On shape and elasticity: bio-sheets, curved crystals, and odd droplets

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Bibliography

[1] L. Landau and E. Lifshitz, *Theory of Elasticity: Volume 7 of Course of Theoretical Physics*. 3rd edition, Pergamon Press (1986).

[2] F. I. Niordson, *Shell Theory*. 1st edition, Elsevier Science Publishers B.V., Amsterdam (1985).

[3] T. J. Willmore, "Note on embedded surfaces". An. Sti. Univ. "Al. I. Cuza" Iasi Sect. I a Mat. (NS) B, **11**: pp. 493 (1965).

[4] D. Caspar and A. Klug, "Physical Principles in the Construction of Regular Viruses". Cold Spring Harbor Symposia on Quantitative Biology, pp. 1–24 (1962), doi:10.1101/SQB.1962.027.001.005.

[5] M. Marder, R. D. Deegan, and E. Sharon, "Crumpling, buckling, and cracking: Elasticity of thin sheets". Physics Today, **60**: pp. 33 (2007), doi:10.1063/1.2711634.

[6] L. E. Helseth and T. M. Fischer, "Physical mechanisms of rehydration in Polypodium polypodioides, a resurrection plant". Phys. Rev. E, **71**: p. 061903 (2005), doi:10.1103/PhysRevE.71.061903.

[7] E. Rivas-Adrover, *Deployable Structures*. EBL-Schweitzer, Laurence King Publishing (2015).

[8] S. Kim, J. Koh, M. Cho, and K. Cho, "Towards a bio-mimetic flytrap robot based on a snap-through mechanism". In *2010 3rd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics*, pp. 534–539, IEEE (2010), doi:10.1109/biorob.2010.5627994.

[9] N. P. Bende, A. A. Evans, S. Innes-Gold, L. A. Marin, I. Cohen, R. C. Hayward, and C. D. Santangelo, "Geometrically controlled snapping transitions in shells with curved creases". Proceedings of the National Academy of Sciences, **112**: pp. 11175 (2015), doi:10.1073/pnas.1509228112.

[10] B. Alberts, A. Johnson, J. Lewis, D. Morgan, M. Raff, K. Roberts, and P. Walter, *Molecular Biology of the Cell*. 6th edition, Garland Science, Taylor & Francis Group, New York, NY (2017).

[11] "A 3D Printed Topology Joke". `https://www.shapeways.com/blog/archives/21752-a-3d-printed-topology-joke.html` (-). Shapeways Blog. Accessed: 24-04-2022.

[12] O. Glatter and S. Salentinig, "Inverting structures: from micelles via emulsions to internally self-assembled water and oil continuous nanocarriers". Current Opinion in Colloid & Interface Science, **49**: pp. 82 (2020), doi:10.1016/j.cocis.2020.05.003.

[13] Z. Chen, C. Majidi, D. J. Srolovitz, and M. Haataja, "Tunable helical ribbons". Applied Physics Letters, **98**: p. 011906 (2011), doi:10.1063/1.3530441.

[14] P. Pavliuchenko, M. Teller, M. Grüber, T. Bremen, and G. Hirt, "Production of bistable fully closed metallic shells by introducing residual stresses during bending processes". Production Engineering, **13**: pp. 201 (2019), doi:10.1007/s11740-019-00875-6.

[15] W. Helfrich, "Elastic Properties of Lipid Bilayers: Theory and Possible Experiments". Zeitschrift für Naturforschung C, **28**: pp. 693 (1973), doi:10.1515/znc-1973-11-1209.

[16] U. Seifert, "Configurations of fluid membranes and vesicles". Advances in Physics, **46**: pp. 13 (1997), doi:10.1080/00018739700101488.

[17] R. Lipowsky, "The conformation of membranes". Nature, **349**: pp. 475 (1991), doi:10.1038/349475a0.

[18] M. Deserno, "Fluid lipid membranes: From differential geometry to curvature stresses". Chemistry and Physics of Lipids, **185**: pp. 11 (2015), doi:https://doi.org/10.1016/j.chemphyslip.2014.05.001.

[19] R. Lipowsky, "Spontaneous tubulation of membranes and vesicles reveals membrane tension generated by spontaneous curvature". Faraday Discuss., **161**: pp. 305 (2013), doi:10.1039/c2fd20105d.

[20] T. M. Fischer, "Shape Memory of Human Red Blood Cells". Biophysical Journal, **86**: pp. 3304 (2004), doi:10.1016/s0006-3495(04)74378-7.

[21] S. Zhang, D. M. Marini, W. Hwang, and S. Santoso, "Design of nanostructured biological materials through self-assembly of peptides and proteins". Current Opinion in Chemical Biology, **6**: pp. 865 (2002), doi:10.1016/s1367-5931(02)00391-5.

[22] J. Ennis, "Spontaneous curvature of surfactant films". The Journal of Chemical Physics, **97**: pp. 663 (1992), doi:10.1063/1.463561.

[23] G. Grosso and G. Parravicini, *Solid State Physics*. Elsevier Science (2013).

[24] Y. Cao, V. Fatemi, S. Fang, K. Watanabe, T. Taniguchi, E. Kaxiras, and P. Jarillo-Herrero, "Unconventional superconductivity in magic-angle graphene superlattices". Nature, **556**: pp. 43 (2018).

[25] M. J. Bowick, L. Giomi, H. Shin, and C. K. Thomas, “Bubble-raft model for a paraboloidal crystal”. Phys. Rev. E, **77**: p. 021602 (2008), doi:10.1103/PhysRevE.77.021602.

[26] A. Pérez-Garrido, M. J. W. Dodgson, and M. A. Moore, “Influence of dislocations in Thomson’s problem”. Phys. Rev. B, **56**: pp. 3640 (1997), doi:10.1103/PhysRevB.56.3640.

[27] M. J. Bowick, A. Cacciuto, D. R. Nelson, and A. Travesset, “Crystalline particle packings on a sphere with long-range power-law potentials”. Phys. Rev. B, **73**: p. 024115 (2006), doi:10.1103/PhysRevB.73.024115.

[28] M. Bowick, A. Cacciuto, D. R. Nelson, and A. Travesset, “Crystalline Order on a Sphere and the Generalized Thomson Problem”. Phys. Rev. Lett., **89**: p. 185502 (2002), doi:10.1103/PhysRevLett.89.185502.

[29] M. Aznar, A. Luque, and D. Reguera, “Relevance of capsid structure in the buckling and maturation of spherical viruses”. Physical Biology, **9**: p. 036003 (2012).

[30] A. R. Bausch, M. J. Bowick, A. Cacciuto, A. D. Dinsmore, M. F. Hsu, D. R. Nelson, M. G. Nikolaides, A. Travesset, and D. A. Weitz, “Grain Boundary Scars and Spherical Crystallography”. Science, **299**: pp. 1716 (2003), doi:10.1126/science.1081160.

[31] T. Einert, P. Lipowsky, J. Schilling, M. J. Bowick, and A. R. Bausch, “Grain Boundary Scars on Spherical Crystals”. Langmuir, **21**: pp. 12076 (2005), doi:10.1021/la0517383.

[32] P. Lipowsky, M. J. Bowick, J. H. Meinke, D. R. Nelson, and A. R. Bausch, “Direct visualization of dislocation dynamics in grain-boundary scars”. Nature Materials, **4**: pp. 407 (2005), doi:10.1038/nmat1376.

[33] W. T. M. Irvine, V. Vitelli, and P. M. Chaikin, “Pleats in crystals on curved surfaces”. Nature, **468**: p. 947 (2010), doi:10.1038/nature09620.

[34] R. E. Guerra, C. P. Kelleher, A. D. Hollingsworth, and P. M. Chaikin, “Freezing on a sphere”. Nature, **554**: p. 346 (2018), doi:10.1038/nature25468.

[35] N. Vogel, S. Utech, G. T. England, T. Shirman, K. R. Phillips, N. Koay, I. B. Burgess, M. Kolle, D. A. Weitz, and J. Aizenberg, “Color from hierarchy: Diverse optical properties of micron-sized spherical colloidal assemblies”. Proceedings of the National Academy of Sciences, **112**: pp. 10845 (2015), doi:10.1073/pnas.1506272112.

[36] M. J. W. Dodgson and M. A. Moore, “Vortices in a thin-film superconductor with a spherical geometry”. Phys. Rev. B, **55**: pp. 3816 (1997), doi:10.1103/PhysRevB.55.3816.

[37] N. Denkov, S. Tcholakova, I. Lesov, D. Cholakova, and S. K. Smoukov, “Self-shaping of oil droplets via the formation of intermediate rotator phases upon cooling”. Nature, **528**: pp. 392 (2015), doi:10.1038/nature16189.

[38] S. Guttman, Z. Sapir, M. Schultz, A. V. Butenko, B. M. Ocko, M. Deutsch, and E. Sloutskin, “How faceted liquid droplets grow tails”. Proceedings of the National Academy of Sciences, **113**: pp. 493 (2016), doi:10.1073/pnas.1515614113.

[39] D. R. Nelson, *Defects and Geometry in Condensed Matter Physics*. Cambridge University Press (2002).

[40] F. C. Frank, “I. Liquid crystals. On the theory of liquid crystals”. Discussions of the Faraday Society, **25**: p. 19 (1958), doi:10.1039/df9582500019.

[41] G. I. Taylor, “The mechanism of plastic deformation of crystals. Part I.—Theoretical”. Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character, **145**: pp. 362 (1934), doi:10.1098/rspa.1934.0106.

[42] S. Cheng and C. L. Brooks, “Viral Capsid Proteins Are Segregated in Structural Fold Space”. PLoS Computational Biology, **9**: p. e1002905 (2013), doi:10.1371/journal.pcbi.1002905.

[43] M. A. Moore and A. Pérez–Garrido, “Absence of a Finite-Temperature Melting Transition in the Classical Two-Dimensional One-Component Plasma”. Physical Review Letters, **82**: pp. 4078 (1999), doi:10.1103/physrevlett.82.4078.

[44] H. S. Seung and D. R. Nelson, “Defects in flexible membranes with crystalline order”. Phys. Rev. A, **38**: pp. 1005 (1988), doi:10.1103/PhysRevA.38.1005.

[45] J. Genzer and J. Groenewold, “Soft matter with hard skin: From skin wrinkles to templating and material characterization”. Soft Matter, **2**: p. 310 (2006), doi:10.1039/b516741h.

[46] D. R. Nelson, “Order, frustration, and defects in liquids and glasses”. Phys. Rev. B, **28**: pp. 5515 (1983), doi:10.1103/PhysRevB.28.5515.

[47] T. Kohyama and G. Gompper, “Defect Scars on Flexible Surfaces with Crystalline Order”. Phys. Rev. Lett., **98**: p. 198101 (2007), doi:10.1103/PhysRevLett.98.198101.

[48] F. L. Jiménez, N. Stoop, R. Lagrange, J. Dunkel, and P. M. Reis, “Curvature-Controlled Defect Localization in Elastic Surface Crystals”. Phys. Rev. Lett., **116**: p. 104301 (2016), doi:10.1103/PhysRevLett.116.104301.

[49] A. Siber, “Buckling transition in icosahedral shells subjected to volume conservation constraint and pressure: Relations to virus maturation”. Phys. Rev. E, **73**: p. 061915 (2006), doi:10.1103/PhysRevE.73.061915.

[50] 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**: pp. 1231 (2005), doi:10.1126/science.1113207.

[51] S. Yefet, E. Sloutskin, L. Tamam, Z. Sapir, M. Deutsch, and B. M. Ocko, “Surfactant-Induced Phases in Water-Supported Alkane Monolayers: II. Structure”. Langmuir, **30**: pp. 8010 (2014), doi:10.1021/la501589t.

[52] M. J. Bowick, D. R. Nelson, and A. Travesset, “Interacting topological defects on frozen topographies”. Phys. Rev. B, **62**: pp. 8738 (2000), doi: 10.1103/PhysRevB.62.8738.

[53] E. Sloutskin, C. D. Bain, B. M. Ocko, and M. Deutsch, “Surface freezing of chain molecules at the liquid–liquid and liquid–air interfaces”. Faraday Discuss., **129**: pp. 339 (2005), doi:10.1039/B405969G. See in particular, the General Discussion, p. 353-366.

[54] J. Renkawitz, A. Kopf, J. Stopp, I. de Vries, M. K. Driscoll, J. Merrin, R. Hauschild, E. S. Welf, G. Danuser, R. Fiolka, and M. Sixt, “Nuclear positioning facilitates amoeboid migration along the path of least resistance”. Nature, **568**: pp. 546 (2019), doi:10.1038/s41586-019-1087-5.

[55] J. C. Meiring, B. I. Shneyer, and A. Akhmanova, “Generation and regulation of microtubule network asymmetry to drive cell polarity”. Current Opinion in Cell Biology, **62**: pp. 86 (2020), doi:10.1016/j.ceb.2019.10.004.

[56] K. Röper, “Microtubules enter centre stage for morphogenesis”. Philosophical Transactions of the Royal Society B: Biological Sciences, **375**: p. 20190557 (2020), doi:10.1098/rstb.2019.0557.

[57] N. Resnik, T. Prezelj, G. M. R. D. Luca, E. Manders, R. Polishchuk, P. Veranivc, and M. E. Kreft, “Helical organization of microtubules occurs in a minority of tunneling membrane nanotubes in normal and cancer urothelial cells”. Scientific Reports, **8**: p. 17133 (2018), doi:10.1038/s41598-018-35370-y.

[58] R. D. Vale, “The Molecular Motor Toolbox for Intracellular Transport”. Cell, **112**: pp. 467 (2003), doi:10.1016/s0092-8674(03)00111-9.

[59] F. Rizzelli, M. G. Malabarba, S. Sigismund, and M. Mapelli, “The crosstalk between microtubules, actin and membranes shapes cell division”. Open Biology, **10**: p. 190314 (2020), doi:10.1098/rsob.190314.

[60] S. Chaaban and G. J. Brouhard, “A microtubule bestiary: structural diversity in tubulin polymers”. Molecular Biology of the Cell, **28**: pp. 2924 (2017), doi: 10.1091/mbc.e16-05-0271.

[61] E. Unger, K. Böhm, and W. Vater, “Structural diversity and dynamics of microtubules and polymorphic tubulin assemblies”. Electron Microscopy Reviews, **3**: pp. 355 (1990), doi:10.1016/0892-0354(90)90007-f.

[62] R. Ayukawa, S. Iwata, H. Imai, S. Kamimura, M. Hayashi, K. X. Ngo, I. Minoura, S. Uchimura, T. Makino, M. Shirouzu, H. Shigematsu, K. Sekimoto, B. Gigant, and E. Muto, "GTP-dependent formation of straight tubulin oligomers leads to microtubule nucleation". Journal of Cell Biology, **220**: p. e202007033 (2021), doi:10.1083/jcb.202007033.

[63] N. B. Gudimchuk and J. R. McIntosh, "Regulation of microtubule dynamics, mechanics and function through the growing tip". Nature Reviews Molecular Cell Biology, **22**: pp. 777 (2021), doi:10.1038/s41580-021-00399-x.

[64] T. Frankel, *The Geometry of Physics: An Introduction*. 3rd edition, Cambridge University Press (2012).

[65] E. Kreyszig, *Differential Geometry*. 1st edition, Dover, New York (1991).

[66] L. Euler, "Elementa doctrinae solidorum". Novi Commentarii academiae scientiarum Petropolitanae, **4**: pp. 109 (1758).

[67] T. M. Fischer, "Bending stiffness of lipid bilayers. III. Gaussian curvature". Journal de Physique II France, **2**: pp. 337 (1992), doi:10.1051/jp2:1992137.

[68] T. M. Fischer, "Bending stiffness of lipid bilayers. V. Comparison of two formulations". Journal de Physique II France, **3**: pp. 1795 (1993), doi:10.1051/jp2:1993230.

[69] L. Giomi. Private communication (2017).

[70] M. Meyer, M. Desbrun, P. Schröder, and A. H. Barr, "Discrete Differential-Geometry Operators for Triangulated 2-Manifolds". In *Mathematics and Visualization*, pp. 35–57, Springer Berlin Heidelberg (2003), doi:10.1007/978-3-662-05105-4_2.

[71] L. Giomi and M. Bowick, "Crystalline order on Riemannian manifolds with variable Gaussian curvature and boundary". Phys. Rev. B, **76**: p. 054106 (2007), doi:10.1103/PhysRevB.76.054106.

[72] M. J. Bowick and L. Giomi, "Two-dimensional matter: order, curvature and defects". Advances in Physics, **58**: pp. 449 (2009), doi:10.1080/00018730903043166.

[73] V. N. Manoharan, "Colloidal matter: Packing, geometry, and entropy". Science, **349**: p. 1253751 (2015), doi:10.1126/science.1253751.

[74] M. J. W. Dodgson, "Investigation on the ground states of a model thin-film superconductor on a sphere". Journal of Physics A: Mathematical and General, **29**: pp. 2499 (1996), doi:10.1088/0305-4470/29/10/028.

[75] J. Lidmar, L. Mirny, and D. R. Nelson, "Virus shapes and buckling transitions in spherical shells". Phys. Rev. E, **68**: p. 051910 (2003), doi:10.1103/PhysRevE.68.051910.

[76] T. T. Nguyen, R. F. Bruinsma, and W. M. Gelbart, “Elasticity theory and shape transitions of viral shells”. Phys. Rev. E, **72**: p. 051923 (2005), doi: 10.1103/PhysRevE.72.051923.

[77] D. J. Wales, H. McKay, and E. L. Altschuler, “Defect motifs for spherical topologies”. Phys. Rev. B, **79**: p. 224115 (2009), doi:10.1103/PhysRevB.79.224115.

[78] D. Roshal, K. Petrov, A. Myasnikova, and S. Rochal, “Extended topological defects as sources and outlets of dislocations in spherical hexagonal crystals”. Physics Letters A, **378**: pp. 1548 (2014), doi:10.1016/j.physleta.2014.03.037.

[79] A. Travesset, “Universality in the screening cloud of dislocations surrounding a disclination”. Phys. Rev. B, **68**: p. 115421 (2003), doi:10.1103/PhysRevB.68.115421.

[80] A. Azadi and G. M. Grason, “Neutral versus charged defect patterns in curved crystals”. Phys. Rev. E, **94**: p. 013003 (2016), doi:10.1103/PhysRevE.94.013003.

[81] G. Gompper and D. M. Kroll, “Freezing Flexible Vesicles”. Phys. Rev. Lett., **78**: pp. 2859 (1997), doi:10.1103/PhysRevLett.78.2859.

[82] C. M. Funkhouser, R. Sknepnek, and M. Olvera de la Cruz, “Topological defects in the buckling of elastic membranes”. Soft Matter, **9**: pp. 60 (2013), doi: 10.1039/C2SM26607E.

[83] M. Dubois, B. Demé, T. Gulik-Krzywicki, J.-C. Dedieu, C. Vautrin, S. Désert, E. Perez, and T. Zemb, “Self-assembly of regular hollow icosahedra in salt-free catanionic solutions”. Nature, **411**: pp. 672 (2001), doi:10.1038/35079541.

[84] S. Guttman, E. Kesselman, A. Jacob, O. Marin, D. Danino, M. Deutsch, and E. Sloutskin, “Nanostructures, Faceting, and Splitting in Nanoliter to Yoctoliter Liquid Droplets”. Nano Letters, **19**: pp. 3161 (2019), doi:10.1021/acs.nanolett.9b00594. PMID: 30986069.

[85] S. Guttman, B. M. Ocko, M. Deutsch, and E. Sloutskin, “From faceted vesicles to liquid icoshedra: Where topology and crystallography meet”. Current Opinion in Colloid & Interface Science, **22**: pp. 35 (2016), doi:10.1016/j.cocis.2016.02.002.

[86] G. Meng, J. Paulose, D. R. Nelson, and V. N. Manoharan, “Elastic Instability of a Crystal Growing on a Curved Surface”. Science, **343**: pp. 634 (2014), doi:10.1126/science.1244827.

[87] K. A. Brakke, “The Surface Evolver”. Experimental Mathematics, **1**: pp. 141 (1992), doi:10.1080/10586458.1992.10504253.

[88] J. S. B. Mitchell, D. M. Mount, and C. H. Papadimitriou, “The Discrete Geodesic Problem”. SIAM Journal on Computing, **16**: pp. 647 (1987), doi: 10.1137/0216045.

[89] "ExactGeodesic.wiki". On: `https://code.google.com/archive/p/geodesic/` (1999). Accessed: 2017-11-17.

[90] S. Guttman, Z. Sapir, B. M. Ocko, M. Deutsch, and E. Sloutskin, "Temperature-Tuned Faceting and Shape Changes in Liquid Alkane Droplets". Langmuir, **33**: pp. 1305 (2017), doi:10.1021/acs.langmuir.6b02926.

[91] D. Cholakova, N. Denkov, S. Tcholakova, I. Lesov, and S. K. Smoukov, "Control of drop shape transformations in cooled emulsions". Adv. Colloid Interface Sci., **235**: pp. 90 (2016), doi:10.1016/j.cis.2016.06.002.

[92] N. Denkov, D. Cholakova, S. Tcholakova, and S. K. Smoukov, "On the Mechanism of Drop Self-Shaping in Cooled Emulsions". Langmuir, **32**: pp. 7985 (2016), doi:10.1021/acs.langmuir.6b01626.

[93] O. Marin, M. Tkachev, E. Sloutskin, and M. Deutsch, "Polyhedral liquid droplets: Recent advances in elucidation and application". Current Opinion in Colloid & Interface Science, **49**: pp. 107 (2020), doi:10.1016/j.cocis.2020.05.006.

[94] P. A. Haas, R. E. Goldstein, S. K. Smoukov, D. Cholakova, and N. Denkov, "Theory of Shape-Shifting Droplets". Physical Review Letters, **118**: p. 088001 (2017), doi:10.1103/physrevlett.118.088001.

[95] P. A. Haas, D. Cholakova, N. Denkov, R. E. Goldstein, and S. K. Smoukov, "Shape-shifting polyhedral droplets". Physical Review Research, **1**: p. 023017 (2019), doi:10.1103/physrevresearch.1.023017.

[96] D. Cholakova, N. Denkov, S. Tcholakova, Z. Valkova, and S. K. Smoukov, "Multilayer Formation in Self-Shaping Emulsion Droplets". Langmuir, **35**: pp. 5484 (2019), doi:10.1021/acs.langmuir.8b02771.

[97] L. Tamam, D. Pontoni, Z. Sapir, S. Yefet, E. Sloutskin, B. M. Ocko, H. Reichert, and M. Deutsch, "Modification of deeply buried hydrophobic interfaces by ionic surfactants". Proceedings of the National Academy of Sciences, **108**: pp. 5522 (2011), doi:10.1073/pnas.1014100108.

[98] I. García-Aguilar, A. Atkins, P. Fonda, E. Sloutskin, and L. Giomi, "García-Aguilar et al. Reply:". Physical Review Letters, **126**: p. 259802 (2021), doi:10.1103/physrevlett.126.259802.

[99] V. N. Paunov, S. I. Sandler, and E. W. Kaler, "A Simple Molecular Model for the Spontaneous Curvature and the Bending Constants of Nonionic Surfactant Monolayers at the Oil/Water Interface". Langmuir, **16**: pp. 8917 (2000), doi:10.1021/la000367h.

[100] Ø. Wilhelmsen, D. Bedeaux, and D. Reguera, "Communication: Tolman length and rigidity constants of water and their role in nucleation". The Journal of Chemical Physics, **142**: p. 171103 (2015), doi:10.1063/1.4919689.

[101] O. Marin, M. Alesker, S. Guttman, G. Gershinsky, E. Edri, H. Shpaisman, R. E. Guerra, D. Zitoun, M. Deutsch, and E. Sloutskin, "Self-faceting of emulsion droplets as a route to solid icosahedra and other polyhedra". Journal of Colloid and Interface Science, **538**: pp. 541 (2019), doi:10.1016/j.jcis.2018.11.111.

[102] I. García-Aguilar, P. Fonda, and L. Giomi, "Dislocation screening in crystals with spherical topology". Physical Review E, **101**: p. 063005 (2020), doi:10.1103/physreve.101.063005.

[103] N. W. Ashcroft and N. D. Mermin, *Solid State Physics*. Holt, Rine Hart and Winston, New York (1976).

[104] R. E. Barker, "An Approximate Relation Between Elastic Moduli and Thermal Expansivities". Journal of Applied Physics, **34**: pp. 107 (1963), doi:10.1063/1.1729049.

[105] G. G. Borisy and E. Taylor, "The mechanism of action of colchicine: binding of colchincine-3H to cellular protein". J. Cell Biol., **34**: pp. 525 (1967), doi:10.1083/jcb.34.2.525.

[106] G. Borisy and E. Taylor, "The mechanism of action of colchicine: colchicine binding to sea urchin eggs and the mitotic apparatus". J. Cell Biol., **34**: pp. 535 (1967), doi:10.1083/jcb.34.2.535.

[107] T. Mitchison and M. Kirschner, "Dynamic instability of microtubule growth". Nature, **312**: pp. 237 (1984), doi:10.1038/312237a0.

[108] I. M. Jánosi, D. Chrétien, and H. Flyvbjerg, "Modeling elastic properties of microtubule tips and walls". European Biophysics Journal, **27**: pp. 501 (1998), doi:10.1007/s002490050160.

[109] M. Knossow, V. Campanacci, L. A. Khodja, and B. Gigant, "The Mechanism of Tubulin Assembly into Microtubules: Insights from Structural Studies". iScience, **23**: p. 101511 (2020), doi:10.1016/j.isci.2020.101511.

[110] G. J. Brouhard and L. M. Rice, "Microtubule dynamics: an interplay of biochemistry and mechanics". Nature Reviews Molecular Cell Biology, **19**: pp. 451 (2018), doi:10.1038/s41580-018-0009-y.

[111] D. Seetapun, B. T. Castle, A. J. McIntyre, P. T. Tran, and D. J. Odde, "Estimating the microtubule GTP cap size in vivo". Curr. Biol., **22**: pp. 1681 (2012).

[112] R. Melki, M. F. Carlier, D. Pantaloni, and S. N. Timasheff, "Cold depolymerization of microtubules to double rings: geometric stabilization of assemblies". Biochemistry, **28**: pp. 9143 (1989), doi:10.1021/bi00449a028.

[113] E. M. Mandelkow, E. Mandelkow, and R. A. Milligan, "Microtubule dynamics and microtubule caps: a time-resolved cryo-electron microscopy study." Journal of Cell Biology, **114**: pp. 977 (1991), doi:10.1083/jcb.114.5.977.

[114] D. Chrétien, S. D. Fuller, and E. Karsenti, "Structure of growing microtubule ends: two-dimensional sheets close into tubes at variable rates." Journal of Cell Biology, **129**: pp. 1311 (1995), doi:10.1083/jcb.129.5.1311.

[115] M. Igaev and H. Grubmüller, "Bending-torsional elasticity and energetics of the plus-end microtubule tip". Proceedings of the National Academy of Sciences, **119**: p. e2115516119 (2022), doi:10.1073/pnas.2115516119.

[116] J. R. McIntosh, E. O'Toole, G. Morgan, J. Austin, E. Ulyanov, F. Ataullakhanov, and N. Gudimchuk, "Microtubules grow by the addition of bent guanosine triphosphate tubulin to the tips of curved protofilaments". Journal of Cell Biology, **217**: pp. 2691 (2018), doi:10.1083/jcb.201802138.

[117] E. Nogales and H.-W. Wang, "Structural intermediates in microtubule assembly and disassembly: how and why?" Current Opinion in Cell Biology, **18**: pp. 179 (2006), doi:10.1016/j.ceb.2006.02.009.

[118] M. Igaev and H. Grubmüller, "Microtubule instability driven by longitudinal and lateral strain propagation". PLOS Computational Biology, **16**: p. e1008132 (2020), doi:10.1371/journal.pcbi.1008132.

[119] V. A. Fedorov, P. S. Orekhov, E. G. Kholina, A. A. Zhmurov, F. I. Ataullakhanov, I. B. Kovalenko, and N. B. Gudimchuk, "Mechanical properties of tubulin intra- and inter-dimer interfaces and their implications for microtubule dynamic instability". PLOS Computational Biology, **15**: p. e1007327 (2019), doi:10.1371/journal.pcbi.1007327.

[120] M. Igaev and H. Grubmüller, "Microtubule assembly governed by tubulin allosteric gain in flexibility and lattice induced fit". eLife, **7**: p. e34353 (2018), doi:10.7554/elife.34353.

[121] A. Grafmüller and G. A. Voth, "Intrinsic Bending of Microtubule Protofilaments". Structure, **19**: pp. 409 (2011), doi:10.1016/j.str.2010.12.020.

[122] V. Hunyadi, D. Chrétien, H. Flyvbjerg, and I. M. Jánosi, "Why is the microtubule lattice helical?" Biology of the Cell, **99**: pp. 117 (2007), doi:10.1042/bc20060059.

[123] H. Wang and E. Nogales, "Nucleotide-dependent bending flexibility of tubulin regulates microtubule assembly". Nature, **435**: pp. 911 (2005), doi:10.1038/nature03606.

[124] Z. Wu, H. Wang, W. Mu, Z. Ouyang, E. Nogales, and J. Xing, "Simulations of Tubulin Sheet Polymers as Possible Structural Intermediates in Microtubule Assembly". PLoS ONE, **4**: p. e7291 (2009), doi:10.1371/journal.pone.0007291.

[125] A. Guesdon, F. Bazile, R. M. Buey, R. Mohan, S. Monier, R. R. García, M. Angevin, C. Heichette, R. Wieneke, R. Tampé, L. Duchesne, A. Akhmanova, M. O. Steinmetz, and D. Chrétien, "EB1 interacts with outwardly curved and

straight regions of the microtubule lattice". Nature Cell Biology, **18**: pp. 1102 (2016), doi:10.1038/ncb3412.

[126] S. F. Stewman, K. K. Tsui, and A. Ma, "Dynamic Instability from Non-equilibrium Structural Transitions on the Energy Landscape of Microtubule". Cell Systems, **11**: pp. 608 (2020), doi:10.1016/j.cels.2020.09.008.

[127] R. Zhang, G. M. Alushin, A. Brown, and E. Nogales, "Mechanistic Origin of Microtubule Dynamic Instability and Its Modulation by EB Proteins". Cell, **162**: pp. 849 (2015), doi:10.1016/j.cell.2015.07.012.

[128] G. J. Brouhard and L. M. Rice, "The contribution of αβ-tubulin curvature to microtubule dynamics". Journal of Cell Biology, **207**: pp. 323 (2014), doi: 10.1083/jcb.201407095.

[129] V. VanBuren, L. Cassimeris, and D. J. Odde, "Mechanochemical Model of Microtubule Structure and Self-Assembly Kinetics". Biophysical Journal, **89**: pp. 2911 (2005), doi:10.1529/biophysj.105.060913.

[130] D. K. Fygenson, E. Braun, and A. Libchaber, "Phase diagram of microtubules". Physical Review E, **50**: pp. 1579 (1994), doi:10.1103/physreve.50.1579.

[131] C. Elie-Caille, F. Severin, J. Helenius, J. Howard, D. J. Muller, and A. Hyman, "Straight GDP-Tubulin Protofilaments Form in the Presence of Taxol". Current Biology, **17**: pp. 1765 (2007), doi:10.1016/j.cub.2007.08.063.

[132] E. A. Welnhofer and J. L. Travis, "Evidence for a direct conversion between two tubulin polymers—microtubules and helical filaments—in the foraminiferan,Allogromia laticollaris". Cell Motility and the Cytoskeleton, **41**: pp. 107 (1998), doi:10.1002/(sici)1097-0169(1998)41:2⟨107::aid-cm2⟩3.0.co;2-b.

[133] A. Habura, L. Wegener, J. L. Travis, and S. S. Bowser, "Structural and Functional Implications of an Unusual Foraminiferal β-Tubulin". Molecular Biology and Evolution, **22**: pp. 2000 (2005), doi:10.1093/molbev/msi190.

[134] F. Matsumura and M. Hayashi, "Polymorphism of tubulin assembly In vitro formation of sheet, twisted ribbon and microtubule". Biochimica et Biophysica Acta, **453**: pp. 162 (1976), doi:10.1016/0005-2795(76)90260-9.

[135] P. Karecla, E. Hirst, and P. Bayley, "Polymorphism of tubulin assembly in vitro". Journal of Cell Science, **94**: pp. 479 (1989).

[136] F. Gaskin and Y. Kress, "Zinc ion-induced assembly of tubulin." The Journal of biological chemistry, **252**: pp. 6918 (1977).

[137] H. Larsson, M. Wallin, and A. Edström, "Induction of a sheet polymer of tubulin by Zn^{2+}". Experimental Cell Research, **100**: pp. 104 (1976), doi: 10.1016/0014-4827(76)90332-3.

[138] M. Wallin, H. Larsson, and A. Edström, "Tubulin sulfhydryl groups and polymerization in vitro". Experimental Cell Research, **107**: pp. 219 (1977), doi:10.1016/0014-4827(77)90403-7.

[139] T. Baker and L. Amos, "Structure of the tubulin dimer in zinc-induced sheets". Journal of Molecular Biology, **123**: pp. 89 (1978), doi:10.1016/0022-2836(78)90378-9.

[140] E. Mandelkow, R. Schultheiss, and E.-M. Mandelkow, "Assembly and three-dimensional image reconstruction of tubulin hoops". Journal of Molecular Biology, **177**: pp. 507 (1984), doi:10.1016/0022-2836(84)90297-3.

[141] K. J. Böhm, W. Vater, P. Steinmetzer, and E. Unger, "Structural dynamics within mixed populations of microtubules and protofilament ribbons". Biochimica et Biophysica Acta (BBA) - Molecular Cell Research, **929**: pp. 154 (1987), doi:10.1016/0167-4889(87)90171-6.

[142] R. Dallai, P. Lupetti, G. Osella, and B. A. Afzelius, "Giant sperm cells with accessory macrotubules in a neuropteran insect". Tissue and Cell, **37**: pp. 359 (2005), doi:10.1016/j.tice.2005.05.002.

[143] T. Fischer, "Bending stiffness of lipid bilayers. I. Bilayer couple or single-layer bending?" Biophysical Journal, **63**: pp. 1328 (1992), doi:10.1016/s0006-3495(92)81710-1.

[144] V. Kralj-Iglic, A. Iglic, G. Gomiscek, F. Sevsek, V. Arrigler, and H. Hägerstrand, "Microtubes and nanotubes of a phospholipid bilayer membrane". Journal of Physics A: Mathematical and General, **35**: pp. 1533 (2002), doi:10.1088/0305-4470/35/7/305.

[145] L. Giomi, "Polymorphism in tubulin assemblies: a continuum mechanics approach" (2009). Unpublished notes.

[146] Y. Malitsky and K. Mishchenko, "Adaptive Gradient Descent without Descent". In H. D. III and A. Singh (editors), *Proceedings of the 37th International Conference on Machine Learning*, *Proceedings of Machine Learning Research*, volume 119, pp. 6702–6712, PMLR (2020).

[147] Q. Guo, A. K. Mehta, M. A. Grover, W. Chen, D. G. Lynn, and Z. Chen, "Shape selection and multi-stability in helical ribbons". Applied Physics Letters, **104**: p. 211901 (2014), doi:10.1063/1.4878941.

[148] E. Sharon and E. Efrati, "The mechanics of non-Euclidean plates". Soft Matter, **6**: pp. 5693 (2010), doi:10.1039/C0SM00479K.

[149] R. Osserman, "The isoperimetric inequality". Bulletin of the American Mathematical Society, **84**: pp. 1182 (1978), doi:bams/1183541466.

[150] E. Kebadze, S. Guest, and S. Pellegrino, "Bistable prestressed shell structures". International Journal of Solids and Structures, **41**: pp. 2801 (2004), doi:10.1016/j.ijsolstr.2004.01.028.

[151] K. Hu, D. S. Roos, and J. M. Murray, “A novel polymer of tubulin forms the conoid of Toxoplasma gondii”. Journal of Cell Biology, **156**: pp. 1039 (2002), doi:10.1083/jcb.200112086.

[152] S. Zwaan, *Polymorphism in Tubulin*. MSc thesis. Lorentz Institute, Leiden University (2020).

[153] “Surface˙energy˙minimizer.py”. On: `https://bit.ly/3dVSW2F` (2020). Accessed: 2021-10-20.

[154] P. Ramachandran and G. Varoquaux, “Mayavi: 3D Visualization of Scientific Data”. Computing in Science & Engineering, **13**: pp. 40 (2011).

List of Publications

- **Ireth García-Aguilar**, Piermarco Fonda, Luca Giomi. "Dislocation screening in crystals with spherical topology". *Physical Review E*, 101(6), **2020**.

  (Chapter 3).

- **Ireth García-Aguilar**, Piermarco Fonda, Eli Sloutskin, Luca Giomi. "Faceting and flattening of emulsion droplets: A mechanical model". *Physical Review Letters*, 126(3), **2021**.
  Editor's suggestion. Also featured in Physics Magazine and highlighted in Leiden University News.

  (Chapter 4).

- **Ireth García-Aguilar**, Ayelet Atkins, Piermarco Fonda, Eli Sloutskin, Luca Giomi. "García-Aguilar *et al.* Reply:". *Physical Review Letters*, 126(25), **2021**.

  (Chapter 4).

- **Ireth García-Aguilar**, Steven Zwaan, Luca Giomi. "Polymorphism in tubulin assemblies: A mechanical model". *submitted to Soft Matter*, **2022**.

  (Chapter 5).