Présentation du projet Metasoft Matter /
Metasoft Matter project presentation

L'Université PSL soutient le Grand programme Metasoft Matter qui a pour but de structurer la communauté "Matière Molle" de PSL, reconnue au niveau international. Outre des appels à projets visant à favoriser des projets scientifiques structurants, Metasoft vise également à fédérer la communauté "Matière Molle" via des actions d'animation scientifique.

Université PSL supports the Metasoft Matter Major Program, which aims to structure PSL's internationally recognized "Soft Matter" community. In addition to calls for projects designed to encourage structuring scientific projects, Metasoft also aims to federate the "Soft Matter" community through scientific leadership actions.

Visit the website for more information : https://www.metasoft-matter.psl.eu/

Trois axes de recherche / Three axes of research

- Axe 1 : Matériaux mous et robotique souple : cet axe combine les expertises en mécanique et structuration des matériaux mous, métamatériaux, robotique souple et design.
  Soft materials and soft robotics: this area combines expertise in the mechanics and structuring of soft materials, metamaterials, flexible robotics and design.
- Axe 2 : Fluides complexes et solides amorphes : investir dans la recherche sur les fluides complexes et les solides amorphes, essentiels pour des applications industrielles stratégiques.
  Complex fluids and amorphous solids: research on complex fluids and amorphous solids, essential for strategic industrial applications.
- Axe 3 : Matière molle et développement durable : utiliser les matériaux déformables pour développer des stratégies innovantes en complément des efforts actuels dans le recyclage, la gestion de l'eau et la valorisation du CO_2...
  Soft matter and sustainable development: using deformable materials to develop innovative strategies to complement current efforts in recycling, water management and CO_2 recovery ...

La description des questions scientifiques de chacun des 3 axes est détaillée en fin de document.

The description of the scientific areas for each of the 3 axes is detailed at the end of the document.

Communauté scientifique / Scientific Community

Metasoft regroupe environ 80 chercheurs issus de 11 laboratoires de PSL : chimistes, physiciens et physico-chimistes de la matière molle.

Metasoft brings together around 80 researchers from 11 PSL laboratories: chemists, physicists and physical-chemists of soft matter.

Chimie ParisTech - PSL

- Institut de Recherche de Chimie Paris

École des Arts Décoratifs – PSL

- EnsadLab

ESPCI Paris - PSL

- Chimie Moléculaire, Macromoléculaire et Matériaux (C3M)
- Gulliver
- Sciences et Ingénierie de la Matière Molle
- Institut Chimie Biologie Innovation
- Physique et Mécanique des Milieux Hétérogènes

École Normale Supérieure - PSL

- Laboratoire de Physique de l'École Normale Supérieure
- Laboratoire PASTEUR
- Laboratoire de Chimie de l'Ecole Normale Supérieure

Mines Paris - PSL

- Centre de mise en forme des matériaux
- Centre de Robotique

Gouvernance / Governance

Comité de pilotage / *Steering Committee* : F. Lechenault (ENS - PSL), C. Monteux (ESPCI Paris - PSL, SIMM), E. Hachem (Mines Paris - PSL), T. Budtova (Mines Paris - PSL), M. Labousse (coordinateur, ESPCI Paris - PSL).

Comité stratégique / *Strategic committee* : Jean-François Joanny (Collège de France - PSL), Aurélie Mossé (ENSAD - PSL), Cécile Cottin-Bizonne (Université Claude Bernard), Yoël Forterre (Aix-Marseille Université), Carine Robert (Chimie ParisTech - PSL), Nicolas Vandewalle (Université de Liège), Sotiris Manitsaris (Mines Paris - PSL).

Partenaires industriels de Metasoft / *Metasoft industrial partners*
Première liste / first list : Syensqo, Saint-Gobain, Urgo, Safran, Softpath, LVMH.

Animation scientifique / *Scientific animation*
Le projet Metasoft prévoit de poursuivre l'organisation des PSL "Soft and Living Matter days" démarré en 2021, l'organisation d'une école d'été (en 2027) et d'une conférence internationale en (2029).

The METASOFT project plans to continue organizing the PSL "Soft and Living Matter days" started in 2021, and to organize a summer school (in 2027) and an international conference in (2029).

Appels à projet

Metasoft permettra notamment de financer au total sur 5 ans, 10 bourses de thèse et 3 post-docs de 2 ans avec un accompagnement financier supplémentaire de 15 k€ en fonctionnement. Parmi ces 10 bourses de thèse, 4 seront fléchées sur des chercheurs·ses récemment recruté·e·s. Il y aura trois appels à projet en 2025, 2026 et 2027.

In particular, METASOFT will fund over 5 years a total of 10 PhD grants and 3 two-year post-docs, with an additional 15 k€ in consumables per project. Of these 10 PhD grants, 4 will be focused on recently recruited researchers. There will be three calls for projects in 2025, 2026 and 2027.

Description détaillée des axes / *Detailed description of axes* (en anglais)

La description des axes scientifiques se décline sous forme de questions scientifiques ouvertes.

The description of the scientific axes is in the form of open scientific questions.

Axis 1: Informed and programmable matter: from material computation to soft robotics

Context and current challenges

The overarching goal of this research direction is to combine the technologies developed at PSL in the domains of mechanical metamaterials with soft materials, such as silicone rubber, gels, or foams that can adapt their mechanical properties as a response to external stimuli by performing in-situ computations [1,2,3] in order to define the new standards of soft and self-haptic robotics.

During the execution of movement-based interactions with materials, the human body mobilizes a set of senses. It collects and processes intrinsic signals, such as "the feeling" of muscle contractions, but also extrinsic ones, which are multisensory signals that are external to the human body. The main source of extrinsic information is related with the physical properties of the material (clay, glass, etc.) that hands/fingers manipulate. The key idea in blending matter and computational principle is that a decentralized control allows one to combine the complex context-sensitive mechanical responses of a device with the flexibility and robustness of a material in order to reach a next generation of robotic function. This long-term goal is decomposed in three broad strokes at the frontier between material science, physics of complex systems, robotics and art/design.

Pioneering research in this field usually prepares the input through computer-controlled motors and the output through load cells or image analysis. We wish to develop the interface with the materials world within the machine-material, based on a mechanical metamaterial program to extract a specific input from a situation, and create a response from the computational output. Metasoft will give a strong boost to combine the skills of the consortium in the field of soft solids, of actuatable and learning materials and of soft robotics.
The outcome of such research will allow us to imagine systems capable of performing tasks, such as grabbing a delicate object with a tool whose morphing shape would conform and adapt to the object's geometry, via a purely passive mechanical sensing, processing and conformation, avoiding the need for electronic sensors and actuators.

Scientific questions

Can we program soft solids?

Can we develop programmable memory-enabled soft solids? Recent progress has been made in the field of memory storage in matter [4-6], as well as in that of programmed computation within model metamaterials [7-10]. In the case of programmable materials, the general idea is to take advantage of results on spin systems, where each spin is seen as a logic variable, and within which it is possible to spatially encode sequences of binary operations such as logic gates to perform computations [11-13]. In particular, this approach enables elaborate operations such as counting and even addition, opening the door to the development of computational materials.

One of the ideas which could be explored in Metasoft is to combine the skills of the consortium to develop a family of cellular materials, where each cell comprises bi/multistable mechanical units. For example, this property can be implemented with elementary units that can buckle or deform in two or multiple directions. The coupling between neighboring units can be done in such a way as to encode the logic gates enabling the desired algorithmic operation to be performed macroscopically. Another strategy would be to encode a bistability in either programmable active units in the spirit of the recent development of active gels and solids or at the molecular scale where foldings and motions can be induced by a DNA-based molecular program [14]. Finally, several systems have been proven to be suitable for "reusable mechanical memory repository". Can plasticity be leveraged as another mechanism in computational materials?

Which materials are suitable for programming soft matter?

Currently, these materials deteriorate under fatigue and often fracture at long-term, making them unsuitable for robotic applications: high fatigue resistance is essential. To provide proof-of-concept for programmable soft materials, several options can be explored at PSL. Magnetic actuation of soft magnetic materials is one of them. It has been used to drive the motion of soft untethered robots [15-17] or to tune the wetting and adhesion properties of engineered surfaces [18-20]. Fast and reversible actuation in different modes was demonstrated. However, because of the incompressibility of the matrix, the design of the structures is limited to elements undergoing bending [21]. For elements under magnetic compression or traction, one needs to include a dead volume allowing the expansion or liberated by the contraction of the actuator.

Recently, compressible magnetic foams with non-toxic matrices, such as silicones [22,23] or biopolymer hydrogels [24] were shown to undergo a magnetic-field induced compression with a low Poisson's ratio and could be other candidates to design multistable units. However, the mechanics of magnetic actuation of such materials remains poorly understood because of the complex magnetically-anisotropic interactions [15,25] between the fillers and by the instability-modulated mechanics of the foam [23]. Designing model foams with controlled porous structure and particle orientation to obtain controlled deformation in a magnetic field, would be a strong asset. Magnetic compression would allow for change of surface morphology and compliance, and will be used to switch the adhesion or wetting properties which are crucial for gripping power of soft robots [26]. Apart from magnetic activation, many biosourced polymers, like collagen or cellulose, and reactive polymers are interesting and natural candidates which remain to be explored. Other promising strategies could include hydrogel swelling and poroelastic materials [27,28] that can deform under the effect of moisture or when brought into contact with a solvent.

Can we create evolving soft matter?

During the grip of a complex object by a robot, the deformation of this material is the result of a fine motor control and transfer of energy from the human to the material, where very fine gestural nuances can have a significant impact on it. But what happens when the human touch stimulates a so-called "active" (or reactive) material? How can we model the impact of parameters resulting from the human touch, such as skin temperature, on a deformable and active material?

In this research effort, we aim to close the loop between computation and mechanics by allowing the “internal computations” done by the materials to act on the material properties: matter can compute and, as a result, can strongly modify the mechanical properties of the material itself. In order to do so, one can rely on several ideas.

Non-linear mechanical modules, such as a buckling element, can provide a switch to tune material properties, or couple/uncouple mechanical parts [29]. This idea could be implemented in two-dimensional generalizations of the so-called Kagome lattices [30], in which modes of deformations with no energy cost can be transformed into bistable elements that can be actuated by finite-amplitude mechanical vibrations.

Can we train soft matter?

The combined implementation of memory and computation into mechanical metamaterials, i.e. compressible materials with macroscopic mechanical properties defined by their structure rather than their chemical composition could make them capable of learning, i.e., of effectively changing their programming based on external inputs. Several examples exist as soft-matter self-assembly [31] which can be directed by the internal computations in order to modify the structure of the metamaterial itself. As the metamaterial affects the “internal computation”, a feedback loop can be created which guides the system to the desired functioning point. This challenging direction could be explored in a model system of colloidal particles where standard self-assembly is well-understood and can be tuned externally, for example with light [32].

One possible strategy to explore would be to implement reservoir-based computation functionalities in hydrogels: the idea in this case is to teach a simple neural network to extract a predefined function of input stresses from the non-linear response of a system. In particular, the first part of the project should enable us to identify the typical micro-structural features of our hydrogels that give rise to material nonlinearities optimizing this type of computational response.

Other strategies would explore the possibilities of dynamically modifying the couplings between cells, for example by applying heterogeneous stresses to the edge, or by modifying the environmental conditions, so as to be able to reprogram the system, or at least switch it to another function. By further coupling this system with micro-fluidic actuation, one could start realizing biomimetic components that reproduce basic features of biological tissues. In particular, we will explore the possibility of learning dynamical behavior such as limit cycles, starting from simple models, such as generalizations of the Hopfield model [33], where a generic framework can be developed and applied to the more complex situation of full-fledged metamaterials.

What are the synergistics applications with robotics?

From the point of view of collaborative robotics, despite the significant progress in AI over the last two decades (i.e. robot learning by demonstration), human-robot interaction is mainly limited to sequential cooperation between the two partners [34]. The introduction of gestures has propelled the digital world towards more flexible machines [35,36]. However, current collaborative robots still lack the necessary perspective layers (human-centered AI) to fully anticipate human behavior both in space and time [37-40].

The objective of this effort of research will be to define and configure a strategic axis on hand/finger – machine/matter interaction based on machine/deep learning which is both human- and robot- oriented. Our ambition is to discover the possibility of creating one of the first datasets on human motion data from hand/finger interaction with active and reactive materials that would be publicly available for AI training purposes. By blurring the boundary between materials and devices, metamaterials that learn, compute, and adapt to their environment hold promise for applications ranging from medicine to space exploration, notably thanks to the definition of a new generation of soft-robots.

Axis 2: Flow and phase transitions in active and complex fluids

Context and current challenges

Complex fluids play a crucial role in cosmetics, construction, pharmaceuticals, aerospace and the car industry. As striking as it sounds, many problems that appear simple on paper are challenging to understand. This includes, but is not limited to, the shear thickening of non-Brownian suspensions [46,47], the nucleation of colloidal crystals [48,50], fracture behavior of soft materials under large deformations and the role of particle activity in their macroscopic behavior. These are fundamental stumbling blocks in establishing industrially realistic self-organizing manufacturing processes. These are strong and urgent needs from our industrial partners to understand two fundamental challenges.

The understanding of suspensions, foams, emulsions and gels has significantly progressed over the last decades [46,47,49]. The rheology of these suspensions can be described using a simple dimensionless number that measures the ratio between viscous stress and particle pressure. These results from the work of Pouliquen and Guazzelli [47] describe well the rheological response of suspensions when the particles are in contact (frictional or not). However, they do not consider changes in the nature of contact with shear or particle pressure, which may be due to the existence of repulsive, attractive or adhesive forces between particles, changes in the coefficient of solid friction with the filler, or chemical reaction.

The advances in controlling interaction forces, tailoring interface properties with surfactants, non-Newtonian fluids, or grafted particles, supercritical drying [47-55], and modifying local solid friction have rapidly progressed during recent years. They opened up a new route towards understanding this scientific issue regarding the behavior of complex fluids. This extraordinary route involves new strategies to synthesize model particles with specific surface properties, new techniques to measure the frictional and adhesion forces directly, and new methods to model these complex systems by combining theory and AI-assisted numerical methods. Metasoft ambitions to tackle this fundamental issue, thanks to the consortium's combined expertise in physical-chemistry, colloidal science and disordered systems to open up new avenues for promising applications.

Scientific questions

How to produce model particles with controlled shapes and surface properties?

Possible strategies to produce model particles with controlled interfacial properties include grafting neutral and charged polymers on colloidal and non-Brownian particles [57]. Polymer brushes adsorbed at solid surfaces are known to entangle when put into contact and enable the control of the adhesion of the particles and produce sticky contacts. Other possible strategies include synthesizing large polymer gel particles that are deformable and eventually present a core-shell structure. Moreover, using novel microfabrication techniques such as in situ polymerization of hydrogel particles, CO_2 drying, non-Newtonian fluid at the microscale, 3D printing, or self-assembly of nanoribbons [58-62] gives us another route to provide particles with controlled anisotropy and deformability. The recent numerical advances coupling AI and computational fluid tools could be a cardinal advantage in understanding the emergence of these varieties of shapes and even predicting the existence of new and unexpected possibilities. Such deformable particles may interact with controlled flows, leading to novel and well-controlled non-Newtonian properties. Another strategy consists in using particles that fluoresce or change color according to the local properties of a medium, shall it be the local shear (mechanophore), chemical properties (solvatochromic), the local vorticity, or conductivity, fluorescent pH probe, magnetic/electric field, or temperature.

How to measure the friction and adhesion between particles?

All these fundamental questions have a unique opportunity to be addressed thanks to recent developments in high-resolution microscopy, Total Internal Reflection Fluorescence microscopy and Atomic Force Microscopy. Fast microscopy and high-resolution microscopy [63] have recently been used, for example, in the colloidal glass transition [64]. Colloidal systems that leverage high-resolution techniques combined with a solvatochromic dye determined for the first time forces between colloidal emulsion droplets to be resolved, opening an entirely new approach to tackle failure in soft amorphous solids [65]. Combined with novel real-space-structural analyses, the new experimental methodology mentioned below can resolve long-standing questions in nucleation, for example, that of polymorph selection [66]. Moreover, new AFM techniques developed in PSL enable the measurement of the friction force between particles as a function of the applied normal force [67]. These techniques may be used to better understand the link between surface properties, frictional forces, and macroscopic flow properties of suspensions.

What is the role of reactivity and activity in the rheology of complex fluids?

There are many industrial applications in which the particles are reactive. For example, in cement, the nature of the contact between particles evolves as a chemical reaction takes place over time. One question will be understanding the coupling between reactivity and the rheological properties. Another class of non-passive particles are living organisms, such as microalgae and bacteria. In this connection, an interesting question would be to understand the coupling between the particle activity, its metabolism and the macroscopic properties of the suspension [68-70]. Finally, another strategy that can be explored to provide a suspension of passive particles with some activity is to induce mechanical vibrations in the system.

How do soft solids behave under large deformations?

Under large deformations, fractures tend to nucleate in soft solids. Recent experimental developments such as confocal microscopy of activated mechanophores made it possible to image the rupture of polymer chains close to a crack. Dynamic light scattering methods can also be used to characterize the local dynamics in deformed soft solids under large deformations [71]. In Metasoft one of the questions that couldl be tackled is whether these techniques, used on model soft solids, can also be used to understand the properties of biobased materials such as protein-sourced systems which self-assemble into fibers (ex, collagen, cellulose) and in which the deformation and stresses may be much more heterogeneous. Another question would be whether we can control the fibers' self assembly and orientation by varying the physico-chemical conditions or by using 3D printing to orient the fibers before solidification. Finally, the obtained experimental-numerical results and the physical mechanisms unveiled throughout the previous stages could be used in training Deep Reinforcement Learning agents [72-74]. The trained agents would then be coupled with supplemental high-fidelity numerical simulations [75] to assist them in exploring a wide range of flow parameters with the final goal (i.e., reward) of optimizing the object generation and shaping processes by shaping its structure in a dynamic programmable way. By doing so, we seek to position PSL as a leader in numerical methods that combine computational and AI-based methods for materials processing.

How to observe and control phase transitions in passive and active suspensions?

The second most significant discrepancy in physics is the theoretical prediction of the nucleation rate of hard spheres as a function of their volume fraction [50]. The lack of understanding of this fundamental issue is one of the central challenges in establishing strategies to define tomorrow's materials and be more respectful of new environmental and societal requirements. For example, a lack of understanding of these fundamental phenomena is one of the reasons why many potentially energy saving self-assembly strategies have never really taken off on an industrial scale. Although promising, these strategies have been hampered by difficulties in understanding fundamental issues such as suspension rheology and nucleation dynamics during the industrial scale-up stages. Using microscopic techniques described earlier is a possible strategy to observe the growth of colloidal crystals in situ. A possible way to control crystallization would be to induce activity in the system by vibrating the suspension or using motile particles such as microalgae.

Axis 3: Soft matter for sustainability

Context and current challenges

Soft matter is a key science in the development of the technologies needed for the ecological transition. Understanding how to recycle, repurpose and sustainably use plastics, how to reduce the use of toxic and polluting solvents, or, in general, to design more sustainable, stronger or more adaptable materials are all, in the end, soft matter problems.
Soft matter processes and concepts also enter non-soft materials, famous examples being water purification, batteries production or building materials. This points to the key role that soft materials can play in reducing the human environmental footprint on our planet. In the context of sustainability, the soft matter community can play a role to advance technical challenges such as carbon capture and valorization, energy production, water filtration.

Scientific questions

Using soft matter science for innovative recycling/upcycling processes?

The recycling of plastics and metals in electronic wastes is a huge issue to preserve natural resources that involves many different fields. In the field of plastic and composite, recycling and upcycling it is highly desirable to be able to trigger the reversible bonding and nonbonding between polymers and inorganic surfaces, a question for which the PSL soft matter community has all the required skills including polymer science and engineering and adhesion as well as photo-induced polymerization and depolymerization. Enzymatic catalysis in aqueous media for plastic depolymerization and microplastics is another topic for which the PSL community can bring new ideas combining artificial intelligence and microfluidics for microorganisms screening as well as innovative polymer engineering favoring depolymerization on demand as for the upcycling of old shredded paper for design applications [82]. Another possible strategy would be to use bacteria to produce calcite to reinforce the mechanical properties of these highly porous materials.

Can flows of liquid in soft materials provide new opportunities for water filtration or evaporative cooling?

Water is a precious asset which may become rare in the context of climate change and world population increase. Water filtration is an important topic for the PSL soft matter community which is very active in this field. Several PSL teams devote efforts to understand the role of ions in nanopores during filtration experiments with applications in desalination. The recent development of innovative hydrogel membranes which can be functionalized chemically and mechanically deformed enables to foresee new opportunities in water desalination or in evaporative cooling, i.e. a reduction of temperature induced by the evaporation through the membrane [73-84]. Important works have been done with electrochemical processes for desalination and with development of electrodes based on hydrogels. In this type of application the coupling between water transport and membrane deformation is expected to play a crucial role [27]. In these applications, an interesting aspect may include the development of biobased and bioinspired materials (i.e., collagen, cellulose...).

Can we use self-assembly to produce soft optical materials with radiative cooling properties?

In building materials, it is possible to improve radiative cooling by developing optical materials that scatter sunlight, minimize absorption and emit thermal radiation efficiently. Two approaches could be explored: the design of Mie resonators using high-index materials and the enhancement of absorptivity through structural correlations in particle position. These approaches take advantage of the self-assembly phenomena specific to soft matter.

Can soft matter and soft materials be used for CO2 capture and valorization?

Microalgae can absorb CO_2 and can be seen as a way to capture CO_2. There is a growing activity focusing on the organization, dynamics and harvesting of microalgae in solution and at interfaces [78-81]. Metasoft is an excellent opportunity to stimulate new projects where the purpose would be to use microalgae to capture CO_2 which would require understanding the coupling between CO_2 transfer at liquid air interfaces and the metabolism of microalgae close to these interfaces.

Another strategy could be to use suspensions of soft piezoelectric particles to catalyze demanding reactions, such as the degradation of certain acids, or the reduction of CO_2 into methanol, which is an original strategy for both CO_2 capture and fuel synthesis. CO_2 conversion is highly energy-demanding, and novel activation modes are among the keys to more selective catalytic processes development. The details of the catalytic mechanisms are an open question, but it is reasonable to assume that the deformation of piezoelectric particles could generate a local electric field sufficient to activate a chemical reaction. The precise role of electrostatic effects at the micro and nanoscale on the new catalytic process remains unresolved. Another avenue to explore is the inclusion of soft electrets in suspensions. All these research directions could lead to new paradigms for one-pot catalysis and the valorization of CO_2.

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