



**UvA-DARE (Digital Academic Repository)**

**Sliding friction**

*From microscopic contacts to Amontons' law*

Weber, B.A.

[Link to publication](#)

*Citation for published version (APA):*

Weber, B. A. (2017). Sliding friction: From microscopic contacts to Amontons' law.

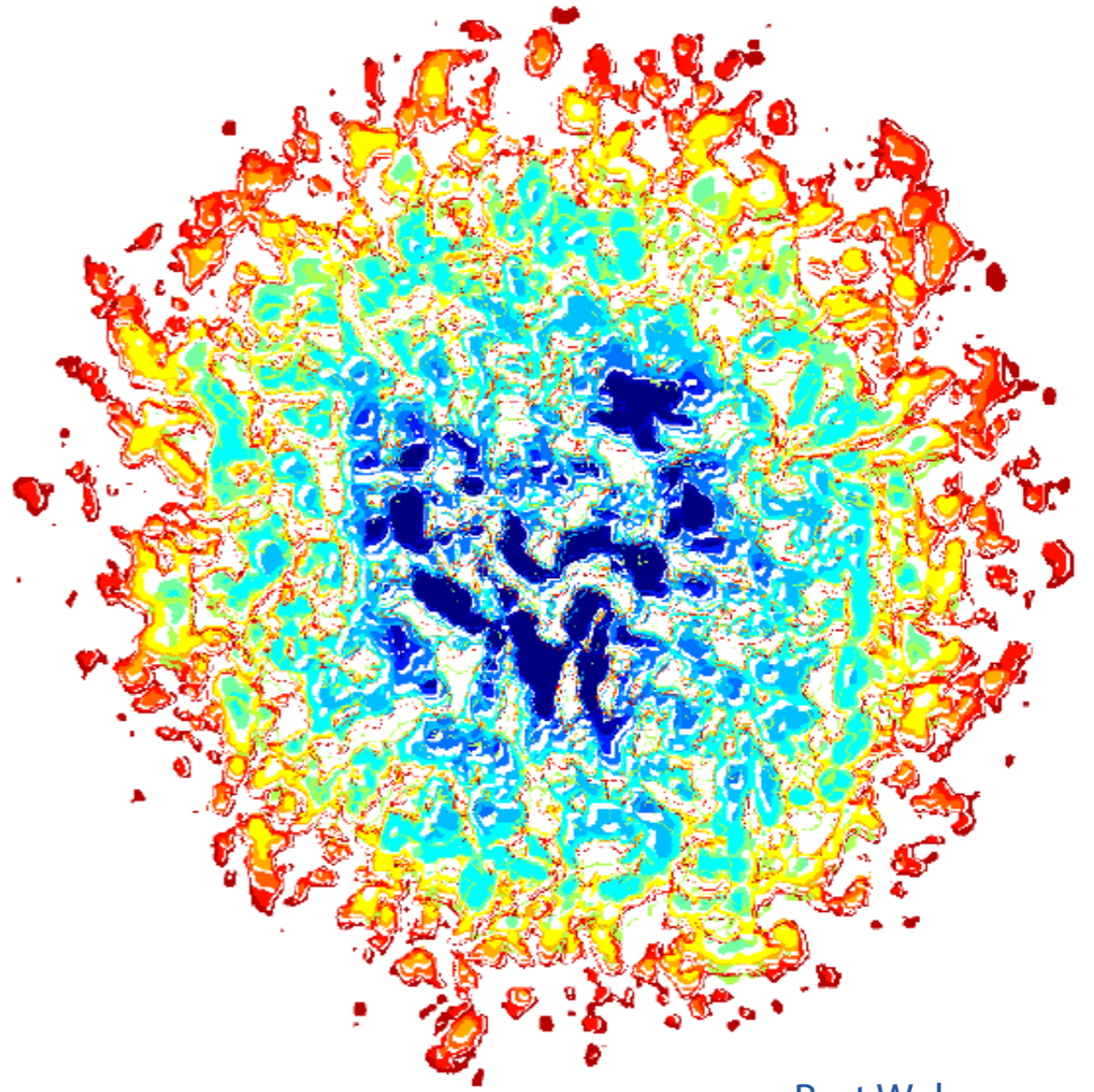
**General rights**

It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

**Disclaimer/Complaints regulations**

If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: <https://uba.uva.nl/en/contact>, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

# Sliding Friction: From Microscopic Contacts to Amontons' Law



Bart Weber

Sliding Friction: From Microscopic Contacts to Amontons' Law

Bart Weber

**Sliding Friction: From  
Microscopic Contacts to  
Amontons' Law**

Bart Weber



# **Sliding Friction: From Microscopic Contacts to Amontons' Law**

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor  
aan de Universiteit van Amsterdam  
op gezag van de Rector Magnificus  
prof. dr. ir. K.I.J. Maex  
ten overstaan van een door het College voor Promoties  
ingestelde commissie,  
in het openbaar te verdedigen in de Agnietenkapel  
op woensdag 4 oktober 2017, te 14:00 uur

door

Bart Alexander Weber

geboren te Amsterdam

## Promotiecommissie

Promotor: Prof. dr. D. Bonn Universiteit van Amsterdam

Copromotor: Prof. dr. A.M. Brouwer Universiteit van Amsterdam

Overige leden: Prof. dr. H. Bakker Universiteit van Amsterdam

Prof. dr. J. Fineberg The Hebrew University of Jerusalem

Prof. dr. J.W.M. Frenken Universiteit van Amsterdam

Prof. dr. J.F. Molinari École Polytechnique Fédérale de Lausanne

Prof. dr. L. Pastewka University of Freiburg

Prof. dr. S. Woutersen Universiteit van Amsterdam

Faculteit der Natuurwetenschappen, Wiskunde en Informatica

The work reported in this thesis was carried out at the Van der Waals-Zeeman Institute, IoP, University of Amsterdam. This work is part of the research programme 'Fundamental Aspects of Friction' of the Foundation for Fundamental Research on Matter (FOM), which is part of the Netherlands Organisation for Scientific Research (NWO)



Netherlands Organisation  
for Scientific Research







---

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>Experimental Techniques</b>	<b>9</b>
2.1	Elastic modulus . . . . .	9
2.1.1	Shear modulus of wet sand . . . . .	9
2.1.2	Young's modulus of polytetrafluoroethylene . . . . .	11
2.2	Penetration hardness . . . . .	13
2.3	Friction tests . . . . .	15
2.3.1	Friction experiments with a tensile tester . . . . .	16
2.3.2	Friction experiments with a rheometer . . . . .	17
	Full rotations . . . . .	18
2.4	Microscopy imaging . . . . .	19
2.4.1	Fluorescence microscopy . . . . .	20
2.4.2	Atomic force microscopy . . . . .	23
<b>3</b>	<b>Sliding Friction on Wet and Dry Sand</b>	<b>27</b>
3.1	Abstract . . . . .	27
3.2	Introduction . . . . .	27
3.3	Experiment . . . . .	28
3.4	Results . . . . .	30
3.5	Conclusion . . . . .	34
<b>4</b>	<b>Fluorescence Microscopy Visualization of Contacts Between Objects</b>	<b>39</b>
4.1	Abstract . . . . .	39
4.2	Introduction . . . . .	39
4.3	Experiment . . . . .	40
4.4	Results . . . . .	43
4.5	Conclusion . . . . .	45

<b>5</b>	<b>Molecular Probes Reveal Deviations from Amontons' Law in Multi-Asperity Frictional Contacts</b>	<b>55</b>
5.1	Abstract . . . . .	55
5.2	Introduction . . . . .	56
5.3	Experiment . . . . .	56
5.4	Results . . . . .	57
5.5	Conclusion . . . . .	62
<b>6</b>	<b>The Onset of Sliding Friction</b>	<b>69</b>
6.1	Abstract . . . . .	69
6.2	Introduction . . . . .	69
6.3	Experiment . . . . .	70
6.4	Results . . . . .	72
6.5	Conclusion . . . . .	77
<b>7</b>	<b>Molecular Insight into the Slipperiness of Ice</b>	<b>81</b>
7.1	Abstract . . . . .	81
7.2	Introduction . . . . .	81
7.3	Results . . . . .	82
7.4	Conclusion . . . . .	89
	<b>Appendices</b>	<b>95</b>
<b>A</b>	<b>Fluorescence Microscopy Visualization of Contacts Between Objects</b>	<b>97</b>
<b>B</b>	<b>Molecular Probes Reveal Deviations from Amontons' Law in Multi-Asperity Frictional Contacts</b>	<b>101</b>
B.1	Experimental methods . . . . .	101
B.1.1	Microscopy . . . . .	101
B.1.2	Mechanical testing . . . . .	108
Roughening . . . . .	108	
Elastic modulus . . . . .	108	
Friction . . . . .	109	
B.2	Numerical contact models . . . . .	109
B.2.1	Greenwood & Tripp model . . . . .	109
B.2.2	Elastic interactions . . . . .	109
B.2.3	Plasticity models . . . . .	110
B.2.4	Comparison with experiments . . . . .	111
B.3	Other materials . . . . .	113

---

<b>C Molecular Insight into the Slipperiness of Ice</b>	<b>121</b>
C.1 Friction on different ice surfaces . . . . .	121
C.2 Normal force dependence . . . . .	121
C.3 Ploughing force . . . . .	123
C.4 Indentation experiments . . . . .	123
C.5 Friction and contact area . . . . .	125
C.6 Frictional heating . . . . .	125
C.7 Sum-frequency generation spectroscopy . . . . .	128
C.8 Simulation protocols . . . . .	128
C.8.1 Molecular dynamics simulation . . . . .	128
C.8.2 SFG spectra calculation . . . . .	129
C.8.3 Definition of free O-H group of water . . . . .	130
<b>Summary</b>	<b>135</b>
<b>Samenvatting</b>	<b>139</b>
<b>List of Publications</b>	<b>143</b>
<b>Acknowledgements</b>	<b>145</b>