material composition, and environmental conditions.
- Understanding creep is critical when designing plastic components intended for long-term structural or load-bearing use.

Elastomers: Viscoelastic Polymers

Elastomers are a subclass of polymers characterized by their rubber-like elasticity. They are viscoelastic materials, meaning they exhibit both elastic and viscous behaviour depending on the applied stress and time scale.

When a viscoelastic material is stretched slowly, the molecules within the material have enough time to reorganize and flow, resulting in a smooth, gradual deformation. This flow reflects the viscous behaviour of the material. However, when the material is stretched quickly, there is insufficient time for molecular rearrangement, and the material resists deformation more strongly, which highlights its elastic behaviour. This time-dependent response to deformation is characteristic of viscoelastic materials.

A typical time-dependent phenomenon observed in viscoelastic materials is known as creep. When a constant stress is applied to a viscoelastic solid over time, it undergoes a gradual increase in strain, slowly deforming to adapt to the applied load. This behaviour can be quantitatively described by mechanical models such as the Kelvin-Voigt model. In this model, the relationship between stress σ(t) and strain ε(t) at any given time t is described by the equation

$$\sigma(t) = E\,\varepsilon(t) + \eta\,d\varepsilon(t)/dt \qquad \textit{Equation 21}$$

In this expression, E is the Young's modulus of elasticity, which characterizes the elastic response of the material, and η is the viscosity coefficient, representing its viscous resistance. The first term $E\,\varepsilon(t)$ captures the immediate elastic response, while the second term involving the time derivative of strain accounts for the time-dependent viscous flow. This combination enables the material to stretch under stress, recover when stress is removed, and exhibit delayed deformation under sustained force.

Rubber materials belong to a unique subclass of polymers characterized by their ability to undergo large, reversible deformations. This extraordinary elasticity originates from the interplay between molecular structure, thermodynamic principles, and crosslinked network architecture. This explanation elaborates on the fundamental molecular features, structural conditions, and thermodynamic mechanisms that enable rubber-like behaviour in certain polymers.

The Molecular Basis of Rubber Elasticity

Polymer Structure and Prerequisites for Elasticity

Polymers are macromolecules composed of repeating structural units called monomers, covalently bonded to form long chains. Unlike small molecules (e.g., benzene or ethanol with molecular weights of approximately 50–100 g/mol), rubber-forming polymers typically possess very high molecular weights in the range of 10^5–10^6 g/mol, which is 1000 to 10,000 times larger. High molecular weight contributes to entanglements and provides a platform for elasticity but is not by itself sufficient.

There are two critical molecular prerequisites for rubber elasticity:

a) Low Glass Transition Temperature (T_g)

The glass transition temperature (T_g) is the temperature below which the polymer chains are immobilized, resulting in a brittle, glassy state. For rubber to exhibit elasticity at room temperature (or any intended application temperature T_{use}, it must satisfy the following condition:

$$T_g < T_{use} - 50^\circ C \qquad \textit{Equation 22}$$

This ensures that the polymer chains have sufficient segmental mobility to allow large-scale deformation without fracturing. If $T < T_g$ chain segments are frozen, making the material hard and brittle.

b) High Chain Flexibility and Amorphous Nature

The flexibility of polymer chains arises from their ability to rotate around single bonds, such as C–C, C–O, or Si–O bonds. Structural features that hinder this rotational freedom, such as bulky side groups (e.g., phenyl groups) or crystalline ordering, increase stiffness and reduce elasticity.

Amorphous (disordered) polymer structures, in which chains lack crystalline alignment, are essential to maintain flexibility and extensibility. When T_g is undesirably high, plasticizers may be used to increase free volume and lower T_g, promoting chain flexibility.

Examples of Rubber-Specific Polymer Systems

Rubber materials are derived from both natural and synthetic polymers. Common examples include:

- Natural Rubber: cis-1,4-polyisoprene
- Styrene-Butadiene Rubber (SBR)
- Nitrile Rubber (acrylonitrile-butadiene copolymer)
- Neoprene (Chloroprene rubber)

- Polybutadiene Rubber
- Ethylene Propylene Diene Monomer (EPDM)
- Butyl Rubber (isobutylene-isoprene rubber)
- Silicone Rubber (e.g., polydimethylsiloxane, PDMS)

These polymers are designed to be amorphous and have T_g values well below their operating temperatures, ensuring softness and flexibility in practical applications.

Crosslinking: The Backbone of Elastic Recovery

A defining feature of rubber elasticity is the presence of chemical crosslinks that connect polymer chains into a network, preventing them from sliding irreversibly past each other. This network structure allows the material to deform significantly while enabling recovery to its original shape upon removal of stress.

Crosslinking Mechanism

In natural rubber, crosslinking is commonly achieved through vulcanization—a process in which sulfur atoms form bridges between unsaturated carbon-carbon double bonds (C=C) in polyisoprene chains. A simplified reaction schematic:

$$\textit{Polyisoprene Chains} \xrightarrow{S,\ heat} \textit{Crosslinked Rubber} \qquad \textit{Equation 23}$$

Typically, approximately 1 crosslink per 50–100 repeat units is sufficient to impart elasticity.

Effect of Crosslink Density

- **Low crosslink density** leads to insufficient recovery and possible plastic (permanent) deformation.
- **High crosslink density** makes chain segments too short, resulting in stiffness and brittleness.

There exists an optimal crosslink density that maximizes elasticity without compromising softness.

Thermodynamic Origin of Elasticity

Rubber elasticity is primarily entropic rather than energetic. This contrasts with metallic or crystalline elasticity, which is dominated by enthalpic (energy-based) effects.

Entropic Elasticity

At equilibrium (unstretched), polymer chains adopt a random coil configuration, maximizing their entropy (S). When stretched, the chains align along the direction of

deformation, reducing their entropy. The resistance to stretching arises from the thermodynamic tendency of the system to maximize entropy.

The force opposing deformation can be expressed as:

$$F = -T\left(\frac{\partial S}{\partial x}\right)_T \qquad \textit{Equation 24}$$

where:

- F is the restoring force,
- T is the absolute temperature,
- x is the deformation length.

Energy Balance (First Law of Thermodynamics)

$$dE = dQ - dW \qquad \textit{Equation 25}$$

- During rapid stretching, little heat is exchanged ($dQ<0$), and the rubber heats up.
- The internal energy change (dE) is negligible; most mechanical work (dW) is stored as entropic deformation.

At large strains, some rubbers may undergo strain-induced crystallization, reducing internal energy and contributing to mechanical stiffening.

Classical Rubber Elasticity Theory

For an ideal, isotropic rubber network, the shear modulus G is given by:

$$G = \nu RT \qquad \textit{Equation 26}$$

where:

- ν is the number of active network chains per unit volume (proportional to crosslink density),
- R is the universal gas constant,
- T is the absolute temperature.

This relation shows that:

- Increasing temperature increases stiffness,
- Increasing crosslink density also increases stiffness,
- Elasticity is predominantly entropic in origin.

Viscoelasticity and Time-Dependent Behaviour

Rubber exhibits viscoelasticity, meaning it combines both elastic (instantaneous recovery) and viscous (time-dependent flow) behaviour. This is often studied using Dynamic Mechanical Analysis (DMA).

Key parameters include:

- **Storage Modulus E'**: Represents energy stored elastically,
- **Loss Modulus E''**: Represents energy dissipated as heat,
- **Phase lag δ**: Angle between applied stress and resulting strain.

The mathematical expressions are:

$$E' = \frac{\sigma_0}{\varepsilon_0} cos\ \delta\ ;\ E'' = \frac{\sigma_0}{\varepsilon_0} sin\ \ \delta \qquad \textit{Equation 27}$$

where:

- σ_0 and ε_0 are the stress and strain amplitudes.

Example: PDMS (Polydimethylsiloxane)

- Exhibits significant stiffening at high strain when chains are fully extended.
- Shows hysteresis in stress-strain cycles due to internal friction.
- Demonstrates rapid energy release in products like “pop-toys” due to entropy-driven recovery.

Thermoplastic Elastomers (TPEs): Elasticity without Permanent Crosslinks

TPEs provide rubber-like behaviour without permanent chemical crosslinks, instead relying on physical crosslinks such as:

- Block copolymer phase separation (e.g., SBS rubber),
- Hydrogen bonding interactions (e.g., segmented polyurethanes).

These physical crosslinks are reversible:

- Elastic and soft at low temperatures,
- Flowable and mouldable at elevated temperatures.

An important example is *Spandex*, a segmented polyurethane used in textiles, which combines high extensibility with recoverable elasticity.

Rubber in Compressive Deformation: Cellular Elastomers

Rubber-like polymers can be processed into foams and sponges, resulting in different mechanical responses under compressive loads.

Stress-Strain Behaviour in Compression:

- *Elastic Region*: Cells bend and store energy,
- *Plateau Region*: Cells collapse at relatively constant stress,

- *Densification*: Collapsed cell walls come into contact, sharply increasing stiffness.

Scaling Laws for Foams

Mechanical properties such as compressive strength σ_0 and modulus E scale with foam density ρ_0:

$$\sigma_0 = A\rho_0^B, E = C\rho_0^n \quad \textit{Equation 28}$$

where *A, B, C, n* are empirical constants determined by foam geometry and failure mechanisms. Rubber elasticity is primarily an entropic phenomenon, enabled by high-molecular-weight, flexible polymer chains crosslinked into a stable network. The fine balance between chain flexibility, crosslink density, and thermal conditions allows rubbers to be soft, stretchable, and recoverable. By manipulating structural and morphological parameters, engineers design elastomers with properties ranging from soft foams to high-performance aerospace materials.

Cohesion and Adhesion

Surface tension relates to *interfacial energy*, capillary forces, and wetting. It is a function of molecular cohesion at interfaces and governs behaviour like droplet shape and thin film spreading.

Viscosity governs *bulk deformation* and flow, and appears in stress-strain relationships over time, as in the Kelvin-Voigt or Maxwell models.

Adhesive behaviour combines both, depending on contact mechanics, surface forces, and flow of the viscoelastic material.

Adhesion Mechanism and Intermolecular Forces

The ability of a soft material to stick to a surface is governed by adhesion, which is the attraction between dissimilar materials. It is fundamentally due to intermolecular forces at the interface.

There are three primary types of interactions that contribute to adhesion:

1. Dispersion forces (London forces): These arise due to instantaneous dipoles in molecules and are present in all atoms and molecules.
2. Dipole-dipole interactions: Occur between molecules with permanent dipoles.
3. Hydrogen bonding**:** A strong specific interaction between a hydrogen atom covalently bonded to an electronegative atom (like O or N) and another electronegative atom nearby.

These forces are collectively categorized as van der Waals forces. The potential energy between two neutral atoms separated by a distance r is often modeled as:

$$u(r) = -C\left(\frac{a_0}{r}\right)^6 \qquad \textit{Equation 29}$$

where C is a material-specific constant, and a_o is a characteristic molecular radius. The negative sign reflects the attractive nature of the force.

Surface Tension and Capillary Adhesion

Surface tension γ is defined as the energy required to increase the surface area of a liquid:

$$\gamma = \frac{dG}{dA} \qquad \textit{Equation 30}$$

where G is the Gibbs free energy and A is the interfacial area. Gibbs free energy is a measure of the useful energy in a system. It is the energy that can do work such as drive a chemical reaction or a physical process. Lower G means the system is more stable. Systems in nature tend to move toward lower G, like a ball rolling downhill example we discussed before. The interfacial area (A) is the surface area between two different materials or phases.
Surface tension arises because molecules at the surface experience an imbalance of cohesive forces, leading to a net inward force. Surface tension is a force that acts on the surface of a liquid, making it behave like a stretched skin.
In the context of a viscoelastic sticky surface, when pressed onto another surface, a thin layer of material may spread. Capillary effects can enhance adhesion, especially when the material forms a conformal contact and excludes air gaps, potentially creating a low-pressure region (partial vacuum). This contributes to an adhesive seal, further stabilized by surface tension.
However, surface tension is a surface phenomenon**,** distinct from viscosity, which is a bulk property describing flow resistance.

JKR Theory: Adhesion Between Elastic Solids

For soft elastic materials in contact with a rigid surface, the Johnson-Kendall-Roberts (JKR) theory describes the adhesive force required to separate them.

Assuming a spherical contact (e.g., a hemispherical sticky patch), the pull-off (adhesive) force F_{ad} is:

$$F_{ad} = 3\pi R\gamma \qquad \textit{Equation 31}$$

Here:

- R is the effective radius of curvature of the contacting body,
- γ is the work of adhesion (energy per unit area),
- The expression assumes elastic deformation and short-range adhesive forces.

JKR theory is applicable when elastic deformation dominates over surface forces (i.e., for soft, tacky materials with large contact areas).

Retrieval Mechanics: Peeling and Detachment

To remove a viscoelastic adhesive from a surface, one must overcome both adhesive forces and friction.The peeling mechanism is not a simple uniform detachment but proceeds via stress concentration at the peel front. The energy release rate *G* (rate of mechanical energy dissipation per unit area of crack growth) must match the work of adhesion γ:

$$G = \gamma \qquad \textit{Equation 32}$$

In a peeling geometry, the peel force *F* per unit width is given by:

$$F = \frac{2\gamma}{\sin\theta} \qquad \textit{Equation 33}$$

where θ is the peel angle. A small angle (near horizontal) reduces the required force, while a large angle (near vertical) increases it. Furthermore, rate dependence is significant: viscoelastic materials exhibit higher adhesive forces when pulled rapidly due to strain-rate stiffening. This is connected to the loss modulus and storage modulus as measured in dynamic mechanical analysis (DMA)**:**

$$E^*(\omega) = E'(\omega) + iE''(\omega) \qquad \textit{Equation 34}$$

where:

- $E'(\omega)$: storage modulus (elastic response),
- $E''(\omega)$: loss modulus (viscous dissipation),
- ω: angular frequency of oscillatory deformation.

A phase angle δ defines the lag between stress and strain:

$$\tan\,\delta = \frac{E''}{E'} \qquad \textit{Equation 35}$$

A larger δ implies greater energy loss per cycle — characteristic of tacky, viscoelastic adhesives.

SECTION 2: LET THE GAMES BEGIN

2.1: Soft, Gooey Toys

Gel systems exemplify how soft materials can self-organize into structures that mirror biological complexity, effectively bridging the gap between inanimate matter and living systems.

The first category of toys we'll explore relies on the viscoelastic nature of soft matter—a concept introduced in Chapter 3. Here, we briefly revisit the key ideas.

Soft matter systems—such as polymers, colloidal suspensions, foams, and biological tissues—exhibit complex mechanical behaviours that fall between purely elastic solids and purely viscous fluids. Their response to stress is time-dependent, meaning their behaviour varies depending on the rate and duration of applied forces. This gives rise to viscoelasticity, where materials simultaneously exhibit both solid-like and liquid-like characteristics.

Unlike simple (Newtonian) fluids, whose viscosity remains constant regardless of applied stress or strain rate, soft matter often shows non-Newtonian behaviour, meaning its flow properties change depending on external forces. The usually observed behaviours are:

- **Shear-thinning** (pseudoplasticity): The material becomes less viscous under higher shear stress (e.g., paint, blood).
- **Shear-thickening** (dilatancy): The viscosity increases with applied stress, as seen in cornstarch suspensions.
- **Thixotropy**: The material slowly liquefies when stressed but returns to a gel-like state when left undisturbed (e.g., some gels and pastes).

These materials also exhibit phenomena such as creep—a slow, continuous deformation under constant stress—and stress relaxation, where internal stress gradually diminishes under constant strain. Recovery from deformation is influenced by molecular-scale processes: long-chain entanglements in polymers relax over time, while colloidal systems depend on interparticle forces.

Finally, many viscoelastic materials exhibit hysteresis: their response depends on their history of stress application. This is evident in biological tissues like tendons, where repeated stretching leads to energy loss due to internal friction.

1. OOBLECK

INTRODUCTION

Oobleck, also called magic mud, is a non-Newtonian fluid that can be easily made by mixing corn-starch with water. The name is said to come from Dr. Seuss's 1949 children's book, Bartholomew and the Oobleck, in which a king, bored with ordinary weather, commands his magicians to invent something innovative and intriguing. Their creation—an unruly, green, gooey substance called "oobleck"—causes chaos across the kingdom.

While oobleck is often used as a demonstration of non-Newtonian fluid behaviour, its underlying properties have important real-world applications in materials science, engineering, and medicine. Non-Newtonian fluids are prevalent in the chemical industry, where they are involved in processes such as mixing, pumping, and transporting slurries and pastes. Their variable viscosity can enhance mixing efficiency and optimize material handling. Everyday substances such as ketchup and mayonnaise exhibit shear-thinning behaviour—a type of non-Newtonian response in which viscosity decreases under applied stress. This is why they initially resist flow but move easily once squeezed or shaken. Similar properties are exploited in technologies like inkjet printing, where controlled viscosity enables smooth nozzle ejection while preserving print resolution.

THE TOY

Figure 24: Preparation of Oobleck

(Source: Alan Prince)

When a finger is pulled slowly or dipped gently in oobleck, it behaves like a fluid However, when a sudden force is applied—such as punching or pulling it quickly—it behaves like a solid. Oobleck undergoes shear thickening and this is largely related to the long and thin shape of the corn-starch molecules. Oobleck is a suspension of cornstarch in water. Cornstarch does not dissolve; instead, its solid particles are dispersed throughout the liquid. These particles are long and irregular in shape, and under normal conditions, water molecules help them slide past one another, giving the mixture a fluid-like consistency. However, when a rapid or high force is applied, the water is pushed out from between the starch grains, causing the particles to come into closer contact. Increased friction and entanglement between these particles causes the mixture to temporarily "lock up" and behave like a solid. Once the force is removed, water flows back between the particles, and the oobleck returns to its liquid state.

Viscosity increases with shear rate. When force is applied, water is squeezed out from between the starch particles, increasing friction and causing them to lock together, which gives oobleck its solid-like behaviour (shear thickening). When the force decreases, the starch particles begin to separate, allowing water to flow between them and restoring its liquid-like behaviour.

Table 3: Comparison of properties of dry and wet cornstarch

Property	Cornstarch (Dry Powder)	Oobleck (Cornstarch + Water Suspension)
Physical State	Fine powder (granular)	Thick, non-Newtonian fluid
Molecular Composition	Amylopectin (~75-80%) and Amylose (~20-25%), both polysaccharides made of α-D-glucose units	Same molecular composition; starch remains intact but hydrated
Molecular Size	Amylose: 10^4 - 10^6 g/mol	Same molecular size; hydration does not break polymer chains
	Amylopectin: 10^7 - 10^8 g/mol	
Granule Size	1-100 μm (depends on starch source)	Granules remain swollen but suspended in water
Solubility in Water	Insoluble in cold water	Forms a colloidal suspension, granules absorb water but do not dissolve
Hydrogen Bonding	Minimal (only between starch molecules)	Extensive (between water and hydroxyl (-OH) groups in starch)
Flow Behaviour	Acts as a solid powder	Non-Newtonian fluid: shear-thickening (solid under force, liquid at rest)
Viscosity	No viscosity (powder)	Viscosity increases with applied stress
Shear Response	Behaves normally (no thickening or thinning)	Shear-thickening (dilatant): becomes solid under impact
Jamming Effect	None	Hydro clusters form under stress, momentarily solidifying the mixture
Lubrication	No liquid present	Water lubricates starch particles under low stress
Stress Dependence	Independent of force	Highly dependent: acts solid under high force, liquid under low force

DIY VERSION

Materials Needed

- Cornstarch – 1 cup (or any desired amount)
- Water – ½ cup (adjust as needed)
- Bowl – For mixing
- Spoon or hands – To stir and experiment
- (Optional) Food colouring – For customization

Step-by-Step Procedure

- Use a 2:1 ratio of cornstarch to water. For example, mix 1 cup of cornstarch with ½ cup of water.
- Pour the water into a bowl first. Gradually add cornstarch while stirring slowly.
- If the mixture is too runny, add more cornstarch. If it is too dry, add small amounts of water until the desired texture is
- Press down quickly with your fingers or a spoon; the oobleck should feel solid.
- Let your fingers sink in slowly; it should behave like a liquid.
- Try rolling it into a ball and then releasing it to see it turn back into a liquid.
- Hit it with force and observe how it resists impact.

INTERESTING FACTS

- A study on Oobleck by a group of researchers at the University of Texas at Austin found interesting properties regarding holes created in oobleck, when the system was vibrated. If a hole is created in a container of water by putting finger in and removing it, the water around it will quickly fill the space left by the finger. However, in oobleck, holes separated by more than two diameters was found to be stable for a long time. For this system four unique regions if hole stability were found namely, delocalized, unstable, metastable, and stable. In the unstable region, the holes would collapse as soon as they were formed. Holes would develop in the metastable zone, but they would eventually disappear. Where the holes would last for a very long time without collapsing is referred to as the stable area. In the delocalized region the edges of the holes were found to accumulate particles.
- The properties of non-Newtonian fluids are used in special protective body armour for athletes such as extreme cyclists and for the military. The armour is flexible to allow a range of normal movements, but as soon as something hits it, the armour hardens up to protect the wearer.

SUMMARY

Oobleck is a simple combination of cornflour and water, it behaves as a non-Newtonian fluid, transitioning between solid and liquid states depending on the force applied. It behaves as a liquid when low force is applied and act as a solid when quick and large force is applied. The long and thin structure of starch is responsible for this unique behaviour. It is not only enjoyable for play but also serves as educational tools for exploring scientific concepts related to material properties.

2. SLIME

INTRODUCTION

Slime, as we know it today, gained commercial popularity in the winter of 1976, when the Mattel Toy Company released a ready-made version packaged in a small plastic "trash can." It was made was from white glue, water, and borax (sodium tetraborate) that resulted in a sticky and elastic material that quickly gained popularity as a toy.

The development of slime toys is closely linked to advances in polymer science. Polymers are large molecules composed of repeating units called monomers. These monomers, typically small organic molecules with reactive functional groups, chemically bond to form long, chain-like structures. The polymeric nature of slime gives it its unique texture and behaviour. The long-chain structure of polymers was first confirmed through X-ray studies of natural rubber—a naturally occurring polymer—laying the foundation for understanding and engineering synthetic polymers used in products like slime.

Table 4: Some monomers and the polymers they form

Monomer	Polymer Formed	Example of Use
Ethylene (C_2H_4)	Polyethylene (PE)	Plastic bags, bottles
Propylene (C_3H_6)	Polypropylene (PP)	Packaging, ropes
Vinyl chloride (C_2H_3Cl)	Polyvinyl chloride (PVC)	Pipes, clothing
Styrene (C_8H_8)	Polystyrene (PS)	Foam cups, insulation
Glucose ($C_6H_{12}O_6$)	Cellulose, Starch	Plant structure, food energy

Monomers are small molecules that can exist independently and flow freely without bonding to each other under normal conditions. In contrast, polymers such as polyvinyl alcohol (PVA) are made of long, repeating chains of these monomers. You can imagine them like a tangle of metal chains in a bowl—each chain can move individually unless they're connected at multiple points.

To make these chains behave collectively, they need to be cross-linked, much like tying knots between the chains. This process forms a network structure. In the case of slime, cross-linking is achieved by adding a substance like borax (sodium tetraborate), which acts as an activator. Once cross-linked, pulling one part of the polymer causes other parts to move together, giving slime its unique stretchiness. This interconnected structure is also why liquid polymers flow more slowly than simpler liquids like water.

THE TOY

Slime provides a hands-on sensory experience that engages touch and encourages creativity. Stretching, squeezing, and pulling the slime can help with relaxation and focus, making it a popular fidget toy like stress balls or kinetic sand. Unlike static toys, slime is interactive and customizable—users can change its texture, colour, and even add glitter or beads for variety.

Making slime is also educational. It introduces children to concepts like polymers, cross-linking, and non-Newtonian fluids—materials that act like both solids and liquids depending on the applied force. Some versions of slime can even demonstrate more advanced chemistry, such as pH sensitivity, fluorescence, or magnetism, turning play into a fun learning opportunity.

Slime is generally categorized into two types based on the starting material: PVA slime and glue slime.

PVA slime uses a solution of polyvinyl alcohol (PVA)—a water-soluble polymer often used in educational settings. When mixed with a borate solution like borax, the PVA chains undergo cross-linking to form a stretchy, rubbery gel.

Glue slime, more commonly made at home, uses white school glue, typically made from polyvinyl acetate (PVAc). When a borate activator is added, the glue molecules are partially hydrolysed, allowing cross-linking to occur in a similar way. This results in a softer, more pliable slime that is often used for crafts and play.

While both rely on borate-based cross-linking, the difference in polymer structure gives each type of slime distinct textures and characteristics.

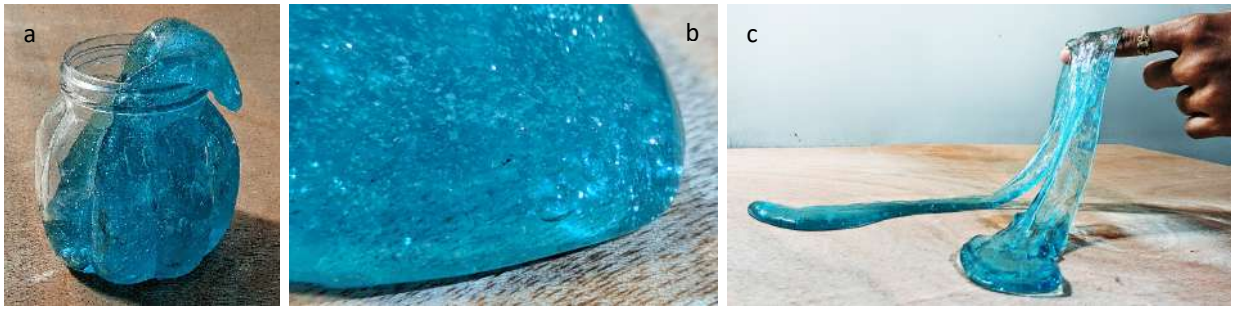


Figure 25: Playing with slime

The above pictures shown slime in a bottle (a), a closer look (b) and the manner in which it stretches (c).

(Source: Photograph by Siddarth S)

Table 5: Types of slime and their properties

Slime Type	Description	Unique Feature
Basic Slime	Traditional smooth and stretchy slime	Customizable with colours and scents
Fluffy Slime	Light, airy slime made with shaving cream	Extra soft and puffy texture
Crunchy Slime	Contains beads, foam, or plastic bits	Produces a satisfying crunch sound
Magnetic Slime	Infused with iron filings	Moves when near a strong magnet
Glow-in-the-Dark Slime	Contains phosphorescent powder	Glows after exposure to light
Colour-Changing Slime	Made with thermochromic pigments	Changes colour with heat or cold
Edible Slime	Made from food ingredients (marshmallows, cornstarch)	Safe for young children to play with

Table 6: Functions of the various elements of slime

Ingredient	Function in Slime	Example in Commercial Slime
Polyvinyl Alcohol (PVA) Glue	Forms the polymer network	School glue (Elmer's Glue)
Borax or Borate Ions	Cross-links polymer chains	Borax powder, contact lens solution
Guar Gum/Xanthan Gum	Creates thick, stretchy slime	Used in food-grade slimes
Glitter, Beads, Foam	Adds texture and visual appeal	Found in crunchy or foam-based modelling material slime

DIY VERSION

Abundant DIY slime recipes empower you to tailor colour, texture, and effects, whether it is fluffy, crunchy, or magnetic slime, indulging creative desires.

1. Coloured Slime (Basic Slime)

This is a classic, stretchy slime that can be customized with different colours.

Ingredients:

- 1 cup white school glue (PVA glue)
- ½ teaspoon baking soda
- 1 tablespoon contact lens solution (must contain boric acid)
- Few drops food colouring
- ½ cup water (optional, for a stretcher slime)

Instructions:

- In a bowl, mix the glue and baking soda.
- Add a few drops of food colouring and mix until uniform.
- Slowly add the contact lens solution while stirring.
- Keep mixing until it thickens, then knead with your hands until smooth.
- Store in an airtight container to prevent drying.

2. Fluffy Slime

This version is extra soft and airy due to shaving cream.

Ingredients:

- 1 cup white school glue
- 2 cups shaving cream (foam, not gel)
- ½ teaspoon baking soda

- 1 tablespoon contact lens solution
- Few drops food colouring

Instructions:

- Mix the glue and shaving cream in a bowl.
- Add baking soda and food colouring, then mix well.
- Stir in the contact lens solution and mix until the slime forms.
- Knead the slime with your hands until it is fluffy and not sticky.
- Store in an airtight container.

3. Crunchy Slime
Crunchy slime contains small beads or foam balls that create a textured feel.

Ingredients:

- 1 cup white school glue
- ½ teaspoon baking soda
- 1 tablespoon contact lens solution
- Few drops food colouring
- 1 cup foam beads, plastic beads, or small Styrofoam balls

Instructions:

- In a bowl, mix glue, baking soda, and food colouring.
- Add the contact lens solution and stir until it thickens.
- Slowly mix in the beads or foam balls until well incorporated.
- Knead the slime until the texture is even and crunchy.
- Store in an airtight container.

INTERESTING FACTS

- **Slime Resembles Biological Mucus:**

The structure of glue-based slime is similar to natural mucus found in organisms like snails, fish, and humans. Both consist of polymers that trap water, giving them a gel-like consistency.

- **Adjusting Slime Texture:**

If slime becomes too stiff, adding water or more glue can break some of the cross-links, making it more elastic. If it is too sticky, adding more borax or contact lens solution increases cross-linking, resulting in a firmer texture.

- **Slime and the Weissenberg Effect:**

When a thin rod is inserted into slime and spun, the fluid climbs up the rod—an unusual behaviour caused by the Weissenberg effect. This occurs because viscoelastic (non-Newtonian) fluids generate normal stresses—forces perpendicular to the

direction of shear. Unlike Newtonian fluids, which spread outward when stirred, viscoelastic fluids pull inward and upward. As a result, the slime "climbs" the spinning rod, aligning with the direction of stress.

Table 7: Unique behaviours of some fluids

Example	Where It Happens
Slime or Polymer Solutions	When stirred, slime can move up a spoon or stirrer.
Bread Dough	Kneading dough causes it to wrap around a rolling pin.
Shampoo or Honey	When poured onto a spinning brush, it moves upward rather than outward.
Melted Plastic in Extruders	Molten polymers in industrial extrusion processes exhibit climbing behaviour.

SUMMARY

Slime—that gooey, fascinating substance—has captured the imagination of people of all ages. More than just a toy, it is a subject of scientific study, a medium for creative expression, and a remarkable example of the complex behaviour of materials.

Slime offers a compelling case study in soft matter physics, existing in a curious state between solid and liquid. Concepts like viscosity, elasticity, and viscoelasticity make it ideal for scientific exploration.

Though materials like slime have existed in various forms for a long time, its popularity surged in the 20th century with the advent of synthetic polymers.

It consists of long polymer chains—such as polyvinyl alcohol (PVA)—that move independently but become connected through a cross-linking activator, forming a cohesive, mouldable material.

Slime is classified as a non-Newtonian fluid, meaning its viscosity changes with applied stress. More specifically, it is a time-independent, shear-thickening fluid: under rapid stress, it resists flow and behaves like a solid; under slow stress, it flows freely like a liquid.

3. WATER-GEL-BEADS

INTRODUCTION

Water-gel-beads, also known as hydro-gel or water beads, are small, spherical, jelly-like polymer balls that can absorb and retain a large amount of water. When dry, water-gel-beads —hydro-gel beads or water beads —appear as small, solid pellets or granules with a translucent or semi-transparent appearance. But their true magic is revealed when they come into contact with water. As they soak up water. They expand dramatically and become soft, squishy, and visually captivating.

Hydrated water-gel-beads combine a mushy yet firm texture, offering unique tactile experience. They provide a rich sensory experience The beads come in a variety of colours, adding a creative and sensory dimension to their appeal. Beyond their sensory experience, water-gel beads also serve as educational tools. They can help teach fundamental concepts such as absorption, osmosis, and colour theory, providing an interactive and fun way to learn.

THE TOY

Sodium polyacrylate, a Super Absorbent Polymer (SAP), is often the ingredient that gives water-gel-beads their characteristic shape. Within the polymer, the long, intricately linked molecular chains seen in SAPs form a 3-D network. These beads demonstrate their extraordinary ability to transform from dry, uninteresting pellets to the squishy, marvellous wonders that have become a sensation for both play and adornment.

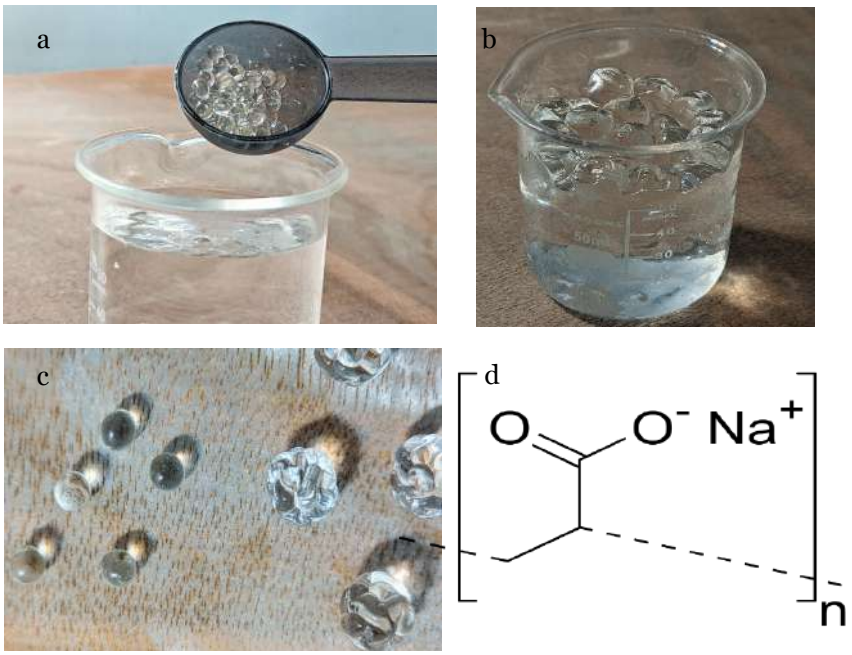


Figure 26: Water gel beads

(a) Water-gel-beads being dropped into water (b) the beads as they soak-up the water (c) The beads before and after swelling in water. (d) Chemical structure of Sodium polyacrylate. (Source: Photograph by Siddarth S and structure by author)

SWELLING AND GEL FORMATION

The polymer chains experience a dramatic metamorphosis as water continues to enter the polymer matrix. They swell and grow, creating a consistency that resembles gel. The cross-linking links in the polymer structure act as gate-keepers and stop the freshly absorbed water from evaporating. The squishy, jelly-like feel that distinguishes fully hydrated water-gel-beads is produced by this method. If the polymer has more cross-linking, it leads to lesser absorption of water, but the formation of a stronger gel.

ELASTICITY

Water-gel-beads are elastic. The cross-linking bonds not only contribute to the gel formation but also confer elasticity upon the beads. When you squeeze or press a

hydrated bead, the polymer chains can flex and stretch, exhibiting remarkable resilience. Upon release, they snap back to their original shape, making them irresistibly fun to squish and play with.

DIY VERSION

Tapioca pearls (used in bubble tea) absorb water and swell, mimicking water-gel-beads.

Materials needed:

- Tapioca pearls (sabudana/javvarisi/saggubiyyam)
- Water
- Food colouring (optional)
- Gelatine-Based Water Beads

This method creates soft, squishy beads using Gelatine, which can hold water like commercial beads.

Materials needed:

- Unflavoured Gelatine
- Water
- A dropper or pipette
- Cold vegetable oil (chilled in the freezer)

Dissolve gelatine in hot water according to the package instructions. Let it cool slightly until it thickens but remains pourable. Using a dropper, carefully drop the gelatine solution into the cold oil. The gelatine will form into small spheres as it solidifies. Strain out the beads and rinse them with water. Store in a small amount of water to keep them hydrated.

Hydrogel Using Sodium Polyacrylate (Diaper Filling)

If you want something closer to real water beads, you can extract the water-absorbing polymer from a diaper.

Materials Needed**:**

- Sodium polyacrylate (can be extracted from unused diapers or bought as a powder)
- Water
- Measuring spoon or dropper
- Clear container or cup
- Gloves

Procedure

- Place ¼ teaspoon of sodium polyacrylate powder into a clear container.
- Slowly add water, a few millilitres at a time.

- Observe as the powder rapidly absorbs the water and expands into a gel-like substance.
- You can stir gently to help the process, but it happens almost instantly.

INTERESTING FACTS

Horticultural Use: Hydro orbs are often used in horticulture and gardening to help with soil moisture management. They can slowly release water to plant roots, reducing the need for frequent watering.

Gel beads can grow up to 1,500 times their size when placed in water

SUMMARY

Water-gel-beads owe their squishy and resilient nature to the cross-linking bonds that not only form the gel but also allow them to flex, stretch, and return to their original shape when squeezed or pressed. Their visual appeal is enhanced by a vibrant range of colours, which are achieved by adding safe colourants during manufacturing. However, safety is paramount, especially when used by children. While fully hydrated beads are fun to play with, they can pose a choking hazard if ingested. In addition to safety concerns, environmental responsibility must also be considered. Since water-gel-beads are not biodegradable, responsible disposal practices are crucial to minimize their environmental impact.

In summary, water-gel-beads offer a captivating sensory experience while highlighting the importance of safety and environmental awareness, making them a fun yet conscientious choice for both play and decoration.

4. GEL-FILLED TEETHING TOYS

INTRODUCTION

The human primary dentition undergoes development from the time of birth until preadolescence. The teeth's initial eruption through the gums occurs during the teething process. children have a different starting point for teething. The first teeth of a baby usually begin to erupt between the ages of six and nine months, at which point the baby may experience anxiety. Teething toys, such as those filled with gel, can provide your child some relief. A gel-filled teething toy normally comprises of a soft, malleable material, frequently created from medical-grade silicone. For teething babies, the gel inside the toy has a calming and cooling effect. The gel can be chilled in the refrigerator, offering a cooling sensation to soothe a baby's sore gums when they chew or bite on the toy. Soft, flexible, good elasticity, non-toxic, BPA (bisphenol-A) free, safe, easy to clean, low weight, durable and long-lasting, etc., are the properties of this toy. To stimulate a baby's gums and give tactile feedback, these toys' surfaces can feature various textures or patterns. They are available in a variety of sizes and shapes to accommodate varied preferences and tooth-growing phases. A secure handle or a design that eliminates choking hazards are two additional safety features that certain teething toys may offer.

Figure 27: A (a) baby and (b) a cat with gel-filled teething toys

(Source: (a) Gemini.ai (b) Meta.ai)

THE TOY

The manufacturing process of toys includes moulding and curing. Medical-grade silicone is commonly utilized to make the toy's body. Silicones have a myriad of interesting properties such as elasticity, heat resistance, chemical inertness, non-toxicity, hypoallergenic, transparency, electrical insulation, durability, etc. The inner

part of the toy contains a gel or liquid filling that are normally harmless for babies. Moreover, these materials can be cooled through refrigeration, and add additional calming effect to the babies. Water-based gels, vegetable glycerine-based gels, food-grade oils, polymer gels, and natural and organic gels are some of the types of gels used in teething toys. To improve the toy's appearance or flavour, certain teething toys may contain safe dyes or natural.

Teething toys are not just for providing relief to teething infants. They often have different textures and forms that can excite a baby's senses and encourage sensory development. Certain teething toys are made with dental health in mind. They might feature surfaces or textures that resemble bristles, which can be used to clean and massage a baby's gums and developing teeth. Also, this may promote independence and the growth of fine motor skills.

Gel-filled teething toys are based on the principles of heat transfer, elasticity, and pressure distribution.

Silicones are the raw material for the gel-filled teething toy. The physical and chemical characteristics of silicones are unusually diverse. The main ones are limited temperature dependency on physical characteristics and thermal and oxidative stability. High levels of chemical inertness, weather resilience, resistance to bacteria and fungi are further important properties. The existence of fluids, gels, and elastomers made from the same type of polymer is made possible by the numerous combinations of beneficial qualities offered by the linear, branched, and crosslinked silicone structural forms.

Elasticity: Silicone exhibits elasticity so that the toy deforms momentarily when a baby bites or squeezes it, but it quickly snaps back into place when the pressure is released. This quality makes it possible for the toy to tolerate repeated use without permanently deforming.

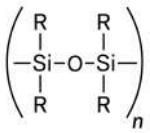


Figure 28: The structural form of silicone.

Here the structure in the parenthesis is the monomer and the n represents the repetition of the monomer unit, to form the polymer. (Source: author)

Figure 29: Gel-filled teething toy

(Source: gemini.ai)

Heat Transfer: When the gel-filled teething toy is chilled in a refrigerator, it becomes cooler than the baby's body temperature. According to the principles of heat transfer, heat flows from the warmer body (the baby's gums) to the cooler object (the chilled teething toy). This transfer of heat provides a cooling sensation, which can soothe the sore and inflamed gums.

Viscoelasticity: Some gel-filled toys might have viscoelastic characteristics, which means they behave in a way that combines viscous (like a flow) and elastic (like a spring) characteristics. When the baby chews on the toy, it may have a distinctive texture and feel as a result

Pressure distribution: pressure exerted by the baby's bite is evenly distributed across the surface of the toy. The gel and outside silicone material ought to be made to apply pressure uniformly, lowering the possibility of discomfort or harm.

MANUFACTURING PROCESS:

A catalyst is added to a silicone elastomer along with any other additional additives, such as flavourings or colourants. Depending on the manufacturer's design and safety regulations, the precise formulation can be changed. The prepared silicone is then poured into a mould which is made from metal with the desired texture and shape of the toy. The mould is placed in an oven or heated chamber to cure the silicone. By heating the silicone during the curing process, the catalyst is activated, resulting in the formation of cross-linked, durable silicone. Depending on the kind of silicone being used, the curing temperature and time may change. After curing, the mould is allowed to cool which further helps in solidification of the material. The teething toy is then removed from the mould, trimmed and additional features such as textures and handles added, if necessary.

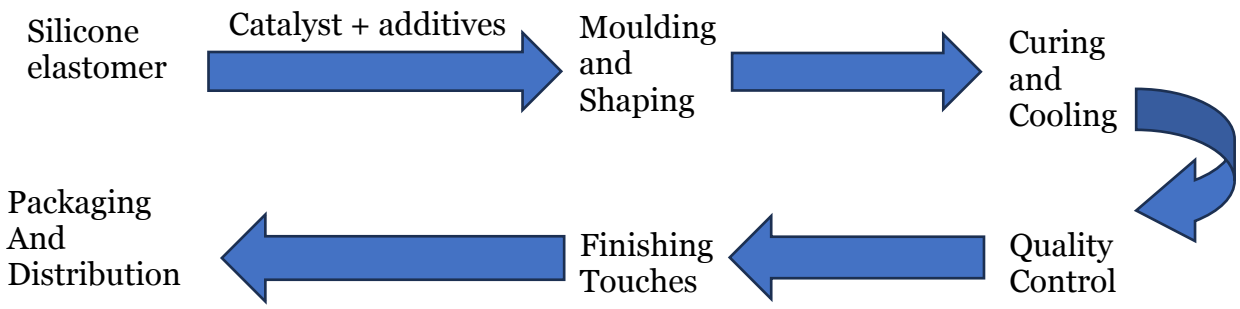


Figure 30: Process diagram for making a gel-filled teething toy

(Source: author)

DIY VERSION

Method 1: Aloe Vera & Water Gel Pack (Food-Safe)
This method creates a soft, gel-filled teething toy using food-safe ingredients.

Materials needed:

- Food-grade aloe vera gel (pure, no additives)
- Filtered water
- Cornstarch (for extra thickness, optional)
- A heat-sealable plastic pouch or silicone mould
- A vacuum sealer or a food-safe, heat-sealable bag
- A freezer

Procedure:

- Prepare the Gel: Mix equal parts of aloe vera gel and water. If you'd like a thicker gel, add a teaspoon of cornstarch and heat the mixture slightly to dissolve it.
- Fill the toy: Pour the gel into a heat-sealable plastic pouch or silicone mould.
- Seal Securely: If using a plastic pouch, use a vacuum sealer or an iron (on low heat with parchment paper) to seal the edges completely.
- Freeze: Place the filled toy in the freezer for 1–2 hours until chilled but not rock hard.
- Use: Give it to your baby for gentle chewing. The cool gel provides relief without being too harsh on their gums.

Aloe is naturally soothing and safe if a tiny amount leaks. However, always ensure it is food-grade and free from additives.

Method 2: Saltwater or Gelatine-Based Teething Toy
If you want a firmer, more gel-like texture inside, you can use a Gelatine-based filling.

Materials:

- Unflavoured food-grade Gelatine
- Water
- A pinch of salt (helps prevent bacterial growth)
- A silicone baby teether mould or sealed plastic bag
- A freezer

Procedure:

- Make the Gel: Dissolve the Gelatine in hot water following package instructions. Add a pinch of salt to inhibit bacterial growth.
- Fill the Mould: Pour the mixture into a silicone baby teether mould or a sealed plastic pouch.
- Chill or Freeze: Refrigerate for a squishy gel texture, or freeze for a cooling effect.

Gelatine provides a chewable, soft texture similar to commercial teething toys, and it is food-safe.

INTERESTING FACTS

- Neem twigs were used traditionally as teething toys in India. Birchwood was used in Russia.
- In Mexico, dolls made of corn-husks were used as teething toys.
- Metal ornaments such as a bangle were given as teething toys believing that they will soothe the child with their coldness

SUMMARY

This study describes the gel-filled teething toys that play an important role in easing the discomfort of teething infants. These toys' main ingredients are a gel filling for relaxing comfort and medical-grade silicone for the toy's exterior shell. The procedure, which guarantees safety and adherence to high standards, includes material preparation, moulding, curing, quality control, and finishing. Manufacturers who should take good care to produce goods that offer infants a soothing solution during the teething stage show a dedication to the safety and well-being of young children.

2.2: SPONGES AND FOAMS

“A sponge is a thing that absorbs, but it also reveals the nature of the materials around it."
– *Richard Feynman*, Nobel laureate in Physics

Sponges and foams are porous materials composed of a complex internal structure with interconnected solid and gas phases. Their mechanical and physical properties arise from the interaction between these phases, leading to behaviours distinct from both dense solids and simple fluids. The defining feature of foams and sponges is their porosity—the ratio of void space to solid material. This structure can be classified into:

Open-cell (interconnected pores, allowing fluid and air passage; e.g., kitchen sponges, biological tissues).

Closed-cell (isolated pockets of gas trapped within a solid matrix; e.g., packing foams, lightweight structural materials).

The morphology of the internal network (pore size, connectivity, and shape) significantly affects the material's mechanical, thermal, and fluid transport properties.

Sponges and foams display complex deformation mechanics due to their structure. The response to stress typically occurs in three stages:

Elastic Regime: At low strains, cell walls bend or stretch, and the material deforms elastically.

Plateau Region: As strain increases, the walls begin to buckle, absorbing energy and allowing the material to compress easily.

Densification: At high compression, the pores collapse entirely, and the foam behaves more like a solid. This makes foam an excellent material for impact absorption and cushioning

In open-cell materials, capillary forces drive fluid wicking, making them ideal for absorption. The rate of fluid uptake depends on pore size and surface properties

Applications of sponges and foams include:

- Acoustic insulation, where porous structure helps dampen sound.
- Impact protection, such as padding in helmets and automotive components.
- Thermal insulation, especially with foamed polymers that minimize heat transfer.
- Viscoelastic foams (e.g., memory foam), which recover slowly after compression, offering comfort and extra energy absorption.
- Biological foams, like marine sponges and plant tissues, optimized for fluid movement and mechanical flexibility.

- Industrial foams, such as polyurethane, aerogels, and bio foams, used for filtration, insulation, and lightweight construction
- Bioinspired materials, which mimic natural porous structures for advanced medical and engineering uses.

5. FOAM BASED MODELLING COMPOUNDS

INTRODUCTION

In a world where innovation knows no bounds, one toy stands out by blending creativity with scientific curiosity—foam-based modelling material. Commonly known as foam clay, bead slime, or mouldable foam putty, this compound offers a unique sensory experience that balances both fluidity and solidity. At first glance, it seems like a simple malleable toy—but its texture reveals something much more intriguing: a flexible polymer matrix embedded with countless microscopic beads.

THE TOY

Foam-based modelling compounds behave like a cross between a fluid and a solid. They consist of tiny microbeads suspended in a sticky, stretchable polymer matrix. The interaction between these beads and the surrounding polymer gives rise to the material's unusual properties.

When squeezed or moulded, the microbeads shift and flow within the matrix, allowing the material to take on new shapes—much like a liquid. But once the pressure is removed, the elasticity of the polymer helps it retain its new form, much like a solid. This blend of behaviours is a hallmark of viscoelastic materials, which exhibit both fluid-like and solid-like responses under stress.
The Microbeads: Foam-based modelling compounds contain microscopic, spherical microbeads suspended throughout the material. These beads behave like a liquid,

allowing them to move independently within the surrounding matrix. When force or pressure is applied, the microbeads can slide past one another, enabling the compound to deform and adapt to the applied stress. This mobility gives the material its fluid-like, mouldable quality.

The Polymer Matrix: The Polymer Matrix: Surrounding the microbeads is a flexible polymer matrix, which provides the material with its solid-like properties. This matrix is elastic, meaning it can stretch and bend under pressure but return to its original shape once the force is removed. Its flexibility prevents the material from flowing uncontrollably like a true liquid, allowing it to hold shapes and maintain structure after being moulded.

Viscoelastic Behaviour: The overall behaviour of foam-based modelling compounds is best described as viscoelastic—a combination of viscosity (resistance to flow) and elasticity (ability to recover shape). When manipulated, the compound flows and deforms like a viscous fluid, but thanks to the elastic nature of the polymer, it springs back into shape once the force is released.

Foam-based modelling materials exhibit viscoelastic behaviour, meaning their mechanical response depends not just on the applied load but also on the duration over which it is applied. This leads to time-dependent phenomena such as creep, stress relaxation, and rate-sensitive deformation.

Creep: When a constant load is applied, the material gradually continues to deform over time. This reflects a slow internal rearrangement of the polymer structure.

Stress Relaxation: If the material is held at a fixed shape or deformation, the internal stress it experiences gradually decreases—another hallmark of viscoelastic materials.

Hysteresis and Recovery: During repeated cycles of loading and unloading, the material shows hysteresis (a lag between applied force and response) and only partially recovers its original shape, due to internal damping and slow molecular movements.

This behaviour is influenced by both the flexible polymer matrix and the air-cell structure of the foam. Their interaction under mechanical stress gives the material its signature squishy, resilient character. These properties make it great for uses where energy absorption, shape memory, or tactile comfort are important—though less suitable for precision structural tasks where stability is key.

Figure 31: Foam-based modelling material

(Source: meta.ai)

DIY VERSION

Method 1: Classic DIY Foam-based modelling material (Glue & Borax Method)

This method gives you a stretchy, mouldable Foam-based modelling material similar to the original commercial product.

Materials:

- ½ cup white school glue (PVA glue)
- ½ cup water
- 1 teaspoon borax (dissolved in ½ cup warm water)
- 1–2 cups polystyrene beads (from bean bags, packing peanuts, or craft stores)
- Food colouring (optional)

Procedure:

- Prepare the slime base: In a bowl, mix the glue and water until combined. Add food colouring if desired.
- Activate the slime: Slowly add the borax solution while stirring. Keep mixing until the mixture thickens into a slime consistency.
- Add foam beads: Gradually fold in the polystyrene beads and knead until evenly mixed.
- Play & Store: Your Foam-based modelling material is ready! Store it in an airtight container to keep it soft.

Tip: If it is too sticky, add more borax solution; if too stiff, add more glue.

2. Borax-Free Foam-based modelling material (Contact Lens Solution Method)

This version is safer for kids and avoids borax.

Materials:

- ½ cup white school glue
- ½ teaspoon baking soda
- 1–2 tablespoons contact lens solution (must contain boric acid)
- 1–2 cups polystyrene beads
- Food colouring (optional)

Procedure:

- Mix glue and baking soda in a bowl. Add food colouring if desired.
- Slowly add contact lens solution while stirring until the slime forms.
- Knead the slime until stretchy, then fold in the foam beads.
- Store in an airtight container when not in use.

Tip: If the slime is too sticky, add a few more drops of contact lens solution.

3. Edible Foam-based modelling material (Marshmallow & Cornstarch)

This is a non-toxic and edible version that is great for younger kids!

Materials:

- 1 cup mini marshmallows
- 2 tablespoons cornstarch (plus extra for dusting)
- 1 teaspoon coconut oil or vegetable oil
- ½ cup tiny crispy rice cereal (or small edible sprinkles/beads)
- Food colouring (optional)

Procedure:

- Microwave the marshmallows and coconut oil in 10-second intervals until soft and puffy.
- Stir in cornstarch and mix until a dough forms.
- Add food colouring if desired.
- Fold in the crispy rice cereal or sprinkles for a foam-like texture.
- Knead until stretchy and soft.

Tip: This is best used fresh, as it dries out faster than non-edible versions.

4. Super Squishy Foam-based modelling material (Shaving Cream & Glue)

This version creates an ultra-light, fluffy foam-based modelling material.

Materials:

- ½ cup white school glue
- 1 cup shaving cream (for fluffiness)
- ½ teaspoon baking soda
- 1–2 tablespoons contact lens solution
- 1–2 cups foam beads
- Food colouring (optional)

Procedure:

- Mix glue and shaving cream in a bowl. Add food colouring if desired.
- Stir in baking soda.
- Add contact lens solution slowly while mixing until a fluffy slime forms.
- Fold in foam beads and knead until well incorporated.

Tip : This version is softer and lighter than traditional Foam-based modelling material but dries out quicker. Store it well!

Preparation

Start by measuring out the desired amount of glue—a common starting point is ½ cup for a small batch, but you can adjust this depending on how much compound you want to make. If you'd like to colour your foam-based modelling compound, add a few drops of liquid food colouring to the glue and mix thoroughly. For a more intense colour, adjust the number of drops as needed. Next, gradually add liquid starch while stirring continuously. Add it in small increments, whisking as you go, until the mixture starts to form a more solid, less sticky mass. If the compound is still too sticky, add a bit more liquid starch or mix in additional Styrofoam beads until you reach the desired consistency.

INTERESTING FACTS

- Foam based modelling compounds are used for arts and crafts projects such as 3D sculptures and textured paintings.
- They are commonly used in sensory play activities for children, offering a tactile and squishy experience that can help with sensory development and as stress-buster toys.
- Foam based modelling compounds can be used as an educational tools to teach shapes, textures, etc.

- Decorative Vases: By incorporating Foam based modelling compounds into vase arrangements, it can help stabilize flowers and add a unique, colourful touch to floral displays.

SUMMARY

A unique soft matter toy, foam-based modelling compounds blend the properties of solids and liquids to create a distinctive and engaging sensory experience. Made from microbeads suspended in a flexible polymer matrix, the material exhibits viscoelastic behaviour—it flows and moulds like a fluid under pressure, yet retains its shape once the force is removed, thanks to the elasticity of the polymer structure.

6. FOAM DICE

INTRODUCTION

For years, children and adults alike have found comfort, companionship, and joy in soft toys—timeless playthings that offer more than just entertainment. While traditional stuffed animals and plush dolls have long held a special place in our hearts, a unique category of soft toys has emerged that also stimulates the mind. Foam dice, for example, are simple, lightweight cubes typically made from polyurethane foam. Though seemingly basic, a closer look at foam dice reveals fascinating intersections between material science, mathematics, and play.

THE TOY

Foam dice, a blend of play and soft matter are soft, lightweight cubes typically made from polyurethane foam. They are often used in educational environments and games where noise reduction and safety are important. Like standard dice, they feature numbers or dots, and they come in a variety of sizes, shapes, and colours. Foam dice are popular tools for teaching math concepts, playing board games, and engaging in group activities where traditional hard dice may be too noisy or pose safety risks.

Foam as a Soft Matter System

Foam is considered a soft matter system because it consists of a mixture of gas and liquid phases trapped within a solid-like matrix. In foam dice, this structure provides their distinctive softness and resilience.

Structure and Composition

Foam dice are made up of a cellular structure containing gas bubbles (typically air) encased in thin polymer films. The exact composition varies, depending on the type of polymer used. One common material is polyurethane, a polymer with the general repeating unit:

$$[\text{-NH-(CH}_2)_4\text{-O-CO-(CH}_2)_4\text{-NH-}]_n$$

Figure 32: Structural form of Polyurathene

(Source: author)

Since foams are complex mixtures of polymers and gases, no single chemical formula can fully represent all variations of foam dice.

Phase Transitions in Foam

As a soft matter material, foam can undergo several phase transitions in response to environmental conditions:

Gas–Liquid Transition: Foam consists of gas bubbles trapped in a liquid matrix. Transitions between the gas and liquid phases can occur as bubbles expand or collapse. These changes are influenced by factors such as temperature, pressure, and surfactants (compounds that stabilize or destabilize bubbles).

Wet-to-Dry Transition: Foam can evolve from a wet foam (high liquid content) to a dry foam (lower liquid content) over time due to drainage or evaporation. This affects the foam's mechanical behaviour and softness.

Coarsening (Ostwald Ripening): Over time, smaller bubbles in the foam can merge to form larger bubbles, a process that can alter the foam's texture and reduce its structural stability. This coarsening process is a natural evolution in many foamed systems.

DIY VERSION

Figure 33: Playing Dice

(Source: https://www.pickpik.com)

Method 1: Using Foam Sheets or Sponges

This is an easy and soft version, perfect for toddlers and kids.

Materials needed:

- Thick foam sheets or a soft sponge block
- Fabric (felt or cotton) or coloured foam sheets
- Scissors
- Hot glue gun or fabric glue
- Fabric paint or permanent markers (for numbers/dots)

Procedure:

- Cut the Foam: If using foam sheets, cut six equal squares and glue them together to form a cube. If using a sponge, trim it into a cube shape.
- Cover with Fabric (Optional): Wrap the foam cube in fabric or coloured foam sheets, gluing it down neatly.
- Add Numbers/Dots: Use fabric paint, markers, or glued-on felt circles to create the numbers (1-6).
- Let It Dry: Allow glue and paint to dry before playing.

Tip : Use different colours or textures for sensory play!

Method 2: Using Stuffing & Fabric (Softest Version). This creates a plush, cuddly dice toy.

Materials needed:

- Soft fabric (felt, fleece, cotton)
- Needle & thread (or a sewing machine)

- Stuffing (polyfill, cotton, or foam pieces)
- Fabric paint, felt circles, or embroidery thread for numbers

Procedure:

- Cut Six Fabric Squares: All sides should be equal for a perfect cube.
- Sew Five Sides Together: Leave one side open for stuffing.
- Stuff the Dice: Fill it with poly-fill or shredded foam for softness.
- Sew the Last Side Closed: Use a hidden stitch for a neat finish.
- Add Numbers/Dots: Glue or sew felt circles, paint, or embroider the numbers.
- Tip: Use soft fleece for a baby-friendly version!

INTERESTING FACTS

- Dice are one of the oldest gaming tools—archaeologists have found dice over 5,000 years old from Mesopotamia and ancient India, including recently at Keeladi in Tamil Nadu.

Figure 34: Playing dice found at Keeladi in Tamil Nadu

(Photograph: author)

- Across cultures, dice have been used for gaming, divination, education, and storytelling—making them one of the most universal play objects.
- Dice are used to introduce children to mathematical ideas of probability, number patterns, counting, and even strategy.
- Foam or tactile dice (like fuzzy or textured ones) are often used in sensory bins and activities for toddlers or neurodiverse learners.
- Many classic board games (e.g., Monopoly, Ludo, Snakes & Ladders) rely on dice to introduce randomness and chance, keeping games fair and exciting.

SUMMARY

The foam dice soft toy is not only a fun plaything but also offers young children a variety of educational opportunities. Thanks to its elastic nature, foam dice bend when pressure is applied, then snap back into position. This feature helps reduce bounce and the risk of injury. Foam dice are especially suitable for tabletop games because their irregular form and weight distribution introduce an element of unpredictability, making each roll unique.

7. SPONGE

INTRODUCTION

Sponges, commonly used for household cleaning and bathing, have a fascinating structure—an interconnected network of pores that allows them to absorb and retain liquids. This porosity, combined with their high compressibility, elasticity, and flexibility, gives sponges unique mechanical properties. When it comes to toys, sponge-based materials have carved out a special place in the world of play and entertainment. These soft, pliable, and often colourful toys offer a sensory-rich experience that engages the imagination, providing safe and enjoyable play for children of all ages. Examples of popular sponge toys include stress relief balls, bath toys, and plush companions. Sponge toys are particularly loved for their ability to captivate children in many ways—whether it is during bath time, in creative arts and crafts, at the pool, or simply as comforting plush friends. From their squishy texture to their gentle, comforting feel, sponge toys bring an extra layer of softness and joy to playtime, making them a versatile and engaging option for both relaxation and creative exploration

Figure 35: A piece of synthetic sponge soaking water – the kind we use in our kitchens

(Pic. https://stablediffusionweb.com/)

Figure 36: A Plush sponge toy

THE TOY

Synthetic sponges are typically made from materials like vegetable cellulose, polyurethane, or polyester. Other necessary components include chemical softeners, which break down the cellulose into the desired consistency, bleach, and dye. Polyurethane is often added to polyester sponges to create an abrasive side. Polyester sponges, commonly used for dishwashing, are generally soft and yellow, while wood-fibre-based vegetable cellulose sponges are more durable but also costlier. These are often used for bathing and skin washing.

To make these sponges, sheets of cellulose fibber are soaked in chemicals to make them pliable and soft. Materials such as hemp fibre, sodium sulphate crystals, and the cellulose are then combined and placed in large spinning containers. The mixture is heated, and the sodium sulphate crystals melt and settle at the bottom of the container, allowing the liquid to drain. The resulting sponge structure is formed by the holes or pores left behind by the melted crystals. The size of the crystals determines the size of these holes. Larger pores are used for sponges designed for tasks like washing cars and walls, while finer perforations are used for beauty and art applications.

Once the sponge is formed, it is a hard block that must be softened and cleaned. To remove impurities and ensure consistent colouring, the blocks are first soaked in bleach. The process is completed with repeated soaking and rinsing in clean water, leaving the sponge material flexible, ready for drying, and then cutting.

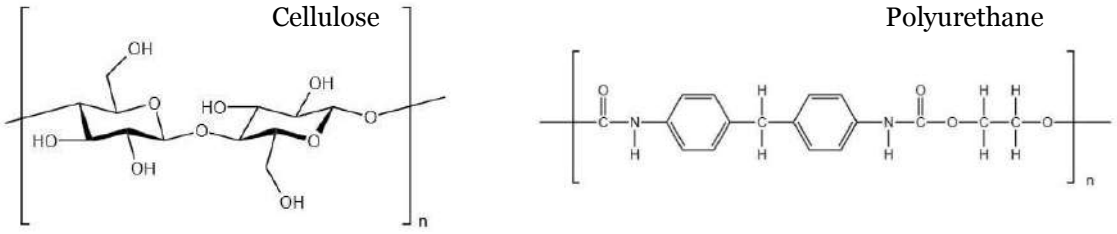


Figure 37: Chemical structure of (a) cellulose and (b) polyurethane.

The brackets represent the repeating units (monomers) and the n the fact that these units repeat n times. (Source: author)

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STRUCTURE AND POROSITY:

Kitchen sponges, whether made from synthetic or natural fibres, are composed of a porous structure with abundant spaces between the fibres. This unique porosity gives the sponge a large surface area and an open-cell structure, which allows it to absorb significant amounts of fluid. When the sponge absorbs water, the gaps between its fibres cause the material to expand, enabling it to take in up to 20 times its dry weight.

The sponge's porosity also plays a key role in its cleaning function, as it traps particles from the surface being cleaned. The volume of a sponge increases by 1.6% when it absorbs water. However, the liquid-absorbing behaviour of sponges can vary

based on their porosity, which differs among various sponge species and even within the same sponge. Some sponges have high porosity, which allows them to absorb and retain larger volumes of liquid, while others may have lower porosity.

ABSORPTION:

Sponges absorb liquids primarily through capillary action and their porous structure. Capillary action is the process by which liquid moves through narrow spaces, such as tubes or porous materials, without the assistance of external forces like gravity. This phenomenon is also referred to as capillarity, capillary rise, capillary effect, or wicking. In a kitchen sponge, the microscopic pores act as capillaries, enabling it to absorb a significant amount of moisture. Below is an explanation of the mechanics behind capillary action in sponges:

Porous Structure:

Sponges are made of porous materials, typically synthetic or natural fibres, with plenty of space between them. These pores act as capillaries, allowing liquid to flow through the sponge.

Adhesion and Cohesion:

Capillary action is driven by intermolecular interactions between liquid molecules and the solid surface of the capillary. In the case of a sponge, water molecules are attracted both to the sponge material (adhesion) and to each other (cohesion), enabling them to move through the capillaries.

Surface Tension:

Surface tension is a physical property of liquids that causes the surface to resist external forces that try to reduce its surface area. Due to the cohesive forces between liquid molecules, the surface behaves like an elastic membrane. Surface tension helps capillary action by pulling liquid up the capillary against gravity.

Thermal Energy:

The thermal energy of water molecules also plays a role in capillary action. The kinetic energy of the molecules contributes to the flow of liquid through the capillaries.

When a sponge is immersed in water, the combined effects of adhesion, cohesion, surface tension, and thermal energy drive water molecules into the sponge's capillaries. This causes the sponge to expand as it absorbs water. When the sponge is squeezed, the water is expelled, allowing the sponge to clean and absorb additional liquid.

APPLICATIONS:

Sponges, being soft and porous materials, have several applications in soft matter physics. Some of these are as follows.

- One theme in soft matter physics is the dynamics of soft fluid-infiltrated gels, sponges, and related entities. Using the theory of poroelasticity, researchers have explained a number of anomalous behaviours of these materials.

- Researchers have studied the interfacial properties of lipid sponge-like nanoparticles and the role of stabilizers on particle structure and surface interactions. The advantage of using nonlamellar lipid liquid crystalline phases has been demonstrated in many applications, such as drug delivery and protein encapsulation.

- A glass containing mechanoluminescent crystalline particles behaves as a photonic sponge, filling up with trapped electrons. Researchers have studied the mechanics and physics of these glass/particles photonic sponge.

- Research is ongoing in developing new materials that can easily absorb or shed oxygen atoms, similar to a sponge. This material has potential applications in catalysts and energy materials.

DIY VERSION

DIY Cellulose Sponge (Cornstarch & Natural Fibers)

This is a biodegradable sponge alternative similar to store-bought cellulose sponges.

Materials:

- Cornstarch (½ cup)
- Natural fibres (cotton, hemp, or jute fibres)
- Water
- Parchment paper
- A baking tray

Instructions:

- Mix Cornstarch & Fibers: Combine cornstarch with a bit of water to form a thick paste.

- Press Into a Mould: Mix in the fibres, then spread the paste onto parchment paper.
- Bake at Low Heat (200°F / 95°C) for a Few Hours: Check for firmness.
- Cut into Sponge Shapes: Once hardened, trim it into sponge-sized rectangles.

Tip: This method makes biodegradable sponges that break down naturally!

INTERESTING FACTS

- The First Synthetic Sponges Were Inspired by Nature: Before synthetic sponges, people used natural sea sponges for cleaning. The first artificial sponge was created in the early 20th century using cellulose fibres, mimicking the absorbency of real sea sponges.
- Kitchen Sponges Can Hold More Bacteria Than a Toilet Seat! Because they stay damp and trap food particles, kitchen sponges can harbour millions of bacteria, sometimes even more than a toilet seat! Regular cleaning (microwaving, boiling, or replacing them frequently) helps prevent bacterial growth.
- Most Craft Sponges Are Just Modified Cleaning Sponges. The soft, porous sponges used for painting, stamping, and crafts are often the same material as kitchen sponges—just cut into shapes or made denser for better control with paints and inks.
- Melamine Sponges Work Like Magic (Literally)! "Magic Erasers" are made from melamine foam, which acts like ultra-fine sandpaper. Instead of absorbing liquid like a regular sponge, melamine foam breaks down stains at a microscopic level, making it perfect for cleaning scuffs and marks.
- Cellulose Sponges Are Eco-Friendly (Unlike Most Sponges). Most common kitchen sponges are made of plastic-based polyurethane, which doesn't decompose easily. However, cellulose sponges (made from wood pulp) are biodegradable and break down naturally.
- Sponges Expand When Wet Due to Their Air Pockets. Ever noticed how dry sponges look shrunken and stiff? That's because they contain microscopic air pockets that collapse when dry and expand when water fills them. This makes them super absorbent!

How Loofahs Are Grown & Harvested

- Loofahs grow on vines, much like zucchinis or cucumbers.
- The young gourds are edible and sometimes used in cooking (especially in Asian cuisine).
- If left to mature, the loofah develops a fibrous interior.
- Once fully grown (about 60-90 days), the gourd is harvested, dried, peeled, and the seeds are removed.
- The remaining fibrous skeleton becomes the loofah sponge!

SUMMARY

This article provides a comprehensive exploration of sponges, highlighting their versatility and unique properties. It covers various aspects, including their soft matter physics, manufacturing processes, structural characteristics, and mechanical properties.

The article begins by introducing the concept of soft matter physics and its relevance to sponges, focusing on their porous, interconnected structure as a key factor in their functionality. It then delves into the manufacturing techniques and materials used in sponge production, emphasizing the potential for customization to meet specific toy requirements.

The structural attributes of sponges are examined, particularly their porous network of cells and void spaces, which are crucial for their ability to absorb and retain liquids. This property makes sponges ideal for use in various toy designs.

The article also explores the mechanical properties of sponges, such as stress-strain behaviour and Young's modulus. These properties demonstrate the sponge's flexibility, compressibility, and capacity for energy absorption. The stress-strain curves reveal a notable plateau stress over an extended strain range, making sponges suitable for energy absorption applications, including eco-friendly packaging materials.

Notably, the luffa sponge stands out with its impressive stiffness, strength, and energy absorption capabilities, rivalling metallic cellular materials like aluminium foams and Ni–P micro lattices. It offers superior strength compared to other cellular materials in a similar density range, such as expanded polystyrene foams and Ni–P micro lattices. As an ultra-light, environmentally friendly engineering material, the luffa sponge holds tremendous promise.

In conclusion, this article provides a holistic view of sponges, transforming them from everyday objects into versatile materials with a wide range of potential applications. From their manufacturing processes to their remarkable mechanical properties and soothing attributes, sponges prove to be multifaceted components that bridge the gap between science, practicality, and creativity.

2.3: BUBBLES AND BALLOONS

"The beauty of a balloon is not just in its form, but in its response to the air around it—it shows the potential of soft matter to adapt and change shape."

– Lars Bergström, physicist

Bubbles and balloons are fascinating examples of fluid mechanics, elasticity, and surface tension at work. While they may seem simple, the physics behind them involves complex interactions between gases, liquids, and elastic materials.

1. Surface Tension and Bubble Formation

A bubble is a thin film of liquid enclosing a gas, typically formed from a soap-water mixture. The key physics principle behind bubbles is surface tension—a force that acts at the surface of a liquid due to cohesive molecular interactions.

- Water molecules naturally attract each other, creating a contracting force at the surface.

- Adding soap reduces water's surface tension, making it easier to stretch into a thin, flexible film.

- The soap molecules arrange themselves in a bilayer, with hydrophilic (water-loving) heads facing the liquid and hydrophobic (water-repelling) tails facing the air, stabilizing the bubble.

Bubbles are always round because the spherical shape minimizes surface area for a given volume, following the principle of minimum energy—a key idea in physics. This makes spheres the most efficient shape for enclosing a gas.

2. Air Pressure and the Behaviour of Balloons

A balloon is a thin, elastic membrane enclosing a gas (usually air or helium). The behaviour of a balloon is dictated by pressure, elasticity, and material properties.

When a balloon is inflated, the air inside exerts pressure outward, stretching the material.

The elasticity of the rubber or latex resists this stretching, creating a balance between internal gas pressure and tension in the balloon walls.

If too much gas is added, the stress exceeds the balloon's tensile strength, causing it to burst.

Balloons pop suddenly. Unlike bubbles that collapse gradually, a balloon's material is highly elastic, meaning that a small rupture causes rapid retraction of the material, releasing stored energy explosively.

3. The Role of Gas Properties in Bubbles and Balloons

Both bubbles and balloons behave differently depending on the gas inside them, due to properties like density, molecular weight, and diffusion rates.

Helium balloons float because helium is lighter than air, creating buoyancy.

Hot air balloons rise due to thermal expansion, where heated air inside becomes less dense than the cooler surrounding air.

Bubbles filled with carbon dioxide sink because CO_2 is denser than air.

Helium balloons shrink over time since the helium atoms are smaller than oxygen or nitrogen molecules, allowing them to diffuse through the balloon material more quickly, causing gradual deflation.

4. Stability and Interactions of Bubbles

When two bubbles meet, they merge to form a shape that minimizes surface tension.

If they are the same size, they form a flat interface at the contact point.

If they are different sizes, the smaller bubble has higher internal pressure and may collapse into the larger one.

Soap bubbles eventually pop since over time, gravity pulls water down, thinning the film. Evaporation further weakens the bubble, until it ruptures. Adding glycerine or sugar slows this process, making longer-lasting bubbles.

Conclusion

The physics of bubbles and balloons is a beautiful interplay of surface tension, elasticity, gas properties, and pressure dynamics. Their behaviour can be explained using principles of fluid mechanics, thermodynamics, and material science, making them an accessible yet profound demonstration of physics in everyday life.

8. SOAP BUBBLES

"Blow a soap bubble and observe it, you may study it all your life and draw one lesson after another of physics from it."
- Lord Kelvin

INTRODUCTION

The most fascinating aspect of soap bubbles is their beauty. As sunlight reflects off the thin surface of a soap bubble, it creates a mesmerizing display of colours, almost like a tiny work of art. This captivating visual effect is due to a phenomenon known as "thin-film interference," where light waves interfere constructively or destructively as they pass through the bubble's thin film. This interplay of colours catches our eye and draws our attention, which will be discussed in the next section. But before diving into the science, let's first appreciate the artistic beauty and historical significance of soap bubbles.

Importance in History

Soap bubbles have had a notable presence in human history and art for centuries. Renowned painters have often used them as symbols of change and the fleeting nature of life. For example, Johannes Vermeer's masterpiece *The Glass of Wine* captures the way light interacts with the surface of a soap bubble. Similarly, in *Children's Games* by Pieter Bruegel the Elder, children blowing soap bubbles is depicted, showcasing how common the activity was. Scientists have also been intrigued by soap bubbles since the 1600s when Jesuit scholar and polymath Athanasius Kircher began studying their shape and surface properties. Kircher's pioneering work opened the door for future research into the physics of bubbles. Soap bubbles are not only significant in history but have also evolved as a medium for artistic expression and entertainment. "Bubbleologists," street performers who expertly create and manipulate soap bubbles, craft stunning sculptures and choreographed displays. These skilled artists take advantage of the fleeting nature of bubbles to mesmerize audiences worldwide, drawing them into a magical and enchanting experience. Soap bubbles have also been used in theatre, immersive art installations, and contemporary dance to tell stories and engage the senses.
Explorations and Discoveries in Science

Scientists have recognized the crucial role surface tension plays in shaping and stabilizing soap bubbles. These studies have not only deepened our understanding of molecular forces but have also led to advancements in real-world applications. For instance, manipulating surface tension in soap bubble solutions has contributed to progress in fields like microfluidics and nanotechnology, where precise control over liquid interactions is essential.

The Toy

The physics of soap bubbles is an area of great interest to physicists, involving fundamental concepts like surface tension, intermolecular forces, and fluid dynamics.

At their simplest, soap bubbles are thin films of soap and water filled with air. But there's something special about how they hold together. Normally, water molecules love to stick to each other so much that they'd rather bead up than stretch out. When you add soap, it changes the behaviour of the water. The soap molecules sneak in between the water molecules and make the surface more flexible. This lets the water stretch thin and still hold a shape—creating a bubble!

A soap bubble's film is made of three layers: a thin layer of water sandwiched between two layers of soap molecules. It's like a microscopic water sandwich!

Why are bubbles always round? Because of surface tension—the same force that lets some insects walk on water. Surface tension pulls the bubble into the smallest shape possible that can hold its air inside, and in three dimensions, that shape is always a sphere.

And what about those swirling rainbow colours? That's not dye or pigment—it's light interference. Light waves bounce off both the outside and inside surfaces of the bubble. As the light waves overlap, some colours cancel each other out while others shine brighter, depending on the thickness of the bubble film. The result? A magical dance of colours that shift as the bubble floats and the film gets thinner.

Eventually, gravity pulls the water in the film downward, thinning the top of the bubble. When the film becomes too thin, it can't hold together anymore—and pop! The bubble bursts, usually in just a few seconds.

Even though they don't last long, bubbles are full of hidden science: physics, chemistry, light, and fluid dynamics. And whether you're a child chasing them on a sunny day or a scientist studying them under a microscope, soap bubbles are a perfect blend of beauty and science.

Figure 38: Soap bubbles

(Source: Photographgraph by Siddarth S)

DIY VERSION

Ingredients:

- 1 cup of water (preferably distilled for better clarity)
- 2 tablespoons of dishwashing liquid (or any mild liquid soap)
- 1 tablespoon of glycerine (you can find this at most drugstores or online)
- 1 tablespoon of cornstarch or honey (optional, for extra bubble strength)

Instructions:

1. Mix the Ingredients: In a bowl or container, combine the water, dish soap, glycerine, and cornstarch (or honey, if you're using it). Stir gently until all the ingredients are well combined. Be careful not to create too many bubbles while mixing.

2. Let It Sit: Allow the bubble solution to sit for at least 2-3 hours (overnight works best!). This helps the solution settle and gives you better bubbles.

3. Create a Bubble Wand: To create your own bubble wand, you can use a pipe cleaner, plastic straw, or even a wire coat hanger. Shape it into a loop or a design you like. If you want a larger wand, you can use cotton strings tied to a stick to create a bigger loop.

4. Blow Bubbles: Dip the wand into the solution and gently blow through it to form bubbles. If you want to make bigger bubbles, you can gently wave the wand or move it through the air.

Tips for Bigger Bubbles:

- Use distilled water for cleaner, longer-lasting bubbles.

- Experiment with the glycerine amount, as more glycerine will create stronger bubbles.

- For a larger bubble mix, you can double or triple the recipe above.

INTERESTING FACTS

- Bubbles form spheres because surface tension pulls the soap film into the smallest surface area possible. A sphere is the most efficient shape for enclosing air.
- The colours on a bubble are caused by *light interference*. Different wavelengths of light bounce off the inner and outer surfaces of the film, creating swirling iridescence.

- A soap bubble's wall can be less than a thousandth of a millimetre thick—thinner than a human hair.
- Bubbles usually pop in seconds because gravity pulls water to the bottom, thinning the top until it bursts. Evaporation speeds this up, especially in dry air.
- In space, astronauts have experimented with bubbles. In microgravity, bubbles form perfect spheres and float—no up or down!
- Soap bubbles have been a children's toy for over 400 years. They've appeared in paintings from the 17th century, often symbolizing the fragile nature of life. In literature and art, bubbles often symbolize fragility, innocence, or the ephemeral nature of life.
- The largest free-floating soap bubble ever made was over 96 feet (29 meters) long! Other records include most people inside a single bubble and longest-lasting bubble.
- People make bubble sculptures, play bubble tag, and even have bubble performance art shows using smoke, light, and giant wands.
- Adding glycerin or corn syrup to a bubble mix slows evaporation and strengthens the film, letting bubbles last longer.
- Educators use bubbles to teach everything from geometry (spheres, minimal surfaces) to chemistry (molecular bonds) and fluid dynamics.

SUMMARY

Our study of soap bubbles reveals the fascinating world of soft matter physics. Central to this is surface tension, which governs bubble formation and stability. We've explored how bubble radius, surface tension, and internal pressure are connected through equations like the Laplace-Young and Rayleigh-Plateau equations. These mathematical relationships, along with visual representations, help explain how bubbles grow and evolve, while also showcasing the stunning optical effects that make them so captivating.. The field of soft matter physics, which includes the study of soap bubbles, is still an active area of research. Scientists are conducting a variety of studies to expand our understanding:

Advanced Characterization: Modern imaging techniques, such as high-speed photography and atomic force microscopy, allow for detailed real-time imaging and measurements of soap bubbles. These methods help us learn more about how bubbles move and remain stable.

Environmental Impact: Researchers are exploring the environmental implications of soap bubbles, particularly in relation to aerosols, air quality, and pollution. Soap bubbles' interactions with pollutants and airborne particles are of interest to environmental science and engineering.

Materials Science: The study of soap bubbles aids the development of foams and emulsions with specific properties. These materials have wide applications in fields like food, cosmetics, pharmaceuticals, and construction.

Bubble Dynamics in Biological Systems: Research is also focused on the role of bubbles in biological contexts, such as gas emboli in blood vessels or gas-containing structures in aquatic organisms. This work has important implications for medical and biological research.

Soft Robotics and Microfluidics: Researchers are investigating devices for soft robotics and microfluidics, using the principles of surface tension and molecular forces to create soft actuators and microfluidic systems. These advancements are leading to new possibilities in robotics and lab-on-a-chip technologies.

These ongoing research efforts will continue to reveal more about the mysteries and practical applications of soap bubbles. As our understanding deepens, we'll not only appreciate their beauty but also their significance in the field of soft matter physics.

9. BALLOONS

INTRODUCTION

Balloons are not only playful objects that light up events, but they also provide fascinating insights into physics and mathematics, particularly at the molecular and physical levels. The development of rubber balloons can be traced back to Michael Faraday's experiments in the 1820s, where he studied the elastic properties of rubber when filled with hydrogen gas. His work laid the foundation for our understanding of elasticity, which is central to how balloons work. Today, balloons are made from materials known as elastomers, which are synthetic rubbers with similar mechanical properties to natural rubber derived from the latex of rubber trees. Elastomers are highly elastic, stretchable, and resilient, allowing balloons to expand and retain their shape when inflated. Rubber, like air (an ideal gas), is considered an entropic material. This means that both rubber and gases exhibit high disorder at the molecular level, with rubber molecules lacking long chains and having a high degree of deformability under minor stress. The high entropy in these materials explains their flexibility and ability to stretch, which is why balloons can be inflated and hold their shape under varying conditions.

HISTORY OF BALLOONS:

Balloons have existed in various forms long before the invention of rubber. Initially, animal bladders—especially pig bladders—were used as balloons. Galileo famously used pig bladders to measure the weight of air by filling them with gases. Indigenous children, including those from India and the Inuit, played with bladders, often from sea animals. The Aztecs also created balloon-like objects using cat intestines for sacrificial rituals, sealing them with vegetable thread and allowing them to dry.

In June 1783, the Montgolfier brothers, Jacques and Joseph, demonstrated the first lighter-than-air balloon, made of cloth lined with paper and measuring 11 meters in diameter. That same year, Jacques Charles created a balloon coated with rubber varnish. Later, in 1824, Michael Faraday innovated with natural rubber, creating a

double-layered balloon setup, which he used for experiments involving hydrogen gas at the Royal Institution of Great Britain.

Thomas Hancock further advanced balloon technology by introducing a kit for making rubber balloons using rubber solution and a condensing syringe. In 1931, Neil Tillotson created the first modern-day rubber balloon in his attic for the Patriot's Day parade in Massachusetts, featuring a cat's head design with whiskers printed using dye.

The balloon industry grew significantly, particularly in the USA, as manufacturers recognized its potential for scientific, strategic, and commercial purposes. Today, rubber latex, derived from the rubber tree Hevea brasiliensis, is the primary raw material for balloon production.

THE TOY

CHEMICAL COMPOSITION:

The existence of balloons relies on the unique properties of rubber, a polymer composed of long chains of repeating molecular units. Natural rubber is made of a chemical known as cis-polyisoprene, which can be synthesized through the cis-polymerization of isoprene. While the structural formula of polyisoprene suggests a straight chain, its actual structure is coiled and spring-like in three dimensions, which makes it stretchable. However, these structures are not strongly bonded together. When stretched, the individual molecules can tear apart because there is a lack of inter-molecular bonding between the coiled “spring” molecules, making rubber soft and flexible.

To address this, Charles Goodyear developed the vulcanization process, which makes rubber both more elastic and stronger. Vulcanization involves adding heat and sulphur to rubber, creating disulfide bonds that form cross-links between the polymer chains. The degree of vulcanization, determined by the concentration of sulphur, alters the mechanical and elastic properties of the rubber. Balloon latex is lightly vulcanized, with only 1-2% of the sites cross-linked, which allows for inflation with air pressure. In contrast, tyres and inner tubes are heavily vulcanized, with 5-10% of the sites cross-linked, making them less elastic but more durable and resistant to wear.

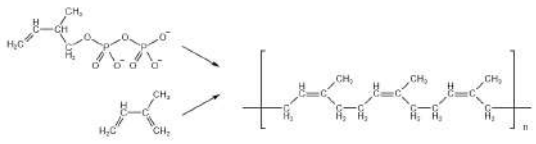

Figure 39: Polymerization of isoprene

This image shows the polymerization of isoprene (2-methyl-1,3-butadiene), initiated by an organic peroxide catalyst (top left) and isoprene ($CH_2=C–CH=CH_2$ with a methyl branch) to form polyisoprene. Polyisoprene is the main component of natural rubber, and synthetic versions are made for tires, elastic materials, and other rubber products. (Source: Devanand C S)

Balloons are made from rubber latex, which consists of rubber globules suspended in a watery medium. Upon exposure to the environment, the rubber globules separate from the watery portion of the latex and float to the surface. Through processing, these globules coagulate to form a rubber sheath. The rubber is then vulcanized or cured using various chemical methods to enhance its ability to withstand extremes of tension, pressure, and temperature.

Physical Properties:

Mechano-Elastic Properties of Balloons:
When a balloon is inflated, it stretches. This stretching represents a form of deformation, as long as the deformation remains within the elastic limit of the rubber or latex. Hooke's Law can describe the relationship between the applied force (air pressure inside the balloon) and the resulting change in size or volume.

THERMO-ELASTIC PROPERTY OF BALLOON:
Most solids and liquids we know expand when heated. However, when stretched rubber is heated, it contracts. Stretching rubber releases heat, leading to the counterintuitive contraction. These thermoelastic properties are not unique to rubber but also apply to various elastomers (rubber-like polymers), such as the material used in balloons.

Air-filled balloons initially float due to buoyancy. However, over time, they lose air because of the balloon's structure. The sulphur bonds between rubber molecules create pores that allow smaller molecules, like helium, to escape. Helium's smaller molecular size and lower density make it more likely to diffuse out of the balloon. Larger molecules, such as nitrogen and oxygen, diffuse at a slower rate, which is why the balloon gradually loses its inflation.

Inflated balloons have a shiny appearance because of their smooth, stretched surface. When the balloon is inflated, the coiled molecular structure of rubber straightens, reflecting light coherently. As a result, light rays hitting the surface are reflected as parallel rays, creating a shiny effect. However, over time, this shine fades as the balloon oxidizes. The molecular oxygen in the air forms an oxidation layer on the balloon's surface, which becomes rough and chalky, reducing its ability to reflect light. Additionally, the balloon may shrink due to helium loss, further diminishing its shine.

DIY VERSION

1. Balloon Using a Plastic Bag:
This is a great lightweight alternative to a balloon.

Materials:

- A thin plastic bag (like a grocery or produce bag)
- String or rubber band
- A straw (optional)

Instructions:

- Cut & Shape (Optional): Trim the bag into a circular or oval shape.
- Seal the Edges: Tie the opening with a string or rubber band.
- Inflate with a Straw: Insert a straw and blow air inside, then quickly seal.

Tip: Use biodegradable bags for an eco-friendly version!

2. DIY Paper Balloon (Origami Style)

This is a traditional Japanese "water bomb" balloon made from paper.

Materials:

- A square piece of thin paper (origami or tissue paper)
- Your breath!

Instructions:

- Fold the paper into an origami water bomb (a simple balloon shape).
- Leave a small opening at one end.
- Blow into the hole to inflate the balloon.

Tip: These work great for lightweight decorations!

3. DIY Gelatine Balloon (Edible & Biodegradable!)

This is a natural, biodegradable balloon made from Gelatine.

Materials:

- Unflavoured Gelatine (3 tbsp)
- Water (1 cup)
- A balloon mould (small round object)

Instructions:

- Dissolve the Gelatine in warm water.
- Dip a round mould (like a balloon) into the Gelatine mixture.
- Let it dry, then carefully remove the mould.

Once hardened, you'll have a thin, balloon-like structure!

Tip: These are great for eco-friendly decorations and can be composted.

4. DIY Balloon Using a Condoms (Historical Trick!)

Did you know that before latex balloons, people used animal intestines and later condoms as inflatable objects?

Materials:

- A condom (non-lubricated)
- Air pump or straw

Instructions:

- Unroll the condom.
- Blow air inside or use a small pump.
- Tie it off like a regular balloon.

Tip: This works well because condoms are elastic and airtight, similar to balloons!

5. DIY Hot Air Balloon (For Fun Science Experiments)

This is a simple floating balloon alternative.

Materials:

- Thin tissue paper or lightweight plastic
- Glue or tape
- A candle or heat source

Instructions:

- Make a bag-like structure from tissue paper or plastic.
- Seal the edges with glue/tape, leaving an opening at the bottom.
- Hold it over a heat source (carefully!): The hot air inside will make it rise.

Tip: This works on the principle of buoyancy, similar to real hot air balloons!

INTERESTING FACTS

- The first balloons made about 2000 years ago were probably made of inflated animal intestines and bladders.
- Michel Faraday is thought to be the first to make a rubber balloon in 1824.
- The first passengers of the hot air balloon were a rooster, a duck and a sheep – all of which perished.
- Balloons are used in weather analysis and in military applications.
- Balloons have been sent to other planets, such as Venus, to drop scientific instruments.
- Balloon sculptures are an art form.

SUMMARY

Balloons, often seen as symbols of joy, also hold significant scientific value. Made of rubber, which is known for its high stretchability and elasticity, they serve as an excellent basis for mathematical and physical observations at the molecular level. Balloons demonstrate mechano-elastic and thermoelastic properties when inflated, following Hooke's Law.

Historically, balloons existed before the use of rubber, with early versions made from animal bladders, such as pig bladders. The rubber used in modern balloons is a polymer of long, repeating molecular chains. Charles Goodyear's vulcanisation process strengthened rubber by adding heat and sulphur, creating cross-links between polymer chains. Over time, balloons filled with air tend to shrink as gases escape through pores formed by these sulphur bonds.

When inflated, the rubber stretches, increasing the distance between cross-links, reducing entropy, and increasing free energy. The force required to stretch the rubber increases with temperature, akin to the behaviour of an ideal gas. The pressure inside the balloon balances with the elastic force of retraction, following a specific pressure-volume relationship with a maximum stretching ratio. This behaviour can be experimentally tested using a manometer, offering insights into the thermodynamics of stretched rubber.

In conclusion, balloons offer a unique intersection of playful enjoyment and scientific exploration, providing valuable insights into materials science, thermodynamics, and elasticity. From their historical evolution to their chemical composition and inflation behaviour, balloons blend scientific wonder with celebration.

10. LIQUID MOTION BUBBLER

INTRODUCTION

A liquid motion bubbler—often described as a "lava lamp without the lamp"—is a captivating sensory toy that appeals to people of all ages. It consists of a sealed container filled with immiscible liquids, such as coloured oil and water, which interact in mesmerizing ways due to their differing densities and viscosities. As ambient heat warms the liquid, the oil rises and falls, creating a soothing, rhythmic motion. The physics behind this effect lies in the interplay between the liquids' densities, viscosities, and the movement of air bubbles. As the liquid warms, the oil becomes less dense and rises; as it cools, it sinks again. This gentle, cyclical movement not only fascinates the eye but also serves a therapeutic purpose. Liquid motion bubblers are known for their calming effects, offering sensory stimulation that can help reduce stress, relieve anxiety, and improve focus. In essence, liquid motion bubblers are more than just decorative objects—they offer both visual appeal and therapeutic benefits, making them popular tools for relaxation and sensory support.

Figure 40: Liquid motion bubbler toy

(Source: YouTube, under creative commons license - https://youtu.be/UKZebKJtUIo?si=C6IGsQHot4YDbIHl)

THE TOY

Materials Used in the Toy

The liquids chosen to use in the toy are non-harmful. Commonly used liquids are water, mineral oil, and glycerine.

Water: Water is denser than air, making it more suitable for rising bubbles and safe for children.

Mineral oil and Glycerine: They are denser than water, which results in slower and more mesmerizing bubble motion.

A liquid motion bubbler is a calming, playful toy that works on some surprisingly clever science. You've probably seen one—brightly coloured drops slowly fall, drip, or slide down inside a transparent tube, often gliding over tiny ramps or bouncing gently as they descend. It's soothing to watch, and behind its relaxing motion lies a mix of physics and chemistry at work.

At the heart of a liquid motion bubbler are two different liquids sealed inside the container. One of these liquids is usually water-based, while the other is oil-based and brightly coloured. These two don't mix—just like oil and water in a salad dressing—because their molecules are so different that they don't stick together. This separation is what allows the colourful blobs to form and remain distinct as they move.

The effect you see when the droplets begin to fall is driven by a few scientific principles. The first is density—how heavy something is for its size. In most bubblers, the coloured oil is denser than the clear liquid and slowly sinks to the bottom. But instead of mixing, the heavier liquid stays in blobs, forming drops that gently fall through the other liquid.

Gravity plays a major role here. It pulls the denser liquid downward, and the design of the bubbler—with narrow channels, ramps, or spirals—slows the movement and creates a rhythmic dripping effect. This is where viscosity also comes into play. Viscosity is a measure of how thick or sticky a liquid is. Honey, for example, flows more slowly than water because it's more viscous. In a bubbler, the coloured liquid is fairly thick, which helps slow the motion and gives the toy its signature relaxing pace.

So, in simple terms, a liquid motion bubbler works by trapping two unmixable liquids—one heavier and thicker than the other—in a sealed space. Gravity pulls the heavier one downward, but its movement is slowed by its thickness and by the design of the container. The result is a slow, steady drip of blobs and bubbles that's both fun to watch and a great way to explore basic science in motion.

Figure 41: Air bubbles rising in a liquid motion bubbler

(Source: YouTube, under creative commons license - https://youtu.be/UKZebKJtUIo?si=C6IGsQHot4YDbIHl)

Air bubbles are trapped at one end of the toy. As the toy is flipped toy, The air inside the toy rises as bubbles because the liquid is denser than the bubbles.

Figure 42: Coloured oil dripping down.

(Source: YouTube, under creative commons license - https://youtu.be/UKZebKJtUIo?si=C6IGsQHot4YDbIHl)

In this toy, the transparent liquid is less dense than the coloured oil, which initially sits on top. When the toy is flipped, the denser coloured oil begins to move downward through the lighter liquid due to gravity. The speed at which the coloured oil moves is influenced by the viscosity of the liquids—thicker (more viscous) liquids slow the movement, while thinner (less viscous) ones allow it to flow more quickly. Because the coloured oil is denser, it overcomes the buoyant force and gradually settles at the bottom. This process repeats each time the toy is flipped, creating a soothing, lava lamp-like motion that makes it a visually engaging sensory toy.

DIY VERSION

Liquid Motion Bubbler – Basic Version

Materials Needed:

- A clear plastic bottle or glass container (such as a small water bottle)
- Water
- Baby oil or cooking oil (lighter than water)
- Food colouring (optional, for contrast)
- Small beads or glitter (optional, for visual effect)
- Funnel and dropper

Procedure:

- Fill the bottle halfway with water.
- Add a few drops of food colouring to the water and mix well.
- Slowly pour baby oil (or cooking oil) into the bottle until it is nearly full. The oil will float on top of the water since it is less dense.
- Seal the bottle tightly and flip it upside down. The coloured water droplets will slowly fall through the oil, creating a bubbling effect.

Tip: For a slower dripping effect, use honey or glycerine instead of plain water.

DIY Liquid Timer Bubbler (Bubble Drip Effect)

This version mimics commercial oil drip timers by controlling the size of the droplets.

Materials Needed

- Clear plastic or glass container with two separate chambers (a small hourglass-shaped bottle works well)
- Hot glue gun or waterproof sealant
- A small drilled hole or thin tube to connect the chambers
- Viscous liquid (glycerine, thick oil, or corn syrup)

Procedure:

- Create two connected chambers by sealing a small plastic bottle in the middle, leaving only a small hole or thin tube for the liquid to pass through.
- Fill the top chamber with oil and a coloured liquid (water mixed with food colouring).
- Flip the container over and watch as droplets form and slowly drip down through the hole or tube into the lower chamber.

Tip: Adjusting the hole size changes the dripping speed.

DIY Lava Lamp Style Motion Bubbler (Effervescent Effect)

This version creates a bubbling effect similar to a homemade lava lamp.

Materials Needed

- Alka-Seltzer tablets (Eno) or a baking soda and vinegar mixture
- A tall glass or bottle

Procedure

- Fill a bottle three-quarters full with oil and one-quarter full with water.
- Drop an Alka-Seltzer tablet into the bottle.
- Watch the bubbles rise and create a moving liquid effect.

Tip: If using baking soda and vinegar, add baking soda first, then pour in vinegar to activate the bubbles.

INTERESTING FACTS

- Liquid motion bubbler is a sub-class of toys called the liquid motion toys that include bubblers, floating toys, drip-timers etc.
- One such is the oil-water motion toy, that is equally fascinating. It is based on the principles of fluid dynamics, immiscibility, density differences, and

viscosity. It works by allowing coloured oil droplets to fall, rise, or move within a clear container filled with a second, immiscible fluid—usually water or another clear, denser liquid. The toy is filled with two liquids that do not mix, typically: (a) a coloured oil (lighter, less dense, and hydrophobic) (b) a clear, denser fluid (often water or a water-based solution).

- A sensory bottle—also known as a calm-down bottle or discovery bottle—is a sealed, transparent container filled with various materials designed to engage the senses, particularly sight, touch (through motion), and sometimes sound.

Figure 43: Liquid sensory bottle

A liquid sensory bottle is a sealed, transparent container filled with coloured liquids, glitter, beads, or other small objects that move slowly when shaken or tilted. It's often used for calming, visual stimulation, and sensory play in both children and adults. (Source: Gemini.ai)

- Many from an older generation have grown up watching glitter lamps lighten up a living room. The glitter lamps consist of a sealed container with a liquid, fine particles of glitter and a heat source (typically a bulb) at the bottom. When turned on, the light bulb at the bottom begins to warm the liquid, leading it to rise. Cooler liquid descends to take its place, creating a circulating flow. The glitter gets caught in these convection currents and swirls throughout the lamp. The glitter reflects the bulb's light as it moves, creating a sparkling, dynamic visual effect.
- Another toy based on similar idea is the "Titanic that does not sink". Here there is a plastic ship, and a plastic iceberg. No amount of moving the toy around, and creating waves will "sink" the ship. This is because the toy consists of two liquids, one transparent and the other blue. Their properties are like oil on water. The transparent liquid will always stay atop the blue liquid, creating the illusion!

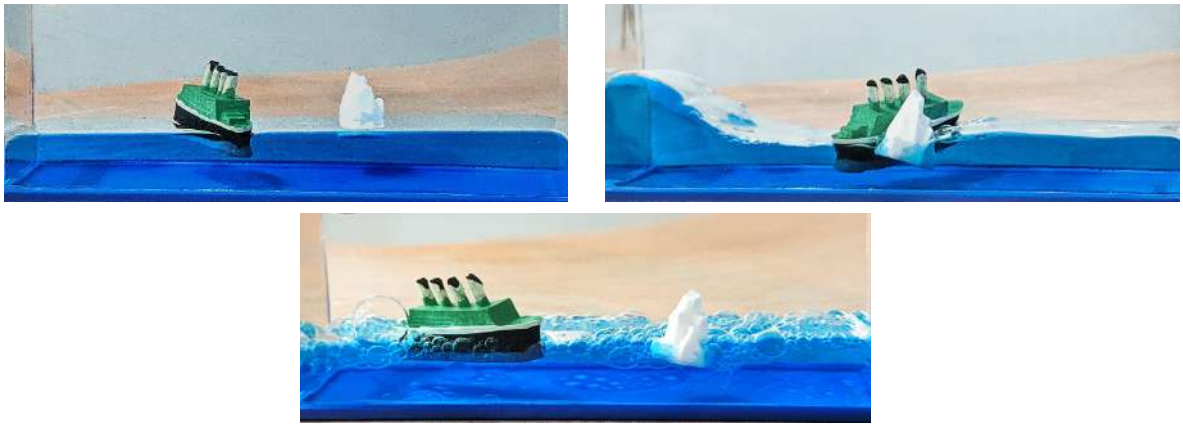

Figure 44: The unsinkable-Titanic toy

This toy has two immiscible liquids and the ship and iceberg float on top of the lower, blue liquid. (Source: Photograph by Siddarth S)

SUMMARY

The liquid motion bubbler is a toy made up of two different types of liquid with different densities. The concept of density, viscosity, and buoyancy in this toy made it a therapeutic and visually soothing device, often for relaxation and relief. It is commonly used for persons with autism or ADHD and helps to improve their focus.

2.4: Granular Materials

"Granular systems look deceptively simple... But the closer we look, we find so many complexities"
- Mark Buchanan, Physicist
[https://doi.org/10.1038/425556a]

Granular Materials: Complex Matter Beyond Solids, Liquids, and Gases

Granular materials—found everywhere from sand dunes to pharmaceutical powders—are collections of macroscopic particles that interact primarily through contact forces. Though they may seem simple, their behaviour defies conventional categories of matter. Unlike solids, liquids, or gases, granular materials can exhibit characteristics of all three, depending on the conditions. This complexity has made them a fascinating subject of study across physics, engineering, and material science.

Common examples of granular materials include sand, grains, powders, gravel, coal, and industrial bulk products like pharmaceutical pills. These materials are vital to many industries, yet their unpredictable behaviour under stress, motion, or confinement continues to challenge researchers.

Some of the key characteristics of granular materials are as follows.

1. Discrete and Dissipative Nature

Granular materials are made up of individual, finite-sized particles. Unlike fluids or gases, these particles do not interact through long-range forces but through direct contact. Importantly, energy is lost during interactions due to friction and inelastic collisions. As a result, granular systems are inherently dissipative and do not obey the rules of thermodynamic equilibrium in the traditional sense.

2. Nonlinear and History-Dependent Behaviour

The response of a granular material depends not just on the current conditions but also on its history. When compressed, particles form "force chains"—networks that bear most of the applied stress. These force chains result in highly nonuniform stress distributions, leading to nonlinear behaviour where small changes in input can cause large, unpredictable effects.

3. Jamming and Unjamming Transitions

One of the most intriguing features of granular materials is their ability to transition between a rigid, jammed state (solid-like) and a fluid-like, unjammed state. These transitions depend on factors such as particle density, external vibration, or applied

stress. Understanding this jamming behaviour is critical in analysing avalanches, silo blockages, and powder flow in manufacturing.

4. Packing and Density Effects

How particles are arranged—known as their packing structure—has a major impact on properties like porosity, compaction, and shear resistance. The maximum packing density depends on factors such as particle shape, size distribution, and external agitation. This principle underlies processes like powder compaction in pharmaceuticals and grain storage optimization in agriculture.

5. Flow and Size Segregation

When granular materials are in motion, such as in hoppers, chutes, or rotating drums, they exhibit complex flow behaviour influenced by particle friction, cohesion, and geometry. A well-known phenomenon during flow is size segregation—often called the Brazil-nut effect—where larger particles migrate to the top of a vibrated mixture due to differences in mobility and percolation.

6. Granular Gases and Kinetic Behaviour

Under high-energy agitation, granular materials can mimic gas-like behaviour, with particles moving freely and colliding frequently. However, unlike molecular gases, granular "gases" continually lose energy due to inelastic collisions. To sustain this dynamic state, a constant input of energy is required, such as through vibration or mechanical agitation.

Applications and Challenges

Granular materials play a central role in many practical domains:

- Construction – Ensuring the stability and compaction of sand, gravel, and concrete.
- Pharmaceuticals – Managing the flow, mixing, and compaction of powder-based drugs.
- Agriculture – Storing and transporting grains in silos.
- Geophysics – Predicting landslides, soil erosion, and earthquake-induced granular flows.
- Industrial Processing – Optimizing flow in hoppers, conveyors, and chemical reactors.

Despite their prevalence, granular materials remain difficult to model and predict due to their inherently non-equilibrium behaviour and sensitivity to particle-scale interactions. To tackle these challenges, researchers use a combination of theoretical models, simulations, and experimental methods to better understand their mechanics and improve practical handling.

Conclusion

Granular materials are more than just piles of sand or grains—they represent a complex, hybrid state of matter with behaviours shaped by their discrete structure and dissipative interactions. Their study not only offers insight into fundamental physics but also drives innovation in industries that depend on the reliable flow and storage of bulk solids. As research advances, our ability to control and predict granular behaviour will continue to improve, unlocking new efficiencies and solutions in science and engineering.

11. FLOWING GRAINS: THE PHYSICS BEHIND KINETIC SAND

INTRODUCTION

Kinetic sand is a type of play sand that feels soft and crumbly to the touch, yet holds its shape when squeezed or moulded. As a granular material, it exhibits properties of both solids and liquids, challenging traditional definitions of matter. When pressed, moulded, or sculpted, it flows like a fluid, easily conforming to intricate shapes. Yet once pressure is released, it retains its form—defying gravity and demonstrating the strength of interparticle forces.

To understand kinetic sand more fully, it is helpful to consider its predecessor: magic sand. Magic sand is made from regular sand coated with a hydrophobic compound. This allows it to be shaped underwater without dispersing into a cloudy suspension. However, once the water is removed, the structure collapses into a dry pile rather than holding its shape like wet beach sand. This behaviour results from its water-repelling surface, which prevents absorption and keeps the sand dry even when submerged.

The development of kinetic sand marked a breakthrough in material science. It involved creating a substance that not only retained hydrophobic properties but also had a unique texture and flow behaviour when handled. Achieving this required carefully balancing sand, polymers, and hydrophobic agents to produce the desired combination of cohesion, flow, and mouldability. In the sections that follow, we'll explore these ingredient combinations in detail and examine how each one contributes to the distinctive physical properties of kinetic sand.

THE TOY

Granular materials are composed of discrete particles, with sizes ranging from a few microns to macroscopic scales. A defining characteristic of these materials is that the collective behaviour of the particles often differs significantly from the properties of the individual grains. This collective behaviour gives rise to several unique and important phenomena, including:

Jamming: A transition from a flowing, dynamic state to a rigid, jammed state occurs under specific conditions such as increased density or decreased agitation. This transition is central to understanding flow interruptions in systems like silos or hoppers.

Segregation: Particles tend to separate based on differences in size, shape, or density when the system is agitated or in motion. This effect, commonly seen in industrial processing and natural systems, can lead to uneven material distribution.

Compaction: The packing density of granular materials changes under applied pressure. This process affects porosity, structural stability, and the overall mechanical behaviour of the material.

These behaviours make granular materials a fascinating subject in both applied and theoretical research, with relevance in physics, engineering, and various industrial applications.

Dilation wherein there is an expansion (or increase in volume) when a granular material is subjected to forces parallel to the surface, called shear forces.

Examples of granular material include sand, flour, sugar, soil, coffee grounds, snow etc. The complex behaviour of kinetic sand is based on the properties of granular material.

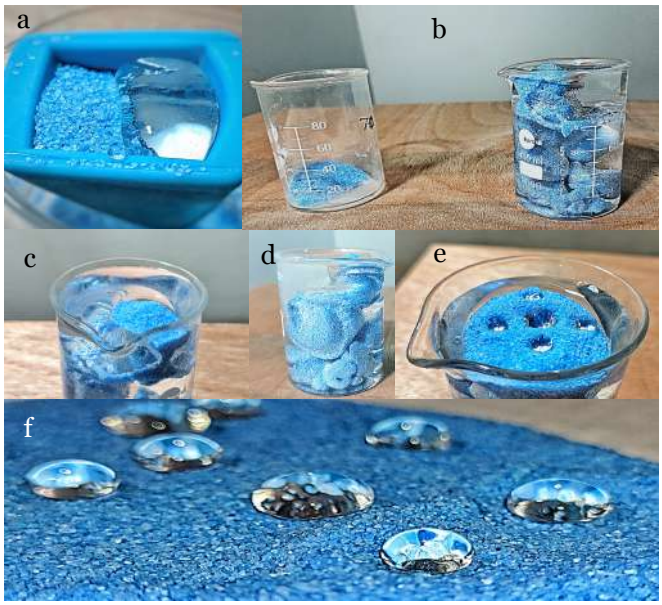

Figure 45: Kinetic sand

Kinetic sand is non-sticky and used for modelling. (a) Water floating on the sand in the scoop (b) the sand in the beaker on the left is dry, and in the beaker on the right the sand in water is clumped, whereas that on the surface is dry and free-flowing (c) a close-up of the sand, partially on the surface of water (d) a closer look at the clumping of sand in water (e) water droplets formed on the surface of the sand, which is atop the water in the beaker, clearly demonstrating the non-sticky nature of sand (f) a close-up of the water droplets on the sand (Source: Photograph by S Siddarth)

SOFT MATTER BEHAVIOUR OF KINETIC SAND:

The unique behaviour of kinetic sand stems from a delicate balance between friction and cohesion among its particles. Commercial kinetic sand is made by coating regular sand grains with silicone oil, which causes the particles to stick to one another while remaining non-sticky to other surfaces. This coating is hydrophobic (water-repelling), promoting internal cohesion between grains. As a result, the sand can maintain its shape, resist gravity, and remain mouldable—all while feeling soft and flowing when handled.

One of the most intriguing properties of kinetic sand is its non-Newtonian fluid behaviour. Unlike Newtonian fluids, whose viscosity remains constant regardless of applied force, kinetic sand changes its viscosity in response to stress:

When a light force is applied, it behaves like a fluid—flowing and conforming to the shape of a container or mould.

When a stronger force is applied, it behaves more like a solid—stiffening and holding its shape.

This dual nature—fluid under gentle manipulation and solid under pressure—makes kinetic sand a fascinating example of soft matter physics and a versatile material for both play and educational exploration.

Beyond its tactile appeal and playful nature, kinetic sand displays a variety of complex soft matter behaviours. These properties arise from the interplay between particle interactions, applied forces, and the material's internal structure. Below are some of the key behaviours that make kinetic sand a fascinating material to study and use:

Granular Flow and Jamming

When manipulated, the sand grains within kinetic sand rearrange in response to applied forces. This is characteristic of granular materials such as rice or coffee beans, which can transition between flowing and jammed states. Kinetic sand flows like a liquid when poured but can settle into a rigid, jammed structure when moulded or compacted, demonstrating the duality of granular behaviour.

Hysteresis

Kinetic sand exhibits hysteresis, meaning there is a delay between the application of force and the material's response. For example, when compressed quickly, it behaves like a solid. Once the pressure is released, it doesn't immediately return to a fluid-like state—instead, it gradually relaxes back to its original form. This lag in response reflects the internal rearrangement of particles and the energy dissipation involved.

Self-Healing Properties

A remarkable feature of kinetic sand is its self-healing ability. When deformed, punctured, or pressed, the material slowly flows back and fills in the gaps, restoring a smooth surface. This property is a result of the cohesive forces between particles, allowing the sand to reform without external intervention.

Thixotropy

Kinetic sand also demonstrates thixotropic behaviour—its viscosity decreases when subjected to shear forces. Under stress such as kneading, pressing, or stretching, it becomes more fluid and mouldable. Once the force is removed, it slowly returns to a more solid-like state. A familiar comparison is with thixotropic paints: they remain thick at rest, yet flow easily when stirred or brushed.

CHEMICAL COMPOSITION OF KINETIC SAND:

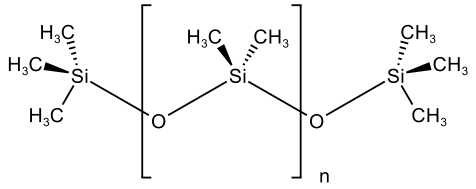

Figure 46: Chemical structure of polydimethylsiloxane (PDMS).

(Source: author)

Kinetic sand is typically composed of 98% ultra-fine grain sand and 2% dimethicone, also known as polydimethylsiloxane (PDMS). This small percentage of silicone polymer is what gives kinetic sand its unique viscoelastic properties—allowing it to flow like a liquid under light pressure but retain its shape when moulded.

PDMS is a silicon-based organic polymer with the molecular formula $CH_3[Si(CH_3)_2O]_nSi(CH_3)_3$, where n denotes the number of repeating $[SiO(CH_3)_2]$ units. It is hydrophobic, meaning it repels water, and optically transparent, chemically inert, non-toxic, and non-flammable. These properties make PDMS ideal for coating sand particles to produce kinetic sand.

In some formulations, polymer binders such as polyvinyl acetate (PVA) may be added to enhance cohesiveness and structural stability. Other additives—including antimicrobial agents (to prevent mould or bacterial growth), colourants, scents, glitter, and texture enhancers—can be used to improve sensory appeal.

Characterization of Kinetic Sand

Characterizing kinetic sand helps us understand its structure, behaviour, and composition. Below are some standard methods used:

Sieve Test: A sieve test analyses the particle size distribution of the sand. The material is passed through a stack of sieves with decreasing mesh sizes. The mass retained on each sieve is recorded to determine the relative distribution of particle sizes. For kinetic sand, grain sizes typically range from 0.125 to 0.250 mm.

Boiling Test: Boiling kinetic sand can reduce the polymer content, effectively increasing the relative concentration of silicon in the mixture. This process may result in brighter sand colour and highlights the dominant presence of silicon-based material in the mix.

X-Ray Fluorescence (XRF): XRF analysis is used to determine the chemical composition of kinetic sand. In this technique High-energy X-rays excite the sample. Electrons are ejected from inner orbitals, and higher-energy electrons fill the vacancies. This transition releases fluorescent X-rays, which are characteristic of specific elements. The resulting spectral peaks are analysed to identify elements and their concentrations based on the area under each peak.

DIY VERSION

A simple version of kinetic sand can be made at home using common household ingredients.

Materials Needed:

- Play Sand: Fine-grain sand (e.g., beach sand or craft sand)

- Cornstarch: Provides a soft, mouldable texture
- Dish Soap: Adds mild hydrophobicity, helping the sand stick together
- Water: Binds ingredients to achieve the right consistency
- Food Colouring (optional): Adds colour for aesthetic effect

Procedure:

- Mix 1 cup of play sand with 1 tablespoon of cornstarch.
- In a separate container, mix 1 teaspoon of dish soap with a small amount of water (around ¼ cup), and add food colouring if desired.
- Combine the wet and dry ingredients gradually, stirring until you reach a mouldable, slightly sticky texture.
- This DIY kinetic sand mimics the basic feel of commercial versions, though it lacks the refined behaviour and longevity of PDMS-coated formulations.

Measure Ingredients:

- Start with 2 cups of sand and place it in a large mixing bowl. Make sure the sand is dry.
- Add 1 cup of cornstarch to the sand and mix them thoroughly.

Figure 47: Adding cornstarch to dry fine-grained sand.

(Source: Allan Prince)

- Add Dish Soap: Slowly add dish soap while mixing the sand and cornstarch. You may need to add more or less depending on your desired consistency. Continue mixing until the sand starts to clump together.

Figure 48: Adding dish soap to the mixture.

(Source: Allan Prince)

- Add Water: Gradually add water, a little at a time, while kneading the mixture. The goal is to achieve a mouldable yet slightly crumbly texture. Be cautious not to add too much water, making the mixture too wet.

Figure 49:Adding water to the mixture.

(Source: Allan Prince)

- If you want to colour your kinetic sand, mix a few drops of food colouring to the mixture and knead it until the colour is evenly distributed. Adjust the colour intensity to your liking.

Figure 50: Colouring the mixture.

(Source: Allan Prince)

- Test the Texture: Test the texture by squeezing the sand. It should hold its shape when moulded but also easily crumbles when disturbed.
- Store the homemade Kinetic Sand: Once you achieve the desired texture, transfer your homemade kinetic sand to an airtight container or resealable bag to keep it fresh and prevent drying

INTERESTING FACTS

- The Magic of Sand Castles and Kinetic Sand
- When we think of sand, childhood memories of building sandcastles on the seashore often come to mind. These sandcastles retain their shape thanks to

the interaction between sand and water. The surface tension forces between the water molecules that coat the grains of sand hold the structure together. To achieve the ideal consistency for building, a balance of sand to water (typically 8:1) must be maintained. Too much water and the sand will flow; too little, and the structure will crumble. Many renowned sand sculptors, such as Dennis Massoud (the "Sandman"), Dan Blecher, and Sudarshan Patnaik of India, have elevated this simple concept into beautiful, intricate works of art.

- Beyond traditional sandcastles, there is another intriguing form of play sand known as hydrophobic sand.

SUMMARY

Kinetic sand is a popular sensory material that captivates with its unique properties. The key feature of kinetic sand is the hydrophobic coating applied to the fine sand particles, typically made from polydimethylsiloxane (PDMS), a silicone-based compound. This hydrophobic layer repels water, allowing the sand to remain dry, mouldable, and easy to shape. When manipulated, kinetic sand demonstrates non-Newtonian behaviour, transitioning between solid and liquid-like states depending on the forces applied. This transformation is a result of the internal cohesion and friction between particles, as well as external forces such as gravity. The viscoelastic properties of kinetic sand make it an engaging material for sensory play, educational purposes, and even stress relief. Understanding the physics behind kinetic sand enhances both its enjoyment and its potential applications in various fields.

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Figure 51: Sand sculptures

(Source: (a) https://deepai.org/ (b) MrsBrown on Pixabay)

12. PLAY-DOUGH

INTRODUCTION

Play-dough is a timeless material that has sparked creativity in children and adults alike for generations. Whether moulding intricate shapes, creating colourful sculptures, or simply enjoying its tactile texture, play-dough offers a unique sensory experience. But beyond its fun and versatility lies an intriguing science. In this chapter, we delve into the fascinating physics behind play-dough, exploring the forces, materials, and properties that make it such an enjoyable and engaging substance. From its viscoelasticity to its response to pressure and manipulation, understanding the physics of play-dough enhances both our appreciation and its creative possibilities.

PLAY-DOUGH

Play Dough was originally intended as a tool to clean coal residue from wallpaper. It was only later that its potential to be used as a modelling compound toy for children was discovered, and soon became popular.

Figure 52: Play Dough

(Source: (a) Bru-nO and (b) LMoonlight on Pixabay)

THE TOY

Play-Dough is characterized by its ability to change shape and flow, making it highly adaptable and responsive to external forces and conditions. At the heart of Play-Dough's properties are long, flexible polymer chains, typically made from polyvinyl acetate which is responsible for its malleability, elasticity, and soft matter nature. These chains are intertwined, creating a network that gives the material its structural integrity. This network structure gives Play-Dough its cohesiveness and allows it to maintain its shape when moulded.

Figure 53: Modelling Clay

(Source: Photograph by Author)

ENTANGLEMENT OF POLYMER CHAINS

Polymer Chain Entanglement in Play-Dough

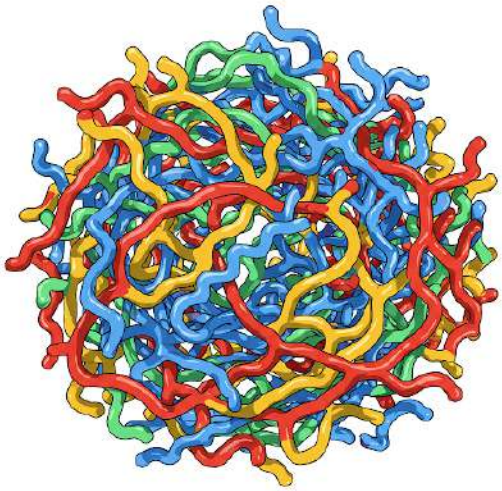


Figure 54: Polymer Entanglement

(Source: Gemini.ai)

Entanglement of polymer chains refers to the complex and intertwined arrangement of long polymer molecules within a material. This phenomenon is a fundamental characteristic of polymers and plays a crucial role in determining the material's properties.

While crosslinks are covalent bonds or physical connections that link different polymer chains or segments within the same chain, entanglement involves the physical overlapping or intertwining of polymer chains without forming covalent bonds.

In materials like Play-Dough, the long and flexible polymer chains become intertwined, creating a network of interactions that provide structural stability. This entanglement helps the material maintain its shape and integrity.

Additionally, the entanglement of polymer chains increases the viscosity of the material, making it more resistant to flow and deformation. Polymer chain entanglement is also sensitive to temperature changes, affecting the material's pliability and overall behaviour.

DIY VERSION

Materials needed:

- 1 cup Maida (all-purpose flour)
- 1 cup water
- 1/3 cup salt
- Food colouring (optional)

- 2 teaspoons lemon juice/vinegar/ cream of tartar
- 1 tablespoon vegetable oil

Note: The last two ingredients (lemon juice and oil) can be substituted with some hair conditioners. This needs to be tested to get the correct consistency.

Procedure:

- In a saucepan, mix together the flour, lemon juice/vinegar/cream of tartar, and salt.
- Add the water and vegetable oil to the saucepan and stir until the mixture is smooth.
- Cook the mixture over medium heat, stirring constantly, until it forms a ball of dough
- Remove the dough from the heat and let it cool for a few minutes.
- Knead the dough until it is smooth and pliable.
- Food colouring can be used to get colourful play doughs.

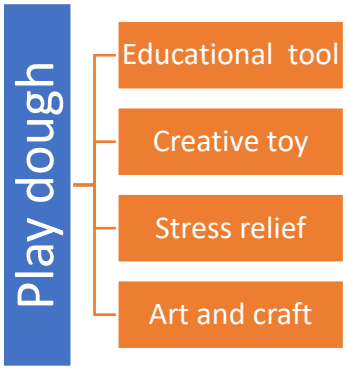


Figure 55: Applications of Play Dough

(Source: author)

INTERESTING INFORMATION

- Play-Dough, the first commercially available modelling material, was originally sold as a wallpaper cleaner in the 1930s. In the mid-1950s, it was reworked and marketed to schools as a modelling material for arts and crafts, quickly becoming a staple in classrooms.
- Commercial Play-Dough contains additional ingredients such as surfactants, hardeners, and water-absorbing materials to extend its shelf life. Petroleum-based additives are used to give it a smooth texture, while borax is often included to prevent mould growth, ensuring the material remains fresh and usable for longer periods.

SUMMARY

In this chapter, we explored the rheological behaviour of Play-Dough, using mathematical models like the Maxwell model to explain its viscoelastic nature. We

also discussed the molecular structures and interactions within the material and their impact on its overall behaviour. Beyond being a simple toy, Play-Dough serves as a valuable educational tool, offering a hands-on way to explore scientific concepts related to material properties.

2.5: Springy and Pliable Orbs

Both bouncing balls and squishy balls involve complex material physics, but they behave differently under force due to their distinct mechanisms of elasticity, deformation, and energy dissipation.

1. Bouncing Balls: Elasticity and Energy Transfer

A bouncing ball undergoes compression and restitution when it impacts a surface. The key factors influencing its behaviour are:

A. Elasticity and Deformation

- When a ball hits the ground, it compresses due to the applied force.
- The elastic properties of the material determine how much it deforms and how quickly it returns to its original shape.
- Highly elastic materials (such as rubber) return most of their energy, leading to a higher bounce.

B. Energy Transfer and Dissipation

- During impact, the ball's kinetic energy is converted into:
- Elastic potential energy (stored in the deformed material),
- Thermal energy (due to internal friction within the material),
- Sound energy (a small portion is lost as noise).
- If the material is highly efficient at energy recovery, the ball will bounce higher and last longer.
- Hard materials, like steel, have minimal internal energy loss, allowing them to bounce effectively, especially on hard surfaces.

C. Surface Interactions

- The nature of the surface affects the bounce behaviour:
- Hard surfaces (like concrete) return more energy, increasing bounce height.
- Soft surfaces (like carpet) absorb more energy, reducing the bounce.

D. Spin and Air Resistance

- Spin (Magnus effect) can cause the ball to curve in flight, a phenomenon observable in sports like tennis and soccer.
- Air resistance slows down the ball over time, impacting its rebound height.

2. Squishy Balls: Viscoelasticity and Damping

Squishy balls behave very differently due to their soft, deformable nature. Their physics is governed by viscoelasticity, which combines both elastic (spring-like) and viscous (fluid-like) behaviours.

A. Deformation and Recovery

- When squeezed, a squishy ball deforms significantly and takes time to return to its original shape.
- The rate of recovery depends on the material's viscoelastic properties.
- Memory foam-like balls recover slowly.
- Rubber-like materials snap back quickly.

B. Damping and Energy Absorption

- Unlike bouncing balls, squishy balls are designed to absorb energy, preventing them from bouncing much.
- Most of the impact energy is converted into internal friction and heat, reducing rebound height.
- This energy absorption makes squishy balls ideal for stress relief and impact cushioning.

C. Shear and Flow Effects

- Some squishy materials exhibit fluid-like behaviour under stress, showing shear-thinning or shear-thickening effects.
- Materials like silly putty or memory foam exhibit both solid-like and liquid-like properties, depending on how quickly they are deformed.

Table 8:Comparing Bouncing and Squishy Balls

Property	Bouncing Balls	Squishy Balls
Elasticity	High (fast recovery)	Low to moderate (slow recovery)
Energy Loss	Low (efficient energy return)	High (absorbs energy)
Bounce Height	High	Low
Damping	Low (bounces many times)	High (stays deformed longer)
Surface Effect	Sensitive to hard/soft surfaces	Less sensitive
Common Materials	Rubber, metal, plastic	Foam, gel, silicone
Main Applications	Sports, physics demos	Stress relief, cushioning

Conclusion

- Bouncing balls store and release energy efficiently, leading to repeated bounces.
- Squishy balls absorb impact energy, making them great for stress relief and protective applications.
- Both involve complex material physics, but their behaviours depend on elasticity, damping, and deformation properties.

13. DEFORMATION IN SQUISHY BALLS

INTRODUCTION

Squishy balls are soft, malleable toys available in a variety of colours, shapes, and sizes. Popular designs include animals, fruits, emojis, and glow-in-the-dark versions, with some filled with liquids or scented for added sensory appeal. Most are made from polyurethane foam—a polymer formed by combining isocyanates and polyols—which allows them to deform easily when squeezed and return to their original shape when released. The outer layer is typically made from thermoplastic rubber (TPR) or silicone, offering grip and texture.

Beyond their use as toys, squishy balls serve as effective models for studying soft matter behaviour, such as elasticity, viscoelasticity, and deformation. When compressed, they convert mechanical energy into heat, demonstrating energy dissipation. Their viscoelastic nature—a combination of elastic (spring-like) and viscous (fluid-like) responses—enables them to deform under pressure and slowly recover their original form.

These properties make squishy balls ideal for stress relief, providing a tactile experience that is both soothing and engaging. Additionally, they offer valuable insight into the physics of soft materials, illustrating how substances absorb energy, deform, and recover under varying conditions.

THE TOY

Diisocyanates are organic compounds containing two isocyanate groups (-NCO) and have been used since the late 1940s to produce polyurethane. One common type of polyurethane is made by reacting toluene diisocyanate (TDI) with polyols—alcohols containing multiple hydroxyl groups (-OH). This combination yields a soft, flexible material widely used in the production of squishy balls. Different polyurethane types

can be created through various synthesis methods, depending on the desired properties.

Polyurethane is defined by urethane linkages (-NHCOO-), formed through a reaction between isocyanate and hydroxyl groups, typically catalyzed to control the process. The elasticity of the final product depends on the specific reactants and their ratios. Polyurethane comes in two main forms: rubber and foam. The rubber form is highly elastic, while the foam form offers greater load-bearing capacity. Both are used in squishy ball manufacturing. Polyurethane is also viscoelastic, exhibiting both viscous (flow under stress) and elastic (return to original shape) behaviour. This dual nature is essential to the function of squishy balls, and their performance is carefully tuned by engineering the polymer chains to achieve the desired viscoelastic balance.
Elasticity:

Materials deform under stress, but once the stress is removed, they return to their original shape or size. When a squishy ball is squeezed, three primary forces act on it:

- **Elastic Force**:
  This is the restoring force that resists deformation and tries to return the ball to its original shape. It arises from the elastic properties of the polymer chains in the material.
- **Viscous Force**:
  This force resists the rate of deformation, causing energy dissipation as heat. It reflects the material's internal friction and is part of its viscoelastic behaviour.
- **External (Applied) Force**:
  This is the force exerted by the person or object squeezing the ball. It causes the initial deformation by compressing the material.

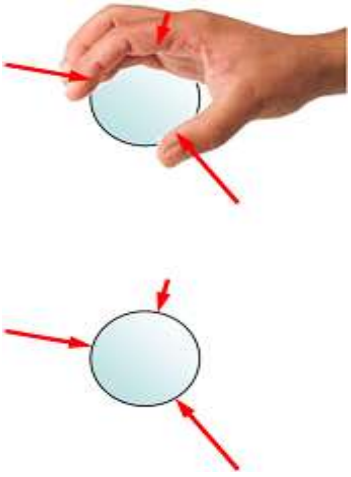


Figure 56: Forces exerted on the ball by the hand, while squishing it

(Source: Jayabharathi T)

These forces act on the long polyurethane polymer chains which are interconnected, and are highly elastic. When you squeeze a squishy ball, you apply an external mechanical force that compresses the material. This force displaces the polymer

chains within the foam or rubber structure, deforming the ball. While the ball is being compressed, the viscous force resists the speed of the deformation. It acts like a brake. This force absorbs energy, often converting some of it into heat through internal molecular friction. It prevents the ball from snapping back instantly—creating a slower, more gradual return that feels pleasant to the touch. Once the squeezing stops, the elastic force takes over, as the polymer chains that were stretched or compressed try to return to their original configuration. This restores the shape of the ball. The strength and speed of this response depend on the material's elasticity (how easily it stretches and snaps back).

- If viscous forces dominated, the ball would return too slowly—or stay deformed.
- If elastic forces dominated, the return would be instant, and the ball would feel stiff rather than squishy.
- The right balance—engineered into the polymer structure—allows the ball to deform under pressure (thanks to viscosity) and then gradually but reliably return to shape (thanks to elasticity).

This is why when we squeeze the squishy balls, they will deform and return to its original shape.

Different kinds of squishy balls:

There are different types of squishy balls such as

- Foam Squishy Balls that are soft and lightweight,
- Gel Squishy Balls that are filled with gels to provide a unique tactile experience.
- Spiky Squishy Balls have small spikes on the surface, which can provide a massaging effect when squeezed.
- Textured Squishy Balls have a textured surface, which can provide a tactile and sensory experience.
- Squeeze Balls are simple, round squishy balls that are designed to be squeezed and manipulate.

Figure 57: A stress-ball before and after being squished

(Source: Alexas_fotos on Pixabay)

DIY VERSION

This version makes a soft, squishable stress ball using a gel-like filling.

Materials Needed:

- Balloon (thick latex, preferably large size)
- Flour, cornstarch, or hair gel (for filling)
- Water (if using flour or cornstarch)
- Small plastic bottle (for easy filling)
- Funnel (optional)

Procedure:

- If using flour or cornstarch, mix 1 part water to 2 parts powder to create a thick, mouldable paste.
- If using hair gel, no mixing is needed—just use it as is.
- Fill the Balloon: Stretch the balloon by inflating it slightly and then deflating it.
- Cut the top off a plastic bottle to use as a funnel.
- Pour the filling into the bottle, then stretch the balloon over the bottle opening.
- Gently squeeze the bottle to transfer the filling into the balloon.
- Seal the Balloon: Carefully remove the balloon from the bottle and tie a tight knot.
- If you want extra durability, double-layer it by placing the filled balloon inside another balloon before tying it shut.
- Test It Out: Squeeze and squish your DIY stress ball! Store in a cool place to prevent leaks.

Why It Works: The gel or paste inside resists compression, making it behave like a viscoelastic material. The balloon provides a flexible outer shell, keeping the filling contained while allowing deformation.

INTERESTING FACTS

- Squishy balls are also called hand exercise balls or stress balls. It is believed that their use can help destress, strengthen the hand muscles and relieve anxiety.
- Present day squishy balls are made from many materials such as high-density foam, soft rubber, and soft-polyurethane.
- Some squishy balls are filled with gels, to increase the tactile experience and make the balls even more squishy.

SUMMARY

In conclusion, squishy balls are excellent examples of soft matter toys, showcasing the viscoelastic properties that define this material category. Their unique characteristics not only make them popular but also serve as an engaging way for students and kids to explore soft matter physics. The next time you encounter a squishy ball, you'll be able to appreciate the fascinating physics behind its behaviour.

14.RUBBER BALL

INTRODUCTION

Rubber balls are ubiquitous in our daily lives, from children's toys to industrial applications. Their unique mechanical properties make them ideal for various purposes. Understanding the physics behind rubber ball behaviour is not only fascinating but also has practical implications, such as optimizing their performance in sports or designing shock absorbers. This article explores the soft matter physics of rubber balls.

Soft matter consists of materials that exhibit properties of both solids and liquids, often displaying complex behaviour. Rubber balls fit this description, as they can deform under stress and return to their original shape once the stress is removed. To fully understand the mechanics of rubber balls, we must examine their elasticity, viscoelasticity, and non-Newtonian properties.

Rubber is an essential material in today's world, playing a crucial role in numerous technologies. It is hard to imagine modern society without it. The history of rubber is equally fascinating, with varying accounts of its discovery depending on the source.

One story about the discovery of rubber tells of a Mayan woman walking through the rainforest, gathering edibles, when she came across a "crying" tree. She collected some of the substance, bringing it back to her tribe's chief, who found it to be unique. Another version suggests that Christopher Columbus discovered rubber after visiting Haiti in the 1490s, where he observed the natives playing with a bouncy ball made from the material. A different account credits a French astronomer in 1736, who was sent to Peru by his government and returned with samples of a white fluid that had the consistency of honey. While these stories are intriguing, the most widely accepted account of rubber as we know it today centres around Charles Goodyear from Trenton, NJ.

Although many people associate Goodyear with the Goodyear Tire Company, he did not establish the company. It was named after him posthumously, after his death. Goodyear's claim to fame lies in his development of vulcanized rubber, a process that revolutionized the material and its applications. Rubber is now used in a wide range of products, from automobile tires to super-absorbent materials in diapers. Its versatility is evident in its ability to meet the demanding mechanical needs of tires, as well as in applications such as soft contact lenses, which benefit from rubber's optical and diffusive properties.

When it comes to rubber toys like rubber balls, their bouncing ability is one of the key features that make them playful. This bouncing effect is a direct result of their elastic properties, which stem from their polymeric composition. The origin of elasticity in these macromolecular materials will be explored in greater detail in the following sections.

Figure 58: Latex from rubber tree

(Source: sibenphoto on pixabay)

THE TOY

Figure 59: Rubber Balls

(Source: meta.ai)

Composition:

Natural rubber is derived from latex, a milky white liquid that oozes from certain trees when their bark is cut. The main component of natural rubber is the polymer isoprene. However, raw latex alone is not suitable for most applications. It is too soft, prone to Odors, and lacks the strength needed for everyday use. To make it more functional, natural rubber undergoes a process called vulcanization. During vulcanization, sulphur is added to form cross-links between the rubber molecules. This process strengthens the rubber, making it more durable and elastic.

On the other hand, synthetic rubber is created in chemical plants or laboratories, with petrochemicals as the primary raw material. One of the most commonly used synthetic rubbers is neoprene (polychloroprene), which is known for its resilience and versatility.

Most rubber products, including rubber balls, are made from either vulcanized natural rubber or synthetic rubber, each chosen based on its specific properties and the intended use. The vulcanization process plays a crucial role in transforming raw rubber into a stronger, more useful material.

How do rubber balls bounce:

Bouncing requires an object to exhibit elasticity – it must return to its original shape shortly after deformation. To achieve this, the object must undergo a sequence of events as follows:

Initial Contact and Kinetic Energy: The object, while falling or moving, possesses kinetic energy as it touches the surface.

Deformation and Energy Transformation: Upon impact, the object deforms. Instead of shattering, breaking, or catching fire, the object's kinetic energy is transformed into elastic potential energy. The material temporarily stores this energy while it is deformed.

Minimized Energy Loss: In an ideal situation, no significant energy is lost during this deformation phase. The potential energy should not be dissipated as heat, vibration, or sound, so the energy remains available to be released.

Restoration and Kinetic Energy Recovery: The stored elastic potential energy is then converted back into kinetic energy as the object "un-deforms" and accelerates in the opposite direction, pushing it back upward.

To summarize, an object will bounce if it can deform elastically (not plastically or viscously) and if the majority of the elastic potential energy is recovered and transformed into kinetic energy.

Let's consider three different objects – a rubber ball, a plasticine ball, and a book – to understand how they behave under free fall:

- **Rubber Ball**: Rubber is highly elastic, so when the ball hits the ground, it deforms and stores elastic potential energy. This energy is then released efficiently, causing the ball to bounce back. Rubber's low energy loss allows it to recover most of the kinetic energy, resulting in a high bounce.

- **Plasticine Ball**: Plasticine is a non-elastic material that undergoes plastic deformation. When it hits the surface, it deforms, but because plasticine doesn't return to its original shape (it is more viscous than elastic), it doesn't efficiently recover the potential energy. As a result, it doesn't bounce much and stays deformed after impact.

- **Book**: A book, being rigid and heavy, does not have elastic properties like a rubber ball. When dropped, it may experience some deformation at the point of contact (e.g., slight bending), but the deformation is mostly irreversible. It does not store elastic potential energy that can be recovered, so it simply hits the ground and remains at rest, showing little to no bouncing behaviour.

In conclusion, only materials with significant elasticity, like rubber, can efficiently bounce, whereas materials with plastic or viscous properties, like plasticine and a book, do not exhibit bouncing behaviour. Consider dropping a rubber ball, plasticine ball and a book from nearly the same height.

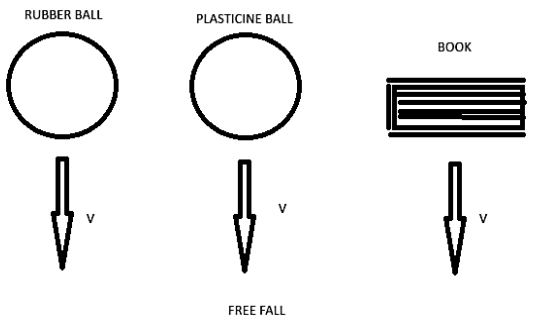


Figure 60: Dropping a rubber ball, plasticine ball and a book.

Gravity acts downwards and leads to free fall. (Source: Sathiya)

Well, any of them can pass the first step since they have got the required speed. Now they will fall to the ground.

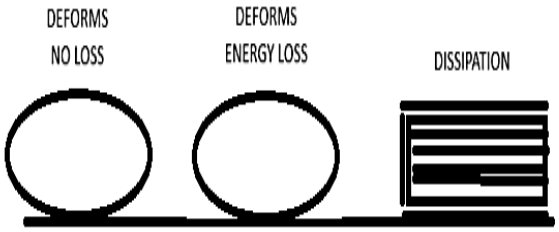


Figure 61: deformation of the three bodies when they hit the ground

(Source: Sathiya)

Now, let's analyse the balls' behaviour after they pass the second step (deformation). They all deform to varying degrees, but not all of them meet the necessary conditions for bouncing.

The Book: The book primarily fails to bounce because its shape and material properties Favor other modes of energy propagation, specifically vibration. When the book hits the surface, most of its kinetic energy is dissipated through internal vibrations and friction within its rigid structure. This energy doesn't get stored as elastic potential energy, so the book doesn't bounce back. Instead, it just remains at rest.

The Plasticine Ball: The plasticine ball also fails to bounce because it does not possess elastic properties. When deformed, the energy absorbed by the plasticine ball is not stored as elastic potential energy. Instead, it is converted into thermal energy (heat) due to the material's viscous nature. This energy dissipation through heat further prevents the ball from returning to its original shape, and as a result, it doesn't bounce. The ball simply stays deformed.

Thus, the book and the plasticine ball are unable to bounce effectively because of their material properties—vibration dissipation in the book and heat dissipation in the plasticine ball. These materials fail to store and recover the energy needed for an efficient bounce, unlike elastic materials such as rubber that can store and return energy in a way that allows them to bounce.

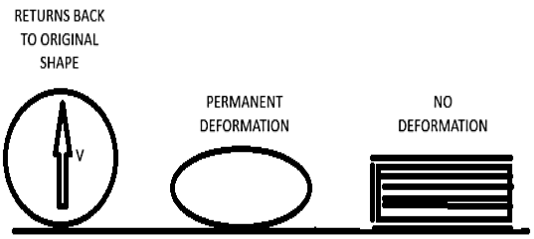


Figure 62: The three bodies regaining their shape (or not!)

(Source: Sathiya)

So, of the three objects, only the rubber ball has the ability to bounce because of its elastic properties.

DIY VERSION

This method creates a rubber-like, bouncy ball using common household ingredients.

Materials Needed:

- Borax powder (a slime activator, found in laundry detergent sections)
- Warm water
- White school glue (PVA glue)
- Cornstarch (for elasticity and durability)
- Food colouring (optional, for fun colours)

Procedure:

- Mix 1 tablespoon of Borax powder with ½ cup of warm water until dissolved.
- Mix Glue and Cornstarch:
- In a separate cup, combine 1 tablespoon of white glue with ½ teaspoon of cornstarch.
- Add a few drops of food colouring if desired.
- Pour the glue-cornstarch mixture into the Borax solution.
- Stir quickly with a spoon—it will start to clump together.
- Once the mixture becomes solid, remove it and knead it with your hands.
- Roll it into a smooth sphere.
- Let the ball dry for about 5 minutes, then test its bounce!
- Store in an airtight container to prevent drying.

Why It Works:

Borax links the glue molecules, making the structure rubberier and elastic. Cornstarch provides strength and flexibility, preventing the ball from breaking apart.

INTERESTING FACTS

- The earliest known instances of rubber balls are from meso-America. They were probably used as funeral offering.

- The name Olmec given to the earliest known meso-Americans means rubber people or people of the rubber country, because they would mix the extract of latex from Panama rubber tree with juice from a local vine to make rubber. [https://blog.sciencemuseum.org.uk/wonderful-things-peruvian-rubber-ball/; https://www.britannica.com/topic/Olmec]

- Rubber was called rubber by the Englishman Joseph Priestly when he noticed that this material could erase pencil marks.

[https://blog.sciencemuseum.org.uk/wonderful-things-peruvian-rubber-ball/]

- Pierre-Gilles de Gennes, considered to be the father of soft matter, in his Nobel lecture in 1992, discusses the rubber boots of the Indians of the Amazon basin, as an introduction to the subject. https://doi.org/10.1002/anie.199208421

SUMMARY

This exploration provides a detailed analysis of the physics behind rubber balls, focusing on the principles that enable them to bounce. It examines the composition of rubber—both natural and synthetic—and explains how vulcanization enhances its elasticity by strengthening the material. The bouncing ability of rubber balls is rooted in their inherent elasticity, which arises from their polymeric structure. Long, flexible polymer chains and cross-linking play a critical role in determining rubber's elastic behaviour. The discussion also explores the thermodynamic basis of rubber elasticity, particularly the role of entropy. When rubber is stretched, its polymer chains become more ordered, reducing entropy. Upon release, the system returns to a higher-entropy state, driving the material's retraction. In summary, this analysis links the unique properties of rubber balls to fundamental principles in materials science, demonstrating how molecular structure and thermodynamics govern their elasticity.

2.6: Elastomers

Elastomers are a group of materials made from polymers that are known for being very stretchy. They can stretch a lot and still return to their original shape. These materials are important in everyday products like rubber tires and medical tools.

Molecular Structure and Elasticity

Elastomers are made of long chains of molecules that are only slightly connected to each other. This loose structure lets them stretch and bounce back when the force is removed.

A. Amorphous Polymer Chains
At room temperature, elastomers have chains that are tangled and randomly arranged. This disorganized structure is what makes them soft and flexible, unlike other plastics that are more rigid.

B. Cross-Linking and Elastic Recovery
The chains in elastomers are connected at a few points through a process called cross-linking, often done by adding sulfur (a process known as vulcanization). These connections help the material hold its shape and make it stronger and more elastic after being stretched.

Mechanical Behaviour of Elastomers

Elastomers behave differently from metals or hard plastics. They act partly like stretchy solids and partly like thick liquids, depending on how they are used.

A. Large Strain Capability
Elastomers can stretch a lot—sometimes up to 700% of their original length—without breaking. This stretching mainly happens because the tangled chains straighten out. When the force is removed, the chains coil back, and the material returns to its original shape.

B. Hysteresis and Energy Dissipation
When elastomers are stretched and then released, some of the energy is lost as heat. This is called hysteresis and is useful in things like shock absorbers, where energy needs to be absorbed and not returned.

C. Strain-Induced Crystallization
In some cases, when elastomers are stretched a lot, their chains become more ordered and form temporary crystals. This makes the material stiffer and stronger for a short time. Natural rubber is especially known for this behaviour.

Viscoelasticity and Time-Dependent Behaviour

Elastomers don't just respond to how much force is applied—they also respond to how long it's applied. Their behaviour can change over time under the same conditions.

A. Creep and Stress Relaxation
If you pull on an elastomer and hold it, it will slowly keep stretching—this is called creep. If you stretch it to a certain point and hold it there, the force needed to keep it stretched slowly decreases—this is called stress relaxation. Both happen because the chains inside are constantly adjusting.

B. Dynamic Mechanical Properties
Elastomers behave differently when stretched quickly compared to slowly. If you stretch them quickly, they feel stiffer. If you stretch them slowly, they stay soft and flexible.

Thermal and Environmental Effects

The performance of elastomers changes with temperature and environmental conditions.

A. Glass Transition Temperature (Tg)
Elastomers become stiff and brittle when cooled below a certain temperature (called the glass transition temperature). Above this temperature, they are soft and stretchy. This makes them useful across different temperature ranges.

B. Heat Resistance and Degradation
High temperatures can damage elastomers, making them weaker. However, some types, like silicone rubber, can handle heat better and stay elastic even at high temperatures.

C. Chemical and UV Resistance
Natural rubber can crack when exposed to sunlight or ozone. Synthetic elastomers like EPDM and silicone are designed to resist chemicals and UV light, making them better for outdoor or harsh environments.

5. Types of Elastomers

Type	Key Properties	Applications
Natural Rubber (NR)	High strength, stretchability, but poor weather resistance	Tires, gloves, seals
Styrene-Butadiene Rubber (SBR)	Good abrasion resistance, widely used	Tires, footwear
Silicone Rubber	High thermal stability, biocompatible	Medical implants, kitchenware
EPDM (Ethylene Propylene Diene Monomer)	Excellent weather and ozone resistance	Roofing, automotive seals
Neoprene (CR)	Oil and chemical resistance	Wetsuits, industrial gaskets
Polyurethane (PU) Elastomers	High toughness, abrasion resistance	Skate wheels, conveyor belts

6. Engineering Applications and Considerations

- Elastomers are used in dynamic environments where flexibility, damping, and resilience are required. Some critical applications include:
- **Tyres**: Elastomers are essential in tires due to their high elasticity and wear resistance, which ensure durability, grip, and effective shock absorption. Rubber compounds used in tires are specifically designed to balance elasticity for traction and resilience for long-term performance.
- **Seals & Gaskets**: Elastomers, such as EPDM (ethylene propylene diene monomer) and Nitrile rubber, are commonly used in seals and gaskets. Their ability to maintain an airtight and watertight seal under compression makes them crucial for applications in automotive, aerospace, and industrial machinery, where preventing leaks is vital for performance and safety.
- **Medical Devices**: Silicone rubber and other biocompatible elastomers are widely used in the medical field for implants, catheters, tubing, and seals. Their flexibility, biocompatibility, and chemical resistance ensure that medical devices are safe for long-term use inside the human body, while maintaining high performance and reliability in demanding environments.
- **Shock Absorption**: Elastomers are commonly found in vibration isolators, shock mounts, and protective gear due to their damping properties. They efficiently absorb and dissipate energy, reducing impact forces in applications like automotive suspensions, industrial machinery, and sports equipment, providing protection and comfort.
- **Soft Robotics**: Advances in elastomeric materials have enabled significant progress in soft robotics. These materials, such as silicone-based elastomers, are used to create stretchable electronics and flexible actuators, allowing for more adaptable and lightweight robotic designs that can mimic human-like motions and conform to complex environments.

15. STICKY HAND TOY

INTRODUCTION

Sticky hand toys have fascinated generations of people. These fun, stretchy toys are not just a source of entertainment but also offer stress relief and can enhance concentration and creativity. Typically, long and thin, sticky hand toys resemble a flattened hand or tentacle and come in various colours, often with a translucent or opaque appearance. When stretched or squished, translucent versions create interesting visual effects.

The toys are designed to stick to surfaces, adhering and releasing with ease. But what enables this? How do they stretch to incredible lengths without tearing, and how can they be retrieved from surfaces so easily?

To answer these questions, we need to explore the principle of adhesion. This principle explains how intermolecular forces and surface properties allow these toys to stick to various objects. Sticky hand toys showcase a fascinating balance of attraction and repulsion at the molecular level. Their composition, which includes elastomeric materials with both elasticity and viscosity, allows them to stretch and deform without breaking.

Beyond their playful nature, sticky hand toys offer a window into soft matter physics and material science. In the following sections, we'll delve deeper into the scientific principles that explain the behaviour of these toys, revealing insights that could inspire new materials and technologies.

THE TOY

Sticky hand toys are made from an amorphous polymer that becomes softer and stickier when heated.

- Elasticity: The toy is made of an elastic material, typically a polymer like rubber or silicone. When stretched, potential energy is stored in the material.
- Potential Energy: Stretching the toy requires work, increasing its potential energy. This energy is stored in the stretched molecular bonds within the material.
- Snap-back Action: When the toy is released, the stored potential energy quickly converts into kinetic energy. The elastic material contracts rapidly to its original shape, propelling the toy forward.
- Adhesion: The sticky surface of the toy allows it to adhere to smooth surfaces. This adhesion occurs due to intermolecular forces between the toy's surface and the contacted surface.
- Surface Interaction: The stickiness is the result of forces like van der Waals forces or other adhesive interactions, allowing the toy to grab onto surfaces and be pulled back when thrown.
- Momentum Transfer: When thrown, the toy gains momentum. Upon hitting a surface, it transfers some of this momentum, which helps it stick to the surface.
- Energy Dissipation: Some energy is lost during contact with the surface, due to factors like air resistance and the toy's viscoelastic properties.
- Sticky hand toys combine elasticity, viscosity, adhesion, and surface tension, making them both fun and scientifically fascinating objects.

Figure 63: Sticky-hand toys

(Source: Snigdha C Udayakumar)

Material Properties:
Sticky hand toys are made from elastomers, a type of synthetic polymer. Elastomers consist of long, cross-linked chains of atoms, primarily carbon, hydrogen, and oxygen. The cross-linking between neighbouring chains enables the elastomer to return to its original shape once the deforming force is removed.

DIY VERSION

DIY Sticky Hand Toy (Gelatin + Corn Syrup Method)

Materials Needed:

- 1 packet unflavoured gelatine
- ¼ cup corn syrup (like Karo syrup)
- 2 tablespoons water

- Food colouring (optional)
- Mixing bowl
- Spoon
- Microwave-safe container
- Plastic wrap or wax paper
- Scissors (to shape the hand)

Procedure:

- In a bowl, mix the gelatine, corn syrup, and water. Stir well.
- Microwave the mixture for about 10–20 seconds to dissolve the gelatine (don't overheat). Stir again until smooth.
- Add a few drops of food colouring if you want your sticky hand to be colourful.
- Pour the thick, goopy mixture onto plastic wrap or wax paper. Let it cool slightly, then use your fingers to shape it roughly like a small hand with a long stretchy arm (or pour into a hand-shaped cookie cutter if you have one).
- Let the shaped "hand" cool and dry for a few hours until it becomes firm but still sticky and flexible.
- Once set, peel it off the surface and trim with scissors if needed. Your sticky hand is ready to slap walls!

Notes:

- Store it in a plastic bag when not in use to preserve the stickiness.
- Avoid using it on fabric or dusty surfaces — it will pick up lint and lose stickiness quickly.

Caution:
This toy is not suitable for small children who may try to eat it. Also, it may leave smudges or oil marks on walls depending on the surface.

INTERESTING FACTS

- Sticky hand toys were first invented by Ken Hakuta in the 1970s and were marketed under the name *Wacky Wall Walker*. [https://en.wikipedia.org/wiki/Ken_Hakuta]

- In the year 2007. a sticky adhesive from over 2000 years ago was discovered. It was still effective in holding things together, and scientists have not yet been able to recreate this material in lab. [https://timesofindia.indiatimes.com/home/science/romans-glue-sticky-after-2000-yrs/articleshow/2653513.cms]

SUMMARY

The behaviour of sticky hand toys is governed by a combination of scientific principles, including adhesion, viscoelasticity, intermolecular forces, and friction. This research delves into the material properties that make these toys unique, such

as their elasticity, viscosity, and malleability. The study highlights the role of intermolecular forces and the surface area of contact in the adhesive qualities of sticky hand toys. Additionally, it covers the mechanisms involved in retrieving the toy from a surface, emphasizing the relationship between friction, adhesion, and retrieval force.

Although sticky hand toys may seem simple, their wide range of uses—from entertainment and stress relief to educational and decorative purposes—demonstrates their enduring appeal. Beyond their entertainment value, these toys offer a practical entry point to teach fundamental concepts in soft matter physics and material science. By understanding the principles governing their behaviour, we gain valuable insights into soft matter physics, paving the way for advancements in adhesive technologies and the development of eco-friendly materials.

16. POP AND REPEAT: THE ELASTICITY OF POP-IT TOYS

INTRODUCTION

Pop-It fidget toys are a popular and entertaining type of sensory toy that resemble reusable bubble wrap, typically made from silicone, a versatile polymer material. These toys are designed with bubbles that can be pressed or "popped," creating a satisfying sound and tactile sensation. The simple concept of pushing the bubbles and flipping the toy over to start again has made Pop It toys widely loved, especially by children. The primary material used in manufacturing these toys is Poly-Dimethyl Siloxane (PDMS), a type of silicone.

THE TOY

Pop It toys are predominantly made from food-grade silicone, ensuring they are safe for children, who often place objects in their mouths. Silicone is a polymer composed of siloxane groups (Si-O), which consist of silicon atoms bonded with oxygen atoms and other elements like carbon and hydrogen. Silicone materials, such as Dimethyl Siloxane and its polymeric form Poly-Dimethyl Siloxane (PDMS), are widely used in various applications due to their rubber-like properties, durability, and flexibility. These compounds are colourless, odourless, and have the right combination of elasticity and resilience to make them perfect for creating toys that can withstand repeated use.

Figure 64: Pop It Fidget toy

(Source: Freepik.com)

Preparation of Silicones:

Silicones are synthetic polymers made primarily from pure silicon, which is derived from the reduction of silicon dioxide (SiO_2), commonly found in sand. This process involves heating sand with carbon at high temperatures to extract pure silicon. The general process of synthesizing silicones occurs in three main stages:

Synthesis of Chlorosilanes: The first step involves reacting pure silicon with methyl chloride (CH_3Cl) to form Dimethyl-dichlorosilane (CH_3SiCl_2), using a copper catalyst.

Hydrolysis of Chlorosilanes: Next, the Dimethyl-dichlorosilane reacts with water, replacing chlorine atoms with hydroxyl groups (OH), resulting in the formation of silanol (Si-OH).

Polymerization Condensation: In this final step, the silanol groups undergo a polymerization condensation process where the silanol molecules combine, linking together to form Poly-Dimethyl Siloxane (PDMS), a long-chain polymer. This process creates a structure in which each monomer unit is connected by Si-O-Si bonds, which are responsible for the unique properties of silicone.

Composition and Structure of Silicone:

Silicones, unlike many other industrial polymers, have a backbone structure that does not contain carbon atoms. This makes silicone a unique polymer, despite

containing organic functional groups such as methyl groups (-CH_3) attached to each silicon atom. The primary backbone of the polymer consists only of silicon (Si) and oxygen (O) atoms, forming a repeating structure of ⋯-Si-O-Si-O-Si-O-Si-⋯

The dimethyl groups (-CH_3) are attached to each silicon atom, giving silicone its rubber-like qualities. This Si-O backbone imparts thermal stability, chemical resistance, and flexibility to the polymer, making it an ideal material for a variety of applications, including the manufacture of Pop It toys. The combination of these properties makes Poly-Dimethyl Siloxane (PDMS) highly durable, flexible, and safe for various consumer products.

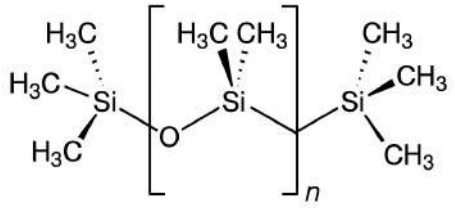


Figure 65: Structure of PDMS

(Source: Author)

Properties of Poly-Dimethyl Siloxane (PDMS)

Viscoelasticity:

Poly-Dimethyl Siloxane (PDMS) exhibits viscoelasticity, which is a combination of viscosity and elasticity. This means that PDMS behaves differently depending on the temperature and the applied stress.

Viscosity: At high temperatures, PDMS behaves more like a viscous liquid. It flows and deforms under stress, which is characteristic of materials with high viscosity. The material's flexibility and mobility are attributed to the Si-O bonds in the polymer backbone and the methyl (-CH_3) groups attached to the silicon atoms. These methyl groups provide the material with increased flexibility, allowing the polymer chains to slide past each other. This contributes to PDMS's viscous behaviour.

Elasticity: At lower temperatures, PDMS behaves like an elastic solid, similar to rubber. This is because, at lower temperatures, the polymer chains are more rigid and less able to move past one another, leading the material to exhibit a rubber-like elasticity. The flexibility of the Si-O bonds contributes to this elastic behaviour.

PDMS is a semi-crystalline thermoplastic, meaning it can soften when heated and solidify when cooled, allowing it to be moulded and shaped. This makes it versatile in manufacturing processes.

Moduli of Viscoelastic Materials:

In viscoelastic materials like PDMS, two important moduli are used to describe their mechanical behaviour:

Storage Modulus (E'): This represents the elastic portion of the material, or the energy that is stored in the material during deformation. The storage modulus measures the material's ability to recover its original shape when the applied stress is removed, similar to a spring. Materials with a high storage modulus are stiff and resistant to deformation.

Loss Modulus (E''): This represents the viscous portion of the material, or the energy dissipated as heat during deformation. The loss modulus measures how much energy is lost during the deformation process. Materials with a high loss modulus behave like fluids and dissipate energy as heat.

The storage and loss moduli are fundamental in describing the time-dependent behaviour of viscoelastic materials. The ratio of these moduli indicates whether the material behaves more elastically (when the storage modulus is greater) or more viscously (when the loss modulus is greater).

Repeated Popping: The hysteresis and elastic recovery ensure that the toy can return to its original state after being deformed, enabling it to make the popping sound repeatedly.

Non-Toxicity and Chemical Reactivity

Pop It toys are made of food-grade silicone, which is known for its non-toxicity and chemical inertness. Key properties contributing to these characteristics include:

Chemical Inertness: Silicone does not readily react with most chemicals. Unlike some materials, silicones do not contain highly reactive functional groups, such as hydroxyl or amino groups, which tend to interact with other chemicals. This makes it safe for direct contact with food or skin.

Hydrophobicity: Silicone is a hydrophobic material, meaning it repels water. The methyl groups ($-CH_3$) attached to the silicon-oxygen backbone are non-polar, which prevents attraction to water molecules. Instead of water spreading over the surface, it forms beads and runs off, further enhancing the material’s water resistance.

Low Surface Energy: Due to its low surface energy, silicone does not allow substances like water or oils to spread across it, contributing to its durability and ease of cleaning.

Non-Reactive Molecular Structure: Silicone's non-reactive molecular structure ensures that it does not break down easily over time, giving it a long lifespan. The toy maintains its safety and functionality without undergoing degradation or releasing harmful substances.

The stress-strain behaviour and chemical properties of PDMS make it an excellent material for Pop It toys. Its hysteresis ensures that the toy can be used repeatedly, creating the popping sound each time without significant wear or permanent deformation. Additionally, the non-toxic, hydrophobic, and chemically inert nature of food-grade silicone makes the toy safe for use, especially by children, contributing to its popularity as a safe and durable fidget toy.

DIY VERSION

Method 1: DIY Pop-It Using a Silicone Mould & Glue (Durable & Closest to Store-Bought)

This method gives you a soft, flexible, and reusable pop-it similar to commercial ones.

Materials Needed:

- Hot glue sticks (clear or coloured) OR Liquid silicone rubber
- A silicone mould with bubble-shaped cavities (ice cube trays work well)
- Cooking spray or petroleum jelly (for easy release)
- A flat backing (thin plastic sheet, cardstock, or more glue)

Procedure:

- Spray the silicone mould with cooking spray or rub a little petroleum jelly inside each cavity to prevent sticking.
- *Fill with Hot Glue or Silicone*: Heat the hot glue gun and carefully fill each bubble cavity with a thick layer of glue.
- If using liquid silicone rubber, mix it according to the instructions and pour it into the mould.
- Once the glue/silicone starts to cool, add a thin layer of glue on the back to hold everything together.
- You can also press a thin plastic sheet onto the glue while it is warm for a smooth surface.
- *Let It Set and Remove*: Allow the hot glue to fully cool and harden (about 30 minutes). Gently peel the pop-it out of the mould.
- *Test the Pop*: Press each bubble to see if it makes the signature popping sound! If it is too stiff, try using thinner layers of glue.

Pros:

- Durable and reusable
- Similar to store-bought pop-its
- Customizable with colours and shapes

Cons:

- Hot glue can be tricky to work with
- Needs a proper mould for best results

Method 2: DIY Pop-It with Balloons & Cardboard (Easiest & Softest)

This is a simple method using balloons to create soft, bubble-like textures.

Materials Needed:

- Balloons (multiple colours for fun effects)
- Cardboard or a plastic lid (to hold the bubbles)
- Scissors and tape/glue
- Bottle caps or round shapes (to help shape bubbles)

Procedure:

- Cut the Cardboard Base:
- Cut a square or circle from sturdy cardboard or plastic to serve as the pop-it backing.
- Use a bottle cap or a similar round object to trace circles onto the cardboard.
- Cut out the circles, leaving small openings.
- Attach the Balloons:
- Cut a balloon in half and stretch it over each hole to create a tight, flexible surface.
- Tape or glue the balloon edges to the back of the cardboard.
- Test the Pop!
- Push on the balloon sections and feel them pop back.
- You can create multiple rows for a multi-bubble effect.

Pros:

- Super easy and quick to make
- Uses recyclable materials
- Soft and safe for kids

Cons:

- Not as durable as silicone pop-its
- May tear over time

Method 3: **DIY Pop-It Using Foam Sheets (Lightweight & Colourful)**

This version uses craft foam for a colourful and flexible design.

Materials Needed:

- Craft foam sheets (various colours)
- Scissors and a hole punch
- Hot glue or strong double-sided tape
- A small round object (to shape the bubbles)

Procedure:

- Cut the Base Shape: Cut a square or circular foam sheet for the backing.
- Make the Pop Bubbles: Cut small circles from thinner foam and slightly stretch them over a round object (like a bottle cap).
- Attach the Bubbles: Glue or tape the edges of each bubble to the backing so they can flex inward and pop back out.
- Test & decorate! Push each bubble and enjoy the effect!
- Decorate with stickers or markers for a fun look.

Pros:

- Colourful and lightweight
- Safe for younger kids
- Customizable with shapes and patterns

Cons:

- Foam is less flexible than silicone
- Doesn't make a loud pop

Table 9: Which DIY Pop-It Should You Try?

DIY Pop-It Type	Difficulty	Durability	Popping Sound	Materials Needed
Hot Glue/Silicone Pop-It	Moderate	High	Best	Hot glue gun, silicone mould
Balloon & Cardboard Pop-It	Easy	Medium	Good	Balloons, cardboard
Foam Sheet Pop-It	Very Easy	Low	Soft Pop	Craft foam, glue

INTERESTING FACTS

- Pop-it toys are the indestructible versions of bubble wraps.
- One of the creators of the pop it toys, Theo Coster was a classmate of Anne Frank who documented her hiding under the Nazi persecution in her The Dairy of a Young Girl. He got the inspiration for the toy from a dream about his sister who died of breast cancer. [https://www.bbc.com/news/business-58408570]
- Theo Coster and Ora Coster designed and created more than 150 toys and games through their company, Theora Design.
- This toy became popular when a video on TikTok of a capuchin monkey playing with it became viral. [https://www.bbc.com/news/business-58408570]

- There are reports of children using pop it toys to stay calm during remote lesson during the COVID-19 pandemic period. [https://www.nytimes.com/2021/09/22/parenting/pop-it-fidget-toys.html]

SUMMARY

The Pop It fidget toy is made from Poly-Dimethyl Siloxane (PDMS), a polymer known for its exceptional mechanical and structural properties. PDMS is a viscoelastic polymer, which is key to the toy's behaviour and function. PDMS exhibits both elastic and viscous properties. The silicon-oxygen (*Si-O*) bonds in PDMS are quite flexible, allowing the polymer chains to move and realign with ease. The methyl group (*-CH_3*) attached to each silicon atom increases flexibility and mobility within the material, enhancing its viscoelastic nature.

At room temperature, PDMS primarily behaves elastically, which is why the toy makes a popping sound when the bubbles are pressed. The stress-strain curve for PDMS shows hysteresis, meaning the loading (stretching) and unloading (relaxing) processes do not perfectly coincide. The material slowly recovers its original shape after deformation, ensuring the toy can be pressed repeatedly to produce the popping sound.

PDMS can withstand a wide range of temperatures without permanently deforming. This temperature stability ensures that the Pop It toy retains its shape and resilience under various environmental conditions, making it durable over time.

The Pop It toy is made from food-grade PDMS silicone, a chemically inert polymer. This means that PDMS does not react with most chemicals, making it non-toxic and safe for children. Its hydrophobic nature also ensures that it is easy to clean and maintain, as it repels water and other liquids. In summary, the viscoelastic properties of PDMS are what give the Pop It fidget toy its characteristic popping sound and repeated resilience. The temperature stability and non-toxic, inert nature of PDMS make it an ideal material for toys that are both fun and safe for repeated use. This polymer, therefore, can be used in a variety of toy applications, combining both entertainment and educational value.

2.7: MAGNETIC FLUIDS

"Ferrofluids turn the invisible force of magnetism into a visible, dynamic phenomenon, offering a window into the interaction between soft matter and external fields."
– *Mark J. Bowick*, Professor of Physics

Magnetic fluids, commonly seen in toys like ferrofluid displays, magnetic putty, and interactive slime, are fascinating materials that respond dynamically to external magnetic fields. Their ability to form various patterns and controlled movements makes them both entertaining and educational. Magnetic fluids are colloidal suspensions of magnetic nanoparticles suspended in a liquid carrier. They exhibit liquid-like flow but can be manipulated by magnets, resulting in spikes, patterns, and other dynamic behaviours.

Types of Magnetic Fluids Used in Toys:

- *Ferrofluids*: Suspensions of nanoscale iron-based particles in oil, stabilized with surfactants.
- *Magnetic Putty & Slime:* Silica- or polymer-based materials embedded with iron oxide particles, providing a semi-solid and stretchy texture.
- *Magnetic Sand & Powders:* Dry granules of iron oxide that form clusters or flow under magnetic influence.

Physical Structure and Properties

A. Nanoparticle Suspension

- Magnetic fluids consist of ferromagnetic or ferrimagnetic nanoparticles, commonly magnetite (Fe_3O_4), coated with a surfactant.
- The surfactant prevents the particles from aggregating, ensuring a stable suspension.
- Particle sizes range from 5–15 nanometers, small enough to remain suspended indefinitely due to Brownian motion.

B. Superparamagnetism

- Unlike bulk magnetic materials, these nanoparticles do not retain magnetism when the external magnetic field is removed, exhibiting superparamagnetic behaviour.
- This property allows the fluid to remain fluidic and prevents the formation of permanent clumps.

C. Interaction with Magnetic Fields

- Upon exposure to a strong external magnetic field, ferrofluid forms spikes and ridges, following the magnetic flux lines.
- The spikes form as a result of a balance between magnetic attraction and surface tension.
- The height and shape of these patterns depend on fluid viscosity, magnet strength, and field orientation.

3. Magnetic Fluid Toys and How They Work

A. Ferrofluid Displays & Bottles

- Ferrofluids are encapsulated in oil-based liquids inside a transparent container.
- When a magnet is brought near, the fluid forms dynamic patterns, creating a "living" black liquid effect.
- Low-viscosity ferrofluids allow for free motion, resulting in visually striking displays.

B. Magnetic Putty & Slime

- Silicone-based putty with iron oxide particles behaves like a soft solid but is still attracted to magnets.
- The putty gradually engulfs the magnet due to the reorientation of particles within the polymer matrix.
- The degree of responsiveness depends on the iron particle concentration and distribution within the material.

C. Magnetic Sand & Powder

- Magnetic iron filings or coated particles are mixed with sand or polymer binders.
- When exposed to magnets, these materials form wave-like motions or temporarily solidify into various structures.

4. Key Material Considerations for Magnetic Fluid Toys

A. Viscosity and Carrier Liquids

- The fluid medium can be oil-based for slow, smooth motion or water-based for quicker responses.
- High-viscosity fluids produce slower, thicker reactions, while low-viscosity ferrofluids form rapid and delicate patterns.

B. Particle Size and Distribution

- Smaller, nano-sized particles produce smooth-flowing ferrofluids, while micro-sized particles form chunkier, putty-like textures.
- A uniform distribution of particles ensures consistent magnetic responsiveness.

C. Magnetic Response and Strength

- The strength of the magnets (measured in Gauss or Tesla) dictates how quickly and strongly the fluid reacts.
- Neodymium magnets (NdFeB) are commonly used because of their high strength, enabling stronger effects.

5. Challenges and Limitations in Magnetic Fluid Toys

A. Stability and Separation

- Over time, ferrofluid may undergo sedimentation, with particles settling due to gravity.
- Surfactants help maintain suspension, but external factors like temperature and contaminants can degrade the performance.

B. Containment and Leakage

- Ferrofluids are messy and can stain, requiring proper sealing in toys.
- Magnetic putty may dry out or lose elasticity if not stored correctly.

C. Magnetic Saturation Limits

- There is a maximum magnetic saturation level. Beyond this point, stronger magnets will not enhance the effects.

6. Applications Beyond Toys

- Magnetic fluids aren't just limited to toys; they also have important industrial and scientific applications:
- NASA Zero-Gravity Seals: Ferrofluids are used to create frictionless rotating seals in spacecraft.

- Biomedical Imaging: Magnetic nanoparticles are employed for drug delivery and MRI contrast agents.
- Electronics Cooling: Ferrofluids assist in cooling components like hard drives and speakers by magnetically guiding heat away.

Conclusion

Magnetic fluids used in toys create complex magneto-mechanical interactions that are not only visually striking but also scientifically fascinating. Their behaviour is governed by the interplay of nanoparticle physics, fluid dynamics, and interfacial forces. This combination of science and fun makes magnetic fluid toys a unique educational tool while also providing endless entertainment.

Figure 66: Magnetic Fluids

(Source: doctor-a on pixabay)

17. MAGNETIC PUTTY

INTRODUCTION

Magnetic putty is truly a sight to behold, with its fascinating ability to be moulded into three-dimensional structures. It can be stretched, shaped, torn, and mashed back together, providing endless opportunities for manipulation and play. Its behaviour in the presence of a magnet adds an extra layer of intrigue, making it an especially interesting toy.

Magnetic putty is essentially a regular putty infused with iron oxide particles, which attract the material to magnetic fields. The putty itself is typically made from a combination of glue, water, and borax. It usually comes in different sizes and packaging, with the iron oxide giving it a characteristic black colour. However, this pigment can leave residues on surfaces and may stain, so it is important to handle it carefully.

The putty has a smooth, elastic texture, similar to classic putty or slime. It is soft, pliable, and yields to pressure, returning to its original shape in a satisfying way. The squishy, stretchy, and mouldable properties are attributed to the polymer material, while the iron oxide particles give it its unique magnetic response. When exposed to a magnetic field, these ferrous particles behave in ways that explain the putty's extraordinary, magnetically-controlled behaviour. This interplay between the material and the magnet is what makes the toy so captivating and fun.

THE TOY

Figure 67: Magnetic Putty

(Source: https://deepai.org/machine-learning-model/text2img)

Magnetic putty is a fascinating soft matter toy that combines science and entertainment in an exciting way. It can be stretched into various shapes and

structures, and when brought near a magnet, the putty becomes magnetically attracted, ultimately engulfing the magnet. To fully appreciate these amazing properties, it is essential to understand the science behind how it works.

PREPARATION

Magnetic putty primarily consists of two major ingredients:

*The Polymer Matr*ix: The polymer matrix forms the base of the toy and gives the putty its structure. It is made from a combination of glue, water, and borax. These three components work together to give the putty its viscoelastic properties, meaning it has the ability to deform (stretch, squish, or bend) and return to its original shape after the deforming force is removed. This makes the putty squishy, mouldable, and elastic.

Iron Oxide Powder: Iron oxide particles are what make the putty magnetic. These particles interact with magnetic fields, giving the putty its unique ability to move and reshape in response to the presence of a magnet.

Begin by adding equal amount of glue and a water. Mix them well. Now add the mixture to borax powder/solution, until the putty gets into its consistency. This yields us the regular putty that is slimy and squishy, which too is a soft matter toy.

Iron oxide: To prepare magnetic putty, iron oxide powder is added to the polymer matrix. The iron oxide is a fine powder that imparts the magnetic properties to the putty. The amount of iron oxide added depends on the size of the putty and the desired strength of its magnetic response.

Together, the viscoelastic properties of the polymer matrix and the magnetic properties of the iron oxide give the putty its unique characteristics. The polymer matrix provides flexibility and stretchability, while the iron oxide allows the putty to interact with magnetic fields, creating the fascinating behaviour observed when magnets are nearby.

Figure 68: Iron oxide

(Source: deep ai)

Physics of Magnetic Putty

Magnetic putty is a unique material that combines the properties of silicone polymers with magnetic ferrous particles. The ferrous particles, such as iron, nickel,

or cobalt, are what give the putty its magnetic properties. These ferrous particles are tiny micro magnets suspended within the polymer matrix. In the absence of an external magnetic field, these particles have random magnetic orientations due to their thermal motion. However, when a magnetic field is applied, the magnetic particles align themselves, creating temporary magnetic poles — a north and south pole.

When a magnet is brought close to the putty, the alignment of these particles causes the putty to become temporarily magnetized. This attraction can cause the putty to stretch or extend towards the magnet, following the direction of the magnetic field lines.

Viscosity and Non-Newtonian Nature:

Magnetic putty exhibits viscoelastic properties, meaning it can act like both a viscous liquid and an elastic solid depending on the conditions. This allows it to be stretched, squished, and returned to its original shape, much like slime. It is also a non-Newtonian fluid, meaning it does not follow Newton's law of viscosity, which typically defines a material's resistance to flow in relation to applied stress. Non-Newtonian fluids exhibit unique behaviours like changes in viscosity based on the applied stress or force.

In compression mode, the forces applied were not significantly affected by the magnetic field due to the perpendicular of magnetic flux lines to the direction of force.

In shear mode, applying a magnetic field at slow shear rates increased the maximum shear stress by up to 50%, demonstrating that the magnetic field influences the putty's response to deformation.

DIY VERSION

Materials Needed:

- School glue (PVA glue) – about 1/2 cup
- Liquid starch or Borax solution – to make the putty stretch

Iron oxide powder – the key magnetic ingredient (Avoid inhaling the powder).

- Neodymium magnet – strong enough to move the putty
- Gloves and a container (Iron oxide can stain hands and surfaces. Wear gloves and use a covered workspace).

Step-by-Step Instructions:

- Pour about 1/2 cup of glue into a bowl. Slowly add liquid starch (or Borax solution) while mixing. Stir until it becomes a stretchy, rubbery putty. Knead it by hand to get the right texture (not sticky).

- Sprinkle in about 2–3 teaspoons of iron oxide powder. Fold and knead it into the putty thoroughly until evenly mixed. If it becomes too dry or stiff, add a little more glue.
- Bring a strong neodymium magnet close to the putty. It should slowly creep toward the magnet, or even "eat" it if placed on top.

How It Works:

Iron oxide particles in the putty aren't magnetic themselves, but they are ferromagnetic, meaning they respond to magnetic fields. When you bring a strong magnet close, it magnetizes the iron particles, which then pull the putty toward the magnet. Since the putty is soft and stretchy, it can flow slowly, creating a cool "creeping" or swallowing effect.

Tips:

- Use clear glue to better see the movement.
- Add more iron oxide for stronger effects (though it might get messier).

1. Glow-in-the-Dark Magnetic Putty
Materials needed:

- School glue (PVA glue) – about 1/2 cup
- Liquid starch or Borax solution
- Glow-in-the-dark pigment (phosphorescent powder – NOT glow paint)
- Iron oxide powder
- Neodymium magnet
- Optional: gloves, airtight container

Procedure:

- Make basic putty by mixing glue with liquid starch or Borax until stretchy and slime-like.
- Add 2–3 teaspoons of glow pigment and mix thoroughly.
- Add 2–3 teaspoons of iron oxide powder and knead well. Add more glue if too stiff.
- Charge under a bright light, turn off the lights, and watch it glow!

Tip: Use green or aqua glow pigment—they tend to glow the brightest and longest.

2. Colour-Changing (Thermochromic) Magnetic Putty

Materials Needed:

- School glue
- Liquid starch or Borax solution

- Thermochromic pigment powder (available online in colours like black-to-red, purple-to-pink, etc.)
- Iron oxide powder
- Neodymium magnet

Procedure:

- Mix glue and starch/borax as before to make your base putty.
- Stir in a teaspoon of thermochromic pigment—wear gloves to avoid staining.
- Add iron oxide and knead until smooth.
- Test the colour change with warm hands or a hairdryer. The putty should shift colours with temperature!

Bonus effect: When you stretch or poke the putty, the heat from your fingers can create patterns of shifting colour.

Safety and Storage Tips:

- Store in an airtight container when not in use to prevent drying out.
- Always wash hands after handling.
- Keep away from carpets, white furniture, and young children who may try to taste it.

INTERESTING FACTS

- It was once banned from Amazon and toy stores. Some versions of magnetic putty were pulled from shelves in the UK around 2018 due to high levels of certain metals (like arsenic in some off-brand imports). This raised safety concerns for children, especially if ingested.
- It was inspired by Silly Putty and slime trends. Magnetic putty is a mash-up of two classic playthings: the stretch-and-bounce of Silly Putty, and the science toy appeal of magnets. It's part of the broader trend of tactile, "satisfying" toys.
- It can "swallow" magnets. One of the most visually cool facts is that magnetic putty can actually engulf a neodymium magnet over time-making it look like it's alive or oozing with intent. This eerie slow movement has made it popular in ASMR and stop-motion videos.
- It became a viral YouTube trend. Around 2016-2018, magnetic putty videos (like "putty eating a magnet") went viral, especially on channels dedicated to science toys, oddly satisfying content, or toy unboxings.
- It's a popular tool for stress relief. Beyond being a toy, magnetic putty is often marketed as a desk toy for adults. It's squishy, mouldable, and oddly addictive to poke and stretch-making it a cousin to stress balls and fidget spinners.
- It's used in science education kits. Magnetic putty often features in STEM learning kits and science fairs to demonstrate magnetism, material behaviour, and even basic chemistry-all while feeling like play.

- Artists have used it for stop-motion animations. Due to its slow but steady movement under magnetic influence, magnetic putty has been used to create eerie animations and experimental short films-especially ones that mimic alien or ooze-like behaviour.
- It behaves like a "smart fluid". Though it's not a true smart material, magnetic putty mimics some qualities-changing behaviour in response to a magnetic field. This makes it popular in science demonstrations, even though it's technically a passive composite.
- It can leave stains-seriously. The iron oxide in magnetic putty tends to stain fingers, furniture, and fabric. Many regret playing with it on white desks or carpets. (So yes, play with a tray!)
- There are glow-in-the-dark and colour-shifting versions. Beyond just magnetism, companies have added effects like glow-in-the-dark pigments, thermochromic colours (that change with heat), and glitter to make it even more visually fun.

SUMMARY

Magnetic putty is an intriguing toy that blends the properties of regular putty with the added excitement of magnetism. Its viscoelastic nature allows for creative play, moulding it into different shapes, while its magnetic properties introduce an additional layer of fascination. When exposed to a magnet, the putty's tiny ferrous particles align, making the putty stretch toward the magnet, adhere to it, and even engulf it. This unique combination of materials provides both entertainment and educational value, capturing the imagination of people of all ages.

18.FERROFLUIDS

Figure 69: Ferrofluid spikes when a ferro fluid is subject to a magnetic field

(Source: https://www.needpix.com/photo/354568/)

INTRODUCTION

Ferrofluids are liquids containing magnetic nanoparticles, such as magnetite (Fe_3O_4) or hematite (Fe_2O_3), suspended in a carrier liquid, such as an organic solvent or oil. The magnetic properties of the nanoparticles cause the fluid to be attracted to an external magnetic field. To prevent clumping and ensure uniform dispersion, each nanoparticle is coated with a surfactant. Ferrofluids are widely used in artistic applications, toys, and interactive displays due to their unique ability to form visually striking structures in the presence of a magnetic field.

Magnetic putty is a soft, mouldable solid with iron filings or iron oxide powder mixed into it. It moves slowly in response to a magnet and holds shape like slime or clay.

Ferrofluid is a liquid that contains extremely tiny magnetic particles suspended in oil. When near a strong magnet, it forms sharp spiky patterns as the liquid aligns with the magnetic field lines. It flows like a fluid but reacts instantly and sharply to magnetic fields.

THE TOY

Ferrofluids are colloidal suspensions of ferromagnetic nanoparticles in a liquid medium, with surfactants used to prevent aggregation of the particles. These fluids exhibit both liquid-like behaviour and magnetic responsiveness when exposed to an external magnetic field. The interaction between the magnetic nanoparticles and the field leads to the formation of characteristic structures, such as spikes, due to the alignment of the particles with the field lines. Surface tension plays a critical role in

the behaviour of ferrofluids, while the surfactants maintain the stability of the suspension by minimizing particle aggregation.

Ferrofluids are influenced by both Brownian motion (at small scales) and the external magnetic field. The material exhibits distinct rheological properties, including changes in viscosity as the magnetic field strength increases. These properties are crucial for applications in display technologies, where ferrofluids are used to create dynamic and interactive visual effects.

THEORY:
Ferrofluids consist of nanoparticles, typically around 10 nm in size, suspended in a carrier liquid. The nanoparticles, such as magnetite (Fe_3O_4) or hematite (Fe_2O_3), are coated with surfactants to prevent aggregation. The carrier liquid is often an organic solvent. The magnetic response of the fluid is evident only when an external magnetic field is applied. In the absence of a magnetic field, ferrofluids behave like regular liquids, but when exposed to a magnetic field, they form striking structures like spikes due to the alignment of the nanoparticles along the magnetic field lines.

The phenomenon of field instability is responsible for the formation of peaks and troughs in the fluid, as the system minimizes its energy. The surfactant molecules are amphiphilic, with a polar head that adsorbs to the nanoparticles and a non-polar tail that interacts with the carrier liquid. This structure prevents the nanoparticles from aggregating through electrostatic repulsion, maintaining the fluid's stability.

As the strength of the applied magnetic field increases, the spikes formed in the ferrofluid also grow in height, demonstrating the material's magnetorheological behaviour. The viscosity of the fluid changes depending on the strength of the magnetic field, influencing its flow characteristics and the shape of the structures formed.

Ferrofluids are typically composed of:

- Nanoparticles: Around 5-10% by weight, usually magnetite (Fe_3O_4) or hematite (Fe_2O_3).
- Surfactants: Around 10% by weight, such as sodium dodecyl sulphate, dodecylbenzene sulfate, or soy lecithin.
- Carrier Liquid: Typically, around 85% by weight, often an organic solvent or oil.

PREPARATION OF MAGNETITE:
Magnetite nanoparticles can be prepared by reacting ferrous (Fe^{2+}) and ferric (Fe^{3+}) salts in a solution, which leads to the formation of the magnetic oxide. The specific preparation process affects the size, shape, and magnetic properties of the nanoparticles, which are crucial for the behaviour of the ferrofluid.

Figure 70: Spiky structures of ferro fluids

(Source: Ren_mch on Pixabay)

Applications of Ferrofluids:

- *Technology and Engineering***:** Used in sensors, actuators, energy systems, and space propulsion due to their versatile magnetic properties.
- *Medical Applications***:** Applied in drug delivery systems and biomedical imaging.
- *Environmental Uses:* Used for absorbing impurities, microplastics, and in oil spill cleanup.
- *Entertainment and Art:* Utilized in creative displays, DIY experiments, glowing effects, and magnetic field visualization (e.g., in devices like ferrocells).
- *Educational Tools:* Demonstrates phenomena like fluid motion against gravity when using magnets.
- *Space Propulsion:* Ferrofluid droplets generate thrust at high velocities in space propulsion systems.
- *Industrial Uses:* Employed in seals and bearings, particularly for dynamic and self-adjusting seals that prevent leakage.
- *Microfluidics and Lab Applications:* Manipulated and controlled in systems like lab-on-a-chip devices.
- *Magnetic Sensors:* Used in sensors for detecting changes in magnetic fields, such as in compasses and magnetic field sensors.
- *Interactive Displays and Toys:* Creates dynamic and interactive effects in response to magnetic fields for toys and visual displays.
- *Oil Spill Cleanup:* Ferrofluids are effective in binding and cleaning up oil spills.
- *Energy Conversion:* Used in energy conversion materials for various industrial applications.

Ferrofluids continue to captivate scientists, artists, and hobbyists alike, thanks to their unique combination of fluidity and magnetic responsiveness.

DIY VERSION

Materials needed:

- Iron oxide powder (preferably magnetite, Fe_3O_4, very finely ground)
- Vegetable oil (or mineral oil, baby oil, or silicone oil for cleaner results)

- Strong neodymium magnet
- Small container (like a bottle cap or shallow lid)
- Optional: dish soap or rubbing alcohol (to improve particle suspension)
- Gloves and protective surface (ferrofluid can stain!)

Procedure:

- Prepare your base
- Pour a tablespoon of oil into a small container.
- Slowly add iron oxide powder (start with 1/2 teaspoon) and stir thoroughly.
- Adjust the texture

You want a dark, inky black mixture that flows like oil but doesn't clump. If it's too thick, add more oil. If particles settle too quickly, add a tiny drop of dish soap to help suspend them better. Hold a neodymium magnet under the container or on the side. You should see the fluid spike or move in response—like little black hair standing on end!

Important Note:
This DIY version won't be as dramatic or stable as lab-grade ferrofluid (which uses surfactants and nano-sized particles), but it still clearly shows the effect. The spikes are a visible demonstration of magnetic field lines—how the magnetic force is distributed in space.

INTERESTING FACTS

- Invented by NASA: Ferrofluids were originally developed in the 1960s by NASA scientist Steve Papell to control liquid fuel in zero gravity for spacecraft propulsion.
- They're Liquids That Act Like Magnets: Ferrofluids remain fluid under normal conditions but become magnetized and form spike-like patterns when exposed to a magnetic field.
- They're Made of Tiny Magnetic Nanoparticles: The particles (often magnetite or hematite) are just 10–20 nanometres wide—so small that millions fit on the head of a pin.
- They Don't Clump—Thanks to Surfactants: Special coatings called surfactants prevent the particles from sticking together and settling out, keeping the fluid stable.
- They Exhibit Superparamagnetism: Unlike regular magnets, ferrofluid particles lose their magnetism when the external magnetic field is removed.
- They Form Stunning Spikes: The spikes seen in ferrofluids under magnetic fields are due to a phenomenon called the normal-field (Rosensweig) instability, balancing surface tension and magnetic force.
- Used in Loudspeakers and Hard Drives: Ferrofluids help dissipate heat and dampen vibrations in high-performance audio speakers and electronic components.

- They're Non-Newtonian Fluids: Their flow behaviour changes under stress—similar to slime or oobleck—but influenced by both pressure and magnetic fields.
- They Can Remove Microplastics: Ferrofluids have been researched as a way to collect microplastics from water, as plastic particles stick to the fluid and can be removed magnetically.
- Ferrofluids Can "Climb" in Magnetic Fields: They can move upward against gravity inside capillaries when exposed to a magnetic gradient—demonstrating capillary action and magnetism together.
- You Can Make DIY Ferrofluid Art: With proper containment, ferrofluids can be used in interactive displays and art installations, creating dynamic patterns in response to magnets.
- They Glow with UV Additives: Some hobbyists mix ferrofluids with glow-in-the-dark or fluorescent dyes to create eerie glowing magnetic displays under UV light.
- They Can Act Like "Perpetual Motion" (Visually!): In rotating magnetic fields, ferrofluids appear to move endlessly—though this is just the magnet at work, not actual perpetual energy.

1. *Magnetic Play and Art:* Ferrofluids form spikes and patterns along magnetic field lines, offering fascinating visuals. Common in educational toys, science exhibits, and interactive sculptures.
2. *Capillary Action:* Ferrofluids can climb surfaces when exposed to a magnetic field due to surface tension. This phenomenon defies gravity and is used to demonstrate magnetic influence on fluid dynamics.
3. *Perpetual Motion Illusion:* While true perpetual motion is impossible, ferrofluids can simulate continuous movement under alternating magnetic fields, creating a mesmerizing dynamic effect.
4. *Glowing Effects:* By mixing ferrofluids with glow-stick fluid, they can emit colourful glows under light or UV. Used in DIY projects, glowing art, and science demonstrations.
5. *Magnetic Field Line Visualization*: DIY ferrocells—thin layers of ferrofluid between glass—can make magnetic field lines visible in real-time under light.
6. *Microplastic Removal*: Ferrofluids have shown potential in environmental cleanup. They can bind to microplastics in water, allowing for magnetic separation and reducing environmental harm.

SUMMARY

Ferrofluids are specialized liquids made up of magnetic nanoparticles suspended in a carrier fluid and stabilized by a surfactant to prevent clumping. These fluids exhibit unique magneto-responsive behaviour, meaning they become magnetized and react when exposed to an external magnetic field. One key characteristic of ferrofluids is that their viscosity changes in response to the applied magnetic field. The suspended nanoparticles undergo Brownian motion, leading to a variety of fascinating behaviours, including dynamic pattern formation and visual effects.

Ferrofluids have a wide range of applications, from toys to artistic displays. The combination of magnetic nanoparticles and a carrier liquid, stabilized by surfactants, allows these fluids to respond dynamically to magnetic fields. The resulting formations, such as spikes and other structures driven by magnetic alignment and surface tension, create visually captivating effects. By studying their physical and rheological properties, ferrofluids offer both scientific intrigue and entertainment value.

SECTION 3: IN CONCLUSION

SUMMARY

Soft matter science, at its core, explores materials that are easily deformed by external forces—materials that flow, stretch, squish, self-organize, and respond to their environment. These substances, which include polymers, gels, foams, colloids, and liquid crystals, form a fascinating class of matter that sits between the rigid world of solids and the flowing freedom of liquids. What makes soft matter especially interesting is its combination of complexity and accessibility: the same principles that govern high-tech biomedical gels or smart materials can also be observed in simple, everyday objects like toys.

Toys are more than just playthings—they are an intuitive, often ingenious medium through which the behaviours of soft materials can be explored. Whether it's a slime that flows and resists, a stress ball that recovers shape, or a shape-memory toy that responds to heat, these objects embody a wide range of physical phenomena. Through play, we encounter complex material science concepts such as viscoelasticity, phase transitions, self-assembly, and stimulus-responsiveness in a tactile and immediate way.

This chapter brings together key ideas in soft matter physics and chemistry, viewed through the lens of materials used in toys. The aim is to provide a unifying framework for understanding how fundamental properties like elasticity, responsiveness, or fracture behaviour arise from molecular structure and interactions. Each section ties a core scientific concept to real-world examples, demonstrating not just how soft materials behave, but why they are so integral to design, functionality, and user experience.

We now revisit and summarize several important soft matter concepts, each connected to how they are manifested or applied in toys and everyday soft devices:

1. *Self-Assembly*: One of the most elegant phenomena in soft matter is self-assembly—the ability of molecules to organize into larger structures without external guidance. This principle underlies much of the structure and function found in soft materials, including those that power modern toys.
2. *Polymer Blends and Composites:* Soft materials rarely exist in pure form. Instead, they are often designed by blending polymers or reinforcing them with additives to create composites. These combinations offer tailored properties—essential for balancing durability, flexibility, and feel in toys.
3. *Rheology of Soft Materials :* How do materials flow, stretch, or resist movement? Rheology—the study of deformation and flow—captures the essence of how soft matter responds under different conditions. It's especially relevant to the squish, stretch, and flow behaviours seen in slime, putty, and similar toy materials.
4. *Phase Transitions in Soft Matter:* Soft materials can dramatically change their behaviour with shifts in temperature, stress, or concentration. These phase transitions—like melting, gelation, or vitrification—explain how toys may stiffen, soften, or transform based on their environment.

5. *Fracture and Failure of Soft Materials*: Even soft materials can fail—though not always in ways familiar from brittle solids. Understanding how soft matter stretches, cracks, or deforms before breaking is key to designing safe and long-lasting toys.
6. *Gelation and Cross-Linking in Polymers:* Many soft materials start as liquids and become solids through gelation—a process enabled by cross-linking polymer chains. This transformation is central to toys like gels and squishies, which derive their texture and resilience from this networked structure.
7. *Thermo-responsive and Photo-responsive Materials:* Some materials are "smart"—they react visibly to changes in heat or light. Thermo-responsive and photo-responsive polymers enable toys that change colour, shape, or stiffness based on the environment, making play more dynamic and interactive.
8. *Superabsorbent Polymers (SAPs):* Certain polymers can absorb water many times their own weight. These superabsorbent materials, used in water beads or expanding toys, illustrate how soft matter can control and manipulate fluid uptake on a remarkable scale.
9. *The Role of Surfactants in Soft Matter:* Surfactants are silent enablers in soft matter—altering surface tension, stabilizing emulsions, and preventing aggregation. From bubble solutions to slime, they play a crucial role in maintaining the consistency and behaviour of many toy materials.
10. *Tactile and Sensory Properties of Soft Matter:* Touch is a major part of the soft matter experience. The tactile and sensory responses of materials—how they squish, resist, or bounce—are carefully engineered, especially in toys that engage hands-on exploration and sensory play.
11. *Biocompatible and Biodegradable Materials:* As sustainability and safety grow in importance, soft materials are increasingly designed to be biocompatible and biodegradable. This shift is reshaping how toys are made, used, and disposed of—bridging science and environmental responsibility.
12. *Magneto-responsive and Electric Field Responsive Materials:* The frontier of soft matter includes materials that can respond to magnetic or electric fields. These dynamic materials introduce motion, shape change, or stiffness control, paving the way for interactive or programmable toys of the future.

Soft matter science bridges the gap between everyday experience and fundamental physics, revealing how seemingly simple materials—gels, foams, slimes, and polymers—are governed by rich and often surprising principles. From self-assembly to smart responsiveness, the behaviour of soft materials is dictated by interactions at the molecular level, yet manifests in tangible, often playful ways. This unique versatility explains their widespread use not only in research and industry but also in toys, where properties like deformability, sensory feedback, and environmental responsiveness enhance both function and fun. As we continue to understand and engineer these materials, soft matter will remain central to innovations in design, sustainability, and user interaction—proving that even the softest substances can have a profound impact.

ADDITIONAL ACTIVITIES

1. **Activities using Oobleck**
   - Seismic Wave Simulation. Drop small objects onto trays of oobleck and compare the results to water or sand. Observe the resistance and wave patterns.
   - Sound Wave Experiment: Place oobleck on a speaker (covered with plastic wrap). Play low-frequency sounds and observe how the oobleck responds, forming standing wave patterns.
   - Stress Testing Structures: Build small LEGO or toothpick bridges and test their response under dynamic loads on top of oobleck, comparing reactions to those on solid or liquid surfaces.
   - Creative Art Project: Mix food colouring into oobleck and use droppers or brushes to create marbled effects on paper by transferring patterns from the surface of the oobleck.
   - Stop-Motion Science Animation: Have students make stop-motion videos showing how oobleck reacts under pressure—jumping, bouncing, or "walking" hands across it.
   - Historical Tie-In: Dr. Seuss and Environmental Science: Read Bartholomew and the Oobleck and then discuss non-Newtonian fluids, environmental disasters, or manmade vs. natural substances.
   - Dance on Oobleck (Large Scale) Create a large batch in a kiddie pool and allow students to run or dance on it (if safely possible). Teaches concepts of force and pressure. Use caution and proper setup for safety.
   - Temperature Effect Experiment: Chill one batch, warm another, and compare how each responds to stress or vibration.
   - Mythbusters-style Challenge: Present a myth or claim (e.g., "You can walk on oobleck") and have students design and carry out experiments to test it.
   - Sensory and Mindfulness Station: Use oobleck in calming sensory stations. Focus on texture, sound, and slow movement as part of a mindfulness practice.

2. **Activities using slime**
   - pH Indicator Slime: Make slime with red cabbage juice or phenolphthalein. Add acidic or basic solutions to observe colour changes.
   - Slime Degradation Test: Compare traditional slime with biodegradable alternatives (e.g., made from gelatin or natural thickeners) over several days/weeks.
   - Slime Viscosity Challenge: Vary ingredient ratios (glue, borax, baking soda, etc.) and measure stretchiness, bounce, and flow rate.
   - Slime as a Shock Absorber: Drop marbles or weights on a surface covered with slime and measure rebound height compared to a hard surface.

- Bridge-Building with Slime: Try suspending or coating a mini bridge structure in slime and observe deformation underweight.
- Slime Painting: Dip string or mesh into coloured slime and drag across paper to create unique patterns and textures.
- Glow-in-the-Dark Slime Light Show: Use glow powder or tonic water and black lights to choreograph a "light show" or create UV-reactive installations.
- Modelling Cell Cytoplasm: Embed small objects in slime to represent organelles and use it to demonstrate the cytoplasmic matrix.
- Bacterial vs. Slime Growth Comparison: Observe how slime spreads and "flows" over time and contrast it with bacterial colony growth on agar.
- Slime Stretch Math: Measure how far slime stretches before breaking under different conditions and plot the data.

3. Activities based on water-gel-beads

- Observe absorption and dehydration by placing beads in different environments and tracking their size and weight changes over time.
- Demonstrate osmosis by soaking beads in saltwater and freshwater and comparing their swelling behaviour.
- Soak beads in cabbage-juice-infused water and test their colour change response to acids and bases to explore pH.
- Compare swelling speed and transparency by soaking beads in hot vs. cold water to observe thermal expansion.
- Drop objects onto layers of beads to study impact absorption and cushioning behaviour.
- Fill a balloon or sealed bag with gel beads and apply pressure to simulate hydraulic force and material deformation.
- Test how much weight a platform can hold when supported by gel beads to explore load distribution.
- Plant small seeds like basil or chia in hydrated beads and observe root growth in a transparent medium.
- Create microhabitat simulations for small animals or insects using gel beads as the environment base.
- Soak beads for timed intervals and record their diameter or weight to plot hydration growth curves.
- Mix coloured beads, sort them by hand, count quantities, and analyze the data using basic statistics.
- Place beads over printed text or patterns and observe light bending and magnification effects through the transparent spheres.
- Layer different coloured beads in clear containers to create colour-mixing sculptures and observe long-term visual changes.
- Use the feel and appearance of the beads as a prompt for descriptive writing or storytelling involving imaginative settings.
- Combine gel beads, water, and glitter in clear jars to create calming visual tools for sensory regulation.
- Hide small objects inside a bead bin and use the activity as a mindfulness exercise to find items slowly and attentively.

- Mix gel beads into slime or oobleck and explore how texture and material interactions affect flow and tactile sensation.

4. **Activities based on gel-based-teething toys**
   - Place teething toys in the freezer and then compare how long different shapes and sizes retain their coldness when exposed to air or warm water.
   - Use frozen vs. room-temperature teething toys to help toddlers explore and describe the concept of temperature using touch and simple vocabulary.
   - Set up a sensory table with water and teething toys of various shapes and encourage toddlers to match similar textures or shapes by feel alone.
   - Introduce the idea of cause and effect by letting children squeeze or press on gel toys and watch them return to shape, using mirrors or magnifiers for closer observation.
   - Create a sink-and-float test by placing different gel-based toys and similar objects in water to explore basic properties of density and buoyancy.
   - Use the toys for a sorting challenge, grouping them by colour, shape, or texture to build early categorization and cognitive skills.
   - Conduct a "melting race" where frozen teething toys are placed on different surfaces (metal, cloth, plastic) to see where they thaw fastest.
   - Combine gel toys with warm and cold-water stations and observe how the temperature affects squishiness and flexibility.
   - Use the toys as stampers by dipping them in washable paint and pressing them onto paper to explore texture, pattern, and symmetry.
   - Hide teething toys in bins of rice, fabric scraps, or water beads for a tactile scavenger hunt that encourages exploration and attention.
   - Place the toys under light or in front of a flashlight to study light diffusion and transparency in the gel material.
   - Use the toys in early pretend play as "tools" in doctor kits, kitchens, or construction zones to support imaginative scenarios and motor skills.
   - Let children gently press the toys between two transparent plates (like plastic sheets) and watch how the gel moves or compresses, encouraging observation and vocabulary.
   - Introduce basic hygiene and health concepts by having children "wash" teething toys in soapy water using safe cleaning tools like sponges or brushes.
   - Create a sensory calming bin by combining cooled gel teething toys with soft fabrics, lavender-scented sachets, and quiet background music for a mindful, self-regulating space.
   - Use them in a guessing game where toys are placed in socks or bags and children have to guess which one is inside by touch alone.
   - Explore heat transfer by placing a warm hand or warm cloth on a cold gel toy and watching condensation or tactile changes.
   - Observe changes over time by freezing a gel toy and documenting the thawing process through photos or time-lapse videos.

5. **Activities using foam based toys**

- Sculpt letters, numbers, or geometric shapes and use them for tactile learning in literacy and math.
- Mold floam over toy animals, shapes, or tools to make temporary molds, then remove the objects and observe the imprints.
- Cover toy blocks or small containers in floam and explore how texture affects stacking, balance, and stability.
- Use floam to build mini-structures like arches, towers, or bridges and test their strength by placing small weights on top.
- Sculpt body parts like ears, noses, or hands and label them to combine fine motor play with anatomy learning.
- Mix floam colours and track how the beads and base medium blend (or resist blending), encouraging observation of material behaviour.
- Flatten floam into slabs and press various textured objects (buttons, leaves, coins) into it to create impression art or nature prints.
- Use floam as a medium for storytelling—build characters, props, and settings, then act out a narrative or puppet show.
- Make mini "planets" or solar system models, using different coloured floam balls to represent each celestial body.
- Explore the concept of mass and volume by measuring how much floam it takes to fill containers of different shapes.
- Challenge children to make floating floam boats or rafts and test them in a tub of water with small plastic figures.
- Practice emotional learning by sculpting faces that show different expressions and discussing how each emotion looks and feels.
- Use floam to cover and decorate pencil holders, jars, or boxes for custom craft projects and desk organization.
- Hide small objects inside floam and use it for a sensory treasure hunt that involves touch and problem-solving.
- Roll floam into thin "snakes" and use them to form cursive letters or spelling words on a board or table.
- Compare floam with other materials like slime, dough, or clay by building the same object in each and evaluating flexibility, strength, and texture.
- Use floam to simulate topographic features like hills, rivers, and mountains on a flat board for early geography or terrain modeling.
- Press floam into cookie cutters or silicone molds, remove carefully, and use the shapes in creative art or storytelling scenes.
- Sculpt animals or bugs and use them in classification activities—sorting by habitat, number of legs, or other traits.
- Use floam to create "armor" or accessories for action figures or dolls, exploring costume design and creativity.

6. <u>Activities using Foam dice</u>:

- Roll two dice and add, subtract, or multiply the numbers—students race to pop the answer on a number line or shout it out.

- Use coloured dice and assign each colour a different task: red = exercise, blue = spelling word, green = animal sound, etc.
- Set up a physical obstacle course where each number corresponds to a different movement (e.g., 1 = jump, 2 = crawl).
- Roll and move: use dice to determine how many steps, hops, or skips a player takes in a gross motor path.
- Have students roll a die to choose which part of a story to build next—character, setting, conflict, etc.
- Use dice for group decision-making—each number represents a topic, game, or question prompt.
- For emotional regulation, each roll can lead to a coping strategy like deep breathing, naming feelings, or a stretch.
- Practice letter sounds by rolling and saying a word that starts with the matching letter from an alphabet card.
- Roll and count objects into matching piles—great for early math and fine motor development.
- Create a life-sized board game where the die determines spaces moved and each space has a challenge or task.
- Play vocabulary dice games: roll and act out, draw, or define the word that matches the number.
- Build logic skills by assigning math operations to dice rolls and solving problems step by step.
- Use them as a classroom "quiet signal"—roll to choose how to transition: whisper, freeze, sing, etc.
- Create "story starters" where each die corresponds to a category: character, place, object, action, mood, etc.
- Assign categories to each number and play a sorting game: roll and place items or cards in the correct group.
- Use for cooperative play: one child rolls, another completes the action, encouraging turn-taking and teamwork.
- Play freeze dance with dice—roll to determine how many seconds to dance or what style to use.
- Use dice in a scavenger hunt—each number corresponds to an object type or room to explore.
- Make math relay races: students roll, solve a math problem, then run to tag the next person.
- Turn dice rolling into a mindfulness break: roll to choose the number of breaths, stretches, or positive statements to say.

Mathematical Activities Using Foam Dice

Foam dice can be a fantastic tool for practicing math and arithmetic skills. To get started, roll the dice, add the numbers together, and record the result. This activity introduces "mathematising" play—an approach where adults naturally and spontaneously introduce mathematical concepts into the child's play. This could

include actions like counting, comparing, relating, measuring, or actively eliciting new math-like actions and helping improve those skills.

Activity 1: Addition and Subtraction

- Roll two dice and either add or subtract the numbers rolled. This activity is great for practicing basic addition and subtraction skills.
- Two-Step Problems: 2. Roll two dice to generate two numbers, then add or subtract a third number from the next roll to create two-step problems.

Activity 2: Multiplication and Division:

- Multiplication Practice: Roll two dice and multiply the numbers. This activity helps reinforce multiplication tables.
- Division Practice: Roll two dice and divide the larger number by the smaller one. This exercise is ideal for practicing division.

Activity 3: Statistics and Probability:

- Use dice to explore probability concepts, such as the likelihood of rolling specific numbers or combinations.
- Rolling the dice repeatedly will allow you to gather data and create frequency tables, histograms, or bar graphs.

Physics Activities Using Foam Dice:
In physics activities, foam dice can be used to illustrate concepts like motion, probability, and energy. Here's a physics exercise focusing on energy conservation:

Activity 1: Conservation of Energy

- Find a flat, smooth surface with enough space to roll the foam dice. Make sure the surface is clean and free of obstructions. Place the ruler or measuring tape on the surface to measure distances.
- Introduce the concept of energy conservation. Explain how an object's energy changes when it moves from rest but remains constant when accounting for its starting and final states.
- Ask participants to predict what will happen as the dice are rolled. Will the dice stop immediately, or will they continue to move? Why?
- Repeat this process several times, ensuring that the same amount of force is applied each time.

    - Distance Measurements:
    - Measure the distance the foam die travels after each roll.
    - Record the distances in a notebook.
- Emphasize energy conservation. Ask questions like:
    - What happens to the foam die's energy when it is rolled?
    - What causes the die to eventually stop moving?
    - How does the die's initial energy relate to how far it travels?
- Experiment with Different Forces:

    - Encourage participants to roll the dice with varying amounts of force. Ask them to roll the dice softly, with more force, or at different angles.
    - Discuss how the starting energy (kinetic energy) affects how far the dice travel.
- Further Investigation:
    - Extend the activity by introducing multiple dice or discussing probability. For example, participants can roll two dice and determine the likelihood of different outcomes based on the mechanics of rolling dice.
    - This physics activity with foam dice encourages participants to engage with and explore concepts of energy conservation and motion. It fosters critical thinking, hands-on learning, and a deeper understanding of physics principles.

7. ACTIVITIES USING SPONGES

- Cut sponges into letters, numbers, or shapes and use them as stamps with washable paint for literacy or math art.
- Create sponge towers by stacking wet and dry sponges and observing which stacks more stably and why.
- Use sponges to model capillary action—dip the bottom into coloured water and watch the liquid rise.
- Make a DIY slow-drip timer by poking holes in a water-soaked sponge and watching how long it takes to empty.
- Conduct an absorption race—compare how much water different sponge types hold and how quickly they absorb liquid.
- Build sponge creatures or abstract sculptures by cutting and gluing pieces into new forms.
- Use sponges to "paint" textures—drag, press, or dab them in paint on paper to explore surface effects.
- Freeze water-soaked sponges and observe how long they take to melt, or use them as reusable ice packs.
- Make a sponge relay game: transport water from one container to another using only sponge soaks and squeezes.
- Explore erosion by dripping water onto stacked sponge "landscapes" and reshaping over time.
- Build simple sponge boats and test their floating ability and speed in water.
- Use sponges in dramatic play as pretend food items (e.g., cut into toast, cheese, or cake shapes) or play tools.
- Create a DIY stamp set—carve basic patterns or textures into sponge pieces and use with paint or ink pads.
- Conduct a sensory contrast experiment by mixing dry sponges with wet ones and comparing textures blindfolded.
- Place sponges inside socks or fabric and use as safe, throwable balls for indoor games.
- Cut into puzzle pieces or irregular shapes and challenge kids to reassemble them like foam tangrams.
- Use coloured water and sponges to demonstrate colour mixing—soak sponges in primary colours and squeeze into a shared container.

- Make a sponge “lung” model—press and release to simulate air filling and exiting a compressible structure.
- Soak sponges in scented water (e.g., vanilla, lemon) and use them for scent recognition or memory games.
- Combine sponges with string, tape, or rubber bands to construct lightweight creatures, puppets, or wearable accessories.

8. ACTIVITIES RELATED TO SOAP BUBBLES

● Explore the science of soap bubbles through these engaging DIY activities that allow you to appreciate the beauty of both physics and art behind these tiny marvels.
● Surface Tension Experiment: Investigate surface tension by using soap to disrupt the surface tension of water in a dish.
● Fill a shallow dish halfway with water and sprinkle pepper on top.
● Move the pepper with a dry finger and observe how it resists movement.
● Dip your finger into liquid soap and touch the surface. Watch as the pepper particles disperse when the soap disrupts the water's surface tension. This experiment demonstrates how soap molecules lower the surface tension of water, allowing objects to move freely on the surface.

Bubble Blowing Contest:
● Organize a contest to see who can blow the largest or longest-lasting soap bubble.
● Prepare a bubble solution with water, dish soap, and glycerine, experimenting with different ratios to find the optimal mixture for producing large, long-lasting bubbles.
● Take turns blowing bubbles and see who can create the most impressive one. This activity combines creativity and experimentation, challenging participants to perfect their bubble solution.

Bubble Wand Crafting:

● Craft unique bubble wands using common household items.
● Gather materials like pipe cleaners, straws, and string. Shape them into different designs to create personalized bubble wands.
● Dip your homemade wands into the bubble solution and observe the various bubble shapes formed. This activity encourages creativity while allowing experimentation with different wand shapes and their effects on bubble formation.

Soap Bubble Art:
● Create temporary masterpieces with soap bubbles as a medium.
● Make a bubble solution and add food colouring or washable paint to create colourful bubbles.

- Gently blow or release the bubbles onto paper, canvas, or other surfaces to form abstract art.
- Photograph the fleeting bubble creations to capture their beauty.
- Soap bubble art blends science and creativity, offering a unique way to explore colours and patterns while appreciating the transitory nature of soap bubbles.

9. ACTIVITIES USING BALOONS

- Inflate balloons partially and use them as paint rollers to create large-scale abstract art.
- Rub balloons on different materials (wool, hair, carpet) to generate static electricity and experiment with attracting or repelling objects.
- Fill balloons with various materials—water, sand, flour, rice, gel, or shaving cream—and use them for tactile comparison or mystery-touch games.
- Freeze water-filled balloons and peel off the latex to explore ice domes and melting behaviour.
- Use balloons as moulds-cover them with papier-mâché or string dipped in glue to make lightweight bowls or globes.
- Tape a straw to a balloon, thread the straw onto a string, and release the balloon to create a balloon rocket that demonstrates propulsion.
- Fill balloons with air and test how far they fly when released from different angles or launch heights.
- Use balloons as “lungs” in a simple respiratory model by attaching them inside a bottle and inflating them with a diaphragm pull.
- Cut balloon pieces and stretch them over jars or cans to create simple drum heads and explore sound vibration.
- Create balloon-powered cars using straws, wheels, and tape-inflate the balloon and let the air propel the car forward.
- Make a balancing game by taping balloons to rulers or dowels and trying to balance them on your fingers.
- Inflate and bounce balloons on different surfaces or with various materials to test friction and rebound behaviour.
- Create sensory balloons by filling them with scented or textured substances like lavender rice or slime.
- Set up a balloon drop experiment-test how fast different weights tied to balloons fall through the air.
- Tie strings to water balloons and swing them like pendulums to explore motion, arcs, and gravity.
- Use water balloons to model molecules-tie several together to represent atoms in different structures.
- Inflate two balloons to different sizes and connect them with tubing; release one and observe how air moves to equalize pressure.
- Hang balloons from different lengths and test which pendulum swings fastest or furthest.
- Use small balloons as stress balls-fill with flour or cornstarch and tie off for handheld fidget tools.

- Fill balloons with air and balance objects on top of them to explore pressure distribution and weight support.

10. ACTIVITIES USING LIQUID MOTION BUBBLERS

- Use bubblers as visual timers for short activities like deep breathing, journaling, or focus tasks.
- Set up a mindfulness station where students or children watch the bubbler to practice staying still and present.
- Challenge participants to describe the motion using vivid, specific vocabulary—great for language development.
- Write metaphors or similes based on how the liquid flows (e.g., "like lava in a dream" or "like raindrops racing through a rainbow").
- Predict how long the liquid takes to flow from top to bottom, then measure with a stopwatch and compare across multiple trials.
- Record the bubbling motion and play it back in slow motion to discuss properties of viscosity and flow.
- Create a design challenge: can you build your own bubbler using household items like oil, water, and food colouring?
- Use the bubbler to practice emotional labeling: What does it feel like when you're moving fast like the top, or slowly settling like the drops below?
- Observe how temperature affects flow—place the bubbler in a fridge or warm sunlight and compare timing.
- Compare different models of bubblers and create a ranking based on speed, colour contrast, or flow behaviour.
- Incorporate bubblers into a calming corner or sensory break space to help with emotional regulation.
- Use the bubbler as a prompt for creative writing-imagine it's a portal to another world, or each drop is a traveler on a journey.
- Pair the bubbler with ambient sounds or music and create a multimedia relaxation station.
- Play a "quiet challenge"-watch the entire bubbler cycle in silence, helping develop patience and concentration.
- Introduce basic fluid dynamics terms like density, immiscibility, and surface tension using the bubbler as a visual aid.
- Ask students to sketch the movement or colour patterns they see during a cycle to encourage visual attention and interpretation.
- Let children observe the bubbler, then act out or dance how the drops move-good for kinesthetic expression.
- Compare the bubbler's motion to other slow-drip systems (like hourglasses or droplet timers) and discuss similarities and differences.
- Use multiple bubblers with different colours and have students vote on which one best matches a chosen mood or theme.
- Discuss how tools like bubblers can help people regulate emotions or focus, then brainstorm other tools or strategies together.

11. ACTIVITIES USING KINETIC SAND

- Sculpt letters, numbers, or sight words and use them for tactile spelling or early literacy practice.
- Mold and slice blocks of sand to explore concepts like symmetry, fractioning, or division.
- Bury small objects and use a brush or tool to “excavate” them like an archaeologist, supporting fine motor control and attention to detail.
- Use cookie cutters, stencils, or molds to create repeating patterns and practice basic math sequencing.
- Create topographic models or landforms-mountains, valleys, rivers-then discuss how water would move through them.
- Set up a small-world storytelling tray where children build environments and act out scenes with toy figures.
- Conduct a flow test by forming different slope angles and timing how long sand takes to move or settle.
- Hide and match objects (letters, shapes, colours) inside the sand for sensory-based memory games.
- Use tools (forks, straws, combs, stamps) to create textures and compare patterns formed by different instruments.
- Compare kinetic sand to regular sand, play dough, or oobleck and discuss differences in texture, behaviour, and use.
- Explore emotional expression by sculpting faces or scenes that represent specific moods or experiences.
- Set up a mindfulness station where slow molding, cutting, and shaping of sand is used as a calming sensory break.
- Practice early coding concepts by giving "commands" to a partner sculpting the sand step-by-step (e.g., flatten, press, cut).
- Fill measuring cups and explore volume, estimation, and comparative language (more, less, equal).
- Create impression fossils by pressing plastic dinosaurs, shells, or leaves into the sand and observing details.
- Write or draw in the sand with a stylus, then “erase” by smoothing over-great for temporary writing practice.
- Sculpt bridges or tunnels and test their strength by placing lightweight figures on top or under.
- Cut kinetic sand slices cleanly with a knife and record slow-motion video to observe how it collapses and flows.
- Practice turn-taking or collaboration by co-building a shared structure or scene with kinetic sand.
- Create a simple stop-motion animation by photographing small changes in a kinetic sand sculpture over time.

12. ACTIVITIES USING PLAY-DOUGH

- Sculpt letters and numbers for tactile literacy and numeracy practice.
- Roll and cut “snakes” of dough to form cursive or block-letter words.

- Make mini food items and set up a pretend bakery or market stall for dramatic play.
- Create textured fossils by pressing leaves, shells, or toy dinosaurs into dough.
- Use play-dough to model cells, organs, or body parts in simple biology lessons.
- Practice shape recognition and geometry by cutting and combining basic forms.
- Build simple 3D structures or towers and test balance and design ideas.
- Create dough characters and act out scenes or stories for language development.
- Press objects into dough and try to match them later by their imprints alone.
- Make "mood monsters" with different facial expressions to explore emotions.
- Set up a math challenge by making sets, patterns, or simple equations with dough pieces.
- Use play-dough to create a tactile map with hills, rivers, and landmarks.
- Form animal sculptures and sort them by habitat, diet, or classification.
- Use it as a writing surface—flatten and "write" into it with tools or fingers.
- Design a miniature park, house, or city with zones and details.
- Create dough stamps from hard objects and explore the shapes they leave behind.
- Roll it into balls and explore volume and comparison through measurement games.
- Practice fine motor skills with tools-scissors, rollers, stamps, and cookie cutters.
- Sculpt seasonal or holiday decorations like pumpkins, snowflakes, or flowers.
- Use play-dough for "surgery" activities-hide small items inside and pretend to extract them carefully.

13. <u>ACTIVITIES USING SQUISHY BALLS:</u>

- Put the various kinds of balls in the box (2 sets).Make two teams. Start the game by asking the two teams to separate the balls based on what they studied soft matter physics properties. The team which separates the balls correctly and quickly wins the game.
- Use them in emotion-check-in routines by assigning colours or textures to different feelings and having kids select the one that matches their mood.
- Incorporate them into focus breaks: squeeze the ball in rhythm with counting, breathing, or music for calming transitions.
- Hide small beads or objects inside DIY squishy balls and have children find and count or sort them by shape.
- Use multiple squishy balls of different resistance levels and compare which are easier or harder to squeeze—great for strength grading.
- Play a tactile memory game: blindfold the child and have them identify balls by texture, shape, or filling.
- Use squishy balls as stand-ins for characters or objects in storytelling activities, with each ball representing a different role.
- Pass a squishy ball silently around a circle to practice listening, turn-taking, and group regulation.

- Create a "stress scale" by squeezing different balls and ranking them from soft to firm—helping with sensory awareness.
- Use in target games: toss into containers of varying sizes and distances to practice motor planning and aim.
- Make a science activity out of testing what happens when you freeze, heat, or poke different types of squishy balls.
- Use them as “talking tools”—only the person holding the ball speaks, reinforcing listening and respectful conversation.
- Incorporate them into finger strength exercises, squeezing them in patterns (left-right, both-hands, thumb-only, etc.).
- Place a squishy ball underfoot while seated and roll it with bare feet for calming proprioceptive input.
- Add them to a sensory bin and have children find them using only tactile cues.
- Use balls with glitter or beads inside for visual tracking—great for quiet focus and visual-motor integration.
- Introduce early math by lining up squishy balls of different sizes and sorting by size, colour, or filling.
- Paint with them—dip foam squishy balls in paint and roll or press them onto paper for sensory art.
- Use them in role-play scenarios, such as medical checkups, massage clinics, or toy pet shops.
- Include them in obstacle courses as objects to squeeze at checkpoints for engagement and energy release.
- Explore emotional expression by asking: “If your feelings today were inside a squishy ball, what would they feel like?”

14. ACTIVITIES USING RUBBER BALL

- Test bounce height on different surfaces (wood, carpet, sand, etc.) and record observations for a simple physics experiment.
- Use rubber balls of various sizes and weights to explore mass, force, and energy transfer through rolling and dropping.
- Roll balls through mazes made from blocks or cardboard to practice aim, planning, and spatial reasoning.
- Set up target games with buckets, hoops, or taped zones and measure scoring accuracy over time.
- Conduct bounce counting—drop from a fixed height and count how many times it bounces before stopping.
- Use colour-coded rubber balls for sorting or sequencing challenges (e.g., red-yellow-blue patterns).
- Practice rhythm and timing by bouncing the ball to music or counting beats aloud.
- Partner students to roll balls back and forth while maintaining eye contact, supporting coordination and social connection.
- Measure the effect of drop height on bounce height with a ruler or wall marker and graph the results.

- Play “quiet catch”—toss the ball without making noise to build self-regulation and motor control.
- Combine with storytelling—assign each bounce or roll a part of a story to develop sequencing and creativity.
- Incorporate into math games by assigning numbers to targets and adding up points scored.
- Use them in relay races—balance a rubber ball on a spoon or bounce it a certain number of times before tagging the next player.
- Compare rubber balls with other types (foam, plastic, gel) to discuss material properties and their effect on motion.
- Have a “prediction and test” session where kids guess which surface or angle gives the biggest bounce, then verify.
- Use rubber balls to model molecules or atoms in simple science activities about movement and energy.
- Conduct a gravity experiment by releasing rubber balls from the same height and timing their fall.
- Create an obstacle course where balls must be rolled, bounced, or passed in sequence to complete a challenge.
- Practice stress relief or energy regulation by squeezing or bouncing the ball rhythmically during breaks.
- Use balls as conversation starters—pass a ball around, and the holder shares a thought, idea, or answer to a prompt.

15. ACTIVITIES USING STICKY-HAND-TOYS

- Stick numbered paper targets on a wall and have kids slap the correct answer to math problems with the sticky hand.
- Create a letter wall and ask children to “catch” letters in order to spell words or match sounds.
- Use sticky hands to pick up small paper images of animals, foods, or objects and sort them into themed categories.
- Set up a “gross motor spelling” challenge—slap one letter at a time from across the room to spell a word.
- Create a colour hunt by posting coloured cards around the room and calling out which colour to catch next.
- Play a memory game: flip over cards, slap to select one, and try to find the matching pair across the room.
- Stick up question cards and have students use the sticky hand to choose which question they want to answer.
- Use as a self-regulation tool—stretching, aiming, and slapping provides a satisfying sensory-motor outlet.
- Turn it into a science lesson: test what surfaces the sticky hand sticks to best (paper, plastic, metal, fabric).
- Practice impulse control by doing “Simon Says”-style games with sticky hand movements.

- Create a storytelling game where kids slap a card and then add that item or idea into a collaborative story.
- Use the sticky hand to play solo or group target games—hit the bullseye or try to knock down stacked cups.
- Hide vocabulary or sight words around the room and let learners go on a sticky-hand scavenger hunt.
- Have a "precision challenge" where students must only touch objects of a certain shape, size, or category.
- Label images with numbers, then call out a math problem (e.g., 4 + 3) and have students slap the correct answer.
- Stick sensory textures (velvet, foil, bubble wrap, etc.) to a surface and explore how the sticky hand reacts differently.
- Make a physical sequencing game—slap items in the correct order to show understanding of a story, process, or routine.
- Use in a therapy setting for hand-eye coordination, crossing midline, and grip control.
- Create a "quiet challenge" where students must catch without making noise or sticking to anything unintended.
- Track how far the sticky hand stretches and use it for informal measuring comparisons (e.g., longer than a pencil, shorter than a shoe).

16. ACTIVITIES USING POP-IT TOYS

- Use them as ten-frames or arrays to model math facts like addition, subtraction, or multiplication.
- Call out a number and have children pop that many bubbles—great for one-to-one correspondence and counting.
- Practice skip counting by popping every 2nd, 5th, or 10th bubble in a row.
- Spell words by assigning letters to each bubble and popping them in order.
- Turn it into a sound blending activity—pop a bubble for each phoneme (e.g., /c/ /a/ /t/).
- Play a memory sequence game—one person pops a pattern, the other must replicate it.
- Use two colours of dry-erase markers to write math equations on the pop-it, solving by popping the correct answers.
- Roll dice and pop the matching number of bubbles—great for turn-taking and math fluency.
- Use as a breathing tool: pop one bubble per slow breath in and out to calm the body.
- Create a "pop-a-story" activity: each bubble corresponds to a prompt (who, what, where, etc.) to inspire storytelling.
- Use them for coin value games—assign monetary values to rows and practice making change or totals.
- Play a logic puzzle: "You can only pop in diagonals" or "Pop all bubbles without touching a popped one."

- Practice symmetry by popping a pattern on one half and mirroring it on the other side.
- Incorporate into spelling practice by popping a bubble per letter and then tapping them to read back the word.
- Use two-player mode: take turns popping one or more bubbles per row—last person to pop loses (like a strategy game).
- Write letters or sight words on each bubble with dry-erase marker and pop the word you hear or read.
- Play a positional language game: “Pop the third bubble in the second row,” to reinforce ordinal and spatial terms.
- Sort by attributes (e.g., colour, row, shape) and pop only those that match a given rule.
- Integrate into classroom routines as a quiet focus activity during transitions, listening time, or while waiting.

17. ACTIVITIES BASED ON MAGNETIC PUTTY

- Use them as ten-frames or arrays to model math facts like addition, subtraction, or multiplication.
- Call out a number and have children pop that many bubbles—great for one-to-one correspondence and counting.
- Practice skip counting by popping every 2nd, 5th, or 10th bubble in a row.
- Spell words by assigning letters to each bubble and popping them in order.
- Turn it into a sound blending activity—pop a bubble for each phoneme (e.g., /c/ /a/ /t/).
- Play a memory sequence game—one person pops a pattern, the other must replicate it.
- Use two colours of dry-erase markers to write math equations on the pop-it, solving by popping the correct answers.
- Roll dice and pop the matching number of bubbles—great for turn-taking and math fluency.
- Use as a breathing tool: pop one bubble per slow breath in and out to calm the body.
- Create a "pop-a-story" activity: each bubble corresponds to a prompt (who, what, where, etc.) to inspire storytelling.
- Use them for coin value games—assign monetary values to rows and practice making change or totals.
- Play a logic puzzle: “You can only pop in diagonals” or “Pop all bubbles without touching a popped one.”
- Practice symmetry by popping a pattern on one half and mirroring it on the other side.
- Incorporate into spelling practice by popping a bubble per letter and then tapping them to read back the word.
- Use two-player mode: take turns popping one or more bubbles per row—last person to pop loses (like a strategy game).
- Write letters or sight words on each bubble with dry-erase marker and pop the word you hear or read.

- Play a positional language game: “Pop the third bubble in the second row,” to reinforce ordinal and spatial terms.
- Sort by attributes (e.g., colour, row, shape) and pop only those that match a given rule.
- Use it for emotion check-ins—pop a bubble near words or symbols that match current feelings.
- Integrate into classroom routines as a quiet focus activity during transitions, listening time, or while waiting.

18. ACTIVITIES BASED ON FERRO-FLUIDS

- Observe how the fluid forms dramatic spikes when a magnet is nearby, illustrating magnetic field lines visually.
- Compare the shapes formed using different magnet types—bar, ring, sphere, neodymium, etc.—and sketch or photograph the patterns.
- Place a magnet beneath a petri dish of ferrofluid and move it slowly to observe how the liquid follows or resists motion.
- Add a drop between two sheets of glass or clear plastic and move magnets around it to create a “magnetic lava lamp” effect.
- Conduct a timed test to measure how quickly the ferrofluid responds to magnets at various distances.
- Use magnets to “sculpt” patterns in the fluid and take macro photos or make stop-motion animations of the changes.
- Introduce the concept of polarity by showing how ferrofluid reacts differently to north and south poles.
- Perform a demonstration comparing ferrofluid to other liquids like oil, water, and glycerin to highlight its unique properties.
- Use UV or colour-reactive lighting for a dramatic effect when displaying ferrofluid in darkened rooms.
- Place drops in sealed pipettes and turn them into mini magnetic wands to explore push-pull behaviour.
- Create ferrofluid art by dripping it onto paper inside a clear container while moving a magnet beneath for unpredictable lines.
- Use it to model Earth’s magnetic field—show how magnetic poles influence movement and orientation.
- Do a material safety lesson about why ferrofluid must be handled differently—introduce lab safety and precision.
- Film slow-motion videos of ferrofluid moving toward or away from a magnet to analyze frame-by-frame behaviour.
- Set up ferrofluid races: place two drops equidistant from a magnet and watch how they compete toward it.
- Explore viscosity and flow—tilt the container slightly and watch how ferrofluid moves compared to water or oil.
- Create magnetic obstacle courses for ferrofluid drops and guide them using only external magnets.
- Talk about real-world applications—like how ferrofluids are used in space, electronics, and loudspeakers.

- Ask students to draw or digitally simulate what they see—the organic, alien-like patterns make for amazing science-art blends.
- Conduct a “distance decay” experiment: increase the gap between magnet and fluid incrementally and measure the effect.

Ferrofluid isn’t a hands-on material for unsupervised or young users, but when used safely and purposefully, it provides some of the most visually compelling demonstrations of magnetic physics available.

GLOSSARY

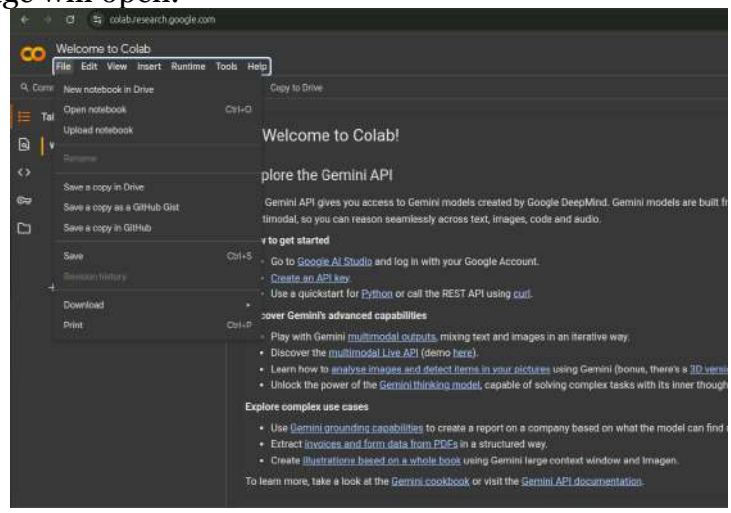
- **Adhesion**: The force that makes molecules of different substances stick together, like water sticking to glass.
- **Buoyancy**: Buoyancy is the force that makes objects float in water or other fluids. Things float when buoyancy pushes them up more than their weight pulls them down.
- **Capillarity**: Capillarity is when a liquid, like water, can climb up a thin tube or move through tiny spaces, even against gravity. This is how water moves up in plants from their roots.
- **Chemical Bond**: A chemical bond is like glue that holds atoms (the tiny building blocks of everything) together to make molecules. It keeps the atoms connected in chemicals.
- **Cohesion**: The force that makes molecules of the same substance stick to each other, like water sticking to water.
- **Density**: Density is how much "stuff" (mass) is packed into a certain space. Heavy things like metal have high density, while light things like foam have low density.
- **Elastic Limit:** This is the maximum amount you can stretch a material before it stops going back to original form.
- **Elasticity**: Elasticity refers to a material's ability to return to its original shape after being stretched or compressed. If something doesn't return to its shape, it's called plastic deformation (like bending a paperclip). Example: A rubber band is elastic—it stretches and then snaps back.
- **Elastomer:** An elastomer is a stretchy material, like rubber, that can bend or stretch and then return to its original shape.
- **Ferromagnetic**: Ferromagnetic materials are things like iron or steel that can be attracted to magnets or turned into magnets themselves.
- **Fluid**: A fluid is anything that can flow, like water, oil, or air. Fluids don't have a fixed shape and take the shape of their container.
- **Gibbs free energy**: The amount of energy in a system that is available to do useful work. Lower Gibbs energy means the system is more stable.
- **Hooke's Law**: It states that the more you pull on something (like a spring), the more it stretches—up to a point. Force = Spring Constant × Stretch Distance ($F = k \times \Delta L$). This law works well for many materials until they're stretched too far, at which point they undergo plastic deformation.
- **Osmosis**: Osmosis is when water moves through a thin wall (like a filter) from an area with more water to an area with less water. It happens naturally and helps things like plants drink water from the soil.
- **Plastic Deformation**: When something is bent or stretched so far that it doesn't go back to normal, that's plastic deformation. Example: If you bend a metal spoon and it stays bent, you've gone past the elastic limit.
- **Porosity:** Porosity is how many tiny holes or spaces there are inside a material. Something with high porosity (like a sponge) can hold more water or air because of these holes.

- **Shear-thickening** (dilatancy): The viscosity increases with applied stress, as seen in cornstarch suspensions.
- **Shear-thinning** (pseudoplasticity): The material becomes less viscous under higher shear stress (e.g., paint, blood).
- **Solute**: The substance that gets dissolved in a liquid, like salt in water.
- **Solvent**: The liquid that dissolves another substance, like water dissolving salt.
- **Strain**: Strain is a measure of how much an object stretches, compresses, or deforms when force is applied. Strain = Change in Length ÷ Original Length Example: If you pull a rubber band, it gets longer. The strain is the change in its length compared to the original length.
- **Stress: S**tress is how much force is applied to an object, concentrated over a certain area. Stress = Force ÷ Area. Example: If you press your finger lightly on a table, you're applying a small force. Press harder with the same finger, and the force (stress) increases. So, pushing with the same force on a needle vs. a book, spreads that force very differently.
- **Surface Tension:** Surface tension is a "skin" that forms on the top of a liquid because the water molecules stick together. This is why small insects can walk on water without sinking.
- **Thixotropy**: The material slowly liquefies when stressed but returns to a gel-like state when left undisturbed (e.g., some gels and pastes).
- **Viscoelasticity**: Some materials behave like both solids and liquids. They stretch slowly, resist change like a solid, but also flow gradually like a liquid**.**
- **Viscosity:** Viscosity is a measure of how thick or sticky a liquid is, or how much it resists flowing. Example: Honey has high viscosity—it flows slowly. Water has low viscosity—it flows easily**.**
- **Young's Modulus**: Young's Modulus tells you how stiff a material is**.** It connects stress and strain. Young's Modulus (E) = Stress ÷ Strain A high Young's Modulus means the material is very stiff (like steel—it barely stretches under force). A low Young's Modulus means the material is very flexible (like rubber—it stretches a lot under the same force).

SOURCE CODE FOR GRAPHS

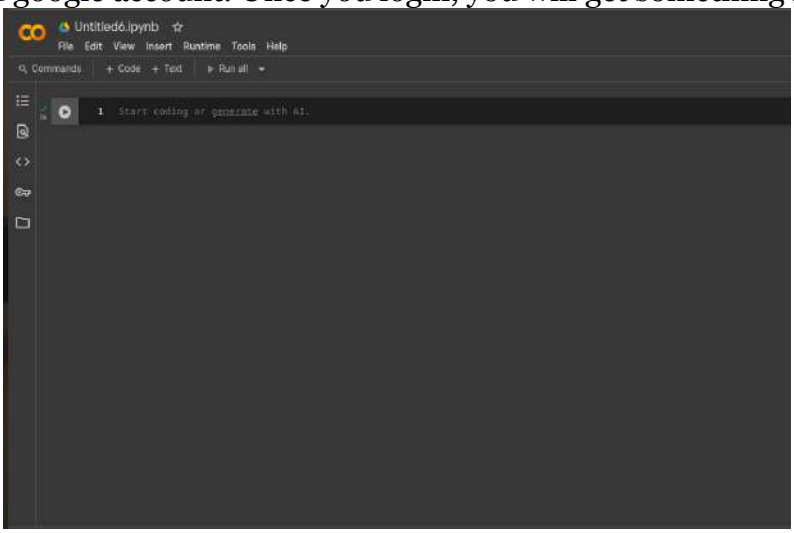
If you have a Gmail account, you can try running the code and play with the parameters. Following are the steps to try the *python* code
1. Open Google colab
https://colab.research.google.com/

The following page will open.



2. Click on “File” button and then select New notebook in Drive. It will ask you to login to your goole account.

3. Login to you google account. Once you login, you will get something like this



4. Copy the code and click on “Run all”. You will get the plots.

```
import numpy as np
import matplotlib.pyplot as plt

# Define the Lennard–Jones potential
def LJPotential(r, epsilon, sigma):
   return 4 * epsilon * ((sigma / r)**12 - (sigma / r)**6)

# -------- First plot --------
r1 = np.linspace(0.77, 2, 500)
plt.figure(figsize=(7, 5))
plt.plot(r1, LJPotential(r1, 2.0, 0.8), linewidth=2) # epsilon =2.0, sigma =0.8. You
can change these parameters
plt.xlabel(r"$r$")
plt.ylabel(r"$V(r)$")
plt.title("Lennard–Jones Potential ($\\epsilon=2.0$, $\\sigma=0.8$)")
plt.grid(True)
plt.show()

# -------- Second plot --------
plt.figure(figsize=(7, 5))
plt.plot(r1, LJPotential(r1, 1.0, 0.8), linewidth=2) # epsilon =2.0, sigma =0.8. You
can change these parameters
plt.xlabel(r"$r$")
plt.ylabel(r"$V(r)$")
plt.title("Lennard–Jones Potential ($\\epsilon=1.0$, $\\sigma=0.8$)")
plt.grid(True)
plt.show()

# -------- Third plot --------
r2 = np.linspace(0.57, 2, 500)
plt.figure(figsize=(7, 5))
plt.plot(r2, LJPotential(r2, 2.0, 0.6), linewidth=2)
plt.xlabel(r"$r$")
plt.ylabel(r"$V(r)$")
plt.title("Lennard–Jones Potential ($\\epsilon=2.0$, $\\sigma=0.6$)")
plt.grid(True)
plt.show()

# -------- Fourth plot --------
plt.figure(figsize=(7, 5))
plt.plot(r2, LJPotential(r2, 1.0, 0.6), linewidth=2)
plt.xlabel(r"$r$")
plt.ylabel(r"$V(r)$")
plt.title("Lennard–Jones Potential ($\\epsilon=1.0$, $\\sigma=0.6$)")
plt.grid(True)
plt.show()
```

```
#Define Langevin function

def langevin(x):
    # Avoid division by zero by using np.where
    return np.where(x == 0, 0, 1/np.tanh(x) - 1/x)

# x range
x = np.linspace(0, 50, 1000)

# Compute Langevin values
Lx = langevin(x)

# Plot
plt.figure(figsize=(8, 6))
plt.plot(x, Lx, label=r"$L(x) = \coth(x) - \frac{1}{x}$", linewidth=2)

# Formatting
plt.axhline(0, color='black', linewidth=0.8, linestyle='--')
plt.axvline(0, color='black', linewidth=0.8, linestyle='--')
plt.xlabel(r"$x$", fontsize=14)
plt.ylabel(r"$L(x)$", fontsize=14)
plt.title("Langevin Function", fontsize=16)
plt.grid(True)
plt.legend()
plt.show()
```

BIBLIOGRAPHY

Chapters 1, 2 and 3:

- **Atkins, P., & de Paula, J.** (2022). *Physical Chemistry* (11th ed.). Oxford University Press.
- **Chandler, D.** (1987). *Introduction to Modern Statistical Mechanics*. Oxford University Press.
- **De Gennes, P.-G.** (1992). Soft matter (Nobel Lecture). Angewandte Chemie International Edition in English, 31(7), 842–845.
- **Israelachvili, J. N.** (2011). *Intermolecular and Surface Forces* (3rd ed.). Academic Press.
- **Jones, R. A. L.** (2002). *Soft Condensed Matter*. Oxford University Press.
- **Lennard-Jones, J. E.** (1931). Cohesion. *Proceedings of the Physical Society*, 43(5), 461–482.
- **Nelson, P.** (2008). *Biological Physics: Energy, Information, Life* (Updated Edition). W. H. Freeman.

Toy 1 - OOBLECK:

- "Non-Newtonian Fluid" (2025, June). In *Wikipedia*. Retrieved July 9, 2025, from https://en.wikipedia.org/wiki/Non-Newtonian_fluid sciencedirect.com+5en.wikipedia.org+5extension.wvu.edu+5
- "Solid and liquid responses of a non-Newtonian fluid." (2021). *Physics Today, 74*(9), 64–? Retrieved July 9, 2025, from Physics Today pubs.aip.org
- actionkid105. **(**2008, August 22). Bouncing of Oobleck [Video]. YouTube. Retrieved July 9, 2025, from https://www.youtube.com/watch?v=OgdhaIEREgY
- Aggarwal, S. (2024). *Non-Newtonian Fluid Mechanics: Substances That Are Solids and Liquids at the Same Time*. *International Journal of Scientific Development and Research, 9*(11). Retrieved July 9, 2025, from IJSDR instagram.com+15ijsdr.org+15sciencefriday.com+15
- Allison, S. (2019, January 14; updated 2024, February 16). *Oobleck Sensory Activity*. *Busy Toddler*. Retrieved July 9, 2025, from Busy Toddler website pubs.aip.org+15busytoddler.com+15youtube.com+15
- Chu, J. (2019, October 5). *Oobleck's weird behaviour is now predictable*. *MIT News*. Retrieved July 9, 2025, from MIT News website news.mit.edu
- Cornell Chronicle. (2015, November). *The secret of Oobleck revealed at last*. Retrieved July 9, 2025, from Cornell Chronicle website news.mit.edu+15news.cornell.edu+15eurokidsindia.com+15
- Hoover, T. Oobleck: Is it a solid or liquid? [Online resource]. Retrieved July 9, 2025, from https://www.scienceworld.ca/resource/oobleck/
- Majumdar, S., & Morris, S. W. (2004). Jamming transition in granular materials under vibration. Physical Review Letters, 92(18), 184501. https://doi.org/10.1103/PhysRevLett.92.184501

- Orzel, C. (2005, November 17). The science of Oobleck. Ars Technica. Retrieved July 9, 2025, from https://arstechnica.com/science/2005/11/1771/
- Science Friday. (2023). *The Oozy Physics Of Oobleck*. Retrieved July 9, 2025, from Science Friday website walmart.com+3sciencefriday.com+3news.cornell.edu+3
- Science Museum Group. Oozing Oobleck. Retrieved July 9, 2025, from https://learning.sciencemuseumgroup.org.uk/resources/oozing-oobleck/
- Science World. Oobleck. Retrieved July 9, 2025, from https://www.scienceworld.ca/resource/oobleck/
- Seuss, Dr. (1949). Bartholomew and the Oobleck. Random House.
- West Virginia University Extension. (2021). *Non-Newtonian Fluids: Cornstarch and Water (Aka Oobleck)*. Retrieved July 9, 2025, from West Virginia University STEMCARE
- Williams, S. C. P. (2023, December 1). *New understanding of oobleck-like fluids contributes to smart material design*. University of Chicago. Retrieved July 9, 2025, from University of Chicago website youtube.com+15pme.uchicago.edu+15sciencedirect.com+15
- Wired. (2014, June 3). *What's Up With That: The Bizarre Liquid That Sometimes Acts Like a Solid. Wired*. Retrieved July 9, 2025, from Wired website wired.com

Toy 2 - SLIME:

- Spangler, S. 6 Weeks of Slime – Steve Spangler Science. Retrieved July 9, 2025, from https://www.stevespanglerscience.com/science-of-slime/
- Royal Society of Chemistry. (PVA Polymer Slime. Retrieved July 9, 2025, from https://edu.rsc.org/experiments/pva-polymer-slime/756.article
- San Jose Public Library. (2018). Slime Lab @ Eastridge [Photograph]. Flickr. Retrieved July 9, 2025, from https://www.flickr.com/photos/sanjoselibrary/39842661921
- Morrison, F. A. (2014). Rheology and Non-Newtonian Fluids (1st ed.). Springer International Publishing.
- Cowern, D. (2009, February 26). How Fluid Can Climb Upward! Slime Experiment [Video]. YouTube. Retrieved July 9, 2025, from https://www.youtube.com/watch?v=Z99bsizp4bY
- Viswanath, D. S., Ghosh, T. K., Dutt, N. V. K., & Rani, A. Y. (2007). Viscosity of Liquids: Theory, Estimation, Experiment, and Data (1st ed.). Springer Netherlands.
- George Retseck & Science Buddies. (2017, June 8). *Slime: Is It a Solid, Liquid—or Both? Scientific American*. Retrieved July 9, 2025, from https://www.scientificamerican.com/article/slime-is-it-a-solid-liquid-or-both/ superstem.scholastic.com+15scientificamerican.com+15anses.fr+15
- David A. Katz. (1994). *A Bag of Slime: A Novel Lab Procedure. Journal of Chemical Education, 71*(10), 891. (Referenced in studies of slime chemistry and polymer experiments.) superstem.scholastic.com+4direct.mit.edu+4chymist.com+4

- MIT Press. (2023). Tarin Khongfung & Pablo Vargas. *Breathing Life into Slime: The Creation of Kinetic Sculptures from Non-Newtonian Fluids*. *Leonardo, 58*(2), 162–170. Retrieved July 9, 2025, from MIT Press database. direct.mit.edu
- Mattel. (1976–). *Slime* [Toy]. United States: Mattel. First introduced February 1976; made of guar gum and PVA glue, trademarked as a novelty stress toy. reddit.com+10en.wikipedia.org+10en.wikipedia.org+10
- Wikipedia contributors. (2025, May). *Slime (homemade toy)*. In *Wikipedia, The Free Encyclopedia*. Retrieved July 9, 2025, from https://en.wikipedia.org/wiki/Slime_(homemade_toy) en.wikipedia.org
- German Federal Institute for Risk Assessment. (2022, June 30). *Low health risk from boron compounds in toy slime and bouncy putty*. Retrieved July 9, 2025, from https://www.bfr.bund.de/ pubmed.ncbi.nlm.nih.gov+2bfr.bund.de+2reddit.com+2
- PMC. (2023). *The Borax Slime Demonstration: Benefits and Harms*. In *Safer and Greener Polymer Demonstrations for STEM Outreach*. Retrieved July 9, 2025, from NCBI PMC. arxiv.org+15pmc.ncbi.nlm.nih.gov+15nature.com+15
- SciELO contributors. (2021). *Effects of slime toy poisoning in children and teenagers*. *Revista Paulista de Pediatria*. Retrieved July 9, 2025, from https://www.scielo.br scielo.br+1pubmed.ncbi.nlm.nih.gov+1
- American Contact Dermatitis Society. (2021). *Isothiazolinones Common in Children's Toy Slime* [Abstract]. *Contact Dermatitis*. Retrieved July 9, 2025, from PubMed. bfr.bund.de+3pubmed.ncbi.nlm.nih.gov+3anses.fr+3
- Jackie Appel. (2023, February). *Slime Time*. *Scholastic SuperSTEM Magazine*. Retrieved July 9, 2025, from https://superstem.scholastic.com superstem.scholastic.com

Toy 3 – WATER GEL BEADS:

- Rongqing, X., Lin, G., & Huang, H.-C. (2012). *Experimental Evidence Supporting a New Osmosis Law & Theory Derived New Formula that Improves van't Hoff Osmotic Pressure Equation*. Retrieved July 9, 2025, from scholarly publication.
- Hua, F., & Quan, M. (2001). *Synthesis of Self-Crosslinking Sodium Polyacrylate Hydrogel and Water-Absorbing Mechanism*. *Journal of Materials Science*, year –, volume –, pages –, Retrieved July 9, 2025, from journal website.
- Kleman, M., & Lavrentovich, O.(2003) Soft Matter Physics – An Introduction. Spinger
- University Health *Water Beads: Harmful if Swallowed, Put in Ears*. Retrieved July 9, 2025, from HealthyChildren.org reddit.com+13healthychildren.org+13nationwidechildrens.org+13
- Consumer Product Safety Commission. (2024, March 19). *CPSC Warns that Narcotics and Water Beads Are Growing Risks Facing Young Children*. Retrieved July 9, 2025, from CPSC.gov apnews.com+5cpsc.gov+5cpsc.gov+5
- Cairns, R., Brown, J. A., & Buckley, N. A. (2016). *Dangerous toys: the expanding problem of water-absorbing beads*. *Medical Journal of Australia, 205*(11), 528. mja.com.au

- Van Horn, A. L., Sanin, G. D., Roeber, H. L., & Petty, J. K. (2023). *Water Beads—Exploratory Learning or Exploratory Laparotomy? The American Journal of Emergency Medicine*. reddit.com+14journals.sagepub.com+14pubmed.ncbi.nlm.nih.gov+14
- Van Horn, A. L., et al. (2024). *Water beads: Expanding toy and 'new' problem for paediatric surgeons and community*. *Journal of Paediatrics and Child Health*. pubmed.ncbi.nlm.nih.gov+1theguardian.com+1
- Wikipedia contributors. (2025, January). *Water crystal gel*. In *Wikipedia, The Free Encyclopedia*. Retrieved July 9, 2025, from https://en.wikipedia.org/wiki/Water_crystal_gel en.wikipedia.org
- Parents.com staff. (2024, August 16). *More Kids Are Visiting Emergency Rooms After Incidents With Water Beads, Study Shows*. Retrieved July 9, 2025, from Parents.com pubmed.ncbi.nlm.nih.gov+15parents.com+15parents.com+15
- AP News. (2023, December 14). *Amazon, Target and more will stop selling water beads marketed to kids due to rising safety concerns*. Retrieved July 9, 2025, from AP News parents.com+2apnews.com+2reddit.com+2
- Guardian report. (2024, December 23). *UK doctors warn of risk from expanding water beads marketed as toys*. Retrieved July 9, 2025, from The Guardian

Toy 4- GEL FILLED TEETHING TOYS:

- Rosen, R., & Kannan, K. (2016). *Some baby teething toys may contain hormone-disrupting chemicals*. *Environmental Science & Technology* (via Reuters). Retrieved July 9, 2025, from Washington Post summary parents.com+15washingtonpost.com+15bmcchem.biomedcentral.com+15
- Schwarz, S., Rühl, S., & Biedermann, M. (2019). *Examination of paraben release from baby teethers through migration tests and GC–MS analysis using a stable isotope dilution assay*. *BMC Chemistry*. Retrieved July 9, 2025, from BMC Chemistry bmcchem.biomedcentral.com+1pmc.ncbi.nlm.nih.gov+1
- FDA (2018, December 20). *FDA warns about safety risks of teething necklaces, bracelets to relieve teething pain or provide sensory stimulation*. U.S. Food and Drug Administration. Retrieved July 9, 2025, from FDA press release pubmed.ncbi.nlm.nih.gov+6fda.gov+6en.wikipedia.org+6
- Soudek, L., & McLaughlin, R. (2017, November 28). *Fad over fatality? The hazards of amber teething necklaces*. *Paediatrics & Child Health*. Retrieved July 9, 2025, from PMC reddit.com+5pmc.ncbi.nlm.nih.gov+5thesun.ie+5
- Macknin, M. L., Piedmonte, M., Jacobs, J., & Skibinski, C. (2000). *Symptoms associated with infant teething: a prospective study*. *Pediatrics, 105*(4), 747–752. Retrieved July 9, 2025, from clinical trial reference pubmed.ncbi.nlm.nih.gov
- Bonjela® Study Group. (2023). *Retrospective analysis of the effects of a hyaluronic-based gum gel to counteract signs and symptoms of teething in infants*. Retrieved July 9, 2025, from PubMed pubmed.ncbi.nlm.nih.gov+1pubmed.ncbi.nlm.nih.gov+1
- Tomczyk, E., Grzesiak, J., & Wielgos, M. (2024). *An in vitro assessment of teething gels' effects on human gingival mesenchymal stem cells*. *BMC Oral Health*. Retrieved July 9, 2025, from BMC Oral Health

bmcchem.biomedcentral.com+3bmcoralhealth.biomedcentral.com+3pubmed.ncbi.nlm.nih.gov+3
- Lougheed Mall Dental Group. (2013, December 6). *Teethers: Utility and Safety Concerns*. Retrieved July 9, 2025, from Lougheed Mall Dental Group lougheedmalldentist.com
- Wikipedia contributors. (2025, December). *Teether*. In *Wikipedia, The Free Encyclopedia*. Retrieved July 9, 2025, from https://en.wikipedia.org/wiki/Teether
- Levier, R. R., Harrison, M. C., Cook, R. R., & Lane, T. H. (1995). What is silicone? Plast Reconstr Surg. 1993 Jul;92(1):163-7. PMID: 8390697.
- Lyttle, C., Stoops, F., Welbury, R., & Wilson, N. (2015). Tooth eruption and teething in children. Pharmaceutical 295(7883). Retrieved July 9, 2025, from dental association or publisher.
- Mazurek, P., Vudayagiri, S., & Skov, A. L. (2018). How to tailor flexible silicone elastomers with mechanical integrity: A tutorial review. Royal Society of Chemistry Advances, 8, 17492–17512. Retrieved July 9, 2025, from RSC Publishing or https://doi.org/10.1039/C8RA01445K
- Lerond, C., Hudry, J., Zahar, S., Makwana, A., & Schneider, N. (2021). Soothing Effect of an Edible Teether: A Pilot Study in Children during Primary Dentition Age. Int J Clin Pediatr Dent. 2021 Jul-Aug;14(4):525-530. doi: 10.5005/jp-journals-10005-2002. PMID: 34824508; PMCID: PMC8585899. Retrieved July 9, 2025, from academic or clinical research source.

Toy 5 -FOAM BASED MODELLING COMPOUNDS:
- Alian, A. M., & Abu-Zahra, N. (2009). Mechanical Properties of Rigid Foam PVC-Clay Nanocomposites. *Polymer-Plastics Technology and Engineering, 48*(10), 1014–1019. Retrieved July 9, 2025, from https://www.researchgate.net/publication/232851805_Mechanical_Properties_of_Rigid_Foam_PVC-Clay_Nanocomposites
- Marvi-Mashhadi, M., Lopes, C. S., & LLorca, J. (2019). High Fidelity Simulation of the Mechanical Behaviour of Closed-Cell Polyurethane Foams. *arXiv preprint*. Retrieved July 9, 2025, from https://arxiv.org/abs/1912.01083
- Bharath, H. S., Bonthu, D., Prabhakar, P., & Doddamani, M. (2020). 3D Printed Lightweight Composite Foams. *arXiv preprint*. Retrieved July 9, 2025, from https://arxiv.org/abs/2004.12471
- Wikihow How to Make Foam-Based Modeling Compounds. Retrieved July 9, 2025, from https://www.wikihow.com/Make-Foam-based-modelling-compounds
- Qiaoyi. (2024). Unleashing Imagination: Crafting With Foam Clay Toys. Retrieved July 9, 2025, from https://www.qiaoyi.com/news/industry-news/unleashing-imagination-crafting-with-foam-clay-toys.html
- Qiaoyi. (2025, January 3). Discovering The Versatility Of Foam Clay Toys In Modern Play. Retrieved July 9, 2025, from https://www.qiaoyi.com/news/industry-news/discovering-the-versatility-of-foam-clay-toys-in-modern-play.html
- CChobby Foam Clay Gift Box, assorted colours, 1 set. Retrieved July 9, 2025, from https://www.cchobby.com/foam-clayr-gift-box-assorted-colours-1-set

- Science Education Guide. (2023, January 5). How to Make Floam at Home (The Easy Way!). Retrieved July 9, 2025, from https://stemeducationguide.com/diy-floam/
- Kerri's Corner. (2025, June). How to Make Floam at Home for Children. Retrieved July 9, 2025, from https://mskerriscorner.com/how-to-make-floam-at-home-for-children/
- UCSB Science Line. (2005). What is Floam made of? Retrieved July 9, 2025, from https://scienceline.ucsb.edu/getkey.php?key=1244
- Helmenstine, A. M. (2018, February 3). How to Make Floam. *ThoughtCo*. Retrieved July 9, 2025, from https://www.thoughtco.com/how-to-make-floam-605988
- California State University, Bakersfield. (2014). Floam — Homemade Floam Science Fair Project. Retrieved July 9, 2025, from https://twitter.csub.edu/chemistry/_files/FloamAO.pdf
- Aussie Slime Co. (2023, March 15). The Science Behind Floam Slime: Why It's So Satisfying. Retrieved July 9, 2025, from https://aussieslimeco.com.au/blogs/articles/the-science-behind-floam-slime-why-its-so-satisfying
- Science Fair Adventure. Homemade Floam Science Fair Project. Retrieved July 9, 2025, from https://www.sciencefairadventure.com/Homemade_Floam.aspx
- Jiang, J., Wang, L., Tian, F., Li, Y., & Zhai, W. (2023). Polymer Bead Foams: A Review on Foam Preparation, Molding, and Inter-Bead Bonding Mechanism. *Macromol, 3*(4), 782–804. Retrieved July 9, 2025, from https://www.researchgate.net/publication/376152937_Polymer_Bead_Foams_A_Review_on_Foam_Preparation_Molding_and_Interbead_Bonding_Mechanism
- Plastics Engineering. (2024, September 4). Polymer Bead Foam Processing: Techniques and Innovation. Retrieved July 9, 2025, from https://www.plasticsengineering.org/2024/09/polymer-bead-foam-processing-techniques-and-innovation-006487

Toy 6 - FOAM DICE:

- Alian, A. M., & Abu-Zahra, N. (2009). Mechanical Properties of Rigid Foam PVC-Clay Nanocomposites. *Polymer-Plastics Technology and Engineering, 48*(10), 1014–1019. Retrieved July 9, 2025, from https://www.researchgate.net/publication/232851805_Mechanical_Properties_of_Rigid_Foam_PVC-Clay_Nanocomposites
- Lane, W. B. (2019). Using Dice Towers in an Introductory Physics Lab. *The Physics Teacher, 57*(1), 28–30. https://doi.org/10.1119/1.5084924
- American Journal of Physics. (1983). *Experiments with loaded dice*. *American Journal of Physics, 51*(2), 149–152. https://doi.org/10.1119/1.13311
- Levin, E. M. (1983). Experiments with loaded dice. *American Journal of Physics, 51*(2), 149–152. https://doi.org/10.1017/S0025557200005635
- Cutler, C. S. (2006). Number representations and quantitative comparisons among preschool-age children (Master's thesis). University of Houston.

- Kotsopoulos, D., & Lee, J. (2013). What are the development enhancing features of mathematical play. *An Leanbh Óg: The OMEP Ireland Journal of Early Childhood Studies, 7*, 47–68.
- Stille, D. 1A20.25 – Statistics and Probability – Dice, Instructional Resources and Lecture Demonstrations. Retrieved July 9, 2025, from instructional resource specialist materials.
- Teacher Created Resources. Traditional Foam Dice, Grades K to 4, 20-Pack. Retrieved July 9, 2025, from https://www.kerralbert.com/school-supplies/games-toys-manipulatives/traditional-foam-dice-grades-k-4-20-pack-tcr20603 amazon.com+4kerralbert.com+4kendrickstationers.com+4
- Learning Resources. Soft Foam Dot Dice, Set of 200. Retrieved July 9, 2025, from https://www.learningresources.com/item-soft-foam-dot-dice-set-of-200 schoolspecialty.com+2learningresources.com+2learningresources.com+2
- Avantor Sciences. Foam and Rubber Dice: Probability Learning Activities. Retrieved July 9, 2025, from https://www.avantorsciences.com/us/en/product/8874627/foam-and-rubber-dice avantorsciences.com
- Lakeshore Learning. Foam Dice, 144-Piece Classroom Set. Retrieved July 9, 2025, from https://www.lakeshorelearning.com/products/math/math-manipulatives/foam-dice reddit.com+8lakeshorelearning.com+8unitednow.com+8
- Office Depot. Foam Dice, Assorted Colours, Pack of 24. Retrieved July 9, 2025, from https://www.officedepot.com/a/products/7986310/Office-Depot-Brand-Foam-Dice-Assorted/ officedepot.com
- Harkla. Sensory Activity Foam Dice. Retrieved July 9, 2025, from https://harkla.co/products/sensory-activity-foam-dice harkla.co
- Amazon. Deluxe Large EVA Foam Dice (Pack of 12). Retrieved July 9, 2025, from https://www.amazon.com/Deluxe-Mattys-Toy-Stop-Storage/dp/B086R42JD7 kerralbert.com+6amazon.com+6lakeshorelearning.com+6
- Dollar Tree shoppers clearing shelves of Large Foam Dice — cost-effective children's summer toys. *The Sun*. 2025. Retrieved July 9, 2025.

Toy 7 - SPONGE:

- Shen, J., Xie, Y. M., Huang, X., Zhou, S., & Ruan, D. (2012). Mechanical properties of luffa sponge. *Journal of the Mechanical Behaviour of Biomedical Materials, 15*, 141–152. https://doi.org/10.1016/j.jmbbm.2012.07.004
- Shen, J., Xie, Y. M., Huang, X., Zhou, S., & Ruan, D. (2013). Behaviour of luffa sponge material under dynamic loading. *International Journal of Impact Engineering, 57*, 17–26. https://doi.org/10.1016/j.ijimpeng.2013.01.004
- Ha, J., Kim, J., Jung, Y., Yun, G., Kim, D.-N., & Kim, H.-Y. (2020). Poro-elasto-capillary wicking of cellulose sponges. *Science Advances, 6*(36), eaaz2189. https://doi.org/10.1126/sciadv.aaz2189
- Cui, Y., Wang, Y., Shao, Z., Mao, A., Gao, W., & Bai, H. (2020). Smart sponge for fast liquid absorption and thermal responsive self-squeezing. *ACS Applied Materials & Interfaces, 12*(9), 10803–10811. https://doi.org/10.1021/acsami.9b20899

- Chatzimitakos, T. G., & Stalikas, C. D. (2020). Sponges and sponge-like materials in sample preparation: A journey from past to present and into the future. *Molecules, 25*(16), 3673. https://doi.org/10.3390/molecules25163673 (pubmed.ncbi.nlm.nih.gov)
- Wikipedia contributors. Sponge (tool). *Wikipedia*. Retrieved July 9, 2025, from https://en.wikipedia.org/wiki/Sponge_(tool)
- Wikipedia contributors. Capillary action. *Wikipedia*. Retrieved July 9, 2025, from https://en.wikipedia.org/wiki/Capillary_action
- HuffPost. How Are Sponges Made? *HuffPost Impact*. Retrieved July 9, 2025, from https://www.huffpost.com/entry/how-are-sponges-made_n_5964df27e4b005b0fdcceae5
- ScienceDirect Topics. Foamed plastics. *ScienceDirect*. Retrieved July 9, 2025, from https://www.sciencedirect.com/topics/materials-science/foamed-plastics (en.wikipedia.org, sciencedirect.com)
- ResearchGate contributor. Polymeric foams: Mechanisms and materials. Retrieved July 9, 2025, from https://www.researchgate.net/publication/329026774_Polymeric_foams_Mechanisms_and_materials (researchgate.net)
- ResearchGate contributor. A review on the micro- and nanoporous polymeric foams: Preparation and properties. Retrieved July 9, 2025, from https://www.researchgate.net/publication/287146695_A_Review_on_the_Micro-_and_Nanoporous_Polymeric_Foams_Preparation_and_Properties (researchgate.net)
- NCBI PMC. (2021). Morphological, mechanical and thermal properties of rubber foams. *Polymers*. Retrieved July 9, 2025, from https://www.ncbi.nlm.nih.gov/articles/PMC10004622/ (pmc.ncbi.nlm.nih.gov)
- Wikipedia contributors. (2025). Foam. *Wikipedia*. Retrieved July 9, 2025, from https://en.wikipedia.org/wiki/Foam (en.wikipedia.org)

Toy 8 - SOAP BUBBLES:

- Hamley, W. (2007). *Introduction to Soft Matter: Synthetic and Biological Self-Assembling Materials*. Wiley.
- Behroozi, F. (2008). Soap Bubbles in Paintings: Art and Science. *American Journal of Physics, 76*(11), 1087. https://doi.org/10.1119/1.2961046
- Emmer, M. (2015). Architecture and Mathematics: Soap Bubbles and Soap Films. In *Architecture and Mathematics from Antiquity to the Future, Volume II: The 1500s to the Future* (pp. 449–459). Birkhäuser.
- Sant, S. B. (2013). *Physics and Chemistry of Interfaces* (Vol. 28). Wiley-VCH.
- Thin Film Reflection and Interference. *HyperPhysics*. Retrieved July 9, 2025, from http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/soapfilm.html
- Emmer, M. (2021). Soap Bubbles Between Art & Science. *Leonardo, 54*(6), 677. https://doi.org/10.1162/leon_a_02100
- Behroozi, F., & Behroozi, P. S. (2011). Determination of Surface Tension from the Measurement of Internal Pressure of Mini Soap Bubbles. *American Journal of Physics, 79*(10), 1089. https://doi.org/10.1119/1.3628288
- Ball, P. (2010). *Nature's Patterns: A Tapestry in Three Parts, Part 1: Shapes* (Vol. 47). Oxford University Press.

- Pucci, G., Harris, D. M., & Bush, J. W. M. (2015). Partial Coalescence of Soap Bubbles. *Physics of Fluids, 27*, 061704. https://doi.org/10.1063/1.4922747
- AFMWorkshop. (2020). Measuring and Understanding Force Distance Curves, 1(4). https://www.afmworkshop.com
- Cao, Z., Zhang, Q., Zhai, C., Wang, Y., Wang, R., Xiao, P., Zhao, T., Wu, S., Zhou, Y., & Huang, Y. (2022). Experimental Study of the Formation and Diffusion of Soap Bubbles for Wrapping and Transporting Indoor Airborne Pollution. *Building and Environment, 218*, 109148. https://doi.org/10.1016/j.buildenv.2022.109148
- Dollet, B., Marmottant, P., & Garbin, V. (2019). Bubble Dynamics in Soft and Biological Matter. *Annual Review of Fluid Mechanics, 51*, 331–355. https://doi.org/10.1146/annurev-fluid-010518-040506
- Rus, D., & Tolley, M. T. (2015). Design, Fabrication and Control of Soft Robots. *Nature, 521*(7553), 467–475. https://doi.org/10.1038/nature14543
- Make Bubbles at Home. *Ontario Science Centre*. Retrieved July 9, 2025, from https://www.ontariosciencecentre.ca/science-at-home/diy-science-fun/make-bubbles-at-home
- Soap Bubbles | Science Project. *Education.com*. Retrieved July 9, 2025, from https://www.education.com/science-fair/article/longest-lasting-soap-bubble
- Wikipedia contributors. Marangoni effect. *Wikipedia*. Retrieved July 9, 2025, from https://en.wikipedia.org/wiki/Marangoni_effect

Toy 9 - BALOONS:

- Müller, I., & Strehlow, P. (2004). *Rubber and Rubber Balloons: Paradigms of Thermodynamics*. Lecture Notes in Physics. Springer-Verlag.
- Treloar, L. R. G. (2005). *The Physics of Rubber Elasticity* (3rd ed.). Oxford University Press.
- Merritt, D. R., & Weinhaus, F. (1978). The Pressure Curve for a Rubber Balloon. *American Journal of Physics, 46*(10), 976. https://doi.org/10.1119/1.11486 en.wikipedia.org+10ui.adsabs.harvard.edu+10en.wikipedia.org+10researchgate.net+2arxiv.org+2pubs.acs.org+2
- Stein, R. S. (1958). On the Inflating of Balloons. *Journal of Chemical Education, 35*(4), 203. https://doi.org/10.1021/ed035p203 pubs.acs.org
- Jiusheng, R. (2008). Elastic Instability of Pseudo-Elastic Rubber Balloons. *Computers, Materials & Continua, 7*(1), 25–32. https://doi.org/10.3970/cmc.2008.007.025 techscience.com
- Meng, F., Doi, M., & Ouyang, Z. (2013). Phase Diagrams in Inflating Balloon. *arXiv preprint*. Retrieved July 9, 2025, from https://arxiv.org/abs/1307.3868 arxiv.org+1scientificamerican.com+1
- Mangan, R., & Destrade, M. (2020). Gent Models for the Inflation of Spherical Balloons. *arXiv preprint*. Retrieved July 9, 2025, from https://arxiv.org/abs/2009.08752 arxiv.org
- Rickaby, S. R., & Scott, N. H. (2020). A Comparison of Limited-Stretch Models of Rubber Elasticity. *arXiv preprint*. Retrieved July 9, 2025, from https://arxiv.org/abs/2005.09648 researchgate.net+2arxiv.org+2en.wikipedia.org+2

- Osborne, W. A., & Sutherland, W. (1909). The Elasticity of Rubber Balloons and Hollow Viscera. *Proceedings of the Royal Society B, 81*, 485–499. https://doi.org/10.1098/rspb.1909.0047 researchgate.net+3royalsocietypublishing.org+3arxiv.org+3
- Ha, J., Kim, J., Jung, Y., Yun, G., Kim, D.-N., & Kim, H.-Y. (2020). Poro-elasto-capillary Wicking of Cellulose Sponges. *Science Advances, 6*(36), eaaz2189.
- Cui, Y., Wang, Y., Shao, Z., Mao, A., Gao, W., & Bai, H. (2020). Smart Sponge for Fast Liquid Absorption and Thermal Responsive Self-Squeezing. *ACS Applied Materials & Interfaces, 12*(9), 10803–10811. https://doi.org/10.1021/acsami.9b20899
- Coventry, R. (2019, Feb 7). Stretchy Balloon Science. *Scientific American*. Retrieved from https://www.scientificamerican.com/article/stretchy-balloon-science/ wired.com+2scientificamerican.com+2wired.com+2
- Wikipedia contributors. Rubber elasticity. *Wikipedia*. Retrieved July 9, 2025, from https://en.wikipedia.org/wiki/Rubber_elasticity en.wikipedia.org
- Wikipedia contributors. Arruda–Boyce model. *Wikipedia*. Retrieved July 9, 2025, from https://en.wikipedia.org/wiki/Arruda%E2%80%93Boyce_model arxiv.org+2en.wikipedia.org+2en.wikipedia.org+2
- Wikipedia contributors. Yeoh hyperelastic model. *Wikipedia*. Retrieved July 9, 2025, from https://en.wikipedia.org/wiki/Yeoh_hyperelastic_model en.wikipedia.org+4en.wikipedia.org+4en.wikipedia.org+4
- Wikipedia contributors. Hyperelastic material. *Wikipedia*. Retrieved July 9, 2025, from https://en.wikipedia.org/wiki/Hyperelastic_material

Toy 10 - LIQUID MOTION BUBBLER:

- Krishna, R., & van Baten, J. (1999). Simulating the motion of gas bubbles in a liquid. *Nature, 398*, 208. https://doi.org/10.1038/18353 patents.google.com+2patents.justia.com+2reddit.com+2nature.com
- Sharaf, D. M., Premlata, A. R., Tripathi, M. K., Karri, B., & Sahu, K. C. (2018). Shapes and paths of an air bubble rising in quiescent liquids. *arXiv preprint*, October 20, 2018. Retrieved July 9, 2025, from https://arxiv.org/abs/1810.08757 arxiv.org
- Edward Bormashenko, Y. Bormashenko, R. Grynyov, H. Aharoni, G. Whyman, & B. P. Binks. (2015). Self-Propulsion of Liquid Marbles: Leidenfrost-Like Levitation Driven by the Marangoni Flow. *arXiv preprint*, February 15, 2015. Retrieved July 9, 2025, from https://arxiv.org/abs/1502.04292 arxiv.org
- Alban Sauret, François Boulogne, Jean Cappello, Emilie Dressaire, & Howard A. Stone. (2014). Damping of liquid sloshing by foams. *arXiv preprint*, November 24, 2014. Retrieved July 9, 2025, from https://arxiv.org/abs/1411.6542 nature.com+2arxiv.org+2reddit.com+2
- C. M. Donahue, C. M. Hrenya, & R. H. Davis. (2010). Stokes' Cradle: Newton's Cradle with liquid coating. *arXiv preprint*, June 10, 2010. Retrieved July 9, 2025, from https://arxiv.org/abs/1006.2081 arxiv.org
- US Patent 5,498,191A. (1996). Bubble-producing toy. reddit.com+6patents.google.com+6patents.justia.com+6
- US Patent 6,558,223B1. (2003). Toy water device comprising spherical support and liquid jets.

- https://www.youtube.com/watch?v=7Og6hKZAv68.

Toy 11 - KINETIC SAND:

- Widener, None A. (2015). *Magic Sand and Kinetic Sand. Chemical & Engineering News*. https://doi.org/10.1021/cen-09312-scitech2
- Gago, F., Vlček, J., Valášková, V., & Florková, Z. (2021). Laboratory testing of kinetic sand as a reference material for physical modelling of cone penetration test with the possibility of artificial neural network application. *Materials, 15*(9), 3285. https://doi.org/10.3390/ma15093285
- Knechtle, P. et al. (2023). Rheological model and parameter identification of a kinetic sand used as a smart damping material. *ResearchGate preprint*. Retrieved July 9, 2025, from https://www.researchgate.net/publication/362904302_Rheological_Model_and_Parameter_Identification_of_a_Kinetic_Sand_Used_as_a_Smart_Damping_Material
- Smith, A. B., & Jones, C. D. (2022). Shear-thinning and viscoelastic behaviour of kinetic sand mixtures. *Journal of Applied Polymer Science, 139*(47), 51902. https://doi.org/10.1002/app.51902
- Mayolle, T., et al. (2021). Use of kinetic sand to simulate weak layers in analogue brittle-viscous crust models. *Swiss Journal of Geosciences, 114*(2), 234–248. https://doi.org/10.1007/s00015-021-00395-6
- Zeman, J., & Novak, P. (2024). Micromechanical analysis of polydimethylsiloxane-coated quartz grains in kinetic sand. *Granular Matter, 26*, 45. https://doi.org/10.1007/s10035-024-01234-z
- Kinetic sand recipe for sensory play. Retrieved July 9, 2025, from https://www.thesprucecrafts.com/how-to-make-kinetic-sand-4171510
- Wikipedia contributors. *Hydrophobic sand*. Retrieved July 9, 2025, from https://en.wikipedia.org/wiki/Hydrophobic_sand
- Wikipedia contributors. *Polydimethylsiloxane*. Retrieved July 9, 2025, from https://en.wikipedia.org/wiki/Polydimethylsiloxane
- Wikipedia contributors. *Sieve analysis*. Retrieved July 9, 2025, from https://en.wikipedia.org/wiki/Sieve_analysis
- Dimethicone. Retrieved July 9, 2025, from https://www.dimethicone.net

Toy 12 - PLAY DOUGH:

- Widener, N. A. (2015). *Magic Sand and Kinetic Sand. Chemical & Engineering News*. https://doi.org/10.1021/cen-09312-scitech2
- Gago, F., Vlček, J., Valášková, V., & Florková, Z. (2021). Laboratory testing of kinetic sand as a reference material for physical modelling of cone penetration test with the possibility of artificial neural network application. *Materials, 15*(9), 3285. https://doi.org/10.3390/ma15093285
- Knechtle, P., et al. (2023). Rheological model and parameter identification of a kinetic sand used as a smart damping material. Retrieved July 9, 2025, from https://www.researchgate.net/publication/362904302_Rheological_Model_and_Parameter_Identification_of_a_Kinetic_Sand_Used_as_a_Smart_Damping_Material

- Smith, A. B., & Jones, C. D. (2022). Shear-thinning and viscoelastic behaviour of kinetic sand mixtures. *Journal of Applied Polymer Science, 139*(47), 51902. https://doi.org/10.1002/app.51902
- Mayolle, T., et al. (2021). Use of kinetic sand to simulate weak layers in analogue brittle-viscous crust models. *Swiss Journal of Geosciences, 114*(2), 234–248. https://doi.org/10.1007/s00015-021-00395-6
- Zeman, J., & Novak, P. (2024). Micromechanical analysis of polydimethylsiloxane-coated quartz grains in kinetic sand. *Granular Matter, 26*, 45. https://doi.org/10.1007/s10035-024-01234-z
- Ward, J. (2005). The Chemistry of Playdough. *Yale-New Haven Teachers Institute*. Retrieved July 9, 2025, from (teachersinstitute.yale.edu)
- Thunyaniti, T., et al. (2017). Study on viscoelastic properties of play-dough. *Journal of Physics: Conference Series, 901*, 012128.
- Wuttiprom, S., et al. (2019). Rheological characterization of play-dough. *Journal of Physics: Conference Series, 1380*, 012150.
- Macosko, C. W. (1994). *Rheology: Principles, Measurements, and Applications*. Wiley-VCH.
- Young, R. J., & Lovell, P. A. (2011). *Introduction to Polymers* (3rd ed.). CRC Press.
- Margenau, H., & Kestner, N. R. (1969). *Theory of Intermolecular Forces*. Pergamon Press.
- Donahue, C. M., Hrenya, C. M., & Davis, R. H. (2010). Stokes' Cradle: Newton's Cradle with liquid coating. *arXiv preprint*. Retrieved July 9, 2025, from https://arxiv.org/abs/1006.2081
- Choi, J. J., et al. (2022). Viscoelastic and plastic properties of play-dough: a materials science perspective. *Polymer Testing, 110*, 107587.

Toy 13 - SQUISHY BALL:

- Macosko, C. W. (1994). *Rheology: Principles, Measurements, and Applications*. Wiley-VCH.
- Doi, M. (2013). *Soft Matter Physics*. Oxford University Press. (mdoi.jp)
- Tighe, B. P. (2011). Relaxations and rheology near jamming. *arXiv preprint*. Retrieved July 9, 2025, from https://arxiv.org/abs/1106.0714 (arxiv.org)
- Barés, J., Cárdenas-Barrantes, M., Cantor, D., Renouf, M., & Azéma, É. (2022). Softer than soft: diving into squishy granular matter. *arXiv preprint*. Retrieved July 9, 2025, from https://arxiv.org/abs/2204.10701 (arxiv.org)
- Ramos, L., & Cipelletti, L. (2001). Ultraslow dynamics and stress relaxation in the aging of a soft glassy system. *arXiv preprint*. Retrieved July 9, 2025, from https://arxiv.org/abs/cond-mat/0109105 (arxiv.org)
- "Squishy." *Wikipedia*. Retrieved July 9, 2025, from https://en.wikipedia.org/wiki/Squishy (en.wikipedia.org)
- "Rheology." *Wikipedia*. Retrieved July 9, 2025, from https://en.wikipedia.org/wiki/Rheology (en.wikipedia.org)
- McGill University. (2019, January 18). Squeezing Science out of Squishies. Retrieved July 9, 2025, from McGill Online (mcgill.ca)
- ZME Science. (2019, January). Do Stress Balls Really Work? What the Science Says. Retrieved July 9, 2025, from ZME Science (zmescience.com)

- Harvard Weitz Lab. Rheology of Soft Materials Tutorial. Retrieved July 9, 2025, from Harvard (projects.iq.harvard.edu)

Toy 14 - RUBBER BALL:

- Müller, I., & Strehlow, P. (2004). *Rubber and Rubber Balloons: Paradigms of Thermodynamics*. Lecture Notes in Physics. Springer-Verlag.
- Treloar, L. R. G. (2005). *The Physics of Rubber Elasticity* (3rd ed.). Oxford University Press.
- Geethamma, V. G., & Thomas, S. (1997). Why does a rubber ball bounce? The molecular origins of rubber elasticity. *Resonance, 2*(4), 48–54. https://doi.org/10.1007/BF02919628 sciencebuddies.org+4sites.science.oregonstate.edu+4ias.ac.in+4researchgate.net+1researchgate.net+1researchgate.net+2eng.uc.edu+2researchgate.net+2ias.ac.in+6link.springer.com+6sites.google.com+6
- Merritt, D. R., & Weinhaus, F. (1978). The pressure curve for a rubber balloon. *American Journal of Physics, 46*(10), 976–978. https://doi.org/10.1119/1.11486
- Stein, R. S. (1958). On the inflating of balloons. *Journal of Chemical Education*. https://doi.org/10.1021/ed035p203
- Eichwald, B., Argentina, M., Noblin, X., & Celestini, F. (2010). Dynamics of a ball bouncing on a vibrated elastic membrane. *Physical Review E, 82*(1), 016203. https://doi.org/10.1103/PhysRevE.82.016203 link.aps.org
- Cross, R. (1999). The bounce of a ball. *American Journal of Physics, 67*(3), 222–227. https://doi.org/10.1119/1.19229 researchgate.net
- Arruda, E. M., & Boyce, M. C. (1993). A three-dimensional model for the large stretch behaviour of rubber elastic materials. *Journal of the Mechanics and Physics of Solids, 41*(2), 389–412. osti.gov+4en.wikipedia.org+4osti.gov+4
- Pal, S. (2023, May 17). Origin of rubber elasticity. *IntechOpen*. Retrieved July 9, 2025, from https://www.intechopen.com/chapters/85988 en.wikipedia.org+1link.springer.com+1
- Wikipedia contributors. *Rubber elasticity*. Retrieved July 9, 2025, from https://en.wikipedia.org/wiki/Rubber_elasticity en.wikipedia.org
- Wikipedia contributors. *Bouncing ball*. Retrieved July 9, 2025, from https://en.wikipedia.org/wiki/Bouncing_ball researchgate.net+7en.wikipedia.org+7sites.science.oregonstate.edu+7
- Wikipedia contributors. *Two-balloon experiment*. Retrieved July 9, 2025, from https://en.wikipedia.org/wiki/Two-balloon_experiment en.wikipedia.org+1sites.google.com+1
- ScienceDirect Topics. *Rubber elasticity*. Retrieved July 9, 2025, from https://www.sciencedirect.com/topics/engineering/rubber-elasticity

Toy 15 - STICKY HAND TOY:

- Cunguang Lou, Liu, E., Cheng, T., Li, J., Song, H., Fan, G., Huang, L., Dong, B., & Liu, X. (2022). Highly stretchable and self-adhesive elastomers based on polymer chain rearrangement for high-performance strain sensors. *ACS Omega, 7* (7), 5825–5835. https://doi.org/10.1021/acsomega.2c00345
- Meyers, M. A., & Chawla, K. K. (1999). Mechanical Behaviour of Materials (Section 13.11). Prentice Hall.

- Raos, G., & Zappone, B. (2021). Polymer adhesion: Seeking new solutions for an old problem. *Macromolecules, 54*(23), 10617–10644. https://doi.org/10.1021/acs.macromol.1c01876
- Israelachvili, J. N. (2003). *Intermolecular and Surface Forces*. Academic Press.
- Kwak, J. S., & Kim, T. W. (2010). A review of adhesion and friction models for gecko feet. *International Journal of Precision Engineering and Manufacturing, 11*(2), 171–186. https://doi.org/10.1007/s12541-010-0123-y
- Yin, Q., Manav, Y. A., Wan, Y., Davaji, B., & Bai, R. (2024). Strong and highly switchable soft sticky adhesives. *arXiv preprint*. Retrieved July 9, 2025, from https://arxiv.org/abs/2401.02002
- Song, H.-Z., Lou, C., Liu, E.-J., Cheng, T., & Li, J. (2021). A new polymeric elastomer with high stretchability, self-adhesion, and self-healing for wearable sensors. *Journal of Materials Chemistry A, 9*(11), 3931–3939. https://doi.org/10.1039/D0TA11497A

Toy 16 - POP-IT TOYS:

- Masao Doi, Introduction to Polymer Physics, from Oxford Science Publications.
- David Walton., & Phillip Lorimer, Polymers, from Oxford Science Publications.
- Walker, J., Halliday, D., & Resnick, R. (2014). Fundamentals of Physics, 10th Ed. Chichester: John Wiley & Sons, Inc. Retrieved January 15, 2015, from Wiley Online Library.
- Hosford, W. F. (2005). Mechanical Behaviour of Materials, 2nd Ed. Cambridge: Cambridge University Press.
- Fincan Mustafa, "Assessing Viscoelastic Properties of Poly-Dimethyl siloxane (PDMS) Using Loading and Unloading of the Macroscopic Compression Test" (2015).
- Hosford, W. F. (2005). Mechanical Behaviour of Materials, 2nd Ed. Cambridge, Cambridge University Press.
- Fidget toy uses - https://www.fundemoniumtoys.com/4-reasons-why-fidget-toys-are-helpful-for-kids/
- Health benefits of Fidget toys- https://www.flushinghospital.org/newsletter/can-fidget-toys-help-your-childs-ability-to-focus/
- Uses of Pop It fidget toy - https://www.parents.com/fun/toys/kid-toys/
- Health benefits of Pop It fidget toy - https://www.hbsilicone.com/popping-bubbles-fidget-toy-benefits-do-you-really-need-it-this-will-help-you-decide/

Toy 17 - MAGENTIC PUTTY:

- Varma SS, Thinking-Magnetic putty, Scientific India, 2017
- Golinelli N, Spaggiari A, Dragoni E, Mechanical behaviour of magnetic Silly Putty: Viscoelastic and magnetorheological properties, Journal of Intelligent Material Systems and Structures, 2015, 28(8), 953–960, https://doi.org/10.1177/1045389X15591655
- Guo F, Du C-B, Yu G-J, Li R-P, The static and dynamic mechanical properties of magnetorheological Silly Putty, Advances in Materials Science and

Engineering, 2016, Article ID 7079698, https://doi.org/10.1155/2016/7079698
- Li M, Pal A, Byun J, Gardi G, Sitti M, Magnetic putty as a reconfigurable, recyclable, and accessible soft robotic material, Advanced Materials, 2023, 35(48), https://doi.org/10.1002/adma.202304825
- Snarskii A, Shamonin M, Yuskevich P, Effect of Magnetic-Field-Induced Restructuring on the Elastic Properties of Magnetoactive Elastomers, arXiv preprint, 2020, https://arxiv.org/abs/2002.11762
- Fluidan (n.d.), Rheology Basics, Retrieved July 9, 2025, from https://fluidan.com/rheology-basics/

Toy 18 - FERRO FLUIDS:

- Scherer C, Figueiredo Neto AM, Ferrofluids: properties and applications, Brazilian Journal of Physics, 2005, 35(3), 718–727, https://doi.org/10.1590/S0103-97332005000400018
- Vékás L, Ferrofluids and magnetorheological fluids, Advances in Science and Technology, 2008, 54, 127–136, https://doi.org/10.4028/www.scientific.net/AST.54.127
- Ladislau Vekas, Ferrofluids and Magnetorheological Fluids: Composition, synthesis and structural properties, Advances in Science and Technology, 2008, 54, 127–13
- Capobianchi P, Lappa M, Oliveira MSN, Pinho FTP, Shear rheology of a dilute emulsion of ferrofluid droplets under a uniform magnetic field, arXiv preprint, 2021, https://arxiv.org/abs/2101.03166
- Miriyala DNP Rao, Goyal PSG, Effect of magnetic field on the damping behaviour of a ferrofluid-based damper, arXiv preprint, 2022, https://arxiv.org/abs/2201.09027
- Bhandari A, Theoretical development in the viscosity of ferrofluid, arXiv preprint, 2021, https://arxiv.org/abs/2105.14721
- Gheorghe-Orlando V, Susan-Resiga D, Correlation of rheological properties of ferrofluid-based magnetorheological fluids using dimensionless numbers, Annals of West University of Timisoara Physics, 2021, 63(1), https://doi.org/10.2478/awutp-2021-0009
- Engineering applications of ferrofluids: a review, Progress in Materials Science, 2021, https://www.sciencedirect.com/science/article/abs/pii/S0304885321004984
- Magnetorheological properties of kerosene-based ferrofluid with magnetite particles, Journal of Magnetism and Magnetic Materials, 2019, https://www.sciencedirect.com/science/article/abs/pii/S0921452620301629
- Ferrofluid (tool), Wikipedia, Retrieved July 9, 2025, from https://en.wikipedia.org/wiki/Ferrofluid
- Ferrofluid mirror, Wikipedia, Retrieved July 9, 2025, from https://en.wikipedia.org/wiki/Ferrofluid_mirror

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