1 Proposal for a collaborative FOM programme

Rheophysics: Connecting Jamming and Rheology

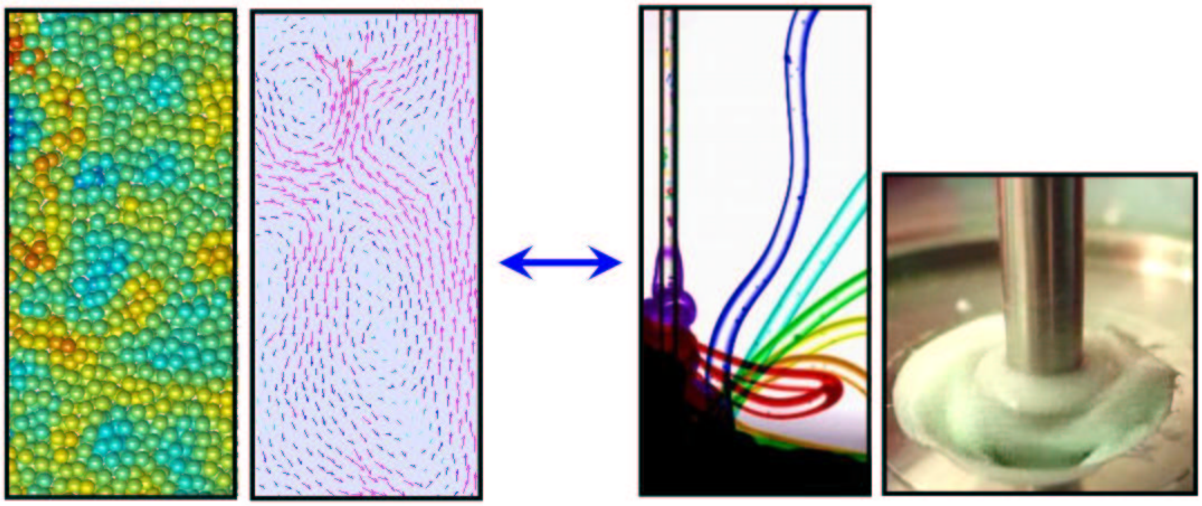

Illustration of the type of microscopic structures near jamming and rheological phenomena that we will connect in this programme. Left: Spatial organization of the displacements of a dense, nearly jammed colloidal suspension that is sheared. The color of the particles indicates how much their motion deviated from a smooth, affine shear (P. Schall). Center Left: Tracks of bubbles in a slowly sheared foam reveal vortical, non-affine structures near jamming (M. van Hecke). Center Right: Time lapse images of leaping shampoo, illustrating how in the flow of a typical shear thinning fluid both very viscous regions (the "mound" of shampoo visible in the left bottom) and less viscous regimes (the colored jets shooting to the right) coexist: a striking example of shear banding (D. Lohse). Right: Snapshot of a suspension (cornstarch) that is sheared by the rotating shaft in the center of the image — if the rotation rate increases above a certain threshold, the resistance to flow suddenly increases and the flow becomes highly unstable: a striking example of shear thickening (D. Bonn).

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[1] Luding will move to the Engineering Department in Twente, where he will take up a full professorship 1/10/2007

3 Objectives and Focus

We propose to initiate a collaborative and focussed FOM programme, aimed at unraveling the yielding/jamming (flow-no flow) transitions exhibited by *yield stress fluids* from a microscopic perspective. This programme will build on the various Dutch groups that recently have developed the experimental and theoretical tools to bridge the gap between microscopic behavior and its macroscopic consequences, and that already are at the forefront of the "rheophysics" interface between jamming and rheology. The closely interconnected scientific questions we will address are:

(i) **What is the microscopic origin of the jamming of sheared yield stress fluids?**
(ii) **What is the relation between jamming and the formation of shear bands?**
(iii) **What causes some suspensions to thicken and jam under increased shear?**

Because of their enormous range of applications, yield stress fluids, such as drilling fluids, toothpaste, shaving foam, coatings and mayonnaise, have been studied intensively and there exists a large body of practical knowledge on their features [1]. However, it is becoming increasingly clear that the classical rheological description of these materials, which assumes a constant yield stress, is not sufficient. Such phenomenological description does not capture that yield stresses often depend on the materials history and vary in space and time, does not always correctly predict when yield stress fluids form shear-bands and does not provide an understanding of the behavior of these materials [2–7].

Novel micro-rheological ideas such as "soft glassy rheology" [8], "shear transformation zones" [9] and "viscosity bifurcation" [3] go beyond the phenomenological descriptions by introducing a coupling between the local flow and the local rheological features, such as yield stress. Unfortunately, there is no clear picture of the microscopic structures and mechanisms that mediate such a coupling. We believe that a clear framework can be developed by incorporating novel microscopic descriptions that have emerged in the study of jamming [10–16] — taking into account that these studies focussed on jammed, non-flowing systems.

The proposed programme thus weaves the two strands of jamming and rheology together, allowing for the first time to provide a microscopic understanding of the rheology of yield stress fluids. Inspired by recent breakthroughs in jamming and rheology that have uncovered unexpected connections between molecular glasses, colloidal glasses and gels, emulsions and granular matter [15–21] — media which span a large range in spatial and temporal scales — we will study a variety of materials, ranging from foam and macroscopic suspensions to colloidal and clay suspensions: our focus is on generic mechanisms.

At present, activities in these fields in the Netherlands are growing — three of the applicants (Mugele, Bonn, Schall) came to the Netherlands very recently — but scattered across institutes and communities. By bundling these parallel efforts, which individually already have a major impact[2], we will create a strong and focussed programme at the forefront of this field. The programma has the required mass to effectively compete with international efforts, will act as a jumping board for collaborations with (non-) Dutch scientists and with industry and will give the Netherlands further international visibility.

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[2] Recent relevant key publications of applicants include respectively 26, 7 and 5 papers in PRL, Nature and Science — see appendix.

4 Scientific Challenges: Jamming and Rheology

4.1 Motivation and Background

The flow properties of a simple Newtonian liquid are set by its viscosity, whereas the mechanical properties of a crystalline solid are given by its elastic moduli. Many complex fluids show both solid and liquid-like behavior: Slurries, colloids, suspensions, pastes and foams can *jam* in solid-like, disordered states in which they respond essentially elastically to small applied shear stresses, but also easily yield and flow when the shear stress (i.e. tangential force per unit area) overcomes a critical yielding value.

Jamming — Jamming and yielding transitions can be induced in disordered systems by tuning different control parameters. These can be thermodynamic variables such as temperature or density, but also mechanical variables such as the stress applied to the sample: colloidal suspensions become colloidal glasses as the density is increased near random close packing, flowing foams become static as the shear stress is decreased below the yield stress, and supercooled liquids form glasses as the temperature is lowered below the glass transition temperature. At first glance, these appear to be unrelated phenomena, but upon closer inspection, a number of common characteristics hint at universal behavior near the jamming transition, including the development of heterogeneities at large scales, sluggish response, and aging (where properties of the sample slowly evolve over time).

Stressing these common features, in 1998 Liu and Nagel presented their provocative jamming phase diagram (Fig. 1), suggesting, for instance, that close to jamming a change in applied stress or a change in temperature could have comparable effects [10]. This idea has inspired a host of studies on the nature of jamming — at recent APS March meetings, some

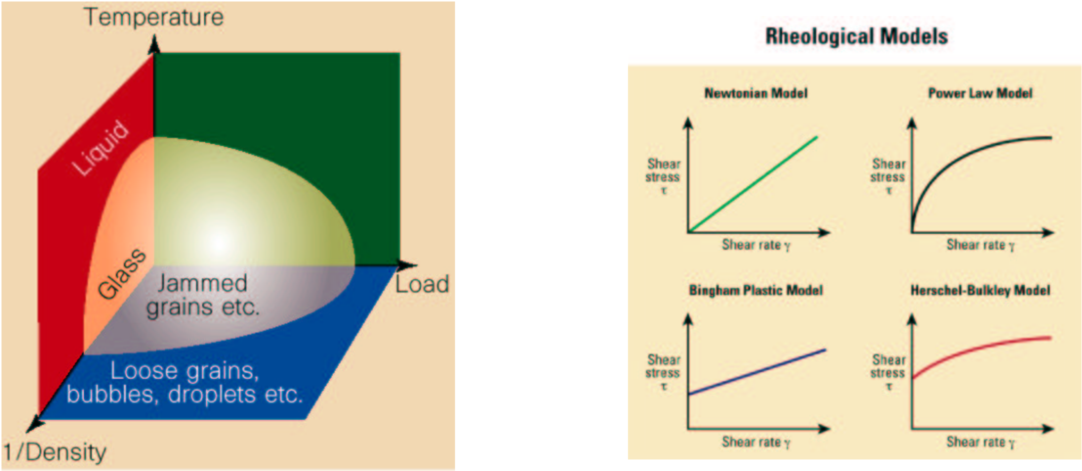

Figure 1: Left: Jamming diagram as proposed by Liu & Nagel [10], illustrating that many disordered materials are in a jammed state where they withstand stresses for low temperature, load and inverse density, but yield when these parameters are increased. Many recent studies have focussed on the critical behavior along the axis of zero temperature and load where jamming occurs as function of density [11–14] — here we focus on jamming and yielding as function of applied shear. Right: Four Rheological models, relating strain rates and shear stresses — Bingham and Herschel-Bulkley models concern yield stress fluids, where the stress remains finite as the flow velocity goes to zero.

of the best attended sessions are the various ’jamming sessions’. Recent exciting developments include the uncovering of large scale, non affine structures [11, 12] in systems near jamming, a more fundamental grasp of scaling relations [13, 14] and the interpretation of fluctuations in athermal systems via effective temperatures [15, 16]. These studies focussed mainly on the critical behavior along the axis of zero temperature and load where jamming occurs as function of density.

Rheology of Yield Stress Fluids — Jammed systems are widely used in cosmetics, food and industry, where they are usually referred to as ’yield stress fluids’: think of toothpaste, lipstick, mayonnaise, shaving foam, and oil drilling fluids. Their utility often directly follows from the fact that these materials are jammed and respond essentially elastically under small stresses, but flow for higher stresses. Because of their enormous range of applications, they have been studied intensively by engineers and rheologists over the past few decades, leading to a wide variety of phenomenological rheological models.

In somewhat simplified terms, in such classical rheology, one characterizes materials by relating their flow rate (c.q. shear rate) to their resistance to flow (c.q. shear stress), and defines the (apparent) viscosity as the ratio of cause and effect, i.e., the shear stress divided by the shear rate (see Fig. 1). In the simplest case of a Newtonian fluid the viscosity is constant. *Shear thinning* fluids exhibit apparent viscosities which decrease with increasing shear rate, while the less frequent *shear thickening* substances have the fascinating property of increasingly building up resistance to the applied deformation rate. Finally, yield stress fluids can be captured by the archetypical Bingham or Herschel-Bulkley models which incorporate a finite stress at vanishing flow rate (Fig. 1).

While these phenomenological models have been quite powerful in capturing the coarse features of a broad range of materials, three main shortcomings in describing real yield-stress fluids have become increasingly clear:

First, these models do not provide an understanding of the behavior of these materials. In comparison, for some complex fluids (e.g. polymer solutions, polymer melts and dilute and semi-dilute particle suspensions) micro-rheological models have been developed that link the macroscopic mechanical behavior of the material to its microstructural properties. However, for real yield-stress fluids no satisfactory micro-rheological models exist.

Second, in many situations the yield stress is in fact not a material property, as is often assumed, but depends on the deformation history of the system and evolves in time [2–4]. In particular, when left at rest, many of these material age and become more rigid, while shearing leads to rejuvenation making them softer — these materials never reach equilibrium. This makes it hard, if not impossible, to measure a well-defined yield stress for a given material.

Third, when a homogenous stress is applied, classical rheology predicts a homogeneous flow. Most jammed systems, however, form shear bands, i.e., inhomogeneous states where only part of the system flows. While shear bands can arise from stress inhomogeneities, shear banding has recently been observed in number of systems for which the stress is homogeneous, such as in cone-plate cells [2, 5], in linearly sheared colloidal glasses [6] and in simulations of linearly sheared foams [7].

Connecting Jamming and Rheology — One has to move beyond phenomenological Herschel-Bulkley models to make progress. The crucial step is to start from the interplay between flow and structure of the fluid. In this picture, flow leads to changes in the microstructure of the flowing material, which in turn influences its local rheological properties — such interplay is incompatible with the ideal "classical" picture of a yield stress material. The measured global rheological features are then an emerging property. We argue that history dependent yield stresses and shear banding can be captured naturally in a framework where flow influences the rheological features of the material, and studying such interplay should also enlighten why and how some materials show shear thickening, while most are shear thinning. Indeed, a number of novel approaches connecting yield stress, aging, shear banding, heterogeneities, instabilities and glassy behavior along these lines have emerged in recent years [2–4, 8, 9].

Focussing on the coupling between microstructure and flow opens up, in our opinion, a very promising avenue for qualitative explanations of many of the puzzling features of real yield stress fluids. The present developments in this field show that attacking these basic issues for a wide variety of systems, ranging from simple models to real life drilling fluids, quicksand, and foams, rapidly leads to new insights, models and ideas. In particular, we believe that microscopic notions which are currently developed for jammed systems, such as scaling, non-affine motion and effective temperatures [11–16, 22–27] are crucial to attack the rheological problems outlined above: the combination of concepts from jamming and problems from rheology provides a fertile ground for this very timely field of research [4].

It is precisely on this "rheophysics" interface, where jamming and rheology meet, that the groups participating in this proposal have successfully started working (see section 4.3). The proposed programme will bundle these efforts, thus combining new ideas with new techniques (fast confocal microscopy, high speed imaging, MRI flow visualization, large scale numerics).

In section 4.2 below, we outline how we will focus on three key questions, concerning structure, shear bands and shear thickening, for a variety of (experimental) systems and from a number of viewpoints. In section 5 we describe then the sub-projects that form the proposed programme, and detail collaborations and connections between these.

4.2 Key Questions

This proposal will concentrate efforts on the jamming and rheological properties of sheared systems, and focusses on three interconnected questions:

(i) What is the microscopic origin of the yielding and jamming of sheared yield stress fluids? A host of new ideas have emerged to describe the microscopy of systems that jam and yield as function of density [11–14], and it is a main challenge to translate these concepts to systems that undergo shear, and to develop order parameters to describe the microscopic structure near the jamming/yielding threshold.

We have defined four experimental projects that focus on the microstructure near the jamming/yielding transition in macro suspensions, foams, colloidal suspensions and micro-gel particle aggregates. We will employ and test innovative order parameters, such as shear transformation zones [9], Minkovski functionals [28] and the displacement angle distribution [11] to this wide range of systems. Furthermore, two theoretical/numerical projects are defined that focus on the connection between microstructure and macroscopic rheology.

(ii) What is the relation between jamming and the formation of shear bands? The formation of shear bands, localized regions where the flow is concentrated, is a common feature of sheared foams, slurries, pastes etc, and is a central feature in the "'viscosity bifurcation" [3] and "shear transformation zone" [9] frameworks. Shear banding hinders the interpretation of rheological measurements — what is the meaning of the "measured" effective viscosity, when multiple local shear rates coexist? In the framework of classical Herschel-Bulkley models shear banding can only be understood when the stresses are inhomogeneous, which is not always the case [2, 5–7, 17].

Two experimental projects address the cause of shear banding from a macroscopic perspective, while several of the microscopic studies are performed in systems that exhibit shear banding, thus providing the necessary structural perspective.

(iii) What causes some suspensions to thicken and jam under increased shear? In exceptional cases, materials actually jam when sheared sufficiently fast — in apparent contradiction with the jamming phase diagram (Fig. 1). Understanding what govern this anomalous behavior will lead to a deeper insight into both shear thinning, shear thickening and yield stress fluids. One theoretical project addresses the relations between shear thickening and shear banding, while one of the experimental projects aims at developing shear thickening suspensions where the individual particles can be tracked easily — aiming at connecting microstructure and rheology.

For a detailed description of our research programme, see section 5.

4.3 Rationale for a collaborative program

By combining new experimental techniques (such as high speed, confocal and magnetic resonance imaging) with new theoretical ideas inspired by jamming, we can now ask and answer questions that could not be posed or addressed before. As soon as we do so, new surprises will come out. Striking recent examples are: (1) the discovery of elastically driven instabilities in polymer flows [29], (2) the unification of the mechanical behavior for a wide range of 'yield stress' materials via the *viscosity bifurcation* [3], (3) the experimental manipulation of shear bands [30], (4) the predictions of non-affine behavior, novel order parameters and various scaling behaviors near the jamming transition [11, 14, 22, 31], and (5) predictions and subsequent experimental finding of a transition between affine and non-affine behavior in biopolymer systems [12, 23, 32].

These examples were not chosen arbitrarily — the applicants, three of whom only recently came to the Netherlands (Bonn, Schall, and Mugele), are at the forefront of these exciting developments. It is important to note that the applicants have become interested in jamming and rheology from different backgrounds (engineering, turbulence, biophysics, rheology, statistical physics, etc), and bring in different points of view: collaboration is thus exciting and fruitful, because the connections are only emerging now. We are eager to combine these strong activities and build on these developments: *this programme is timely*.

The questions we wish to answer in this programme reach beyond what can be achieved in individual small projects, since our key questions are not related to a single material, but very much in spirit of the jamming-diagram, involve a broad spectrum of materials with length scales ranging from micron scale colloidal suspensions to centimeter-scale foams. We have selected the participating groups with these needs in mind. The experimental groups are all well-equipped to probe the microstructure of these materials, as they bring in fast 3D confocal microscopy for colloidal systems (Schall, Lekkerkerker), high speed imaging (van Hecke, van der Meer, Lohse), a unique AFM/confocal setup (van den Ende, Mugele) a variety of standard rheometric equipment (Bonn, van Hecke, Lekkerkerker, van den Ende), and the necessary chemical know-how for dealing with colloids and clays (Bonn, Schall, Lekkerkerker, van den Ende). Theoretically, both van Saarloos and Mackintosh have worked extensively the development of order parameters characterizing non-affine structures near jamming [11, 12, 23], and the Uva and VU groups in Amsterdam have together constructed an 'out-of-equilibrium thermometer' that has successfully been applied to a glassy colloidal system [16]. Luding brings in strong numerical and theoretical expertise on micro-macro approaches to understand structure-property relations of, e.g., hard spheres, Lennard-Jones fluids and granular media. Without any additional investments in equipment, *this programme has the required critical mass*.

Industry and engineering contacts are brought in by many of the applicants (Bonn, Lekkerkerker, Lohse, Luding, van den Ende, van Hecke). There is a clear wish of the Dutch industry to have home-trained scientists in state-of-the-art rheology, but presently the Dutch industry is importing PhDs trained in rheology from Belgium (Leuven). As the recent FOM-Shell meeting indicated, there is a clear interest in the fundamental science of soft materials, and need for the application of first class physics to industrially relevant problems. This programme addresses these needs, and has a *strong application horizon*.

An explicit advantage of a concentrated programme is that it allows a comparison of the results for the different order parameters and systems (that, we recall, show a very similar rheology), to see whether a universal microscopic description of jamming can be obtained. Our approach provides a natural breeding ground for cross fertilization — each subproject starts from one microscopic measure in one system, but applying the most successful approaches to other systems will be a logical step to take. The programme leader will ensure that the PhD and postdoctoral students in the various sub-projects spend a substantial amount of their time in one of the other groups (see section 5 and 6)[3]

Besides forging new and stronger connections between the participating research groups, creating a high-profile, concentrated effort will have two additional benefits. Firstly, a concentrated effort will make it even more interesting for people from top institutes like Chicago, Harvard, University of Pennsylvania, Edinburgh, and Paris to visit the Netherlands, start new collaborations and reinforce existing ones. Secondly, the programme will serve as the critical nucleus from which new contacts and collaborations with industry will grow. To help the organic growth of such fruitful contacts, one PhD position is *explicitly* reserved for an industrial problem, to be decided by the programme leader after visits and consultation with several industrial partners (see section 6).

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[3] Many of the applicants have already shared students or published together in the past.

4.4 Dutch ScienceScape and Relation to existing (FOM) programmes

At present, there is no concerted effort or programme concerning the broad field of jamming, rheology, and yield stress fluids, and consequently, individual research projects on these topics are funded by a diversity of resources, including the FOM projectruimte and FOM programmes 46, *Collective and cooperative statistical physical phenomena* and programme 79, *Dynamics of patterns*.

The J. M. Burgers Center, in which the Twente, Delft, and Leiden groups participate, used to have extensive rheology programmes, which however have largely disappeared – for incidental reason. Already in 2001 the industrial advisory board pointed out its concern that rheology would disappear from the Netherlands if no action would be undertaken, and in 2006 this committee concluded that for classical rheology this was effectuated with the leaving of prof. Mellema (UT). As we have argued above, there has been a renewed interest in rheological questions from groups coming from various backgrounds in recent years, and by bundling these strongly converging activities in the 'Connecting Jamming to Rheology' programme, these efforts will have the required visibility, thus constituting a timely effort to bring this field to the forefront of physics research.

There is personal overlap between this proposed programme and FOM programme 63, *Physics of granular media*, but it is important to note that the scientific focus of these are very different. Hard, dry granular media –the focus of FOM programme 63– are inherently interesting disordered systems, for which it has become increasingly clear that they are very atypical as far as jamming and rheology are considered. This stems from their hardness combined with their non-attractive interactions. Softer and wetter systems, such as the cornstarch, colloidal glasses, foams etc discussed in the current program, have many more features in common and in many aspects are quite distinct from granular media. As a consequence, no studies on granular media will be undertaken in the proposed programme. Of course, the programme will benefit considerably from the methods, techniques and contacts/collaborations that have been developed in the framework of FOM programme 63.

Research in the Dutch Polymer Institute (DPI) has a small rheological component, but clearly focusses on polymers, which are not part of this programma. In particular, many of the interesting rheological features of polymers stem from visco-elastic behavior, not from yield stresses.

Furthermore, there is a large community in the Netherlands working on colloidal systems, funded by, e.g., FOM programme 61, *Physics of colloidal dispersions in external fields*. In general, focal points in this community have been more of a purely equilibrium statistical physical nature, often focussing on ordered systems (e.g., questions about bulk freezing, nucleation rates), and on manipulation of local interactions between colloidal particles to control global features. The research in FOM programme 27, *Structure, Function and Flow of Soft Materials* is also related, but has a more biophysical and numerical focus.

Finally, we should mention the former Softlink programme, which contained some rheological work, focussed on the relation between molecular scale and rheology, with little attention to jamming, yield stress etc. This programme ended in the beginning of 2006.

It is worth mentioning that there have been now two annual "Amsterdam-New Amsterdam" meetings (organized by MacKintosh and others), first in Amsterdam (end 2005) and then in New York (fall 2006) where a number of outstanding scientist from the US (Weitz, Reichman, Chaikin, Pine, etc) meet with the Dutch soft matter community — jamming and rheology are very important focal points in these meetings.

The proposed programme clearly will fill an important hiatus in the Dutch science-scape and will be of clearly distinct nature. There is a strong need to exchange ideas and collaborate with other workers in soft matter also, as illustrated by the Dutch soft matter meetings which Schall, MacKintosh, and van Hecke have started to organize, and which typically draw some 60 participants.

5 Distribution of scientific tasks

The programme will be organized via ten sub-projects containing one PhD or postdoctoral student each.

Six of the projects start from the micro scale and focus on order parameters and microstructure near the jamming transition. A general introduction to this approach is described in section 5.1, while the detailed projects are described in section 5.3, pages 17-22. Four projects start from the phenomenological, macroscopic perspective, concerning shear banding and shear thickening. A general introduction to this approach is described in section 5.2, while the detailed projects are described in section 5.3, pages 23-26.

The ten projects, carried out by the OIOs and PDs applied for, will be supervised by the eleven applicants, who belong to eight FOM-workgroups: Bonn and Schall (UvA A-03), Luding (Delft D-38), van Saarloos (Leiden L-07), Lohse and van der Meer (Twente T-03), van den Ende and Mugele (Twente T-17), Lekkerkerker (Utrecht U-06), MacKintosh (VU V-13) and van Hecke (Leiden L-25) — for brief biographies, see section 10. They have been selected on the basis of their scientific expertise in the light of the key goals of the proposal.

There is strong synergy between the various projects. All OIOs and PDs are expected to spend a substantial amount of their time (at least 6 months) away from their principle group, and all projects have a designated 2nd supervisor - a table compiling the foreseen exchanges can be found in section 5.4.

5.1 From Microscopic to Macroscopic: Order Parameters and Structure near the Jamming/Yielding Threshold

General Motivation and State of the Art — What happens when a disordered, jammed material is subjected to external shear stresses? For small stress, the material remains jammed and the resulting deformations may be elastic and reversible, while for larger stresses, the material yields, leading to irreversible, plastic events and ultimately yielding and flow of the material. Hence, by varying the amount of stress, we can approach the jamming transition from both directions.

In recent years, it has been realized that even in the reversible regime, jammed disordered systems exhibit strongly inhomogeneous, non-affine deformations [11, 13, 24]. This can be understood as follows: imagine enforcing a uniform, affine shear on a disordered material, and then let the system relax — due to local disorder, the elastic energy can be lowered by further particle motion [13]. Surprisingly, this motion often organizes in vortex-like patterns (Fig. 2) [11]. Similarly non-affine deformations have been predicted and observed in biopolymer networks [12]: non-affinity is a general feature of disordered systems near the jamming/yielding threshold. A crucial macroscopic consequence of this non-affine organization is that it lowers the resistance to shear — in some cases, the modulus vanishes as a powerlaw with the distance to the jamming point, making this distance a crucial quantity [11, 13].

This programme deals in large part with the case when the material is flowing, i.e., above the jamming transition. Similarly non-affine flow patterns have been observed in a variety of

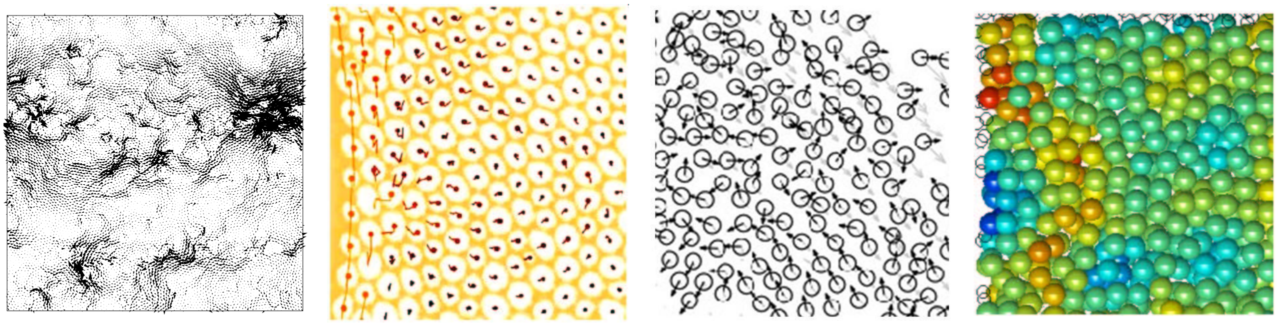

Figure 2: From left to right: Non-affine deformation field observed in computer simulations near the jamming transition [11]. Non affine flow in sheared foam [33]. Non affine granular flow [34]. Computer rendering of non-affine flow in sheared colloidal glass, where the red particles form shear transformation zones [35].

systems [33–35] (Fig. 2), but these have not been described in much detail and neither their cause nor their effect on the flowing behavior are well understood. Similarly to how the elastic non-affine deformations control the elastic shear modulus, the non-affine flow patterns may control the resistance to shear flow. The non-affine flow patterns provide an important avenue for unravelling the mechanisms that mediate the coupling between the local flow and the local rheological features — the key goal of the present proposal.

Order Parameters — How to characterize the spatio-temporal organization in systems near jamming? A variety of order parameters based on the non-affine nature of the deformation/flow field have been introduced [11, 23, 24]. When the system is flowing, the situation is particularly rich, with the non-affine flow patterns fluctuating rapidly. This situation can be characterized by a number of order parameters, such as single particle self-diffusion coefficients, four-point correlation functions [25] and order parameters inspired by turbulence [26]. In particular, the flow of disordered systems organizes into localized irreversible rearrangements, called Shear Transformation Zones [9] (Fig. 2) — how these relate to the short-time non-affine flow patterns is not well understood.

This is a very active field of research, with many open questions regarding the order parameters near jamming [27]: Do characterizations for small deformations carry over to characterization of flowing systems? What is the connection between non-affine deformations and shear transformation zones? How do structures in Brownian and non-Brownian systems compare? How to connect local structural measures to the local rheological properties of the materials?

This Programme's Approach — To address these questions, and to connect the microscopic structure and jamming properties of yield stress materials to their macroscopic, phenomenological rheological features, four experimental and two theoretical / numerical projects test the applicability of various order parameters. Specifically, in project **I** (Lohse) tools from turbulence and Minkovsky functionals are applied to a novel system of particles floating on surface waves, which jam upon increasing density and/or lowering wave intensity. In project **II** (van Hecke), oscillatory sheared 2D foams are characterized by their local non-affinity via the displacement angle distributions — wetness and strain amplitude control the jamming/yielding transition. In project **IV** (Schall), sheared colloidal suspensions are imaged in 3D, their shear transformation zones are characterized, and the effect of particle size (i.e.

crossing over from Brownian colloids to non-Brownian pastes) is investigated. In project **V** (van den Ende/Mugele), the deformations of micronic gel particles as function of packing fraction and strain are imaged in 3D and probed by AFM.

The two theoretical/numerical projects (**III**,**VI**), start from the micro scale, and aim at making the connections with the rheological features. Specifically, in project **III** (MacKintosh) an effective medium theory will be developed, in which structural inhomogeneity is modelled by variations of the local elastic moduli throughout the material, and in project **VI** (Luding), direct simulations of sheared particle/bubble assemblies will allow us to connect local non-affinity and global flow features.

5.2 Jamming and unjamming: from the macroscopic to the microscopic scale.

General Motivation and State of the Art — Shear banding, where the globally imposed flow localizes in one or more narrow bands while the remaining part of the fluid remains jammed, is a generic feature of yield stress fluids, glassy materials, and shear thinning fluids. Classical, phenomenological rheological models such as the Herschel-Bulkley model (see Fig. 1) do not describe all observations of shear banding satisfactory [4, 6, 7, 17]. In our view, shear banding is a prime manifestation of the coupling between the local flow and its local rheological features, and provides an excellent opportunity for probing this coupling.

Shear thickening is the phenomenon that some dense suspensions such as mud and cornstarch increasingly jam when their flow rate is increased. This is an extremely important issue to understand, since it forms the exception to the ubiquitous shear-thinning behavior, and uncovering the (microscopic) causes of shear thickening will also provide insight in the causes of shear thinning.

Shear bands in both shear thinning and shear thickening systems often grow with the shear rate, but the effect of these are radically different in these two classes of systems. Whereas shear thinning fluids *unjam* by such growth, recent observations for shear thickening systems found that, surprisingly, the system *jams* when the flow has become fully homogeneous [36]. Unravelling the intricate connections between shear banding, jamming, shear thinning, shear thickening and microstructure is the key in advancing our rheological knowledge.

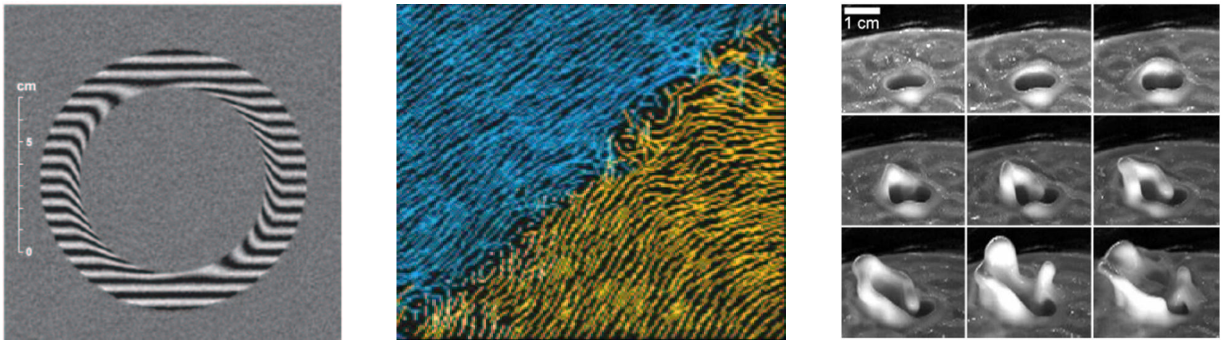

Figure 3. From left to right: Magnetic resonance image of shear band in Bentonite clay [37]; shear band observed in simulations of granular media [38]; shear thickening fluids turn unstable and grow fingers when vibrated [39].

New Approaches to Shear Banding and Shear Thickening — Order parameters models constitute an important first step in capturing the coupling between the local flow and the local rheological features, such as yield stress. For example, the aging and rejuvenation of yield stress fluids can be captured in the so-called λ-model that was recently introduced by Coussot, Bonn and coworkers [2, 4]. Here λ is an order parameter which represents the degree to which the system is jammed, and a simple differential equation then makes λ grow with time (aging), but decreases λ by shear (rejuvenation). Such a model predicts a number of aspects of shear banding observed in colloidal glasses qualitatively correct [2, 4]. The main open questions are: Is it possible to find a simple theoretical model for which the λ-model can be derived explicitly? Can we make the λ-model quantitative? Is it applicable to all yield stress materials, and if not, what is missing?

Why would most systems exhibit shear thinning, while some exhibit shear thickening? One intriguing solution that was proposed recently [40] is that shear-thickening is due to a re-entrant jamming transition. Similarly to systems that have a re-entrant 'solid' transition as a function of temperature, for shear thickening systems the 'solid' phase may then be induced by shear. Open questions are: What order parameter model captures the connection between shear banding and shear thickening? How can we characterize shear thickening from a microscopic perspective, and experimentally probe the re-entrant phases idea?

This Programme's Approach — To address these questions, two experimental projects (**IX**/**X**) will study shear banding in shear thinning systems, and one theoretical (**VII**) and one experimental project (**VIII**) will study shear thickening. In project **IX** (Bonn), shear banding in Brownian (colloidal suspensions) and non-Brownian (pastes) systems will be studied, in particular aiming to make the aforementioned λ-model quantitative and predictive. In project **X** (Lekkerkerker), the rheology and shear band formation of mixed dispersions of natural clay with differently shaped (rods, plates, spheres) synthetic colloids will be studied, and order parameter models involving flow-mediated building and disruption of fluid structure will be developed.

In the theoretical project **VII** (van Saarloos), order parameter models for shear thickening will be developed starting from the experimental observations that shear thickening and rheochaos sets in when the shear band spans the full system. In project **VIII** (van der Meer), shear thickening will be probed both in vibrated cornstarch and in suspensions of spherical particles of varying sizes, to provide model systems in which the individual particles can be tracked, and where the models of van Saarloos can be tested.

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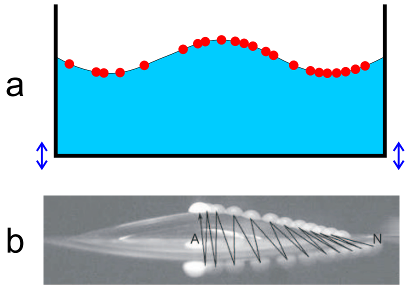
5.3 Project Descriptions

PhD Student Prof. Dr. D. Lohse, Twente

I: Jamming of particles on a surface — We would like to examine experimentally, theoretically, and numerically the distribution and dynamics of particles on surface waves, in the limit of large particle concentration ϕ.

The crucial new element in these experiments is that the particles that jam are driven through the surrounding flow, thus bridging the gap to turbulent two-phase flow. In the low concentration limit, the particles congregate either at the nodes or antinodes, depending on their hydrophobicity [1]. For increasing particle concentration, jamming will occur beyond some threshold. The mobility of the particles will then be limited. Around the transition we expect shear-thickening behavior: The particles will still be able to follow slow movements which allow for non-local particle re-arrangements, but on faster timescales they will be stuck due to inertia effects.



Standing Faraday waves are generated on a vertical shaker (a). Hydrophobic particles on the surface congregate at the antinodes (b, from [1])

Important questions to address are: Does the jamming transition show critical behavior? Do correlation lengths diverge? Is the transition hysteretic? What are appropriate order parameters? What is the connection to the shear-thickening behavior of, e.g., corn-starch?

We will probe these questions by measuring, using high speed imaging and particle tracking, quantities such as relative diffusion, structure functions, velocity and acceleration statistics, borrowing recent techniques developed for *Lagrangian turbulence*. In addition, we will explore the use of so called *Minkowski functionals* which give more complete statistical information than simple pair-correlation functions — these morphological measures had first been introduced in an astrophysical context (cluster formation of galaxies). On the numerical side we will employ effective forces such as drag and added mass to describe the particle dynamics on the moving liquid, similarly as we did for bubbles in turbulence.

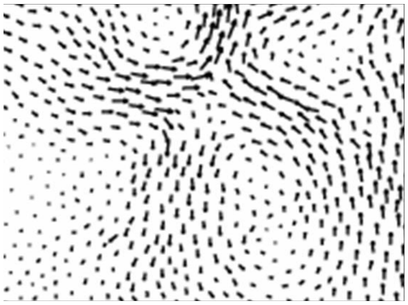
System — The surface (Faraday) waves will be created with a shaker. The control parameters are the shaking strength and amplitude and particle size, shape, density, surface property, and concentration. The particles are followed with high-speed imaging techniques.

Expected Results — We expect to bridge the gap between jamming in one-component systems and strongly driven high-concentration multi-component systems (two-phase flow). Moreover, we will introduce new order parameters to characterize the jamming transition.

Collaborators and Connections — The student will spend at least six months in the group of van Saarloos (**VII**), where he/she will either focus on the shear thickening features of this experiment, or compare results on the local structure to non-affine order parameters developed by van Saarloos. This project will furthermore interact with the other order parameters projects (**II**-**VI**) and will benefit from the project on shear thickening from van der Meer (**VIII**).

[1] G. Falkovich, A. Weinberg, P. Denissenko and S. Lukaschuk, Nature **435** 1045 (2005).

II: Non Affine Foam Flows — We propose to study the fluctuations and non affine bubble motion in 2D foams, that are driven by an oscillatory shear.



Bubble motion in sheared foam.

Strong non-affine deformations are a hallmark of the jamming transition. The focus has been on deformation fields seen in theoretical studies of elastic behavior, but there are numerous unsystematic observations of non-affine flows which bear a striking resemblance to these (see Figure). Two dimensional foams are eminently suited for studying these flows, as they are easily imaged and allow for a precise experimental control of wetness of the bubbles, which corresponds to the 'density' axis of the jamming diagram.

We propose to study experimentally the bubble motion and deformation fields of flowing foams. We characterize the deformations by a recently introduced local measure of non-affinity, the displacement angle distribution, which exhibits scaling and a divergence near yielding that signals singularly strong non-affine deformations [1]. We will vary the wetness of the foam, the strain amplitude and strain rate to study the crossover from reversible to irreversible displacements and flow. Do shear rate and filling fraction control non-affinity of flowing foams? How do non-affine structures in the reversible and irreversible regime compare? Depending on our parameters, shear bands will form, which will allow us to connect microstructure and macro rheology: Does non-affinity determine the degree of shear banding?

System — The foam flows will be generated in an innovative new flow geometry, which we recently developed, consisting of two parallel, coaxial, counter-rotating and rough wheels immersed in a layer of frothy soap solution. In pilot studies, we found that this geometry allows to shear 2D foams for large aspect ratios, over long periods of time, and for a wide range of liquid fractions.

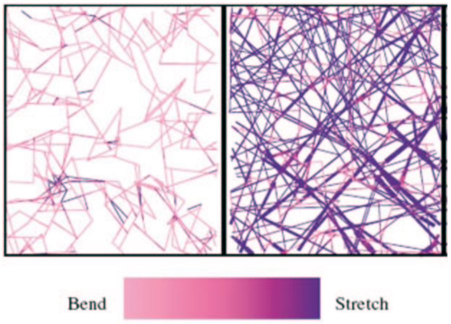
Expected Results — We aim at obtaining an experimental determination of the degree of non-affinity as function of wetness and strain amplitude, thus connecting the structure in elastic and flowing regimes. Moreover, we will establish the relevance of these structure for the rheology, i.e., shear banding of the foam.

Collaborators and Connections — The student will spend at least six months in the group of Lohse, where he/she will compare different measures for the affinity of particles on a surface (Project **I**). The project is closely related to project **IV** (sheared colloids), **III** (theory of non-affine deformations) and **VI** (numerics of sheared systems), and will further benefit from the rheology expertise of Bonn and the continuing work of van Saarloos on non-affine deformations in weakly jammed systems.

[1] W. G. Ellenbroek, E. Somfai, M. van Hecke and W. van Saarloos, Phys. Rev. Lett. **97**, 258001 (2006)

III: Modelling of non-affine deformations and flow — We will develop order parameters and an effective medium theory for deformations in multi-component soft matter systems, and probe the relationship between structure and inhomogeneity of their flow.

It is perhaps surprising that a general framework for understanding large, non-affine strains and complex/inhomogeneous flows of soft matter remains a challenge. One of the areas of recent progress, both by us and by others, has been motivated by biopolymer networks (see right). We believe that many of the same principles apply to colloidal suspensions, slurries, and foams. For example, it has been shown that local connectivity plays a key role in determining whether filamentous gels deform/flow homogeneously or not.



Deformations in polymer networks

Connectivity and local structure are similarly crucial for colloidal gels and suspensions, where packing constraints limit their connectivity. We and others have recently found and exploited analogies between colloidal gels and stiff polymer gels, even though these are seemingly unrelated systems [1]. In particular, these observations strongly suggest the role of bending elasticity in colloidal gels. We are also pursuing analogies in the load-bearing structures (e.g., force chains) in fiber gels and jammed colloidal suspensions.

Our first aim is to build on these recent developments and construct appropriate order parameter for non-affine strain. These will be confronted to other order parameters employed in this programme, notably the shear transformation zones employed by Schall, and the displacement angles introduced by van Saarloos and van Hecke. Our second aim is to develop an effective medium theory for composite, multi-component soft matter systems. We propose to introduce structural inhomogeneity in the form of random elastic moduli that vary on the characteristic length scales of the system. Furthermore, we will investigate the role of the hydrodynamic coupling to a solvent which is a general property of many composite materials. Finally, we will extend our techniques to understand the relationship between structure and inhomogeneity of flow. We shall explore this by both numerical simulations and effective medium theory, within which we are currently developing techniques to identify how forces/loads are borne at the mesoscopic scale in soft materials.

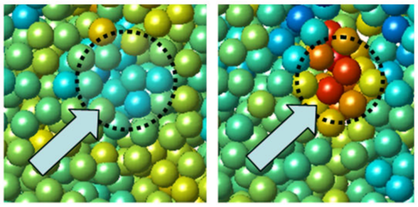
Expected Results — We will elucidate the relationship between various order parameters for non-affine strain, and develop an effective medium theory for disordered systems that can predict the influence of local structure on the heterogeneity of flow.

Collaborators and Connections — The postdoc will regularly visit and work with the Schall (**IV**), but also van den Ende (**V**), and van Hecke (**II**) groups, to develop and test experimental measures (order parameters) for sheared foams and colloidal/microgel particle suspensions. We also anticipate extensive collaborations with the Luding group (**VI**), in both the development and interpretation of numerical approaches.

[1] V. Trappe and D. A. Weitz, Phys. Rev. Lett. **85**, 449 (2000); M. L. Gardel, J. H. Shin, F. C. MacKintosh, L. Mahadevan, P. A. Matsudaira, and D. A. Weitz, Phys. Rev. Lett. **93**, 188102 (2004).

IV: Jamming and the Glass transition — What is the relation between the glass transition of Brownian colloidal particles and the jamming transition of non-Brownian particles (pastes)?

The glass transition for Brownian particles occurs at a particle density of 58%, while jamming for non-Brownian particles occurs at 64%. Are these two distinct transitions, or does the critical density smoothly cross over between these limits? How do Brownian fluctuations affect the spatio-temporal organization of non-affine regions observed in non-Brownian system ? Can we extract characteristic length scales when we approach the jamming/glass transition? We will probe these questions by shearing suspensions with particles ranging in size from 1 μm to several tens of micrometers and imaging the individual particles in three dimensions with fast confocal microscopy.



A shear transformation zone (red region, right) nucleates from a thermally induced strain fluctuation (blue region, left). Color indicates local shear direction.

We start our investigations in the regime of slow flow, and we will vary both the density, which controls the distance to jamming, and the particle size. We will track the motion of tens of thousands of particles simultaneously and determine the microscopic strain distribution associated with the particle displacements. From this, we will determine the location of the glass/jamming transition, characterize the shear transformation zones and investigate how characteristic length scales change as function of density and particle size. The jamming diagram suggests that the critical densities increase when the system is sheared rapidly, and by increasing the strain rate, we will probe the effect of flow on the jamming transition and the spatio-temporal organization of the non-affine regions.

The microscopic detail afforded by three-dimensional strain distributions together with the individual particle trajectories will allow unique insight into the flow mechanism and the nature of the jamming transition in both Brownian and non-Brownian systems.

System — Colloidal particles will be imaged in a fast confocal microscope (120 frames/sec), which is suitable for imaging larger non-Brownian particles also. A plate-plate shear cell has already been constructed and is ready for use. The code for characterizing non-affine deformation patterns needs to be developed further, partly in collaboration with van Saarloos.

Expected Results — We will elucidate the connections (or differences) between the glass and jamming transition, and determine the nature of the non-affine regions near both transitions. We will connect measures appropriate for quasistatic and flowing systems by varying the strain rate.

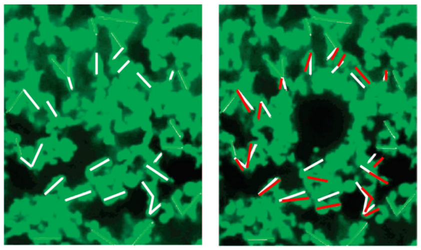
Collaborators and Connections — The student will spend at least six months in the group of van den Ende, where he/she will compare the results obtained in this project to the displacement fields observed in the sheared gel-particles (Project **IV**). This project will directly interact with the proposed work of van Hecke and Lohse on the formation of structures near jamming, and will benefit from the expertise of MacKintosh, van Saarloos and van Hecke on effective temperature and non-affine deformations.

PhD student Dr. H. T. M. van den Ende and Prof. dr. F. Mugele, Twente

V: Jamming and yielding of microgel particle dispersions— We will probe the progressive yielding of a jammed microgel system under local indentation.

A microgel particle is an intramolecularly cross-linked, soluble macromolecule of colloidal dimensions. The size depends on the degree of cross-linking and the nature of the solvent and is comparable to very high molecular weight polymers; its internal structure is that of a swollen network. Therefore the effective volume fraction of the microgel particles in the suspension can be controlled during the experiment by adjusting the temperature and/or solvent quality. Microgel pastes are highly concentrated suspensions of such particles, where due to excluded volume effects the particles are deformed and jam. Microgels are used as binders in organic coatings and in food products, while pastes in general are applied in various area's, like pharmaceutical, food and cosmetic industries.

We will probe and manipulate the mechanical properties of the sample by atomic force microscope and with a surface forces apparatus (SFA)-like device, and measure the structural changes in microgel pastes by tracking particle displacements in a confocal microscope. To access the transition from jammed hard particle to soft particle suspensions, we will use thermosensitive microgel particles, and hard silica spheres coated with a polymer layer of variable thickness and density. We will probe the structural rearrangements in the jammed system at the onset of non-linear behavior and also in the presence of shear bands in regions of high stress and strain. Furthermore, we want to explore the role of vibrational excitations to induce jamming or un-jamming in the system.



Confocal images for an aggregated sample, before (left) and after (right) indentation. The white and red bars present the orientation of chains before and after indentation.

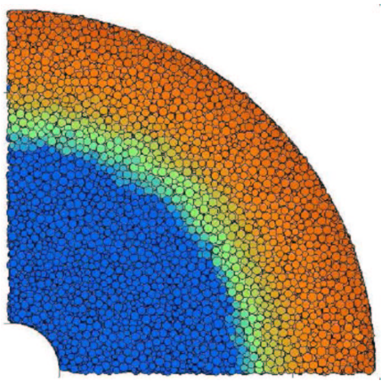
System — The microgel particles we will use are thermosensitive PNIPAM (poly-N-isopropylacrylamide) microgel particles. At temperatures above $T_c \approx 30$ °C these particles are shrunken to a typical radius of $R \simeq 100$ nm, while below T_c they are swollen to a radius twice as large, thus allowing tuning of the effective particle volume over almost a decade. For both systems the radius temperature dependence is determined from dynamic and static light scattering experiments. To study the hard sphere limit, colloidal monodisperse silica particles will be used.

Expected Results — By varying the effective volume fraction of the suspension, we will probe the mobility of the particles, and so the rheology of the suspension, around the jamming transition. We expect to find regions where the system is jammed (no mobility) and regions where the system can still flow which will be reflected by a higher mobility of the particles. Jamming can be probed and controlled using the SFA/confocal setup.

Collaborators and Connections — The student will spend at least six months in the group of Schall (**IV**), to study the deformation field of the microgel assemblies under homogenous shear. This study will also benefit from interactions with MacKintosh (**III**) for interpretation of the non-affine deformations, and from interactions with Luding (**VI**).

VI: Jamming, shear banding and microstructure — We will numerically probe the connections between jamming, shear banding and microstructure in numerical simulations of sheared Brownian and non-Brownian systems with various interaction potentials.

We will numerically probe the connections between jamming, shear banding and microstructure in numerical simulations of sheared Brownian and non-Brownian systems with various interaction potentials. This will be done in close collaboration with the experimental projects **IV** (Schall) and **IX** (Bonn), where the microstructure and macroscopic rheology are also probed simultaneously. The numerics allows for full access to the system at small and large time ($1 - 10^6 t_c$) and length ($1 - 200d$) scales, where t_c and d are the typical single particle response time and the particle diameter. Long simulation runs will be performed to scan the system response as function of, e.g., the intensity of the Brownian noise, the rigidity of the particles, or their adhesivity.



Shear band (green) in 3D simulation of $4 \cdot 10^4$ dry grains.

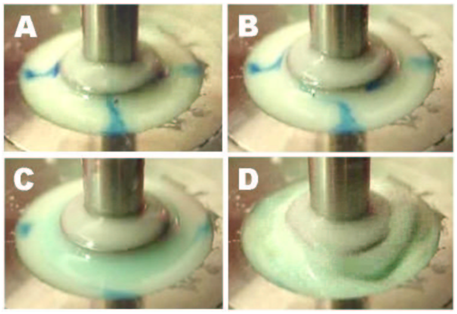
By reproducing essential aspects of the experimental projects **IV** and **IX**, our numerics allow to probe both the relation between jamming and shear banding, as well as the microscopic origin of the yielding and jamming of sheared systems, this programme's first and second key questions. In addition, we will be able to compare particle displacements over a wide range of timescales, and elucidate relations between short time scale non-affine flow patterns, intermediate scale shear transformation zones and long time average flow profiles.

System — Discrete element simulations in 2D and 3D will be performed with Ludings code that has in recent years evolved from a purely granular code to include Brownian fluctuations, drag interactions with interstitual fluid and a wide range of particle interactions. Reasonable simulations times can be achieved for systems up to 10^5 particles.

Expected Results — We will further develop and test numerical models suitable to describe sheared Brownian and non-Brownian suspensions using effective pair interaction potentials and simple drag relations. Goals are to relate non-affine microstructure and macroscopic shear banding phenomena, to obtain local and global flow-rheology, and to unravel the order parameters for jamming and yielding.

Collaborators and Connections — Besides the regular interactions with various other projects, the student will spend at least 6 months in the group of Bonn (**IX**). Aim is a quantitative comparison of numerical and experimental results for shear bands and microstructure. In particular, numerical results are to be combined with microscopic probes of the structure of the experimental systems by, e.g., confocal microscopy or light scattering. There will also be close collaboration with Schalls experiments (**IV**), and the project will further benefit from related developments and insights of MacKintoshs project, e.g., concerning the interpretation of non-affine flow fields.

VII: Competition of jamming and shear banding — We will investigate the competition of jamming and shear flow instabilities in complex, shear thickening fluids.



Sheared cornstarch (Experiments by Bonn)

A surprising transition has recently been observed by Bonn in a Taylor-Couette cell filled with cornstarch (see right). Initially, when the rotation rate of the inner cylinder is increased, a strong shear banding is observed: only near the inner cylinder there is a measurable shear flow (A-B). The flow in this band remains laminar. As the rotation rate is increased, the width of this zone increases smoothly (C). The cornstarch does exhibit shear thinning but there is no significant normal stress effect in this regime, and MRI experiments give no sign of any density difference between the bands. As soon as the shear band reaches the outer cylinder, however, the fluid becomes strongly unstable and there is a large normal stress effect – W it essentially appears as if the fluid Tjumps T to another dynamical regime (D).

We will develop an order parameter model guided by the following questions: Are the normal stress effects the cause or the effect? Is the observed Tjump T a signature of a nonlinear (subcritical) flow instability? Can we develop insight into what happens microscopically, i.e. could it be that this sudden transition is a form of jamming? Why does the critical shear rate at which the transition occurs increase linearly with gap size?

The experimental observations naturally pose the question whether the chaotic motion can be seen as “elastic turbulence”, and whether the shear thickening is due to this turbulence — it is well known that for regular turbulence the flow resistance increases dramatically at the laminar/turbulent transition. We will investigate the transition to elastic turbulence theoretically, in order to see how large the increase in dissipation can be at the transition.

Expected Results — Development of models to connect the experimentally observed shear banding, shear thickening, rheo-chaos and normal stress effects.

Collaborators and Connections — The student will spend at least six months in the group of van der Meer, where experimental studies in shear thickening are undertaken (Project **VIII**). Furthermore, we will directly interact with Bonn who performed the experiments shown above, and with Lohse (**I**) who may see shear thickening in 2D systems.

VIII: Vibration induced jamming and shear thickening — We will develop model systems for shear thickening suspensions and probe their rheology and configurational changes close to the vibration-induced jamming point.

This work is motivated by recent work describing the formation of persistent holes and finger like protrusions in thin layers of cornstarch that are shaken at high accelerations [1]. Other than that these phenomena must be connected to the shear-thickening properties of the cornstarch and a change from a fluid to a more solid-like, jammed state, it is unknown what mechanism causes these shapes.


Fingers on vibrated cornstarch

In a first series of experiments, a thick layer of cornstarch will be vibro-fluidized using a shaker. We will probe its macroscopic properties by measuring the force response of a sphere which is submersed into the layer. Towards the jamming point the buoyancy and drag forces present in the fluid-like state will be transformed into yield force behavior. By slowly moving the intruder through the medium we will be able to distinguish between the two regimes. Important control parameters are the shaking strength —- at varying frequencies, amplitudes, and driving modes — and the particle concentration in the suspension.

Repeating the experiments in an index-matched suspension of micron-sized glass spheres (diameter 10-50μm) will allow us to at the same time measure the microscopic properties of the fluid. We will add colored tracer particles to the suspension and record their movement with high speed imaging, and deduce the diffusive properties of the medium. Thus, we obtain simultaneous information on the transition towards jamming on both the microscopic length scale of a single particle and the macroscopic scale of the scale of a single particle and the macroscopic scale of the intruder. Important questions to answer are: How does the diffusion constant change with time? Do the signatures of the jamming transition at both length scales occur for the same parameter values? If not, of what size must the jammed structures at the particle scale be to be noticeable on the macroscopic scale?

The results will be connected to the rheology of the used suspensions, measured by combining more traditional rheological measurement techniques available in the groups of Bonn and van Hecke with vibro-fluidization.

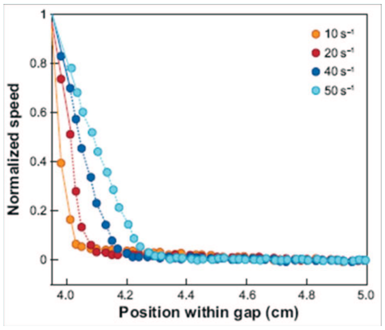
System — We will use cornstarch and glass-sphere suspensions mounted on a powerful shaker, studied using high speed imaging techniques and force transducers.

Expected Results — The creation of a model system for shear-thickening suspensions, leading to a thorough understanding of the structural changes on the microscopic scale and how these connect to the macroscopic rheological properties of the model system.

Collaborators and Connections — The student will spend at least six months in the group of van Hecke (**II**) to characterize our suspensions using rheological measurement. In addition there will be strong interaction with Bonn, and with the proposed projects on shear thickening of Lohse (**I**) and van Saarloos (**VII**).

[1] F.S. Merkt, R.D. Deegan, D.A. Goldman, E.C. Rericha, and H.L. Swinney, *Phys. Rev. Lett.* **92**, 184501 (2004).

IX: Shear banding in glasses and suspensions — We will probe shear banding in Brownian and non-Brownian suspensions, and quantitatively model the flow with a microscopic model accounting for shear banding.



The most striking and general feature common to all shear-thinning systems is the observation of shear banding, where part of the system flows, whereas the rest remains jammed. Upon increasing the globally imposed shear rate, a larger and larger fraction of the materials flows (see left). This shows that shear banding is the mechanism by which yield stress fluids unjam. The key question remains what the relation is between the local organization or structure and the macroscopically observed shear banding.

For going from the macroscopic to the microscopic level, we will use the phenomenological λ-model introduced by Bonn and co-workers [1-2]. For colloidal systems, this model qualitatively predicts the correct shear banding behavior observed for low shear rates. The new experimental data obtained in this project will to be used to improve the model to make it quantitative and predictive. For this, a microscopic model for the coupling between the flow and the structure/organization needs to be introduced. The latter will be tested experimentally using microscopic probes of the structure of the experimental systems by e.g. confocal microscopy and light scattering. This will provide us with the necessary relation between the microscopic organization/structure of the particles and the parameters of the shear banding model.

In addition, a statistical mechanical description will be developed to see whether, in the spirit of the jamming phase diagram, the effect of shear can be described as an effective temperature. A comparison between Brownian and non-Brownian systems will also allow to assess the importance of thermal fluctuations on the jamming/unjamming behavior.

System — We will here focus on simple systems: suspensions of particles, both Brownian (colloidal) and non-Brownian (paste), since these appear to be the most amendable to comparison with theory, and allow for detailed experimental scrutiny.

Expected Results — A microscopic understanding of the relation between jamming and shear banding for one or two specific systems.

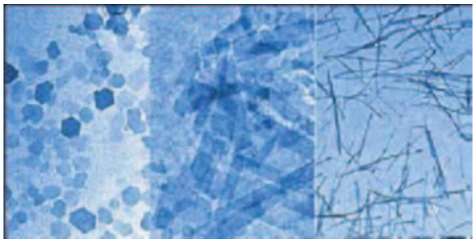
Collaborators and Connections — The student will spend at least six months in the group of Lekkerkerker, where related studies on shear banding are undertaken (Project **X**). Furthermore, the project will directly interact with Ludings simulations of shear banding (Project **VI**), Schalls project on shear transformation zones in sheared glasses (Project **IV**), and MacKintosh ongoing work on effective temperatures.

[1] P. Coussot *et al.*, Phys. Rev. Lett. **88**, 218301 (2002)
[2] P.C.F Moller, J. Mewis and D. Bonn, Soft Matter **2**, 274 (2006)

X: Rheology modification in colloidal clay dispersions — We will study the rheology enhancement in mixed dispersions of natural clay with synthetic colloids of various shapes (rods, plates, spheres).

The flow behavior of colloidal clay dispersions is crucial for many applications, in particular for oilfield and construction drilling fluids. For these fluids to function, they must jam and be able to suspend pieces of gravel with no settling (like fruit suspended in gelatin) when left at rest, and must flow like viscous liquids at high shear rates. We discovered that these desired rheological properties can be enhanced significantly by adding colloidal particles of different size and shape [1]

To get insight into the mechanism of this phenomenon, we will study mixed shape colloidal systems whose shape changes systematically from plate-like (gibbsite aluminasol), through a lath-like smectite clay (hectorite), to rod-like aluminasols (boehmite). We will probe their rheology by oscillatory, transient and steady shear experiments. Moreover, we will characterize their flow profiles by confocal microscopy, since shear banding is expected to accompany the transition from elasto-plastic solid to visco-elastic liquid.



Mixed shape colloidal dispersions, from left to right gibbsite (plates), hectorite (laths) and boehmite (rods)

On the one hand, this project will provide much better insight in the practical question how size, shape, interactions, deformability and volume fraction of mixed colloidal suspensions can be used to design and control the rheological and filtration characteristics of oilfield fluids. On the other hand, to understand the shear banding and rheology, a physical model involving flow-mediated building and disruption of fluid structure will be developed, that likely needs more ingredients than the simple λ-model discussed above.

System— The base clay to be used will be a well-characterized Hectorite clay (a dioctahedral smectite clay.) Dispersions of this clay will be modified by the addition of a series of aluminasol particles whose shape varies systematically from rod (boehmite) to platelet (gibbsite) to sphere (alumina-coated silica).

Expected results— Physical understanding of rheology enhancement in mixed shape colloidal dispersions. This understanding will lead to the formulation of a much broader class of enhanced rheology fluids using mixtures of mineral oxide and hydroxide sols with non-bentonite clays.

Collaborators and Connections— The postdoc will spend at least four months in the group of Bonn (**IX**), comparing shear banding and rheology of the colloidal clay mixtures to the pure colloidal suspension there. This project will further interact with the planned experiments of Schall on colloidal glasses (**IV**), and the simulations of Luding (**VI**).

[1] Process Fluid. Inventors F.M. van der Kooij, H.N.W. Lekkerkerker, E.S. Boek, United Kingdom patent number 2378716, granted 14 January 2004.

5.4 Overview of Exchanges

In the table below, the arrows indicate the principle exchanges of students — Lohse's student visiting van Saarloos, van Saarloos' student visiting van der Meer etc. The "quadrant" **I-II-VII-VIII** focusses on microstructure and shear thickening, the "triangle" **III-IV-V** focusses on order parameters and small amplitude strains, while the triangle **VI-IX-X**, focusses on shear banding and large amplitude strains — i.e., flow. These three groups all span theory and experiment, different approaches and different institutes.

Collaborations are clearly not restricted to what is indicated in this diagram. Interactions between projects in the same universities and between the three theory/numerical projects will be natural, as many other collaborations as well.

	From micro to macro			**From macro to micro**
I	Jamming on a Surface - Lohse	→	**VII**	Jamming and Shear Bands - Van Saarloos
	↑			↓
II	Foam Flow - Van Hecke	←	**VIII**	Shear Thickening - Van Der Meer
III	Non-Affinity: Theory - Mackintosh			
	↓			
IV	Shear Transformation Zones - Schall			
	↕			
V	Micro Rheology - Van Den Ende & Mugele			
VI	Numerical Models - Luding	→	**IX**	Shear Bands in Colloids - Bonn
				↕
			X	Rheo-transitions in Clays - Lekkerkerker

6 Organisational Structure

The scientific programme is described in section 5, and is tightly focused with projects chosen such that they profit maximally from each others strengths and should lead to effective collaborations. No open rounds or calls for proposals will be organized. A single PhD position is reserved for a project defined in close collaboration with industry, following the industrial visits of van Hecke (see below).

The applicants prefer to put the responsibility for organizing the programme in the hands of a single programme leader, and they propose that M. van Hecke will take on this role. He will be the central contact between FOM and the consortium regarding all correspondence regarding this programme and will be responsible to FOM for the scientific direction. He will monitor the scientific direction, progress and coherence of the program, initiate the scientific meetings, coordinate visits, exchanges and joint projects, and will develop existing and new contacts in industry. Specifically:

(i) Graduate students and postdocs in this programme are expected to spend a substantial period, ranging from 6 months up to one year in one of the other groups, and the programme leader will be responsible for effectuating this. Besides the many collaborations and exchanges that already can be foreseen, we see it as an important task to spot, at an early stage, further opportunities for exchange and collaboration, and effectuate these.

(ii) The programme leader will be coordinating the attracting of high-profile colleagues from places like Chicago, Harvard, University of Pennsylvania, Edinburgh, UCLA, Paris to visit the Netherlands. The existence of a focussed programme on Jamming and Rheology will be of tremendous help, and we see it as an important task of the programme to push this field forward. We will coordinate such exchanges with the Amsterdam-New Amsterdam meetings and soft matter meetings mentioned earlier (see section (4.4)).

(iii) The programme leader will organize an annual scientific meeting with all participants, and industrial guests. At each annual meeting at least one industrial scientist will be invited to give a presentation of the current state of ’soft matter’ science in industry.

(iv) The programme leader will also be responsible for developing contacts with industry and to this end Unilever, Akzo, Corus and GeoDelft have already been contacted and have expressed their vivid interest in the program. Other companies and organizations are presently being contacted. We have reserved one PhD position to work on a problem suggested by industry, and will invite suggestions together with our first annual meeting. We suggest that this is an effective manner in which contacts between academia and industry can grow.

A fraction of the budget (about 5%) is set aside for flexible steering of the program. This will allow the programme leader to provide funds for inviting guests, extended visits of young scientists abroad, additional technical support, additional investment budget, and the organisation of an international workshop. Requests for such funding will be balanced against the progress of the project and the importance of the proposed activity for the final goals of the program.

7 Application perspective

The projects in this proposal have a strong fundamental focus. However, the questions we address have an important horizon for the food industry, chemical and oil-industry, since as we described above, yield stress fluids are widely used; well-known examples are toothpaste, mayonnaise, shaving foam, and oil drilling fluids. The project thus proposes a fundamental step forward in our comprehension of these industrially very important fluids. Examples of earlier impact of the applicants work on industrially relevant processes concern improving the delivery of pesticides by modifying droplet pinch-off (Bonn), controlling microbubbles in inkjet printers (Lohse), improving the rheology of drilling fluids (Lekkerkerker) and describing meltfracture in polymer extrusion (Bonn/van Saarloos).

Examples of practical situations where a deeper knowledge of the occurrence and manipulation of yield strength may bear fruit include:

Drilling fluids — The flow behavior of suspensions of colloidal clay particles are of considerable interest in many applications such as in oil fields and for the construction of drilling fluids. Drilling fluid engineers have realized since a long time that the yield stress is not a well-confined concept. In computer programs they use to predict and control drilling mud injection it is customary to introduce a ’static’ and a ’dynamic’ yield stress. However, this is still insufficient to predict the rheology of their drilling fluids.

Reconstitution of oilfields — When oil fields are depleted, fluid has to be pumped back into the soil to prevent consolidation (shrinking) and potential collapse of the material. Simply pumping water into the soil may lead to catastrophic liquifaction, quite the opposite of what one attempts to achieve. Using clay suspension can help strengthening the soil — the control of yield stress by clay concentration and the role of flow in weakening these material is thus of the greatest practical importance.

Margarine — Margarine contains a mixture of saturated and unsaturated fats. For health reasons, one might want to lower the amount of higher saturated and trans-fats, but these also give the margarine its solid-like (jammed) appearance at room temperature — without these, the material becomes fluid-like. Therefore, techniques that can increase the yield stress of margarine with low saturated fat content are actively researched.

Geophysics — Clayey soils are present virtually everywhere, and can be subject to landslides accompanied by a spectacular liquefaction due to the viscosity bifurcation mentioned above. Such behavior is however not taken into account by the geophysicists assessing the constructability in certain areas, causing much damage. The understanding of the ’yield stress’ of soils AND their post-yielding behavior (the subject of the current proposal for yield stress fluids in general) is thus of the utmost importance for risk control.

Rubbers and plastics — Understanding the mechanical properties of, often particle-reinforced, polymeric glasses upon approach and beyond the glass transition is of utmost importance for virtually all applications of plastics; rubber for tires is one good example of such a system for which the mechanical properties are incompletely understood. Bonn has an ongoing collaboration with Michelin on this problem; the Dutch Polymer Institute is likely to join in.

Bulletproof vests — The shear thickening fluids we propose to study also have a number of applications. The most enticing one is probably that of the bullet-proof vest [41], filled with a shear-thickening material. The fluid is liquid when wearing the vest under normal circumstances, but as soon as a bullet hits the fluid, it solidifies instantly, and the bullet is stopped.

As described above, a single PhD position on these or similar questions is reserved for a project defined in close collaboration with industry. Contacts with Unilever, DSM, Akzo and Geodelft have already been established, and we will use this programme to establish more and new contacts.

8 Duration and requested budget

The programme will run for a period of 6 years (to allow some flexibility when hiring PhD students), and will consist of nine PhD students and two three-year postdocs. No large investments will be made in this project, so that for these projects, only a running budget of 15K€ / year for the experimental, and 5K€ / year for the theoretical projects (van Saarloos, MacKintosh) is requested. As explained in section 6, a 5% fraction of the budget is set aside for flexible steering of the programme (guests, visits of young scientists abroad, workshops etc).

Budget Summary

	2008	2009	2010	2011	2012	2013	total
personnel							
PhD Students (yr):	5	7	9	9	4	2	36
Postdocs (yr):	1	2	2	1	-	-	6
personnel (costs)	280 k€	428 k€	516 k€	456 k€	176 k€	88 k€	1944 k€
running budget	70 k€	109 k€	135 k€	116 k€	60 k€	30 k€	520 k€
flexible steering	20 k€	20 k€	20 k€	20 k€	20 k€	20 k€	120 k€
total	370 k€	557 k€	671 k€	592 k€	256 k€	138 k€	2584 k€

In comparison to the earlier version of this proposal (”vooraanmelding”), one extra PhD student is part of the programme, to honor the request of the FeF committee and UB to include one or more ’engineering’ groups in the proposal, specifically, Luding. The UB, in its letter of June 13th, suggests that we nevertheless stick to the original budget, k€ 2388. Since we only included a bare minimum of non-salary funds (5% for steering, standard running budgets) in the original proposal, we have little room for financing this extra PhD position, and we therefore request the budget outlined above.

In case the arbitrary boundary of k€ 2388 needs to be honored, we see no other option than to diminish the running budgets below the FOM standard, to 9 instead of 15k€ for the experimental positions, and 4 instead of 5k€ for the theoretical positions — this brings the total budget to 2387 k€ :

	2008	2009	2010	2011	2012	2013	total
personnel							
PhD Students (yr):	5	7	9	9	4	2	36
Postdocs (yr):	1	2	2	1	-	-	6
personnel (costs)	280 k€	428 k€	516 k€	456 k€	176 k€	88 k€	1944 k€
running budget	44 k€	66 k€	84 k€	75 k€	36 k€	18 k€	323 k€
flexible steering	20 k€	20 k€	20 k€	20 k€	20 k€	20 k€	120 k€
total	344 k€	514 k€	620 k€	551 k€	232 k€	126 k€	2387 k€

9 Subfield Classification

100% FeF (Fenomenologische Fysica)

10 Appendix: Applicants

The order of the applicants reflects the order of the projects **I-X**.

I: Detlef Lohse (Twente)

The Physics of Fluids group works on a variety of aspects in the fundamentals of fluid mechanics. The subjects include (i) turbulence and multiphase flow, (ii) granular matter, (iii) micro- and nanofluidics, and (iv) biomedical flow. Both experimental, theoretical, and numerical methods are used. On the experimental side the key expertise of the group lies in high-speed imaging. Further information, including an updated list of publications, is available under http://pof.tnw.utwente.nl/

Recent publications :

- G. Ahlers, F. Fontenele Araujo, D. Funfschilling, D. Grossmann, and D. Lohse, **Non-Oberbeck-Boussinesq Effects in Gaseous Rayleigh-Bnard Convection**, Phys. Rev. Lett. **98**, 054501 (2007).
- T.H. van den Berg, D.P.M. van Gils, D.P. Lathrop and D. Lohse, **Bubbly Turbulent Drag Reduction Is a Boundary Layer Effect**, Phys. Rev. Lett. **98**, 084501 (2007).
- B.M. Borkent, S.M. Dammer, H. Schonherr, G.J. Vancso and D. Lohse, **Superstability of Surface Nanobubbles**, Phys. Rev. Lett. **98**, 204502 (2007).
- S. Dammer and D. Lohse, **Gas-enrichment at liquid-wall interfaces**, Phys. Rev. Lett. **96**, 206101 (2006).
- N. Bremond, M. Arora, C.-D. Ohl, and D. Lohse, **Controlled multi-bubble surface cavitation**, Phys. Rev. Lett. **96**, 224501 (2006).

II: Martin van Hecke (Leiden)

The experimental research in this group focusses on the jamming transition and flow of disordered media such as foams and granular media, with image analysis and rheological measurements being the main tools. Recent highlights include experiments on the manipulation of shearbands and the rheology of sand and foam, and theoretical work, in close collaboration with the group of Van Saarloos, on an geometric order parameter and diverging length scale near jamming. Van Hecke received a VIDI grant in 2002.

Recent Publications:

- M. van Hecke, **Shape Matters**, Science **317**, 49 (2007)
- M. Depken, J. B. Lechman, M. van Hecke, W. van Saarloos and G. S. Grest, **Stresses in Smooth Flows of Dense Granular Matter**, Europhys. Lett. **78**, 58001 (2007).
- D. Fenistein, J. W. van de Meent, and M. van Hecke, **Core Precession and Global Modes in Granular Bulk Flow.** Phys. Rev. Lett. **96** 118001 (2006).
- J. H. Snoeijer, W. G. Ellenbroek, T. J. H. Vlugt, and M. van Hecke, **Sheared Force Networks: Anisotropies, Yielding, and Geometry.** Phys. Rev. Lett. **96** 098001 (2006).
- D. Fenistein and M. van Hecke, **Wide shear zones in granular bulk flow.** Nature **425**, 256 (2003).

III: Fred MacKintosh (VUA)

The research focusses on theoretical condensed matter physics and biophysics, with particular emphasis on complex fluids, including membranes, polymers, biopolymers, granular materials, and other soft condensed matter. The group uses and develops both analytic and computational approaches to study these systems, usually in very close collaboration with experiment. Recent highlights include both microscopic modeling and experiments on far-from-equilibrium active gels and aging colloids, and biological gels that exhibit anomalous elastic properties. A major focus of our theoretical work has been the discovery and exploration of affine to non-affine transitions/crossovers in heterogeneous networks and jammed soft matter systems, which we are currently studying experimentally in collaboration with the Weitz group (Harvard) using confocal imaging of sheared systems. MacKintosh established a new theory group at the VU in 2001, after 10 years on the faculty at the University of Michigan.

Recent Publications:

- D. Mizuno, C. Tardin, C. F. Schmidt and F. C. MacKintosh, **Nonequilibrium mechanics of active cytoskeletal networks**. Science, 315:370 (2007).
- S Jabbari-Farouji, D Mizuno, M Atakhorrami, FC MacKintosh, CF Schmidt, E Eiser, GH Wegdam and D Bonn, **Fluctuation-dissipation theorem in an aging colloidal glass** Phys. Rev. Lett. **98**, 108302 (2007).
- 3. PA Janmey, ME McCormick, S Rammensee, J Leight, P Georges, and FC MacKintosh, **Negative normal stress in semiflexible biopolymer gels.** Nature Materials, 6:48 (2007).
- 4. C Storm, JJ Pastore, FC MacKintosh, TC Lubensky and PA Janmey, **Nonlinear elasticity in biological gels.** Nature, (2005). 435: 191-194.
- 5. DA Head, AJ Levine and FC MacKintosh, **Deformation of crosslinked semiflexible polymer networks.** Phys. Rev. Lett. (2003). 91: 108102.

IV: Peter Schall (UvA)

The experimental research in this group focuses on the microscopic mechanism of jamming and flow in soft matter systems on the one hand, and on phase behavior, interfaces and defect dynamics in these systems on the other. Experimental tools include fast 3D confocal microscopy, laser diffraction microscopy, and light scattering. Recent highlights include the laser-diffraction imaging of defects in ordered systems, the microscopic observation and continuum modeling of defect nucleation and propagation, and the investigation of non-affine strain distributions in disordered systems. Schall received a VIDI grant in 2006.

Recent Publications:

- P. Schall, I.Cohen, D.A. Weitz, and F. Spaepen, **Visualization of Dislocation Dynamics in Colloidal Crystals**, Science **305**, 1944 (2004).
- P. Schall and F. Spaepen,**Dislocation imaging in fcc colloidal single crystals**, Int. J. Mater. Res. **97**, 958 (2006).
- P. Schall, I. Cohen, D.A. Weitz and F. Spaepen, **Dynamics of dislocations in thin colloidal crystals**, in *Nanomechanics of Materials and Structures*, eds. T.J. Huang, P.M. Anderson, M.-K. Wu and S. Hsieh (Dordrecht: Springer, 2006) p. 255.
- P. Schall, I. Cohen, D.A. Weitz and F. Spaepen, **Visualizing dislocation nucleation by indenting colloidal crystals**, Nature **440**, 319 (2006).

V: Dirk van den Ende (UT)

The research focusses on the rheology of aggregating colloidal and non-colloidal dispersions. Central issue of our experimental research is the relation between the macroscopic mechanical properties of these complex fluids and their microstructure under flow. Using CSLM techniques this microstructure is probed. The microstructural information is used as input for succesful modelling of the macroscopic behavior of these dispersions, which is measured using conventional rheometry.

Recent publications :

- E. H. Purnomo, D. van den Ende, J.t Mellema and F. Mugele, **Rheological properties of aging thermosensitive suspensions**, Phys. Rev. E **76**, (2007) accepted for publication.
- N. D. Vassileva, D.van den Ende, F. Mugele and J. Mellema, **Fragmentation and erosion of two-dimensional aggregates in shear flow**, Langmuir **23**, 2352 (2007).
- D. Filip, V.I. Uricanu, M.H.G. Duits, D. van den Ende, J. Mellema, W.G.M. Agterof, F. Mugele, **Microrheology of Aggregated Emulsion Droplet Networks, studied with AFM-CSLM**, Langmuir 22, 560 (2006).
- J. Kromkamp, D. T.M. van den Ende, D. Kandhai, R. G.M. van der Sman and R. M. Boom, **Shear-induced self-diffusion and microstructure in non-Brownian suspensions at non-zero Reynolds number**, J. Fluid Mech. **529**, 253 (2005).
- V.A. Tolpekin, M.H.G. Duits, D. van den Ende and J. Mellema, **Aggregation and break-up of colloidal particle aggregates in shear flow, studied with video microscopy**, Langmuir **20**, 2614-2627 (2004)

V: Frieder Mugele (Twente)

The group performs experimental research in three main areas: nanofluidics, electrowetting and microfluidics, and complex fluids. Fundamental aspects of electrowetting and fluid dynamics in the presence of electric fields have been the core activity of the group for some time. The complex fluids activities are currently expanding. The focus in this area has recently been on the mechanical properties and aging in soft glassy materials. New activities also include mechanical and aging studies of living cells.

Recent publications:

- T. Becker and F. Mugele, **Nanofluidics: viscous dissipation in a layered liquid film**, Phys. Rev. Lett. **91**, 166104 (2003).
- A. Staicu and F. Mugele, **Electrowetting-Induced Oil Film Entrapment and Instability**, Phys. Rev. Lett. **97**, 167801 (2006).
- E.H. Purnomo, D. van den Ende, J. Mellema, F. Mugele, **Linear viscoelastic properties of aging suspensions**, Europhys. Lett. 76, 74 (2006).
- D. Geromichalos, M. M. Kohonen, F. Mugele, and S. Herminghaus, **Mixing and Condensation in a Wet Granular Medium**, Phys. Rev. Lett. **90**, 168702 (2003).
- N. D. Vassileva, D. van den Ende, F. Mugele, and J. Mellema, **Restructuring and Break-Up of Two-Dimensional Aggregates in Shear Flow**, Langmuir 22, 4959 (2006).

VI: Stefan Luding Delft

The group multi-scale mechanics deals with non-classical fluids, like particles with adhesive contacts, microfluid systems in nano-geometries, self-healing materials, and various multi-scale theory and modeling approaches. Among these are:
- Microscopic/discrete approaches for the modeling of fluid flows,
- Micro-Macro Transition Methods to understand the effects of micro-parameters and structure on the macroscopic constitutive behavior, and
- the long-term goal to derive constitutive relations for large/continuum applications.

The research is interdisciplinary in collaboration with research groups from Mechanical Engineering, Chemical Engineering, Materials Science, and Physics as well as industrial partners.

Recent Publications:

- T. S. Majmudar, M. Sperl, S. Luding, and R. P. Behringer, **Jamming transition in granular systems**, Phys. Rev. Lett. **98**(5) 058001 pp.1-4, 2007
- R. Garcia-Rojo, S. Luding, J. Javier Brey, **Transport coefficients for dense hard-disk systems**, Phys. Rev. E **74**(6) 061305 pp.1-11, (2006).
- S. Luding, **Granular media - information propagation)**, Nature **435**(7039), 159-160, (2005).
- S. Luding, **The effect of friction on wide shear bands**, Particulate Science and Technology Journal, (almost) accepted, (2007).
- S. Luding, **Cohesive frictional powders: Contact models for tension**, Granular Matter, accepted, (2007).

VII: Wim van Saarloos (Leiden)

The theoretical research in this group is centered around two themes, the statistical and rheological behavior or granular media and polymer flow instabilities and turbulence. Recent highlights include work on the scaling behavior of the statics and response in granular media near the jamming transition, in close collaboration with van Hecke, and a quantitative prediction that parallel shear flows of polymer solutions exhibit a nonlinear transition to turbulence. This latter work was done in collaboration with the group of Bonn. In addition there is work on the rheology of supercooled glass-forming liquids like glycerol, in close collaboration with the experimental group of Orrit. Further information on the CV of van Saarloos and on the group is available at http://www.lorentz.leidenuniv.nl/ saarloos

Recent Publications:

- W. G. Ellenbroek, E. Somfai, M. van Hecke and W. van Saarloos, **Critical Scaling in Linear Response of Frictionless Granular Packings near Jamming.** Phys. Rev. Lett. **97**, 258001 (2006).
- J. H. Snoeijer, T. J. H. Vlugt, M. van Hecke and W. van Saarloos, **Force network ensemble: a new approach to static granular matter**, Phys. Rev. Lett. **92**, 054302 (2004).
- E. Somfai, J.-N. Roux, J. H. Snoeijer, M. van Hecke and W. van Saarloos, **Wave propagation in confined granular systems**, Phys. Rev. E 72, 021301 (2005).
- M. Depken, J. B. Lechman, M. van Hecke, W. van Saarloos and G. S. Grest, **Stresses in Smooth Flows of Dense Granular Matter**, Europhys. Lett. **78**, 58001 (2007).
- A. Roy, A. Morozov, W. van Saarloos, and R. G. Larson, **Mechanism of polymer drag reduction using low-dimensional models**, Phys. Rev. Lett. **97**, 234501 (2006).

VIII: Devaraj van der Meer (Twente)

The current research interests of van der Meer focus around dissipative (granular) media on one side and jetting phenomena on the other. Recent highlights include experimental and theoretical studies on granular gases, the interaction of granular materials and air, impacts and jet formation in granular solids, and various studies of jetting phenomena in a liquid.

Recent Publications:

- G.A. Caballero Robledo, R.P.H.M. Bergmann, D. van der Meer, A. Prosperetti and D. Lohse, **Role of Air in Granular Jet Formation**, Phys. Rev. Lett. **99**, 018001 (2007).
- R.P.H.M. Bergmann, D. van der Meer, M.A. Stijnman, M. Sandtke, A. Prosperetti, and D. Lohse, **Giant Bubble Pinch-Off**, Phys. Rev. Lett. **96**, 154505 (2006).
- P. Eshuis, D. van der Meer, K. van der Weele, and D. Lohse, **Granular Leidenfrost effect: Experiment and theory of floating particle clusters**, Phys. Rev. Lett. **95**, 258001 (2005).
- D. Lohse, R Rauhé, R.P.H.M. Bergmann, and D. van der Meer, **Creating a dry variety of quicksand**, Nature **432**, 689. (2004).

- D. van der Meer, P. Reimann, K. van der Weele, and D. Lohse, **Spontaneous ratchet effect in a granular gas**, Phys. Rev. Lett. **92**, 184301. (2004).

IX: Daniel Bonn (UvA)

Bonn just arrived in the Netherlands after having been the group leader of the complex fluids group at the ENS in Paris. The research in his group focuses on the one hand on the rheology of complex fluids, mainly 'yield stress fluids' and the unified description of these very different systems (gels, foams, sand...) with the viscosity bifurcation. On the other hand, the glass transition is investigated using colloidal glasses; here the key question is the relation between structure (or absence of structure) and flow. There is also a project on the shear thickening in cornstarch in relation to shear banding.

Recent Publications:

- Sara Jabbari-Farouji, Gerard H. Wegdam, and Daniel Bonn **Gels and Glasses in a Single System: Evidence for an Intricate Free-Energy Landscape of Glassy Materials**, Phys. Rev. Lett. **99**, 065701 (2007).
- Sara Jabbari-Farouji, Daisuke Mizuno, Maryam Atakhorrami, Fred C. MacKintosh, Christoph F. Schmidt, Erika Eiser, Gerard H. Wegdam, and Daniel Bonn **Fluctuation-Dissipation Theorem in an Aging Colloidal Glass**, Phys. Rev. Lett. **98**, 108302 (2007).
- D. Bartolo, C. Josserand and D. Bonn, **Singular jets and bubbles in drop impact**, Phys. Rev. Lett. **96**, 124501 (2006).
- N. Huang, G. Ovarlez, F. Bertrand, S. Rodts, P. Coussot and D. Bonn **Flow of wet granular materials** Phys. Rev. Lett. **94**, 028301 (2005).
- A. Khaldoun, E. Eiser, G.H. Wegdam, D. Bonn, **Liquefaction of quicksand under stress**, Nature **437** 635 (2005).

X: Henk Lekkerkerker (UU)

The experimental work focuses on the structure, dynamics, phase behavior and interfaces in colloidal systems. Recent highlights include the observation of columnar phases in suspensions of plate-like particles, capillary waves and devitrification in mixed suspensions of spherical colloids and polymers and grain boundaries in mixed suspensions of large and small spherical colloids. Lekkerkerker received the Onsager medal of the University of Trondheim in 1999, the Rhodia medal of the European Colloid and Interface Society in 2003 and the Bakhuys-Roozeboom medal of the Royal Dutch Academy of Science in 2003.

Recent publications:

- D.G.A.L. Aarts, M. Schmidt and H.N.W. Lekkerkerker, Direct visual observation of thermal capillary waves, Science (2004) 304 847-850
- V.W.A. de Villeneuve, R.P.A. Dullens, D.G.A.L. Aarts, E. Groeneveld, J.H. Scherff, W.K. Kegel and H.N.W. Lekkerkerker, **Colloidal hard-sphere crystal growth frustrated by large spherical impurities**, Science **309** 1231 (2005).
- A.V. Petukhov, D. van der Beek, R.P.A. Dullens, I.P. Dolbnya, G.J. Vroege and H.N.W. Lekkerkerker, **Observation of a hexatic columnar liquid crystal of polydisperse colloidal disks**, Phys. Rev. Lett. **95** 077801 (2005).
- D. van der Beek and H.N.W. Lekkerkerker, **Liquid crystal phases of charged colloidal platelets**, Langmuir **20**, 8582 (2004)
- J.W. ten Brinke, L. Bailey, H.N.W. Lekkerkerker and G.J. Maitland, **Rheology modification in mixed shape colloidal dispersions. Part I: pure components**, Soft Matter (2007) 3, 1145-1162