



## UvA-DARE (Digital Academic Repository)

### Multi-scale simulations with complex automata: in-stent restenosis and suspension flow

Lorenz, E.

**Publication date**  
2010

[Link to publication](#)

#### **Citation for published version (APA):**

Lorenz, E. (2010). *Multi-scale simulations with complex automata: in-stent restenosis and suspension flow*.

#### **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.

# Bibliography

- [1] B. Chopard and M. Droz. *Cellular Automata Modeling of Physical Systems*. Cambridge University Press, 1998.
- [2] A. G. Hoekstra, J. Krok, and P. M. A. Sloot, editors. *Simulating Complex Systems by Cellular Automata (Understanding Complex Systems)*. Springer, 2010.
- [3] K. Zuse. Rechnender raum. *Schriften zur Datenverarbeitung*, 1:74, 1969.
- [4] E. Fredkin. An introduction to digital philosophy. *Int. J. Theor. Phys.*, 42(2):189, 2003.
- [5] S. Wolfram. *A New Kind of Science*. Wolfram Media, 2002.
- [6] A. Einstein. *The Meaning of Relativity (1921)*. Princeton University Press, 1954.
- [7] W. E. B. Engquist, X. Li, W. Ren, and E. Vanden-Eijnden. Heterogeneous multiscale methods: A review. *Commu. Compu. Phys.*, 2(3):367, 2007.
- [8] A. Deutsch and S. Dormann. *Cellular Automaton Modeling of Biological Pattern Formation: Characterization, Applications, and Analysis*. Birkhäuser, Basel, 2005.
- [9] P. Sloot and A. Hoekstra. *Modeling Dynamic Systems with Cellular Automata*, chapter 21. Chapman & Hall/CRC, London, 2007.
- [10] S. Lloyd. Computational capacity of the universe. *Phys. Rev. Lett.*, 88(23):237901, 2002.
- [11] K. Zuse. The computing universe. *Int. J. Theor. Phys.*, 21(6):589, 1982.
- [12] D. Bader. *Petascale Computing: Algorithms and Applications*. Chapman and Hall/CRC, London, 1 edition, 2008.
- [13] A. Hoekstra, S. Portegies Zwart, M. Bubak, and P. Sloot. Towards distributed petascale computing. In D. Bader, editor, *Petascale Computing: Algorithms and Applications*, chapter 8. Chapman & Hall/CRC, London, 2008.
- [14] P. Sloot, D. Frenkel, and H. van der Vorst. White paper on computational e-science, studying complex systems insilico, a national research invitiative. <http://www.science.uva.nl/research/pscs/papers/archive/sloot2007a.pdf>.

- [15] Special issue on multiphysics modeling. *IEEE Comput Sci Eng*, (7):14, 2005.
- [16] SIAM Multiscale Modeling and Simulation. <http://epubs.siam.org/sam-bin/dbq/toclist/mms>.
- [17] International Journal for Multiscale Computational Engineering. <http://www.edata-center.com/journals/61fd1b191cf7e96f.html>.
- [18] A. Finkelstein, J. Hetherington, Linzhong Li, O. Margoninski, P. Saffrey, R. Seymour, and A. Warner. Computational challenges of systems biology. *Computer*, 37(5):26, 2004.
- [19] D. Noble. Modeling the heart - from genes to cells to the whole organ. *Science*, 295(5560):1678, 2002.
- [20] B. Di Ventura, C. Lemerle, K. Michalodimitrakis, and L. Serrano. From in vivo to in silico biology and back. *Nature*, 443(7111):527, 2006.
- [21] P. Hunter, W. Li, A. McCulloch, and D. Noble. Multiscale modeling: Phys-iome project standards, tools, and databases. *Computer*, 39(11):48, 2006.
- [22] P. Sloot, A. Tirado-Ramos, I. Altintas, M. Bubak, and C. Boucher. From molecule to man: Decision support in individualized e-health. *Computer*, 39(11):40, 2006.
- [23] S. Smye. Mathematical modelling for the new millenium: medicine by numbers. *Med. Eng. Phys.*, 24(9):565, 2002.
- [24] G. D. Ingram, I. T. Cameron, and K. M. Hangos. Classification and analysis of integrating frameworks in multiscale modelling. *Chem. Eng. Sci.*, 59(11):2171, 2004.
- [25] R. White. Modeling multi-scale processes in a cellular automata framework. In J. Portugali, editor, *Complex Artificial Environments, Simulation, Cognition and VR in the Study and Planning of Cities*, page 165. Springer, 2006.
- [26] B. Ribba, T. Alarcón, K. Marron, P. K. Maini, and Z. Agur. The use of hybrid cellular automaton models for improving cancer therapy. In P. Sloot, B. Chopard, and A. Hoekstra, editors, *Cellular Automata*, volume 3305 of *Lecture Notes in Computer Science*, page 444. Springer, 2004.
- [27] C. Long Lin and Y. G. Lai. Lattice boltzmann method on composite grids. *Phys. Rev. E*, 62(2):2219, 2000.
- [28] N. A. Baas and T. Helvik. Higher order cellular automata. *Adv. Complex Syst.*, 8(2):169, 2005.
- [29] N. Israeli and N. Goldenfeld. Computational irreducibility and the predictability of complex physical systems. *Phys. Rev. Lett.*, 92(7):074105, 2004.
- [30] A. Hoekstra, E. Lorenz, J. L. Falcone, and B. Chopard. Towards a complex automata framework for multi-scale modeling: Formalism and the scale separation map. In Y. Shi, G. D. Albada, J. Dongarra, and P. M. A. Sloot, editors, *Computational Science ICCS 2007*, volume 4487 of *Lecture Notes in*

- 
- Computer Science*, chapter 121, page 922. Springer Berlin Heidelberg, Berlin, Heidelberg, 2007.
- [31] A. G. Hoekstra, E. Lorenz, J. L. Falcone, and B. Chopard. Towards a complex automata formalism for multi-scale modeling. *Int. J. Mult. Comp. Eng.*, 5(6):491, 2007.
- [32] D. J. W. Evans, P. V. Lawford, J. Gunn, D. Walker, D. R. Hose, R. H. Smallwood, B. Chopard, M. Krafczyk, J. Bernsdorf, and A. Hoekstra. The application of multiscale modelling to the process of development and prevention of stenosis in a stented coronary artery. *Philos. T. Roy. Soc. A*, 366(1879):3343, 2008.
- [33] The COAST project. <http://www.complex-automata.org>.
- [34] B. Chopard, J. L. Falcone, R. Razakanirina, A. Hoekstra, and A. Caiazzo. On the collision-propagation and gather-update formulations of a cellular automata rule. In H. Umeo, S. Morishita, K. Nishinari, T. Komatsuzaki, and Stefania Bandini, editors, *Cellular Automata*, volume 5191 of *Lecture Notes in Computer Science*, chapter 19, page 144. Springer Berlin Heidelberg, Berlin, Heidelberg, 2010.
- [35] J. A. Kaandorp, C. P. Lowe, D. Frenkel, and P. M. A. Sloot. Effect of nutrient diffusion and flow on coral morphology. *Phys. Rev. Lett.*, 77(11):2328, 1996.
- [36] J. A. Kaandorp and J. E. Kübler. *The Algorithmic Beauty of Seaweeds, Sponges and Corals*. Springer, 1 edition, 2001.
- [37] R. Merks. Models of coral growth: spontaneous branching, compactification and the laplacian growth assumption. *J. Theor. Biol.*, 224(2):153, 2003.
- [38] R. M. H. Merks, A. G. Hoekstra, J. A. Kaandorp, and P. M. A. Sloot. Polyp oriented modelling of coral growth. *J. Theor. Biol.*, 228(4):559, 2004.
- [39] G. Agha. *Actors: A Model of Concurrent Computation in Distributed Systems*. MIT Press, 1986.
- [40] J. Hegewald, M. Krafczyk, J. Tölke, A. Hoekstra, and B. Chopard. An agent-based coupling platform for complex automata. In *Computational Science ICCS 2008*, volume 5102 of *Lecture Notes in Computer Science*, page 227. Springer, 2008.
- [41] S. Succi. *The Lattice Boltzmann Equation for Fluid Dynamics and Beyond*. Oxford University Press, 2001.
- [42] D. Alemani, B. Chopard, J. Galceran, and J. Buffle. Lbgk method coupled to time splitting technique for solving reaction-diffusion processes in complex systems. *Phys. Chem. Chem. Phys.*, 7(18):3331, 2005.
- [43] A. Caiazzo, J. L. Falcone, B. Chopard, and A. G. Hoekstra. Error investigations in complex automata models for reaction-diffusion systems. In H. Umeo, S. Morishita, K. Nishinari, T. Komatsuzaki, and Stefania Bandini, editors, *Cellular Automata*, volume 5191 of *Lecture Notes in Computer Science*, chapter 33, pages 260–267. Springer, Berlin, Heidelberg, 2010.

- [44] A. Caiazzo, J. L. Falcone, B. Chopard, and A. G. Hoekstra. Asymptotic analysis of complex automata models for reaction-diffusion systems. *Appl. Numer. Math.*, 59(8):2023, 2009.
- [45] J. Haga, Y. Li, and S. Chien. Molecular basis of the effects of mechanical stretch on vascular smooth muscle cells. *J. Biomech.*, 40(5):947, 2007.
- [46] Y. S. Li, J. H. Haga, and S. Chien. Molecular basis of the effects of shear stress on vascular endothelial cells. *J. Biomech.*, 38(10):1949, 2005.
- [47] A. Morton. The influence of physical stent parameters upon restenosis. *Pathol. Biol.*, 52(4):196, 2004.
- [48] H. Kitano. Computational systems biology. *Nature*, 420(6912):206, 2002.
- [49] P. M. A. Sloot and A. G. Hoekstra. Multiscale modeling in computational biology. *Brief. Bioinf.*, 11(1):142, 2010.
- [50] J. Southern, J. Pitt-Francis, J. Whiteley, D. Stokeley, H. Kobashi, R. Nobes, Y. Kadooka, and D. Gavaghan. Multi-scale computational modelling in biology and physiology. *Prog. Biophys. Mol. Bio.*, 96(1-3):60, 2008.
- [51] A. Hoekstra, J. L. Falcone, A. Caiazzo, and B. Chopard. Multi-scale modeling with cellular automata: The complex automata approach. In H. Umeo, S. Morishita, K. Nishinari, T. Komatsuzaki, and Stefania Bandini, editors, *Cellular Automata*, volume 5191 of *Lecture Notes in Computer Science*, chapter 25, pages 192–199. Springer Berlin Heidelberg, Berlin, Heidelberg, 2010.
- [52] J. S. Forrester, M. Fishbein, R. Helfant, and J. Fagin. A paradigm for restenosis based on cell biology: clues for the development of new preventive therapies. *J Am Coll Cardiol*, 17(3):758, 1991.
- [53] A. Farb, G. Sangiorgi, A. J. Carter, V. M. Walley, W. D. Edwards, R. S. Schwartz, and R. Virmani. Pathology of acute and chronic coronary stenting in humans. *Circulation*, 99(1):44, 1999.
- [54] R. Ross. The pathogenesis of atherosclerosis: a perspective for the 1990s. *Nature*, 362(6423):801, 1993.
- [55] The Multiscale Coupling Library and Environment MUSCLE. <http://muscle.berlios.de>.
- [56] A. Artoli, A. Hoekstra, and P. Sloot. Mesoscopic simulations of systolic flow in the human abdominal aorta. *J. Biomech.*, 39(5):873, 2006.
- [57] L. Axner, A. Hoekstra, A. Jeays, P. Lawford, R. Hose, and P. Sloot. Simulations of time harmonic blood flow in the mesenteric artery: comparing finite element and lattice boltzmann methods. *Biomed. Eng. Online*, 8(1):23, 2009.
- [58] C. W. Hwang, D. Wu, and E. R. Edelman. Physiological transport forces govern drug distribution for stent-based delivery. *Circulation*, 104(5):600, 2001.

- 
- [59] A. D. Levin, N. Vukmirovic, C. W. Hwang, and E. R. Edelman. Specific binding to intracellular proteins determines arterial transport properties for rapamycin and paclitaxel. *P. Natl. Acad. Sci. USA*, 101(25):9463, 2004.
- [60] R. Schwartz. A proliferation analysis of arterial neointimal hyperplasia: lessons for antiproliferative restenosis therapies. *Int. J. Cardiol.*, 53(1):71, 1996.
- [61] K. Resmi. Procedure for quantification of platelet adhesion to biomaterials by radioscintigraphy. *Thromb. Res.*, 114(2):121, 2004.
- [62] V. T. Turitto and H. J. Weiss. Red blood cells: their dual role in thrombus formation. *Science*, 207(4430):541, 1980.
- [63] Y. Cadroy and S. R. Hanson. Effects of red blood cell concentration on hemostasis and thrombus formation in a primate model. *Blood*, 75(11):2185, 1990.
- [64] E. Sjøfteland, T. Framstad, T. Thorsen, and H. Holmsen. Porcine platelets in vitro and in vivo studies: Relevance to human thrombosis research. *Eur. J. Haematol.*, 49(4):161, 1992.
- [65] J. Latt, B. Chopard, S. Succi, and F. Toschi. Numerical analysis of the averaged flow field in a turbulent lattice boltzmann simulation. *Physica A*, 362(1):6, 2006.
- [66] T. M. Alkhamis, R. L. Beissinger, and J. R. Chediak. Red blood cell effect on platelet adhesion and aggregation in low-stress shear flow: Myth or fact? *ASAIO Transactions*, 34(3):868, 1988.
- [67] D. Bluestein, C. Gutierrez, M. Londono, and R. T. Schoepfoerster. Vortex shedding in steady flow through a model of an arterial stenosis and its relevance to mural platelet deposition. *Ann. Med. Eng.*, 27(6):763, 1999.
- [68] L. Spieker, F. Ruschitzka, J. J. Badimon, G. Noll, and R. Corti. Shear stress-dependent platelet function after ldl cholesterol apheresis. *Thromb. Res.*, 113(6):395, 2004.
- [69] M. Yamazaki, S. Uchiyama, Y. Xiong, T. Nakano, T. Nakamura, and M. Iwata. Effect of remnant-like particle on shear-induced platelet activation and its inhibition by antiplatelet agents. *Thromb. Res.*, 115(3):211, 2005.
- [70] A. L. Fogelson and R. D. Guy. Platelet-wall interactions in continuum models of platelet thrombosis: formulation and numerical solution. *Math. Med. Biol.*, 21(4):293, 2004.
- [71] H. Schmid-Schönbein, G. V. Born, P. D. Richardson, N. Cusack, H. Rieger, R. Forst, I. Rohling-Winkel, P. Blasberg, and A. Wehmeyer. Rheology of thrombotic processes in flow: the interaction of erythrocytes and thrombocytes subjected to high flow forces. *Biorheology*, 18(3-6):415, 1981.
- [72] B. Chopard, R. Ouared, and D. Rufenacht. A lattice boltzmann simulation of clotting in stented aneurysms and comparison with velocity or shear rate reductions. *Math. Comput. Simulat.*, 72(2-6):108, 2006.

- [73] S. E. Harrison, S. M. Smith, J. Bernsdorf, D. R. Hose, and P. V. Lawford. Application and validation of the lattice boltzmann method for modelling flow-related clotting. *J. Biomech.*, 40(13):3023, 2007.
- [74] A. L. Fogelson. Continuum models of platelet aggregation: Formulation and mechanical properties. *SIAM Journal on Applied Mathematics*, 52(4):1089, 1992.
- [75] E. N. Sorensen, G. W. Burgreen, W. R. Wagner, and J. F. Antaki. Computational simulation of platelet deposition and activation: I. model development and properties. *Ann. Med. Eng.*, 27(4):436, 1999.
- [76] D. Basmadjian. The effect of flow and mass transport in thrombogenesis. *Ann. Med. Eng.*, 18(6):685, 1990.
- [77] K. Boryczko, W. Dzwinel, and D. A. Yuen. Dynamical clustering of red blood cells in capillary vessels. *J. Mol. Model.*, 9(1):16, 2003.
- [78] N. Filipovic, M. Kojic, and A. Tsuda. Modelling thrombosis using dissipative particle dynamics method. *Philos. T. Roy. Soc. A*, 366(1879):3265, 2008.
- [79] A. Masselot and B. Chopard. A lattice boltzmann model for particle transport and deposition. *Europhys. Lett.*, 42(3):259, 1998.
- [80] E. F. Leonard. The role of flow in thrombogenesis. *B. New York Acad. Med.*, 48(2):273, 1972.
- [81] T. Karino and H. L. Goldsmith. Aggregation of human platelets in an annular vortex distal to a tubular expansion1. *Microvasc. Res.*, 17(3):217, 1979.
- [82] T. Karino and H. L. Goldsmith. Adhesion of human platelets to collagen on the walls distal to a tubular expansion1. *Microvasc. Res.*, 17(3):238, 1979.
- [83] H. L. Goldsmith and V. T. Turitto. Rheological aspects of thrombosis and haemostasis: basic principles and applications. *Thromb. Haemostasis*, 55(3):415, 1986.
- [84] T. David. Platelet deposition in stagnation point flow: an analytical and computational simulation. *Med. Eng. Phys.*, 23(5):299–312, 2001.
- [85] S. E. Harrison. *The Use of Lattice Boltzmann Simulations in Thrombosis Modelling*. PhD thesis, University of Sheffield, 2007.
- [86] L. Axner, J. Bernsdorf, T. Zeiser, P. Lammers, J. Linxweiler, and A. Hoekstra. Performance evaluation of a parallel sparse lattice boltzmann solver. *J. Comput. Phys.*, 227(10):4895, 2008.
- [87] B. Stahl, B. Chopard, and J. Latt. Measurements of wall shear stress with the lattice boltzmann method and staircase approximation of boundaries. *Comput. Fluids*, 39(9):1625, 2010.
- [88] J. Gunn, N. Arnold, K. H. Chan, L. Shepherd, D. C. Cumberland, and D. C. Crossman. Coronary artery stretch versus deep injury in the development of in-stent neointima. *Heart*, 88(4):401, 2002.

- 
- [89] S. Succi, O. Filippova, G. Smith, and E. Kaxiras. Applying the lattice boltzmann equation to multiscale fluid problems. *Comput. Sci. Eng.*, 3(6):26, 2001.
- [90] H. A. Barnes. Shear-thickening (dilatancy) in suspensions of nonaggregating solid particles dispersed in newtonian liquids. *J. Rheol.*, 33(2):329, 1989.
- [91] J. F. Brady. Computer simulation of viscous suspensions. *Chem. Eng. Sci.*, 56(9):2921, 2001.
- [92] D. A. Drew. Mathematical modeling of two-phase flow. *Annu. Rev. Fluid Mech.*, 15(1):261, 1983.
- [93] S. Sacanna, L. Rossi, A. Wouterse, and A. P. Philipse. Observation of a shape-dependent density maximum in random packings and glasses of colloidal silica ellipsoids. *J. Phys.*, 19(37):376108, 2007.
- [94] H. A. Barnes, J. F. Hutton, and K. Walters. *An Introduction to Rheology (Rheology Series)*. Elsevier Science, 1989.
- [95] A. Einstein. *Ann. Phys.*, 19:289, 1906.
- [96] A. Einstein. *Ann. Phys.*, 34:591, 1911.
- [97] J. J. Stickel and R. L. Powell. Fluid mechanics and rheology of dense suspensions. *Annu. Rev. Fluid Mech.*, 37:129, 2005.
- [98] R. L. Hoffmann. *J. Colloid Interf. Sci.*, 46:491, 1973.
- [99] H. M. Laun, R. Bung, E. Hadicke, and R. Hingmann. In P. Moldenaers and R. Keunings, editors, *Theoretical and Applied Rheology*, page 616. Elsevier Science, 1992.
- [100] A. J. Liu and S. R. Nagel. Nonlinear dynamics: Jamming is not just cool any more. *Nature*, 396(6706):21, 1998.
- [101] P. Hébraud. Normal and tangential stress fluctuations during jamming. *Rheol. Acta*, 48(8):845, 2009.
- [102] J. So, S. M. Yang, and J. C. Hyun. Microstructure evolution and rheological responses of hard sphere suspensions. *Chem. Eng. Sci.*, 56(9):2967, 2001.
- [103] J. Hyväluoma, P. Raikkinmäki, A. Koponen, M. Kataja, and J. Timonen. Strain hardening in liquid-particle suspensions. *Phys. Rev. E*, 72(6):061402, 2005.
- [104] G. Amati, S. Succi, and R. Piva. Massively parallel lattice-boltzmann simulation of turbulent channel flow. *Int. J. Mod. Phys. C*, 8(4):869, 1997.
- [105] V. T. O'Brien and M. E. Mackay. Stress components and shear thickening of concentrated hard sphere suspensions. *Langmuir*, 16(21):7931, 2000.
- [106] J. F. Brady. The rheological behavior of concentrated colloidal dispersions. *J. Chem. Phys.*, 99(1):567–581, 1993.



- [107] P. D'Haene. Scattering dichroism measurements of flow-induced structure of a shear thickening suspension. *J. Colloid Interf. Sci.*, 156(2):350, 1993.
- [108] R. Hoffman. Discontinuous and dilatant viscosity behavior in concentrated suspensions iii. necessary conditions for their occurrence in viscometric flows. *Adv. Colloid Interfac.*, 17(1):161, 1982.
- [109] W. H. Boersma, P. J. M. Baets, J. Laven, and H. N. Stein. Time-dependent behavior and wall slip in concentrated shear thickening dispersions. *J. Rheol.*, 35(6):1093, 1991.
- [110] V. Gopalakrishnan and C. F. Zukoski. Effect of attractions on shear thickening in dense suspensions. *J. Rheol.*, 48(6):1321, 2004.
- [111] Y. S. Lee and N. J. Wagner. Dynamic properties of shear thickening colloidal suspensions. *Rheol Acta*, 42:199, 2003.
- [112] A. Philipse. Preparation and properties of nonaqueous model dispersions of chemically modified, charged silica spheres. *J. Colloid Interf. Sci.*, 128(1):121, 1989.
- [113] E. Lorenz, A. Caiazzo, and A. G. Hoekstra. Lees-edwards boundary conditions for lattice boltzmann suspension simulations. *Phys. Rev. E*, 79(3):036706, 2009.
- [114] J. Kromkamp, D. vd Ende, D. Kandhai, R. vd Sman, and R. Boom. Lattice boltzmann simulation of 2d and 3d non-brownian suspensions in couette flow. *Chem. Eng. Sci.*, 61(2):858, 2006.
- [115] A. Shakib-Manesh, P. Raiskinmäki, A. Koponen, M. Kataja, and J. Timonen. Shear stress in a couette flow of liquid-particle suspensions. *J. Stat. Phys.*, 107(1):67, 2002.
- [116] A. Jäsberg. Hydrodynamical forces acting on particles in a two-dimensional flow near a solid wall. *Comput. Phys. Commun.*, 129(1-3):196, 2000.
- [117] D. R. Foss and J. F. Brady. Structure, diffusion and rheology of brownian suspensions by stokesian dynamics simulation. *J. Fluid Mech.*, 407:167, 2000.
- [118] J. F. Morris and J. F. Brady. Self-diffusion in sheared suspensions. *J. Fluid Mech.*, 312(-1):223, 1996.
- [119] J. F. Brady and J. F. Morris. Microstructure of strongly sheared suspensions and its impact on rheology and diffusion. *J. Fluid Mech.*, 348(-1):103, 1997.
- [120] R. Car and M. Parrinello. Unified approach for molecular dynamics and density-functional theory. *Phys. Rev. Lett.*, 55(22):2471, 1985.
- [121] V. Shenoy. An adaptive finite element approach to atomic-scale mechanics - the quasicontinuum method. *J. Mech. Phys. Solids*, 47(3):611, 1999.
- [122] C. Gear. 'coarse' integration/bifurcation analysis via microscopic simulators: micro-galerkin methods. *Comput. Chem. Eng.*, 26(7-8):941, 2002.

- 
- [123] M. K. Lyon and L. G. Leal. An experimental study of the motion of concentrated suspensions in two-dimensional channel flow. part 1. monodisperse systems. *J. Fluid Mech.*, 363(-1):25, 1998.
- [124] M. K. Lyon and L. G. Leal. An experimental study of the motion of concentrated suspensions in two-dimensional channel flow. part 2. bidisperse systems. *J. Fluid Mech.*, 363(-1):57, 1998.
- [125] A. J. C. Ladd. Numerical simulations of particulate suspensions via a discretized boltzmann equation, part 2, numerical results. *J. Fluid Mech.*, 271:311, 1994.
- [126] S. Chen and G. D. Doolen. Lattice boltzmann method for fluid flows. *Annu. Rev. Fluid Mech.*, 30(1):329, 1998.
- [127] J. P. Rivet and J. P. Boon. *Lattice Gas Hydrodynamics (Cambridge Nonlinear Science Series)*. Cambridge University Press, 1 edition, 2001.
- [128] B. Chopard, A. Dupuis, P. Luthi, and A. Masselot. Cellular automata and lattice boltzmann techniques: An approach to model and simulate complex systems. *Adv. Complex Syst.*, 5:103, 2002.
- [129] Y. H. Qian, D. D’Humières, and P. Lallemand. Lattice bgk models for navier-stokes equation. *Europhys. Lett.*, 17(6):479, 1992.
- [130] D. d’Humières. Generalized lattice boltzmann equations. *Progr. Astronaut. Aero.*, 159:450, 1992.
- [131] D. d’Humières, I. Ginzburg, M. Krafczyk, P. Lallemand, and L. S. Luo. Multiple-relaxation-time lattice boltzmann models in three dimensions. *Phil. Trans. Math. Phys. Eng. Sci.*, 360(1792):437, 2002.
- [132] J. B. W. Geerdink and A. G. Hoekstra. Comparing entropic and multiple relaxation times lattice boltzmann methods for blood flow simulations. *Int. J. Mod. Phys. C (IJMPC)*, 20(5):721, 2009.
- [133] S. Ansumali and I. V. Karlin. Stabilization of the lattice boltzmann method by the h theorem: A numerical test. *Phys. Rev. E*, 62(6):7999, 2000.
- [134] R. A. Brownlee, A. N. Gorban, and J. Levesley. Stability and stabilization of the lattice boltzmann method. *Phys. Rev. E*, 75(3):036711, 2007.
- [135] I. Ginzburg. Equilibrium-type and link-type lattice boltzmann models for generic advection and anisotropic-dispersion equation. *Adv. Water Res.*, 28(11):1171, 2005.
- [136] I. Ginzburg and D. d’Humières. Multireflection boundary conditions for lattice boltzmann models. *Phys. Rev. E*, 68(6):066614, 2003.
- [137] U. Frisch, B. Hasslacher, and Y. Pomeau. Lattice-gas automata for the navier-stokes equation. *Phys. Rev. Lett.*, 56(14):1505, 1986.
- [138] M. Junk and Z. Yang. Asymptotic analysis of lattice boltzmann boundary conditions. *J. Stat. Phys.*, 121(1-2):3, 2005.

- [139] P. Lallemand, L. Luo, and Y. Peng. A lattice boltzmann front-tracking method for interface dynamics with surface tension in two dimensions. *J. Comput. Phys.*, 226(2):1367, 2007.
- [140] R. Verberg and A. J. C. Ladd. Lattice-boltzmann model with sub-grid-scale boundary conditions. *Phys. Rev. Lett.*, 84(10):2148, 2000.
- [141] M. Bouzidi, M. Firdaouss, and P. Lallemand. Momentum transfer of a boltzmann-lattice fluid with boundaries. *Phys. Fluids*, 13(11):3452, 2001.
- [142] Y. Sui, Y. T. Chew, P. Roy, and H. T. Low. A hybrid immersed-boundary and multi-block lattice boltzmann method for simulating fluid and moving-boundaries interactions. *Int. J. Numer. Methods Fluids*, 53(11):1727, 2007.
- [143] C. K. Aidun and J. R. Clausen. Lattice-boltzmann method for complex flows. *Annu. Rev. Fluid Mech.*, 42(1):439, 2010.
- [144] A. J. C. Ladd. Numerical simulations of particulate suspensions via a discretized boltzmann equation, part 1, theoretical foundation. *J. Fluid Mech.*, 271:285, 1994.
- [145] N. Q. Nguyen and A. J. C. Ladd. Lubrication corrections for lattice-boltzmann simulations of particle suspensions. *Phys. Rev. E*, 66(4):046708, 2002.
- [146] C. K. Aidun and Y. Lu. Lattice boltzmann simulation of solid particles suspended in fluid. *J. Stat. Phys.*, 81(1):49, 1995.
- [147] E. J. Ding and C. K. Aidun. Extension of the lattice-boltzmann method for direct simulation of suspended particles near contact. *J. Stat. Phys.*, 112(3):685, 2003.
- [148] C. P. Lowe, D. Frenkel, and A. J. Masters. Long-time tails in angular momentum correlations. *J. Chem. Phys.*, 103(4):1582, 1995.
- [149] J. Kromkamp, D. T. M. vd Ende, D. Kandhai, R. G. M. vd Sman, and R. M. Boom. Shear-induced self-diffusion and microstructure in non-brownian suspensions at non-zero reynolds numbers. *J. Fluid Mech.*, 529:253, 2005.
- [150] K. Han, Y. Feng, and D. Owen. Coupled lattice boltzmann and discrete element modelling of fluidparticle interaction problems. *Comput. Struct.*, 85(11-14):1080, 2007.
- [151] A. Caiazzo. Analysis of lattice boltzmann nodes initialisation in moving boundary problems. *Prog. Comput. Fluid Dy.*, 8:3, 2008.
- [152] A. Caiazzo and M. Junk. Boundary forces in lattice boltzmann: Analysis of momentum exchange algorithm. *Comput. Math. Appl.*, 55(7):1415, 2008.
- [153] A. W. Lees and S. F. Edwards. The computer study of transport processes under extreme conditions. *J. Phys.*, 5(15):1921, 1972.
- [154] P. J. A. Hartman-Kok, S. G. Kazarian, C. J. Lawrence, and B. J. Briscoe. Near-wall particle depletion in a flowing colloidal suspension. *J. Rheol.*, 46(2):481, 2002.

- 
- [155] S. A. Gulmus and U. Yilmazer. Effect of volume fraction and particle size on wall slip in flow of polymeric suspensions. *J. Appl. Polym. Sci.*, 98(1):439, 2005.
- [156] J. Hyvaluoma, P. Raiskinmäki, A. Koponen, M. Kataja, and J. Timonen. Lattice-boltzmann simulation of particle suspensions in shear flow. *J. Stat. Phys.*, 121(1-2):149, 2005.
- [157] W. R. Hwang and M. A. Hulsen. Direct numerical simulations of hard particle suspensions in planar elongational flow. *J. Non-Newtonian Fluid Mech.*, 136(2-3):167, 2006.
- [158] S. V. Lishchuk, I. Halliday, and C. M. Care. Shear viscosity of bulk suspensions at low reynolds number with the three-dimensional lattice boltzmann method. *Phys. Rev. E*, 74(1), 2006.
- [159] R. M. MacMeccan, J. R. Clausen, G. P. Neitzel, and C. K. Aidun. Simulating deformable particle suspensions using a coupled lattice-boltzmann and finite-element method. *J. Fluid Mech.*, 618(-1):13–39, 2008.
- [160] C. K. Aidun, Y. Lu, and E. J. Ding. Direct analysis of particulate suspensions with inertia using the discrete boltzmann equation. *J. Fluid Mech.*, 373(-1):287, 1998.
- [161] A. J. Wagner and I. Pagonabarraga. Lees-edwards boundary conditions for lattice boltzmann. *J. Stat. Phys.*, 107(1):521, 2002.
- [162] P. Raiskinmäki, A. Shakib-Manesh, A. Jäsberg, A. Koponen, J. Merikoski, and J. Timonen. Lattice-boltzmann simulation of capillary rise dynamics. *J. Stat. Phys.*, 107(1):143, 2002.
- [163] A. Komnik, J. Harting, and H. J. Herrmann. Transport phenomena and structuring in shear flow of suspensions near solid walls. *J. Stat. Mech.-Theory E*, 2004(12):P12003, 2004.
- [164] G. P. Krishnan and D. T. Leighton. Inertial lift on a moving sphere in contact with a plane wall in a shear flow. *Phys. Fluids*, 7(11):2538, 1995.
- [165] I. M. Krieger and T. J. Dougherty. A mechanism for non-newtonian flow in suspensions of rigid spheres. *J. Rheol.*, 3(1):137, 1959.
- [166] A. Caiazzo. *Asymptotic Analysis of lattice Boltzmann method for Fluid-Structure interaction problems*. PhD thesis, Scuola Normale Superiore, Pisa, and Technische Universität Kaiserslautern, 2007.
- [167] R. M. MacMeccan. *Mechanistic Effects of Erythrocytes on Platelet Deposition in Coronary Thrombosis*. PhD thesis, Georgia Institute of Technology, 2007.
- [168] P. Lallemand and L. S. Luo. Lattice boltzmann method for moving boundaries. *J. Comput. Phys.*, 184(2):406, 2003.
- [169] E. C. Eckstein, D. G. Bailey, and A. H. Shapiro. Self-diffusion of particles in shear flow of a suspension. *J. Fluid Mech.*, 79(01):191, 1977.

- [170] G. Drazer, J. Koplik, B. Khusid, and A. Acrivos. Microstructure and velocity fluctuations in sheared suspensions. *J. Fluid Mech.*, 511:237, 2004.
- [171] D. Leighton and A. Acrivos. The shear-induced migration of particles in concentrated suspensions. *J. Fluid Mech.*, 181(-1):415, 1987.
- [172] R. H. Davis. Microhydrodynamics of particulate : Suspensions. *Adv. Colloid Interfac.*, 43(1):17, 1993.
- [173] A. M. Leshansky and J. F. Brady. Dynamic structure factor study of diffusion in strongly sheared suspensions. *J. Fluid Mech.*, 527(-1):141, 2005.
- [174] B. Chapman. *Shear-induced migration phenomena in concentrated suspensions*. PhD thesis, University of Notre Dame, 1990.
- [175] M. Marchioro and A. Acrivos. Shear-induced particle diffusivities from numerical simulations. *J. Fluid Mech.*, 443(-1):101, 2001.
- [176] A. Sierou and J. F. Brady. Accelerated stokesian dynamics simulations. *J. Fluid Mech.*, 448(-1):115, 2001.
- [177] K. Tsunematsu, J. L. Falcone, C. Bonadonna, and B. Chopard. Applying a cellular automata method for the study of transport and deposition of volcanic particles. page 393. 2008.
- [178] P. Mathieu. What is wrong with isopycnal diffusion in world ocean models? *Appl. Math. Model.*, 22(4-5):367, 1998.
- [179] T. L. van Stijn, N. Praagman, and J. van Eijkeren. *Positive advection schemes for environmental studies*, page 1256. Pineridge Press, Swansea, 1987.
- [180] C. Zheng and G. D. Bennett. *Applied Contaminant Transport Modeling*. Wiley-Interscience, 2 edition, 2002.
- [181] R. M. H. Merks, A. G. Hoekstra, and P. M. A. Sloot. The moment propagation method for advection-diffusion in the lattice boltzmann method: Validation and peclet number limits. *J. Comput. Phys.*, 183(2):563, 2002.
- [182] D. J. Thomson. Criteria for the selection of stochastic models of particle trajectories in turbulent flows. *J. Fluid Mech.*, 180(-1):529, 1987.
- [183] D. Spivakovskaya, A. Heemink, G. Milstein, and J. Schoenmakers. Simulation of the transport of particles in coastal waters using forward and reverse time diffusion. *Adv. Water Res.*, 28(9):927, 2005.
- [184] D. R. Foss and J. F. Brady. Self-diffusion in sheared suspensions by dynamic simulation. *J. Fluid Mech.*, 401(-1):243, 1999.
- [185] W. H. Press, S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery. *Numerical Recipes 3rd Edition: The Art of Scientific Computing*. Cambridge University Press, 3 edition, 2007.
- [186] M. Matsumoto and T. Nishimura. Mersenne twister: a 623-dimensionally equidistributed uniform pseudo-random number generator. *ACM Trans. Model. Comput. Simul.*, 8(1):3, 1998.

- 
- [187] M. P. Wand and M. C. Jones. *Kernel Smoothing (Chapman & Hall/CRC Monographs on Statistics & Applied Probability)*. Chapman and Hall/CRC, 1 edition, 1994.
- [188] J. G. M. Schoenmakers and A. W. Heemink. Fast valuation of financial derivatives. *Journal of Computational Finance*, 1:47, 1997.
- [189] J. Q. Broughton, F. F. Abraham, N. Bernstein, and E. Kaxiras. Concurrent coupling of length scales: Methodology and application. *Phys. Rev. B*, 60(4):2391, 1999.
- [190] I. G. Kevrekidis, C. W. Gear, J. M. Hyman, P. G. Kevrekidis, O. Runborg, and C. Theodoropoulos. Equation-free, coarse-grained multiscale computation: Enabling microscopic simulators to perform system-level analysis. *Commun. Math. Sci.*, 1(4):715, 2003.
- [191] R. A. Berk. *Regression Analysis - A Constructive Critique*, volume 11 of *Advanced Quantitative Techniques in the Social Sciences*. SAGE Publications, Inc, Thousand Oaks (California), London, New Delhi, 2004.
- [192] P. R. Nott and J. F. Brady. Pressure-driven flow of suspensions: simulation and theory. *J. Fluid Mech.*, 275(-1):157, 1994.
- [193] Z. Fang, A. A. Mammoli, J. F. Brady, M. S. Ingbera, L. A. Mondyc, and A. L. Grahamd. Flow-aligned tensor models for suspension flows. *Int. J. Multiphase Flow*, 28(1):137, 2002.
- [194] R. J. Phillips, R. C. Armstrong, R. A. Brown, A. L. Graham, and J. R. Abbott. A constitutive equation for concentrated suspensions that accounts for shear-induced particle migration. *Phys. Fluids A: Fluid Dynamics*, 4(1):30, 1992.
- [195] S. R. Subia, M. S. Ingber, L. A. Mondy, S. A. Altobelli, and A. L. Graham. Modelling of concentrated suspensions using a continuum constitutive equation. *J. Fluid Mech.*, 373(-1):193, 1998.
- [196] R. E. Hampton, A. A. Mammoli, A. L. Graham, N. Tetlow, and S. A. Altobelli. Migration of particles undergoing pressure-driven flow in a circular conduit. *J. Rheol.*, 41(3):621, 1997.
- [197] V. Cristini and G. Kassab. Computer modeling of red blood cell rheology in the microcirculation: A brief overview. *Ann. Med. Eng.*, 33(12):1724, 2005.
- [198] C. Sun and L. L. Munn. Particulate nature of blood determines macroscopic rheology: a 2-d lattice boltzmann analysis. *Biophys. J.*, 88(3):1635, 2005.
- [199] F. Parsi and F. Gadala Maria. Fore-and-aft asymmetry in a concentrated suspension of solid spheres. *J. Rheol.*, 31(8):725, 1987.
- [200] J. F. Morris and B. Katyal. Microstructure from simulated brownian suspension flows at large shear rate. *Phys. Fluids*, 14(6):1920, 2002.
- [201] A. Sierou and J. F. Brady. Rheology and microstructure in concentrated noncolloidal suspensions. *J. Rheol.*, 46(5):1031, 2002.

- [202] C. J. Lin, J. H. Peery, and W. R. Schowalter. Simple shear flow round a rigid sphere: inertial effects and suspension rheology. *J. Fluid Mech.*, 44(01):1, 1970.
- [203] P. Raiskinmäki. *Dynamics of multiphase flows: liquid-particle suspensions and droplets spreading*. PhD thesis, University of Jyväskylä, 2004.
- [204] Y. Yan, J. F. Morris, and J. Koplik. Hydrodynamic interaction of two particles in confined linear shear flow at finite reynolds number. *Phys. Fluids*, 19(11), 2007.
- [205] P. M. Kulkarni and J. F. Morris. Suspension properties at finite reynolds number from simulated shear flow. *Phys. Fluids*, 20(4), 2008.
- [206] G. K. Batchelor and J. T. Green. The hydrodynamic interaction of two small freely-moving spheres in a linear flow field. *J. Fluid Mech.*, 56(02):375, 1972.
- [207] K. Higashitani. Suspension rheology fundamentals and application to industrial processes. *Chem. Eng. Sci.*, 56(9):2899, 2001.
- [208] J. R. Melrose, J. H. van Vliet, and R. C. Ball. Continuous shear thickening and colloid surfaces. *Phys. Rev. Lett.*, 77(22):4660, 1996.
- [209] P. Raiskinmäki, J. A. Aaström, M. Kataja, M. Latva Kokko, A. Koponen, A. Jäsberg, A. Shakib Manesh, and J. Timonen. Clustering and viscosity in a shear flow of a particulate suspension. *Phys. Rev. E*, 68(6):061403, 2003.
- [210] E. Lorenz, A. Caiazzo, and A. G. Hoekstra. Corrected momentum exchange method for lattice boltzmann simulations of suspension flow. *Phys. Rev. E*, 79(3):036705, 2009.
- [211] G. Drazer, J. Koplik, B. Khusid, and A. Acrivos. Deterministic and stochastic behaviour of non-brownian spheres in sheared suspensions. *J. Fluid Mech.*, 460:307, 2002.
- [212] E. J. Ding and C. K. Aidun. Cluster size distribution and scaling for spherical particles and red blood cells in pressure-driven flows at small reynolds number. *Phys. Rev. Lett.*, 96(20):204502, 2006.