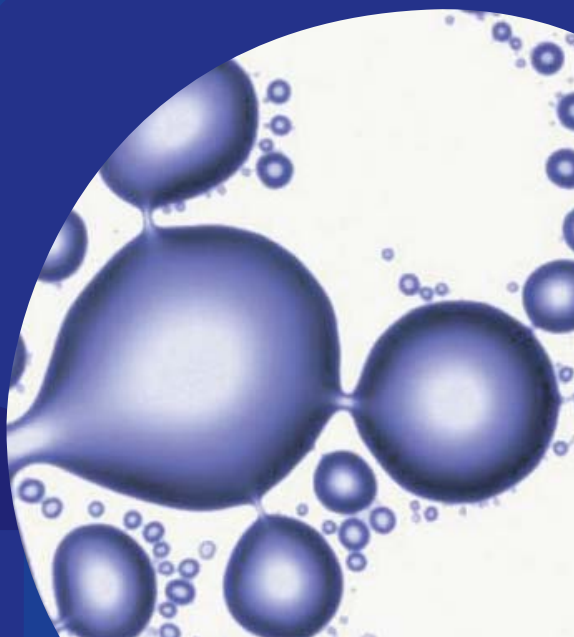


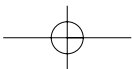
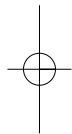
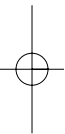


Universiteit Twente
de ondernemende universiteit



Drop by Drop

by Prof. dr. F. Mugele



Drop by Drop

Lecture presented
on the occasion of the
appointment as professor for

Physics of Complex Fluids

at the Faculty of Science and Technology
of the University of Twente
on the 5th of October 2006
by

Prof. dr. F. Mugele

Introduction

Mijnheer de Rector Magnificus, Ladies and Gentlemen,

The world around us is wonderful. Wherever we go, wherever we look, it is full of physics. Most of you probably started the day with an experiment of applied droplet physics. You went into the shower, turned on the faucet, and there they came: myriads of water droplets impinging on your body, covering it, flowing down and ultimately disappearing in the sink. If you had looked carefully, you could have seen that there are little jets of water coming out of the nozzles of the shower head that break up a little later into the trains of drops that hit you. Subsequently, the drops spread on your body, merged with other drops, formed a film that covered you either completely or only partially, etc. Probably none of you had the time or the muse to think about the beautiful physics in these daily processes. Being a physicist – in particular a physicist who is working with liquids and drops – I have the privilege of being allowed to study such phenomena in detail and to analyze how they work.

Today, I would like to share with you my personal fascination for the physics of small quantities of liquids ranging from the millimeter scale all the way down to a few molecular diameters. I want to give you a flavor of both fundamental aspects as well as technological applications of microfluidic drops at interfaces and I will present some fundamental challenges in the emerging field of nanofluidics. Finally, I want to discuss a few general aspects and lessons that I have learned from my teachers and that I would like to pass on to my students and coworkers.

Why becoming a physicist?

I grew up in an environment where natural sciences always played a big role. My parents were teachers for biology and chemistry. Curiosity and the spirit of looking at Nature with open eyes were attitudes that accompanied me from my early childhood on and that shaped my mind. At high school the rigorous and quantitative character of physics and mathematics attracted me. By the time I decided to study physics it were the big questions that fascinated me. What does our universe look like? Where does it come from? Was hält die Welt im Innersten zusammen? To use the words of Goethe's Faust. Physics promised answers to these daring questions.

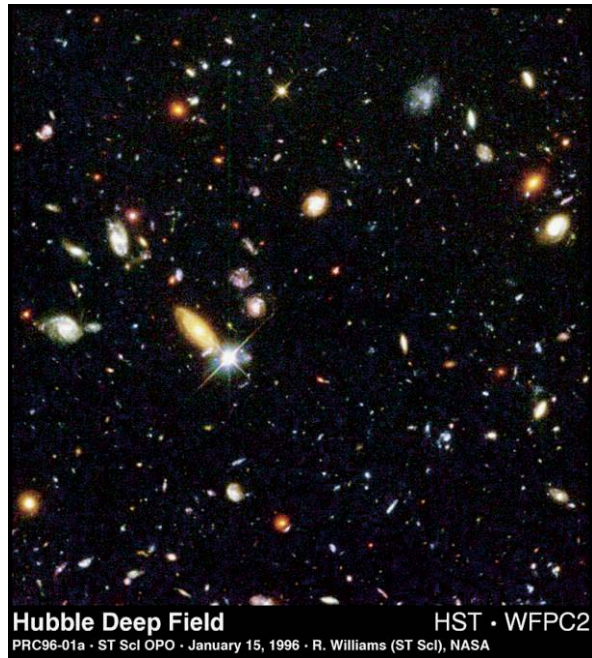


Figure 1: *Physics on the largest scales: the oldest galaxies of our universe as seen by the Hubble telescope (1).*

Another aspect that made physics attractive to me in those days was the aura of being particularly difficult. In retrospect, I think this view is based on a misunderstanding. Today, I would say that one of the major charms of physics is that it is in fact simple. Think of two balls on a pool table bumping into each other. Each one comes in with a certain speed along a certain direction. A few principles, a few equations, and you know how they will fly apart. Compare this to the situation of two people running into each other. Maybe one of them could not sleep the night before, plus he really hates the color of the shirt that the other one happens to wear. This will affect his reaction. Could we ever know all these details? Could we ever predict the outcome of this encounter? *This is a difficult problem.* In contrast we physicists put our experiments into little boxes, we eliminate all external disturbances, if necessary we pump out all the air and deep freeze our object

¹ <http://hubble.nasa.gov>.

of interest almost down to the absolute zero of temperature. All this can be quite an effort, but in the end we get the reward: things become simple. Just a few parameters are left to stimulate the little beast in the box, and the beast itself has only very few options to react. We watch it for a while, then we come up with a couple of equations and we know for all times how this type of beast behaves. This is clear. This is simple. None of it will ever be possible with our two friends with wrong shirt and the bad sleep. I think we should tell high school students that it is in fact the exact sciences and not the social ones that deal with the simple problems. Maybe that would help to take away their fears and motivate more of them to study physics.

Why physics of SMALL drops?

Nanoscience and -technology

Unfortunately the method that I just described is not really applicable to cosmology. Although the vacuum in space is outstanding and also the temperature is quite low, the universe does certainly not fit into a box and lend itself to perform experiments in the way that I just described. This is part of the reason, why I am asking today the question: what is interesting about the physics of drops, and in particular about the physics of small drops? The answer has various aspects. First of all, there is the general technological trend of miniaturization, which provides the context. In 1959, the later Nobel prize winner Richard Feynman gave a famous lecture entitled "There is plenty of room at the bottom", in which he outlined more or less the entire vision of what we know now as micro- and nanotechnology. In his introduction he characterized the field as follows:

This field is not quite the same as the others in that it will not tell us much of fundamental physics (in the sense of, "What are the strange particles?") but it is more like solid-state physics in the sense that it might tell us much of great interest about the strange phenomena that occur in complex situations. Furthermore, a point that is most important is that it would have an enormous number of technical applications (2).

² The full text of the lecture can be found at: <http://www.zyvex.com/nanotech/feynman.html>.



Figure 2. Richard Feynman
(1918-1988; Nobel Prize
in Physics 1965).

Even now, almost fifty years later, these sentences characterize “our business” of micro- and nanotechnology rather well. It is not about fundamentally new physics like the “strange particles” that Feynman mentions. They belong to what was then the forefront of high energy physics and elementary particles - truly new physics thus. Our business is much more down to earth. Micro- and nanotechnology is essentially about practical applications of the laws of classical physics and quantum physics. However, in contrast to the exotic world of particle physics, our field has the advantage of being technologically applicable and economically relevant. It is amazing to see how much of the technological development of the last

decades Feynman predicted in 1959. Computers with enormous computational power, storage devices with gigantic capacities, electronic circuitry with a few hundreds of atoms, the manipulation individual atoms, etc. Many of these developments would not have been possible without substantial efforts in a kind of research that is nowadays considered as “fundamental” in the sense that it is not directly related to a technological application. Ladies and Gentlemen, this is precisely how I define the role of my research: I am interested in a better fundamental understanding of the “strange phenomena” and the complexity that arise in the context of small drops. Within this area, I select problems based on their physical challenge and on the general validity of the results that I expect to obtain. Often the goals are initially formulated in a somewhat global manner. As a project runs, inspiration from the experiment then contributes to refining and shaping the specific research question. This process can be somewhat erratic. However, this should not threaten us. There is no research without search. As long as we make sure that we achieve a substantial physical result, the project will contribute to our understanding of Nature. In a situation where the trend of miniaturization continuously generates new applications in which small quantities of liquid play a crucial role, I would like to claim that any new fundamental result does also contribute to technological innovation – even if it is indirectly.

Microfluidics

Before addressing a few specific interesting issues of small scale fluid physics let me point out one general aspect of miniaturization: “small” automatically means “interface”. If we consider for instance a drop with a radius of one millimeter, approximately one molecule in a million is located at the surface. For a thousand times smaller drop, the relation is approximately one molecule in a thousand. Thousand times more molecules belong to the interface! If we extrapolate to the nanometer scale, we end up with a situation where more or less every molecule is part of an interface. For this reason micro- and in particular nanotechnology is to an important extent an art of understanding and controlling interfaces. Hence this is what the physics of small drops is about: understanding and controlling tiny amounts of liquids at interfaces.

When we analyze the physics of small drops, we find that there are two levels of “small”. The first one begins at a length scale of approximately one millimeter where surface tension begins to dominate over gravity. This is the world of microfluidics. From a fundamental perspective this world is described by the classical laws of fluid mechanics. The second level of “small”, the world of nanofluidics, begins where these classical laws break down - typically on a length scale of several nanometers. This is where we are faced with fundamentally new physics.

I will now proceed to discuss the characteristic aspects of both worlds separately and give a few examples of our recent work for both cases.

Characteristics of small drops

From our daily experience, we are all familiar with the striking transition in the behavior of drops around a scale of one millimeter. For a substantially larger “drop”, like for instance water filling a glass, gravity determines that the liquid fills the lower part of the container. This holds independent of the specific liquid and of the material of the container: interfacial effects do not matter. If, however, we deposit a millimeter-sized water drop onto a surface, we all know that it can either spread into a thin liquid film covering the surface – or it can retain its spherical shape and sit as a round drop on the surface. A surface of the former type, for instance a clean glass surface, is said to be “hydrophilic”. A surface of the latter type, such as a freshly waxed car, is said to be “hydrophobic”. On the millimeter scale and below interfacial effects thus control not only quantitatively but qualitatively the behavior of liquid drops.

The physical concept of surface tension that controls these wetting phenomena was developed in the early 19th century by Simon de Laplace, Thomas Young and a few others. Their equations turn out to be valid over a very wide range of length scales: more than six orders of magnitude, from one millimeter down to the nanometer scale surface tension controls the behavior of liquid drops.

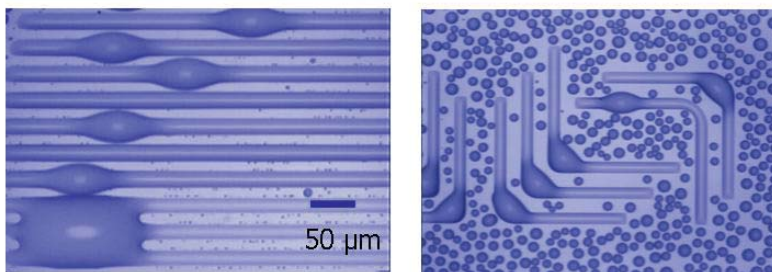


Figure 3. Liquid microstructures on a chemically patterned substrate (3).

Let me illustrate the control over drops that can be achieved by patterning the surface tension of solid substrates with an example taken from the work of the group of Prof. Stephan Herminghaus. In Figure 3 water is deposited on a composite surface with a series of alternating hydrophilic and hydrophobic stripes. The water accumulates on the hydrophilic stripes and forms one-dimensional segments of cylinders. As you can see, overall the liquid follows indeed the prescribed wettability pattern. However, the control is incomplete. Sometimes, the liquid forms peculiar bulges rather than simply covering the hydrophilic stripes. These unusual shapes give a flavor of the challenges related to presence of free liquid surfaces. By patterning the substrate surface we provide boundary conditions. However, the liquid is still free to adjust its surface. As a consequence, the combination of complex surface patterns and the intrinsic complexity of the underlying equations gives rise to a wide range of “strange phenomena” (in Feynman’s words) that can be used to shape and direct liquid drops.

One limitation of such surface patterns is, however, that they lend themselves only to a passive control of drops. If we want to shape and move drops actively, we need a tool to switch the wettability of surfaces. This

3 H. Gau, S. Herminghaus, P. Lenz, R. Lipowsky, *Science* 46, 283, 1999.

switchability can be achieved by the so-called electrowetting effect. This effect allows for transforming intrinsically hydrophobic surfaces into more hydrophilic (see Figure 4). What you see here is a drop of water sitting on such a hydrophobic surface. A wire is immersed into the drop in order to apply a voltage – the counter electrode is embedded in the substrate. As you apply a voltage, the drop spreads on the surface. Upon reducing the voltage again, it returns to its original shape. The effect is perfectly reversible and can be reproduced hundreds of thousands of times without any sign of degradation.

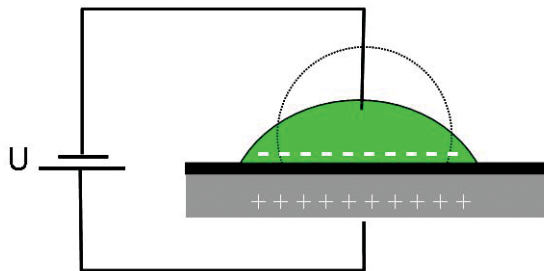


Figure 4. Generic electrowetting setup. Drop of conductive liquid (green) on a conductive substrate (gray) with an thin insulating coating. The dotted line indicates the drop shape in the absence of an external voltage.

On the micrometer scale, technological applications are never far away. For instance, a drop is a lens. A drop with a tunable radius is thus a tunable lens. This allows for adjustable optics without any moving mechanical parts. Philips as well as the French company Varioptic are currently trying to commercialize electrowetting-driven lenses. If they are successful, we will be able to buy mobile phones next year with cameras that allow for focusing instead of the current fixed focus systems.

Another target application of electrowetting are so-called laboratories-on-a-chip. The idea of such devices is to perform various chemical reactions with tiny amounts of liquid, e.g. in order to analyze their content (see Figure 5). Broad applications of such devices are foreseen in the biomedical context. One idea is that patients could monitor their own health status by delivering themselves a drop of, say, blood or urine to a little hand-held device. The device then carries out automatically various tests that are nowadays

done at much higher costs in medical laboratories. The patient only needs to see a doctor if the device signals that one of the health markers behaves in an unusual manner. From a fluid mechanical perspective, the challenge is to provide tools for handling the small drops. Our own prototype of such a device is shown in Figure 6. What you see is an electrowetting device with patterned electrodes on the substrate that can be addressed independently. Thereby, we can switch the wettability of the surface at any location and at any time, which allows us to move drops along the surface, merge them, split them, etc. This capability makes electrowetting arguably the most flexible method for actuating microdrops on surfaces. As a first step to biological applications we are exploring how this device can be used to manipulate living cells for diagnostic purposes.

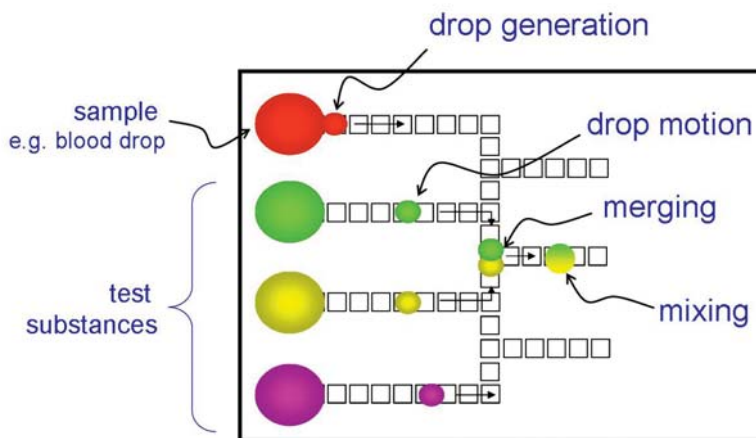


Figure 5. Schematic drawing of a lab-on-a-chip system based on individual drops.

Examples of our work on electrowetting

The basic operations of moving, splitting, merging, and mixing drops in an electrowetting chip involve various rather fundamental problems of drop physics. Let me describe one of our recent experiments that relates to several of these applied problems.

The experiment starts out as a very basic electrowetting experiment (see Figure 7). A drop sits on a surface, a wire is immersed in order to apply

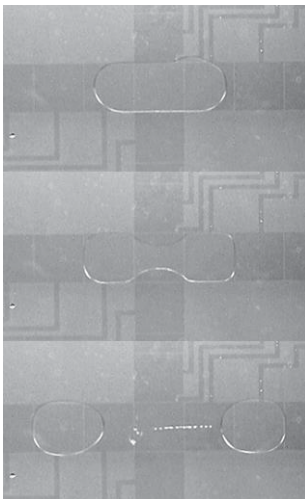


Figure 6. Drop splitting in an electrowetting lab-on-a-chip device. (electrode size: $1 \times 1 \text{ mm}^2$)

the voltage. However, the wire is only barely immersed into the drop. As the voltage is turned on, the drop spreads out on the surface and detaches from the wire. After the detachment, the drop contracts until it touches the wire again. Then the cycle begins all over and the drop starts to oscillate indefinitely. When we analyzed this process in detail, we found that the occurrence of the oscillations depends on the charge that the drop acquires upon breaking off the wire. The amount of this charge turns out to be completely determined by the very last moments before the break off. Only if the drop gets completely discharged, it is able to oscillate.



Figure 7. Electrowetting-driven drop oscillations (4).

What do I like about this experiment? On the one hand, I find the phenomenon in itself aesthetically very appealing. On the other hand, some rather general conclusions can be drawn from this experiment. The mechanism that controls the drop charge applies to any situation, in which drops are generated in the presence of electric fields. The drop splitting process in the lab-on-a-chip device is one example; electrospray ionization, spray painting, and certain types of inkjet printers are others.

⁴ J.C. Baret, F. Mugele, *Phys. Rev. Lett.* 96, 016106, 2006.

Furthermore, this experiment is a nice example of a problem that can be reduced to a very simple principle: the relevant physics can be represented by a basic electrical circuit model that any physicist in the room will understand immediately. A single dimensionless parameter in that model controls whether the drop gets discharged or not.

On top of that, the oscillations can also be applied to address one of the most challenging problems in microfluidics: mixing. Efficient mixing is a prerequisite for efficient chemical reactions. However the laws of fluid dynamics tell us that the physical principles of stirring that we use to mix on macroscopic scales, for instance when we use a spoon to distribute the milk in our coffee, do not work on small scales. As a consequence it takes several minutes until the dye in a millimeter-sized drop is homogeneously distributed. If we turn on drop oscillations, however, internal flow fields redistribute the material in such a way that mixing is accelerated more than hundred times (see Figure 8). Thus, an experiment that started out with the nice, but somewhat curious physical phenomenon of drop oscillations, ends up producing a solution for an important physical and technological problem in microfluidics.

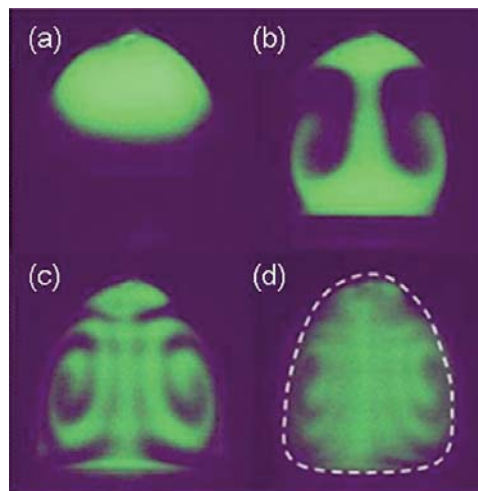


Figure 8. Oscillation-induced mixing inside a liquid drop. The oscillatory drop motion is not visible because the camera is synchronized with the oscillations (5).

5 F. Mugele, J.C. Baret, and D. Steinhauser, *Appl. Phys. Lett.* 88, 204106, 2006.

Nanofluidics

Let me move from microfluidics to nanofluidics, the world of the smallest drops. Compared to the transition from large drops to small drops the transition from small ones to “very small” ones is much more complex. There is neither a unique criterion that determines on what length scale the transition takes place nor is there a unique behavior on the nanometer scale. Different intrinsic length scales in the fluid can give rise to new physical effects depending on the specific interactions. Despite this variability there are a few general aspects. On the one hand we all know that matter is “granular” in a fundamental sense: it is made of discrete atoms and molecules. The size of the molecules is thus a length scale that is definitely intrinsic to any liquid. Furthermore, I mentioned already in the beginning that basically every molecule in a nanodrop belongs to an interface. Hence every single molecule in a nanodrop is subject to the specific interaction forces with the material at the other side of the interface. With this increased importance of specific interactions, it is clear that nanofluidics has much stronger chemical and materials science aspects than macroscopic fluid dynamics – a conclusion that applies obviously for many aspects of nanosciences.

Nanodrops and -films

In addition to the open fundamental questions, performing nanofluidics experiments poses substantial experimental challenges. On the one hand, surfaces have to be extremely smooth in order to provide a geometry that is well-defined on the nanometer scale. On the other hand, we need new experimental techniques to detect and characterize liquids on that scale. Simple optical microscopy as we use it in the case of microfluidics does not provide sufficient resolution. Let me discuss with you two examples in which we studied thin liquid films confined between two solid substrates at a distance of a few nanometers. In both experiments we make use of so-called multiple beam interferometry in order to visualize the liquids. With this technique, the liquid film thickness can be measured with a sensitivity of a fraction of a molecular diameter.

The first example is an experiment in which we confine a liquid film between two atomically smooth substrates. The surfaces are mounted in a crossed-cylinder geometry, such that there is a well-defined point where they come in contact. As we press the two surfaces together, the contact area increases due to elastic deformation. Simultaneously, the liquid is squeezed out from the gap in a discrete fashion. Figure 9 shows snapshots taken during one of these discrete events. Each squeeze-out is initiated by

the nucleation of a small hole of the reduced film thickness close to the center of the contact area, which is subsequently growing (bright area in Figure 9). From the intensity contrast we can calculate that each one of these events corresponds to a reduction of the liquid film thickness by one molecular layer. The thickness of the *liquid* film is thus discretized in units of the molecular diameter. Over a lateral distance of tens of thousands diameters, the molecules in this film arrange themselves in a coherent layer structure, as shown here schematically. When this layering phenomenon was first reported by Roger Horn and Jacob Israelachvili in the early 1980's it was a sensation⁽⁶⁾. Their experiment marked the ultimate break-down of any continuum mechanical description of liquids.

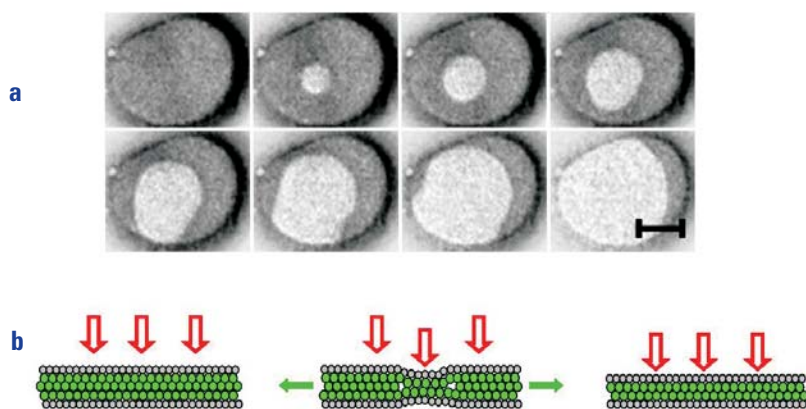


Figure 9. Squeeze-out of a layer of Octamethylcyclotetrasiloxane between two atomically smooth mica surfaces in a Surface Forces Apparatus. a) video snapshots during the squeeze-out process (total time: approx. 3s). b) schematic view of the squeeze-out. Left: initial state with three layers. Middle: transient state with nucleated hole in the center. (Note the elastic deformation of the gray substrate layers.) Right: final state with two layers. Read arrows indicate the normal pressure that drives the squeeze-out. ⁽⁷⁾

⁶ R. Horn and J.N. Israelachvili, *J. Chem. Phys.* 75, 1400 (1981).

⁷ T. Becker and F. Mugele, *Phys. Rev. Lett.* 91, 166104, 2003.

The goal of our experiment was to understand the dynamics of the squeeze out process. To this end, we analyzed the motion of the moving fronts. From that, we calculated the friction within the film. The result was very surprising: the liquid was flowing essentially as predicted by a classical continuum hydrodynamic calculation that ignores the discrete layer structure completely. This schizophrenic situation is characteristic of the current understanding of nanofluidics: overall continuum models work well down to surprisingly small scales. However, when they fail, in which respect they fail, is impossible to predict.

In the second example I want to show you a fluidic chip micromachined from glass with embedded nanochannels (see Figure 10). This device offers greater flexibility than the setup just described. Making it requires state of the art nanofabrication knowhow and facilities. In the groups of Prof. Albert van den Berg and Prof. Miko Elwenspoek we found partners who were already working on similar problems. In their experiments they were ultimately limited by the poor visibility of liquids in channels with just a nanometers thickness. In a joint effort, we integrated our multiple beam interferometry

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Drop by Drop

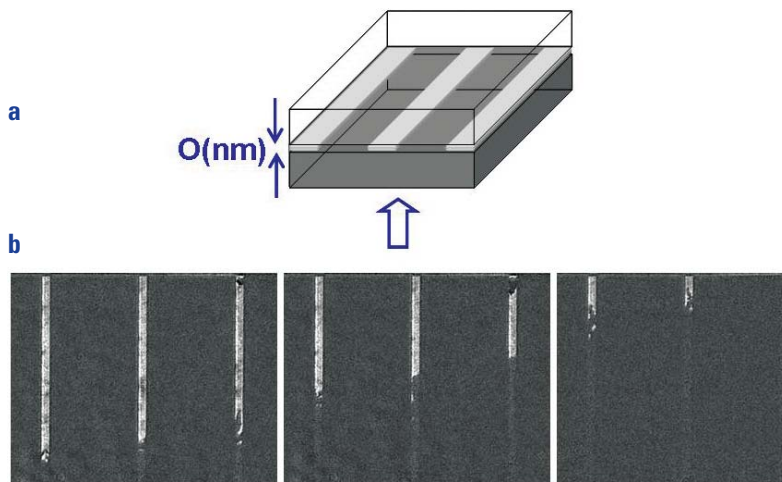


Figure 10. Capillarity-induced filling of a nanofluidic channel. a) schematic view of the device. (channel width: $10\mu\text{m}$; length: 1mm) b) snapshot of moving liquid menisci. ⁽⁸⁾

8 K.M. van Delft, J.C.T. Eijkel, D. Mijatovic, H. Rathgen, N.R. Tas, A. van den Berg and F.Mugele (submitted).

technique into their devices. In a first set of experiments, we admitted liquid to the device and watched from above how it was dragged into the channels by capillary forces. As you can see, the motion of a liquid film with a thickness of just about twenty molecules can be followed easily. Even details can be resolved such as the meandering of the moving meniscus along unavoidable surface corrugations and the formation and subsequent slow dissolution of tiny gas bubbles. Although the experiments are still in a preliminary stage, these results show already that a lot of new exciting physics becomes accessible with this cutting-edge nanotechnology device.

Why Twente?

This last experiment is also an illustration of what makes the University of Twente an attractive place for me. This university offers a rather unique concentration of high quality scientists in the fields of fluid dynamics, microfluidics, and nanotechnology. The MESA+ institute offer outstanding nanofabrication facilities. For me this opens research opportunities that would be hard to realize elsewhere. This applies to both our more fundamental activities as well as the more practical ones at the interface between fundamental research and applications. Internal research programs on Micro- and Nanofluidics as well as Dispersed Two-Phase Flow with contributions from both the Impact institute and MESA+ provide a good forum for information exchange and for establishing contacts within the university for a newcomer. Furthermore, they also provided funds required for a smooth start of my activities here in Twente. The sum of all these factors make this university the right place for me and for my research.

Beyond research topics

Research is always performed by humans. The students, PhD students, postdocs, and staff members in the group perform the daily work in the laboratory. Their motivation, their creativity, and their open eyes are crucial for the success of the entire team. What can I do to support them and to help them develop and become strong and independent researchers?

Apart from defining the general research lines, I see myself to a large extent in the role of a facilitator and mediator. I want to stimulate by asking questions, to give support with specific problems, and to point out interesting scientific directions. I want to be a good example of a researcher who is honestly and continuously searching for the best scientific ideas and answers to problems. This is the style of leadership that I experienced as very inspiring and motivating under the supervision of my teachers and mentors, Prof. Paul Leiderer, Dr. Miquel Salmeron, and Prof. Stephan Herminghaus.

In such a team, everybody has his own experience and knowhow and his own strengths and weaknesses. To exploit all these in a positive manner, we have to work together. One prerequisite for a fruitful exchange within the group is the mutual awareness of each others knowhow and skills. Unfortunately, experience tells that this kind of exchange does not occur naturally - even in a comparably small group of the order of twenty people. I will therefore always keep an open eye for internal communication and try to provide structures to make them it more efficient whenever necessary.

What does it take for a student to become a good physicist? A certain degree of cleverness and an intrinsic interest in physical phenomena are indispensable. On top of that it is crucial to bring enough mental strength and determination to succeed. I said in the beginning that I like physics because it is so simple. I stick to that claim, however, I have to admit that Nature is often not willing to reveal her charms right away. You have to beat around the bush for a while, find the right way of asking your question, and watch patiently and carefully how she is reacting. In the beginning, you will probably not understand. You are likely to follow a wrong path for some time and there may be periods of drought. But don't give up. You have to keep on searching. Once you have found a handle, keep asking your questions and perform your experiments in a precise and systematic way. If you do it right, Nature will reveal her secrets and you will get to see that the solution of your problem is indeed simple. All the projects that I worked on myself as a Diploma student, as a PhD student, or as a Postdoc went through these phases. For me, this is how it works being a physicist.

Going through this process several times, one can eventually develop an “intuitive understanding” of physics. Let me give you an example: I was a Diploma student in the group of Prof. Paul Leiderer at the University of Konstanz. An external PhD student came to give a talk in the group seminar. He was working on some switchable dielectric coatings. Various questions were asked after the talk about the optical properties of his samples. The student did not know the answer and he proposed to perform a number of systematic experiments. To me, this seemed a convincing answer. Paul Leiderer, however, asked the student for one of the samples that he had brought with him. He held it against the light, looked at the reflection under various angles – and he told us what the outcome of those measurements would be. I was stunned and impressed. Open eyes and an intuitive “feeling for matter” were enough for him to solve the problem. The latter ability, the feeling for matter, has a lot to do with a specific way of approaching physical problems. Physics is not so much about complicated equations and how to solve them. Equations are an important tool, however they remain a tool. The physics out there in the world just happens. If we say that we “understand” something or someone we usually mean that we can follow a certain line of arguments and that we experience it as natural. In the same sense, “understanding” physics has a lot to do with that intuitive feeling of how matter behaves. In my view this is an important aspect that we should never forget when we teach physics in our lectures.

Let me end this speech with a wish. I wish that every student leaving my group can experience at least once a “magic moment”. To illustrate what I mean, let me tell you about my first magic moment in physics. It is contained in the curve shown in Figure 11. The curve was recorded on the 5th of March 1993, a Friday evening, around eight o'clock, three weeks before I had to submit my diploma thesis. I had planned to do a few final measurements on Saturday to fill in some remaining gaps in my thesis. I had prepared my sample, a thin solid hydrogen film, during the day. In the evening, I wanted to record one final test curve to see whether the preparation had been successful before going out with friends. All of a sudden things were different. I had recorded many of these curves in the preceding months. This one looked completely different from all the others. First I was afraid that the preparation had gone wrong and that the effort had been in vain. But then I realized that the opposite was true. What I was seeing was real – in fact it was what I had been after for an entire year. I had finally managed to prepare a sample that was much better than all the previous ones. I was completely excited, I was literally jumping through laboratory. This was my moment,

my victory. There were two aspects that made this moment magic: on the one hand, there was the instant of understanding what was going on, the moment when it made “click” – and then there was the deep satisfaction of finally reaching the goal that I had worked for so hard and so long. I called my friends and cancelled all the plans that I had made for the evening and for the weekend. The next two days I did not sleep very much, but I ended up producing the data for my first two papers. If you ask me why I am a physicist – this story is my answer. And I wish that all my students can make the same experience while they are working in my laboratory.

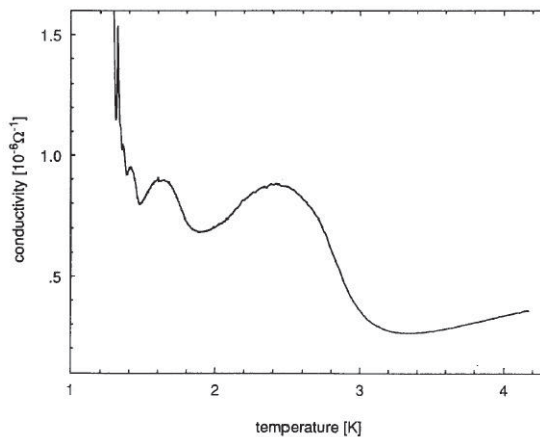


Figure 11. Conductivity of a two-dimensional electron system on a solid hydrogen film as a function of temperature. (9)

9 F. Mugele, U. Albrecht, and P. Leiderer, *J. Low Temp. Phys.* 96, 177, 1994.

Acknowledgements

Ladies and Gentlemen, this concludes my speech. I want to thank the College van Bestuur of the University of Twente and the dean of the faculty of Science and Technology, Prof. Alfred Blik, for the confidence they have in me and for the great opportunity to perform my research here.

I am indebted to my teachers from whom I learned so much about physics and about how to perform it. Paul Leiderer opened my eyes for the beauty of experimental condensed matter physics. He guided me through the world of liquid helium and later gave me the freedom to find my own way during my PhD in the field of scanning tunneling microscopy. To him, I owe much of my spirit of addressing physical problems. Miquel Salmeron in Berkeley brought my interests to confined liquids. Do something new! You know already how tunneling microscopy works, were his words when I joined his lab. Miquel also taught me a respect for simple models. Even if it is very simple, to have a model or not makes all the difference. Finally, Stephan Herminghaus. Unfortunately, I heard yesterday from his secretary, that he fell sick. Stephan gave me a lot of freedom and a lot of support during the five years that I spent in Ulm. Again and again I was excited and ignited by his enthusiasm and by his quick and sharp way of thinking. He was always open for new ideas. He picked them up immediately and added his own thoughts to help me develop the ideas further. I hope that I will be able to create a similarly stimulating atmosphere in my group as he did in Ulm – even if I will never sing and mix drinks at group parties. I thank all my Diploma, Master, and PhD students and postdocs and other coworkers who worked with me over the years for all our discussions, our joint discoveries and for the results that I would never have been able to produce on my own.

I want to thank very much my dear colleague Prof. Detlef Lohse. Dear Detlef, you pointed out to me the prospects and the opportunities of working at the University of Twente. Without you, I would not stand here today. Also, without you and your family our private start as a family here in Enschede would have been much more difficult. Detlef, Gabi, and Mareike and Hendrik – thank you very much. In the latter respect, I would also like to thank Prof. Kelly and Prof. Wessling and their families; thank you, Paul and Andrea, and Matthias and Marion – and all the children – for helping to make Enschede a new home for us.

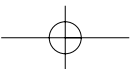
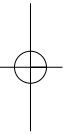
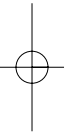
I thank my parents for raising me the way they did. Mama und Papa, I always felt safe and secure as a child. I never lacked your support. You showed me the world around me. And you were always there to answer my questions and to stimulate me to ask new ones. I hope that I will be able, together with Katja, to pass this spirit on such that Henri and Moritz will look back with the same thankfulness at some point.

Lieber Henri, lieber Moritz. Ihr habt im vergangenen Jahr eure erste Fremdsprache gelernt – und jetzt benutze ich für so eine lange Rede ausgerechnet eine andere, die ihr noch nicht versteht. Das tut mir leid. Ich freue mich sehr, dass wir seit einem guten Jahr hier in Enschede endlich wieder unter einem Dach leben und dass ich so eure Liebe und eure Energie jeden Tag erfahren darf. Vielleicht solltet ihr mich abends etwas häufiger anrufen und mich daran erinnern rechtzeitig nach Hause zu kommen, damit ich nicht so viel verpasse.

Dear Katja, thank you very much for being with me and for being here with me. Thank you for supporting me in my career despite all the time that it absorbs and that is left empty for us. I know how difficult it was for you to leave behind Southern Germany and all the friends you had there. Thank you for exchanging all this for this then unknown place Enschede.

Dear audience, thank you very much for your attention.

Ik heb gezegd.





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