

Selected Publications of Frank Wilczek, with Brief Commentary

The full bibliography has grown by accretion. It contains quite a bit of secondary material (that is, conference proceedings, reviews, and so forth) and lacks cohesive organization. The following version is less complete, but better organized. It also contains considerable explanatory material. For most purposes, it should be more useful. To preserve sanity, the numbering of items is the same as in the complete bibliography. Quite a few papers straddle the boundary between categories, but I always chose a unique classification.

Nobel Lecture and Biography

In 2004 I shared the physics Nobel Prize “for the discovery of asymptotic freedom in the theory of the strong interaction”. Laureates are asked to prepare a public scientific lecture for delivery in Stockholm, and later to supply a brief biography to be published along with it. I took the opportunity to talk about the wide-ranging scientific impact of our work, which extends far beyond the profound but esoteric paradoxes that provoked it. In preparing the biography, I reflected on my great good fortune in having supportive people and institutions.

- 373 Asymptotic Freedom: From Paradox to Paradigm *Les Prix Nobel* 100-124 (Almqvist & Wiesell International, Stockholm) (2004)
- 373a Photograph *ibid*, 96
- 373b Biography *ibid*, 97-99

QCD: Foundational Papers

In the first three papers listed below, Gross and I did several things. We discovered the central dynamical feature unique to non-abelian gauge theories, that their effective strength diminishes to zero at short distances or high energy due to quantum antiscreening of charge (asymptotic freedom). We explored many examples, including some with scalar fields and some with non-trivial weak-coupling infrared fixed points. We proposed one such gauge theory, now known as

quantum chromodynamics (QCD), as the fundamental theory of the strong interaction. And we proposed specific experimental tests of our ideas. In the fourth paper some technical objections to the theory were cleared up, and in the fifth and sixth papers further experimental consequences, regarding the pointwise evolution of structure functions, were derived. The most dramatic of these, that protons viewed at ever higher resolution would appear more and more as field energy (soft glue), was only clearly verified at HERA twenty years later. Item 68, an early review, was among the first to discuss QCD as an established theory.

- 1. Ultraviolet Behavior of Non-Abelian Gauge Theories (with D. Gross), Phys. Rev. Lett. 30, 1343 (1973).
- 2. Asymptotically Free Gauge Theories, I (with D. Gross), Phys. Rev. D8, 3633 (1973).
- 3. Asymptotically Free Gauge Theories, II (with D. Gross), Phys. Rev. D9, 980 (1974).
- 4. Gauge Dependence of Renormalization Group Parameters (with W. Caswell), Phys. Lett. B49, 291 (1974).
- 5. Possible Non-Regge Behavior of Electroproduction Structure Functions (with A. DeRujula, S.L. Glashow, H.D. Politzer, S.B. Treiman and A. Zee), Phys. Rev. D10, 1649 (1974).
- 6. Scaling Deviations for Neutrino Reactions in Asymptotically Free Field Theories (with S. Treiman and A. Zee) Phys. Rev. D10, 2881 (1974).
- 68. QCD - The Modern Theory of Strong Interactions, Ann. Rev. Nucl. Sci. V32, 177 (1982).

QCD: Reflections

Item 235 was my lecture on receipt of UNESCO's Dirac Medal. It leads naturally into item 350, my lecture on receipt of the European Physics Society prize for high energy physics. The first of these is more concerned with putting the early concepts in perspective, while the second emphasizes how they've evolved, and points to the future. Items 282 and 332 are perspectives on the broadest implications of QCD. Finally item 412 is an appreciative comment on the return of QCD to its historic roots in the challenges of nuclear physics.

- 235. Asymptotic Freedom, Lecture on receipt of the Dirac Medal, October 1994, published by ICTP, Trieste, Italy. hep-th/9609099 [96-95]
- 282 What QCD Tells Us About Nature - and Why We Should Listen *Nucl. Phys.* **A663-4**, 3c-20c (2000).
- 298 QCD Made Simple *Physics Today*, **53N8** 22-28 (2000).
- 332 QCD and Natural Philosophy *Annales Henri Poincare* **4** S211-S228 (2003).
- 350 From Concept to Reality to Vision *Eur. Phys. J.* **C33** S38-S42 (2004).
- 412 Hard-Core Revelations *Nature* **445** 156 (2007).

QCD: High Temperature

Item 91 is foundational. In it, Pisarski and I applied the renormalization group to the QCD chiral transition. We argued that for three massless flavors it could not be a second-order transition, while for two massless flavors it might be second-order in the $O(4)$ universality class, and in reality a crossover. This seems to be borne out by numerical simulation work, as explained in item 407. In Items 181 and 186 the full machinery of the renormalization group was brought to bear on this problem, and a host of universal predictions are made, including the existence and properties of a tricritical point as both temperature and strange quark mass are varied. Some of these have been crudely tested already. I anticipate that in future work many more will be. In Item 189 Rajagopal and I demonstrated a mechanism whereby the return to equilibrium after a quench following chiral symmetry restoration can be accompanied by dramatic non-thermal radiation. This suggestion stimulated a lot of activity, both theoretical and experimental. Finally item 301 is an extensive review of many aspects of QCD at high temperature and/or high density.

- 91. Remarks on the Chiral Phase Transition in Chromodynamics (with R. Pisarski), *Phys. Rev. D* **29**, 338 (1984).
- 181. Application of the Renormalization Group to a Second Order QCD Phase Transition, *Int. Jour. Mod. Phys. A* **7**, 3911 (1992). [91/65]
- 186. Static and Dynamic Critical Phenomena at a Second Order QCD Phase Transition (with K. Rajagopal) *Nucl. Phys. B* **399** (1993) 395. hep-ph/9210253 [92/60]

- 189. Emergence of Coherent Long Wavelength Oscillations After a Quench: Application to QCD, (with K. Rajagopal), Nucl. Phys. B404 (1993) 577. hep-ph/9303281 [93/16]
- 301. The Condensed Matter Physics of QCD (with K. Rajagopal) *Handbook of QCD* ed. M. Shifman 2016-2151 (World Scientific, 2001).
- 407. Did the Big Bang Boil? *Nature* **443** 636 (2006).

QCD: High Density

This is a cluster of papers wherein the methods of superconductivity theory are applied to QCD at high density. Item 261 is foundational. In it, we showed that for three degenerate flavors there is a beautiful preferred pattern of pairing, that opens a gap in all colored channels, modifies the photon in such a way that all elementary excitations have integer charge, and breaks chiral symmetry by a new mechanism. All this happens at weak coupling, in a tractable, controlled theoretical framework. In Item 271 we made the case that there need be no phase transition between this color-flavor locked phase and 3-flavor nuclear matter, and in Item 276 we made went deeper into the analytic theory, and also considered more flavors. Item 298 is an enthusiastic brief review. Item 310 describes the interesting, thin but highly structured wall that will separate normal nuclear matter from the much denser CFL phase in neutron stars, if no other phases intervene.

- 248. QCD at Finite Baryon Density: Nucleon Droplets and Color Superconductivity (with M. Alford and K. Rajagopal), Phys. Lett. B 422, 247-256, (1998). hep-ph/9711395 [97/119]
- 261. Color-Flavor Locking and Chiral Symmetry Breaking in High Density QCD, (with M. Alford and K. Rajagopal), Nucl. Phys. B537, 443-458, (1999). hep-ph/9804403 [98-29]
- 266. Imaginary Chemical Potential and Finite Fermion Density on the Lattice (with M. Alford and A. Kapustin), Phys. Rev. D59, 054502, (1999). hep-lat/9807039 [98-67]
- 270. High Density Quark Matter and the Renormalization Group in QCD with two and three flavors (with T. Schäfer), Phys. Lett. B450, 325-331, (1999). hep-ph/9810509 [98-90]
- 271. Continuity of Quark and Hadron Matter, (with T. Schäfer), *Phys. Rev. Lett.* **82** 3956-3959 (1999).
- 276. Quark Description of Hadronic Phases (with T. Schäfer), *Phys. Rev.* **D60** 074012 (1999).

- 280. Superconductivity from Perturbative One-Gluon Exchange in High Density Quark Matter (with T. Schäfer) *Phys. Rev.* **D60** 1140331-1140337 (1999).
- 283. The Recent Excitement in High-Density QCD *Nucl. Phys.* **A663-4** 257c-271c (2000).
- 302. Enforced Neutrality of the Color-Flavor Locked Phase (with K. Rajagopal) *Phys. Rev. Lett.* **86** 3492-3495 (2001).
- 310. The Minimal CFL-Nuclear Interface (with M. Alford, K. Rajagopal, and S. Reddy) *Phys. Rev.* **D64** 074017 (2001).

QCD: Diquarks

The attractive force between quarks plays a central role in the theory of QCD at high density. We have good control of it at ultrashort distances, thanks to asymptotic freedom. At larger distances a more phenomenological approach is called for. I've had some fun dirtying my hands with this. In Item 425, I made a case for a very specific exotic (tetraquark) hadron. The jury is still out.

- 294. Backyard Exotica *Nature* **404** 452-453 (2000).
- 358. Quarks, Diquarks, and Pentaquarks (with R. Jaffe) *Physics World* **17** 25-30 (2004).
- 363. Diquarks as Inspiration and as Objects *From Fields to Strings: Kogan Memorial* v. 1 ed. M. Shifman 77-93 (World Scientific, 2004).
- 397. Hadron Systematics and Emergent Diquarks (with A. Selem) *Ringberg 2005* ed. Grindhammer, Kniehl, Kramer, and Ochs 337-356 (2006).
- 425. QCD Meets BCS Meets $Q\bar{Q}$, *QCD Down Under 2* [MIT-CTP 3945] (January 2008).

Heavy Quarks

These papers were all inspired, in one way or another, by the experimental discovery of the J/ψ family of particles, which were beautifully adapted to serve as a demonstration system for the newly emerging Standard Model. Items 36 and 37 contain especially original uses of QCD. They have been both developed and “rediscovered” in subsequent literature.

- 11. Remarks on the New Resonances at 3.1GeV and 3.7GeV (with C.G. Callan, R.L. Kingsley, S.B. Treiman and A. Zee), Phys. Rev. Lett. 34, 52 (1975).
- 12. Weak Decays of Charmed Hadrons (with R.L. Kingsley, S.B. Treiman and A. Zee), Phys. Rev. D11, 1919 (1975).
- 13. Weak Decays of Charmed Hadrons, II: Soft Meson Theorems (with R.L. Kingsley, S. Treiman and A. Zee), Phys. Rev. D12, 106 (1975).
- 32. Instantons and Spin Forces Between Massive Quarks (with A. Zee), Phys. Rev. Lett. 40, 83 (1977).
- 36. Low Energy Manifestations of Heavy Particles: Application to Neutral Current (with J. Collins and A. Zee), Phys. Rev. D18, 242 (1978).
- 37. Effect of Instantons on the Heavy Quark Potential (with C. Callan, R. Dashen, D. Gross and A. Zee). Phys. Rev. D18, 4686 (1978).
- 43. SU(3) Predictions for Charmed Meson Decays (with S. Treiman), Phys. Rev. Lett. 43, 816 (1979).
- 44. Interference Effects in Charmed Meson Decays (with S. Treiman), Phys. Rev. Lett. 43, 1059 (1979).

Standard Model Phenomenology

Item 25 contains, I believe, the first discussion of kinetic neutrino mixing, and shows how it can arise in simple gauge theory models. Item 30 introduced the Higgs-gluon-gluon coupling, which plays a central role in the anticipated phenomenology of that particle.

- 25. Rare Muon Decays, Heavy Leptons and CP Violations (with S. Treiman and A. Zee), Phys. Rev. D16, 152 (1977).
- 29. Sum Rules for Spin-Dependent Electroproduction - Test of Relativistic Constituent Quarks (with S. Wandzura), Phys. Lett. B72, 195 (1977).
- 30. Decay of Heavy Vector Mesons into Higgs Particles, Phys. Rev. Lett. 39, 1304 (1977).

- 309. Observability of Earth-Skimming Ultra-High Energy Neutrinos (with J. Feng, P. Fisher, and T. Yu) *Phys. Rev.* **88** 161102 (2001).

Axions, Including Axion Cosmology

In Item 33 I introduced and named the axion. It also contains a discussion of the theoretical background and alternatives that holds up well today. Item 78 demonstrates the non-thermal production mechanism for axions during the Big Bang. This mechanism established axions as a plausible dark matter candidate. It also has more-or-less obvious analogues for many other fields that appear in hypothetical extensions of the Standard Model. Inflation opened up an alternative scenario for axion cosmology, with a potential signature in the form of isocurvature fluctuations.

- 33. Problems of Strong P and T Invariance in the Presence of Instantons, *Phys. Rev. Lett.* 40, 279 (1977).
- 78. Cosmology of Invisible Axions (with J. Preskill and M. Wise), *Phys. Lett. B* 120, 127 (1983).
- 79. Axions and Family Symmetry Breaking, *Phys. Rev. Lett.* 49, 1549 (1982).
- 88. Formation of Structure in an Axion-Dominated Universe (with M. Turner and A. Zee), *Phys. Lett. B* 125, 35, 519(E) (1983).
- 93. The U(1) Problem: Instanton, Axions, and Familons, in *How Far Are We from the Gauge Forces*, ed. A. Zichichi (Plenum, 1985).
- 110. Calculations for Cosmic Axion Detection (with L. Krauss, J. Moody and D. Morris), *Phys. Rev. Lett.* 55, 1797 (1985).
- 159. Inflationary Axion Cosmology (with M.S. Turner), *Phys. Rev. Lett.* 66, 5 (1991).
- 361. A Model of Anthropic Reasoning, Addressing the Dark to Ordinary Matter Coincidence. Solicited article for “Universe or Multiverse” ed. B. Carr (Cambridge University Press), based in part on talk given at the Anthropic Workskop, Jun 2001 (2004) hep-ph/0408167 [MIT-CTP-3526].
- 392. Dimensionless Constants, Cosmology and Other Dark Matters (with M. Tegmark, A. Aguirre, and M. Rees) *Phys. Rev.* **D73** 023505 (2006).

- 424. Axion Cosmology and the Energy Scale of Inflation, (with Mark Hertzberg and Max Tegmark) *Phys. Rev. D.* **78** 083507. astro-ph/0807.1726 [MIT-CTP3950] (2008).

Supersymmetric Phenomenology: Foundational Papers

Each of the first three papers in this cluster presents an idea that plays a continuing major part in assessing the possible role of supersymmetry in the description of Nature. In Item 56 we discussed how allowing for low-energy supersymmetry changes the analysis of coupling constant unification, raising the scale without grossly modifying the structure. In Item 58 we showed how supersymmetric models based on the group $SO(10)$ (or, of course, a larger group) contain a very natural mechanism for lifting the troublesome Higgs color triplet to very high mass, leaving the doublet behind. This is now known as the Dimopoulos-Wilczek mechanism. Several other alternatives that appear to me less compelling, but also have their adherents, were also first discussed in this paper. In Item 66 we introduced a discrete matter symmetry sufficient to banish catastrophic proton decay in supersymmetric models. It still appears as if this symmetry, or some closely related variant, is also necessary. Also in this paper we provided the foundational analysis of branching modes. Finally Item 172 is an attempt to portray the big picture, for a wide physics audience.

- 56. Supersymmetry and the Scale of Unification (with S. Dimopoulos and S. Raby), *Phys. Rev. D* **24**, 1681 (1981).
- 58. Supersymmetric Unified Models (with S. Dimopoulos), in *The Unity of the Fundamental Interactions*, ed. A. Zichichi (Plenum, New York, 1983).
- 66. Proton Decay in Supersymmetry Theories (with S. Dimopoulos and S. Raby), *Phys. Lett. B* **112**, 133 (1982).
- 172. Unification of Couplings, (with S. Dimopoulos and S. Raby), *Physics Today* **44**, October 1991, p.25. [91/63]

Supersymmetric Phenomenology: Special Topics

Items 253 and 269 continue the discussion of proton decay in unified models with low-energy supersymmetry. They were provoked by the SuperK observation of neutrino mass, which greatly

encourages this circle of ideas. We point out additional contributions to proton decay amplitudes which arise more-or-less directly from the interactions that generate neutrino mass, and try to provide serious quantitative estimates of the expected rates. Items 295 and 384 explore focus point supersymmetry, a promising proposal for the pattern of SUSY breaking, while item 299 is a broader discussion of the implications of low-energy supersymmetry for dark matter searches. Items 385 and 386 explore some novel possibilities for dynamical flavor symmetry breaking.

- 253. Suggested New Modes in Supersymmetric Proton Decay, (with K.S. Babu and J. Pati), *Phys. Lett. B* **423**, 337-347, (1998). hep-ph/9712307 [97/136]
- 269. Fermion masses, neutrino oscillations, and proton decay in the light of SuperKamiokande (with K.S. Babu and J. Pati) *Nucl. Phys.* **B566** 33-91(2000).
- 295. Neutralino Dark Matter in Focus Point Supersymmetry (with J. Feng and K. Matchev) *Phys. Lett.* **B482** 388-399 (2000).
- 299. Prospects for Indirect Detection of Neutralino Dark Matter (with J. Feng and K. Matchev) *Phys. Rev.* **D63** 4502-4505 (2001).
- 384. Advantages and Distinguishing Features of Focus Point Supersymmetry (with J. Feng) *Phys. Lett.* **B631** 170-176 (2005).
- 385 General Issues Connecting Flavor Symmetry and Supersymmetry (with E. Bilgin, B. Patt, and D. Tucker-Smith) *Phys. Lett.* **B634** 69-73 (2006).
- 386 Example of a Hidden Flavor Sector (with B. Patt and D. Tucker-Smith) hep-ph/0509295 (2005).

Other Beyond the Standard Model Phenomenology

Item 31 was a pioneering attempt to interpret regularities of quark mass matrices in terms of symmetry; item 269 is a later, more comprehensive foray. Item 45 was an early model for how to use effective field theory ideas to analyze possible deviations from the Standard Model in a systematic way. Item 55 was an early use of higher-dimensional spinor representations, when this was considered quite adventurous. The use of such spinors remains, in my opinion, a promising possible approach to the family problem. Item 92 was a pioneering discussion of the possibility of deviations from Newton's law at short distances, both from an experimental and from a theoretical

point of view. Especially original is the discussion of monopole-dipole forces, which I believe remains an important subject for experimental investigation. Items 106 and 109 present ideas for neutrino and dark matter detection, that have influenced experimental work. Item 286 was commissioned by the director of Brookhaven National Laboratory, Jack Marburger, in response to a kerfluffle in the press about possible exotic, catastrophic risks associated with the RHIC turn-on. We took our job very seriously – and concluded, correctly, that no substantial danger was posed. In item 354 I emphasized, I believe for the first time, the special sensitivity of the Higgs field, with its dimensional coupling, as a probe of hidden-sector dynamics. That “portal” idea, elaborated in item 401, has become quite influential. Item 419 is a grand overview of the state of my (widely shared) expectations, on the eve of LHC.

- 31. Discrete Flavor Symmetries and a Formula for the Cabibbo Angle (with A. Zee), *Phys. Lett.* **B70**, 418 (1977).
- 45. Operator Analysis of Nucleon Decay (with A. Zee), *Phys. Rev. Lett.* 43, 1571 (1979).
- 49. Symmetry Relations in Nucleon Decay (with Anya Hurlbert), *Phys. Lett.* B92, 95 (1980).
- 55. Families from Spinors (with A. Zee), *Phys. Rev.* D25, 553 (1982).
- 92. New Macroscopic Forces? (with J. E. Moody), *Phys. Rev.* D30, 130 (1984).
- 106. Bolometric Detection of Neutrinos (with B. Cabrera and L. Krauss), *Phys. Rev. Lett.* 55, 25 (1985).
- 107. Solar Neutrino Oscillations (with L. Krauss), *Phys. Rev. Lett.* 55, 122 (1985).
- 109. Solar System Constraints and Signatures for Dark Matter Candidates (with L. Krauss and M. Srednicki), *Phys. Rev.* D33, 2079 (1986).
- 286. Review of Speculative “Disaster Scenarios” at RHIC (with W. Busza, R. Jaffe, and J. Sandweiss) *Rev. Mod. Phys.* **72** 1125-1140 (2000).
- 354. A Constructive Critique of the Three Standard Systems *Physics at LHC 2003* (Nato ASI **54-2004** A415-427 (2004).
- 401. Higgs-field Portal into Hidden Sectors (with B. Patt) hep-ph/0605188 (2006).

- 419. Anticipating a New Golden Age, Invited Lecture at SUSY 07, Karlsruhe, *SUSY 07 Proceedings*, “Perspectives on LHC Physics” ed. G. Kane and A. Pierce (World Scientific, July 2008), *Int. J. Mod. Phys. A* **23** 1791-1811, *The European Physical Journal C*, **59** N2 185, hep-ph/07084236 (2007) [MIT-CTP 3858].
- 269. Fermion masses, neutrino oscillations, and proton decay in the light of SuperKamiokande (with K.S. Babu and J. Pati), *Nuclear Physics* **B 566** 33-91 (2000) hep-ph/9812538 [98-80].

Baryogenesis

These papers present pioneering discussions of how the phenomenon of baryon number violation, natural within unified gauge models, can lead and initially symmetric Universe to evolve an asymmetry between matter and antimatter, as observed. We discovered the main phenomena for ourselves, as presented in Item 39, but we were scooped by Yoshimura as we were developing them. Later we learned that they had been anticipated in a general way by Sakharov. Item 40 is a clean discussion of the minimal requirements. Item 50 was the first to address the problem that later interactions tend to restore equilibrium in a serious, quantitative fashion.

- 39. Matter-Antimatter Accounting, Thermodynamics, and Black Hole Radiation (with D. Toussaint, S. Treiman and A. Zee), *Phys. Rev. D* **19**, 1036 (1979).
- 40. Elementary Examples of Baryon Number Generation (with D. Toussaint), *Phys. Lett.* **B81**, 238 (1979).
- 50. Thermalization of Baryon Asymmetry (with S. Treiman), *Phys. Lett.* **B95**, 222 (1980).
- 52. Cosmic Asymmetry Between Matter and Antimatter, *Scientific American*, December 1980, p. 82.

Other Cosmology

The titles of most of the papers in this section give a pretty clear idea of their subject matter. Items 80-82 were talks at the famous Nuffield conference. Item 346 explores thermal, as opposed to quantum, transitions between “vacua” or black-hole states. Item 353 is a high-level discussion of

the interface between cosmology and high-energy physics, addressed to professionals. I liked the title so much that I took it over for a more popular talk (item 390) which, in evolved forms, I've given in dozens of places around the world over several years.

- 71. Reheating an Inflationary Universe (with A. Aubrecht, P. Steinhart and M. Turner) *Phys. Rev. Lett.* 48, 1437 (1982).
- 72. Might Our Vacuum be Metastable? (with M. Turner), *Nature* 298, 633 (1982).
- 74. Positivity Conditions on SU(5) Potentials (with R. MacKenzie), *Phys. Rev. D* 26, 3679 (1982).
- 80. Particle Physics and Cosmology: Foundation and Working Pictures, in *The Very Early Universe*, eds. Gibbons, Hawking, Siklos (Cambridge University Press, 1983).
- 81. Fun with Monopoles and Axions, in *The Very Early Universe*, eds. Gibbons, Hawking, Siklos (Cambridge University Press, 1983).
- 82. Conference Summary, in *The Very Early Universe*, eds. Gibbons, Hawking, Siklos (Cambridge University Press, 1983).
- 157. Positron Line Radiation as a Signature of Particle Dark Matter in the Halo (with M.S. Turner), *Phys. Rev. D* 42, 1001 (1990).
- 161 Relic Gravitational Waves and Extended Inflation (with M.S. Turner), *Phys. Rev. Lett.* 65, 3080 (1990).
- 163. Cosmological Implications of Axinos (with K. Rajagopal and M.S. Turner), *Nucl. Phys. B* 358, 447 (1991). [90/79]
- 165. Cosmology and Broken Discrete Symmetry (with S. Trivedi, J. Preskill and M.B. Wise), *Nucl. Phys. B* 363, 207 (1991). [91/11]
- 346. Thermal Decay of the Cosmological Constant Into Black Holes (with A. Gomberoff, M. Henneaux, and C. Teitelboim) *Phys. Rev. D* 69 083520 (2004).
- 353. The Universe is a Strange Place *Nucl. Phys. B Proc. Suppl.* 134 3-12 (2004).

Quantum Properties of Solitons

In Item 57 we generalized the halving of quantum numbers discovered abstractly by Jackiw and Rebbi, and in the context of polyacetylene by Su, Schrieffer, and Heeger, to a much wider class of field theories, featuring other fractions. The method used, tracing the flow of quantum numbers as one turns on some external field or control parameter, has been fruitfully applied to many other problems since. Several examples are presented in Items 97, 98, and 104. Item 102 is of some methodological interest; it identifies a limit in which heavy particles can be shown to spontaneously form semi-classical bags, substantially deforming the vacuum around themselves. Several of the other papers here are devoted to analysis of exotic dynamics around non-abelian strings. Especially interesting I think is Item 147, where the concept of (delocalized) Cheshire charge was first introduced. Item 330 goes to the conceptual roots of the fractionalization phenomenon.

- 57. Fractional Charge on Solitons (with J. Goldstone), Phys. Rev. Lett. 47, 986 (1981).
- 97. Illustrations of Vacuum Polarization by Solitons (with R. MacKenzie), Phys. Rev. D30, 2194 (1984).
- 98. Examples of Vacuum Polarization by Solitons (with R. MacKenzie), Phys. Rev. D30, 2260 (1984).
- 102. Possible Form of Vacuum Deformation by Heavy Particles (with R. MacKenzie and A. Zee), Phys. Rev. Lett. 53, 2203 (1983).
- 104. Adiabatic Methods in Field Theory, in TASI Lectures in Elementary Particle Physics, ed. Williams (TASI Publications, Ann Arbor, MI, 1984).
- 135. Aharonov-Bohm Interaction of Cosmic Strings with Matter (with M. G. Alford), Phys. Rev. Lett. 62, 1071 (1989).
- 141. Enhanced Baryon Number Violation Around Cosmic Strings (with M. Alford and J. March-Russell), Nucl. Phys. B328, 140 (1989).
- 147. The Interactions and Excitations of Nonabelian Vortices (with M. Alford, K. Benson, S. Coleman and J. March-Russell), Phys. Rev. Lett. 64, 1632 (1990). [89/69]
- 150. Zero Modes of Non-Abelian Vortices (with M. Alford K. Benson, S. Coleman, and J. March-Russell), Nucl. Phys. B349, 414 (1991).
- 178. Internal Frame Dragging and a Global Analogue of the Aharonov-Bohm Effect (with J. March-Russell and J. Preskill), Phys. Rev. Lett. 68, 2567 (1992). hep-th/9112054 [91/92]

- 330. Some Basic Aspects of Fractional Charge *Selected Papers of J. Robert Schrieffer* ed. N. Bonesteel, L Gor'kov 135-152 (World Scientific, 2002).

Statistical Transmutation, Anyons, and Chern-Simons Theory

In this cluster of papers the possibility of fractional statistics for two-dimensional particles was introduced and extensively analyzed. Some earlier work on this subject had been done by Leinaas and Myrheim, and roughly contemporary independent work on the foundations was done by Goldin, Menikoff, and Sharp. I discovered the possibility of fractional statistics for myself, and put it in the context of gauge theories, in the first three items listed below. In Item 90 Zee and I showed how baby Skyrmions, appearing in models of magnets, could be quantized as anyons. The Chern-Simons construction of statistical transmutation is implicit in that paper, made more explicit (and used!) in Item 94, and spelled out so even the blind can see it in Item 129. Item 94 also contains a calculation of the virial coefficient for the ideal anyon gas; this was perhaps the first physical consequence of anyon statistics to be cleanly identified. Item 131 contains a pioneering use of concepts that later became extremely popular, both in condensed matter and high energy theory, using duality transformations to identify theories with apparently quite different coupling constants. After an injection of ideas from Laughlin, the analysis of many-body problems using statistical transmutation became quite sophisticated; this is reflected in the papers Items 142, 143, 154, and the book Item 155. (See also the following group of papers.) Extremely interesting possibilities, as yet insufficiently explored, arise in theories with several Chern-Simons fields, particularly when several distinct two-dimensional planes are involved. Item 241 introduces an essentially new phenomenon in this context, providing limp models that exhibit confinement of discrete quantum numbers. Item 244 is, I think, a “sleeper”. It demonstrates an unusual mechanism whereby symmetry can be hidden. Item 263 proposes another sort of unusual quantum statistics, based on projective representations of the symmetric group, that can work in any dimension. It was later found to be embodied, with some refinements, in the “projective ribbon statistics” of Freedman, Hastings, Nayak et al.

- 64. Magnetic Flux, Angular Momentum, and Statistics, *Phys. Rev. Lett.* 48, 1144 (1982).
- 65. Remarks on Dyons, *Phys. Rev. Lett.* 48, 1146 (1982).
- 76. Quantum Mechanics of Fractional Spin Particles, *Phys. Rev. Lett.* 49, 957 (1982).

- 90. Linking Numbers, Spin, and Statistics of Solitons (with A. Zee), *Phys. Rev. Lett.* 51, 2250 (1983).
- 94. Statistical Mechanics of Anyons (with D. Arovas, J.R. Schrieffer and A. Zee), *Nucl. Phys.* B251, [FS13], 917 (1985).
- 129. Peculiar Spin and Statistics in 2+1 Dimensions (with R. MacKenzie), *Int. J. Mod. Phys.* A3, 2827 (1988).
- 131. Self-Dual Models with θ Terms (with A. Shapere), *Nucl. Phys.* B320, 669 (1989).
- 132. Field Corrections to Induced Statistics (with A. Goldhaber, R. MacKenzie), *Mod. Phys. Lett.* A4, 21 (1989).
- 142. On Anyon Superconductivity, (with Y-H. Chen, E. Witten and B. Halperin), *Intl. Jour. Mod. Phys.* B3, 1001 (1989).
- 149. Space-Time Approach to Holonomy Scattering (with Y.-S. Wu), *Phys. Rev. Lett.* 65, 13 (1990). [90/2]
- 154. States of Anyon Matter, *Intl. Jour. of Mod. Phys.* B5, 1273 (1991). [90/29]
- 155. Fractional Statistics and Anyon Superconductivity, a monograph and reprint collection, World Scientific (September, 1990).
- 176. Disassembling Anyons, *Phys. Rev. Lett.* 69, 132 (1992). [91/70]
- 241. Cross-Confinement in Multi-Chern-Simons Theories (with Lorenzo Cornalba), *Phys. Rev. Lett.* 78, 4679, (1997). hep-th/9703131 [97/22]
- 244. Mass Splittings from Symmetry Obstruction (with L. Cornalba), *Phys. Lett.* **B 411**, 112-116, (1997). hep-th/9706014 [97-48]
- 263. Projective Statistics and Spinors in Hilbert Space, hep-th/9806228 [98-61]
- 394. From Electronics to Anyonics *Physics World* **19** 22 (2006).

Quantum Hall States

In this group of papers I applied the ideas of Chern-Simons theory and statistical transmutation more specifically to the quantum Hall effect. Item 100 started the whole subject. Items 153,

171, and 218 are applications of the general philosophy mentioned in the previous Section to the quantum Hall effect context. In Items 229 and 241 partially elucidate the new, nonabelian statistics that arises for the paired Hall (or Pfaffian) state. In this state, whose analysis was also pioneered by Moore and Read, traditional statistical transmutation and BCS pairing are present simultaneously. I am told it is the leading candidate to describe the observed incompressible state at $\nu = 5/2$.

- 100. Fractional Statistics and the Quantum Hall Effect (with D. Arovas and J.R. Schrieffer), Phys. Rev. Lett. 53, 722 (1984).
- 153. Heuristic Principle for Quantized Hall States (with M. Greiter), Mod. Phys. Lett. B4, 1063 (1990). [90/35]
- 167. Paired Hall State at Half Filling (with M. Greiter and X.G. Wen), Phys. Rev. Lett. 66, 3205 (1991) [91/18].
- 171. Exact solutions and the adiabatic heuristic for quantum Hall states (with M. Greiter), Nucl. Phys. B370, 577 (1992). [91/45]
- 174. Paired Hall States (with M. Greiter and X.G. Wen), Nucl. Phys. B374, 567 (1992). [91/66]
- 180. Paired Hall States in Double Layer Electron Systems (with M. Greiter and X.G. Wen), Phys. Rev. B46, 9586, (1992). [92/1],
- 197. Non-Fermi Liquid Fixed Point in 2+1 Dimensions, (with Chetan Nayak), Nucl. Phys. B417, (1994) 359. cond-mat/9312086 [93/89]
- 199. Exclusion Statistics: Low Temperature Properties, Fluctuations, Duality, Applications, (with C. Nayak), Phys. Rev. Lett. 73, (1994) 2740. cond-mat/9405017 [94/25]
- 210. Quantum Hall States of High Symmetry (with C. Nayak), Nucl. Phys. B 450, 558, (1995). cond-mat/9501052 [94/109]
- 218. Spin-Singlet to Spin Polarized Phase Transition at $\nu = 2/3$: Flux-Trading in Action (with C. Nayak), Nucl. Phys. B 455, 493, (1995). cond-mat/9507016 [95/59]
- 222. Quantum Numbers of Textured Hall Effect Quasiparticles (with C. Nayak), Phys. Rev. Lett. 77, 4418, (1996). cond-mat/9512061 [95/104]

- 229. $2n$ Quasihole States Realize 2^{n-1} -Dimensional Spinor Braiding Statistics in Paired Quantum Hall States (with Chetan Nayak), Nucl. Phys. B 479, 529, (1996). condmat/9605145 [96/52]
- 249. A Chern-Simons Effective Field Theory for the Pfaffian Quantum Hall State (with E. Fradkin, C. Nayak, and A. Tsvetlik), Nucl. Phys. B 516, 704-718 (1998). condmat/9711087 [97-120]

Models of Condensed Matter

This somewhat disparate group of papers contains my additional work in condensed matter theory, that does not fall comfortably into the earlier categories. I am especially proud of Items 95 and 122. Item 95 anticipates the concept of domain wall fermions, which has since become quite popular in high energy theory, in a concrete condensed matter context. Item 122 proposes and derives major consequences of a universality class motivated by analogy and mathematical esthetics, that subsequently proved to provide, in essence, the effective theory of topological insulators. Item 136 describes a possible subtle new form of spin ordering, that exhibits a gap but no easily accessible order parameter, and supports exotic quasiparticle excitations. One co-author (Wen) went on to generalize this idea under the rubric “topological order”, which has grown into a cottage industry. Item 200 defined the important critical exponents for non-fermi liquids, and calculated them in a specific gauge model. It was an honor to be asked to write item 444, for the major book celebrating 50 years of BCS theory. In it, I show how the theme of symmetry transmutation through locking is a major thread connecting charge re-quantization, emergent anyons, quark-hadron continuity, and more.

- 95. Solitons in Superfluid $^3\text{He-A}$: Bound States on Domain Walls (with J. L. Ho, J. R. Fulco and J. R. Schrieffer), Phys. Rev. Lett. 52, 1524 (1984).
- 122. Two Applications of Axion Electrodynamics, Phys. Rev. Lett. 58, 1799 (1987).
- 136. Chiral Spin States and Superconductivity (with X.G. Wen, A. Zee), Phys. Rev. B39, 11413 (1989).
- 143. Hydrodynamic Relations in Superconductivity, (with M. Greiter and E. Witten), Mod. Phys. Lett. B3, 903 (1989).

- 200. Renormalization Group Approach to Low Temperature Properties of a Non-Fermi Liquid Metal, (with C. Nayak), *Nucl. Phys.* **B 430**, (1994) 534. cond-mat/9408016 [94/59]
- 209. Space-Time Aspects of Quasiparticle Propagation (with R. Levien and C. Nayak) *Int. J. of Mod. Phys. B* 9, 3189, (1995). cond-mat/9501050 [94/108]
- 211. Physical Properties of Metals from a Renormalization Group Standpoint (with C. Nayak), *International Jour. of Mod. Phys.* **B 10**, 847, (1996). cond-mat/9507040 [94/60]
- 225. Possible Electronic Structure of Domain Walls in Mott Insulators (with C. Nayak), *Int. J. Mod. Phys. B* 10, 2125, (1996). cond-mat/9602112 [95/111]
- 233. Populated Domain Walls (with C. Nayak), *Phys. Rev. Lett.*, 78 , 2465, (1997). cond-mat/9609094 [96/93]
- 348. Spin Dependent Hubbard Model and a Quantum Phase Transition in Cold Atoms (with W. V. Liu and P. Zoller) *Phys. Rev.* **A70** 033603 (2004).
- 421. Near-Zero Modes in Superconducting Graphene (with Pouyan Ghaemi) (August, 2007) cond.-mat:supr-con/0709.2626 v2 (September 2011) *Phys. Scr.* **T146** 014019 (January 2012) [MIT-CTP 3864].
- 444. BCS as Foundation and Inspiration: The Transmutation of Symmetry, *Mod. Phys. Lett. A* **Vol. 25, No. 38** (2010) pp. 3169-3189. (August 2010) cond-mat.supr.con 1008.1741

Time Crystals and Branched Quantization *Items 449 and 450 explore the question whether time-translation symmetry might be spontaneously broken, in classical and quantum theory respectively. Apparent difficulties confronting that idea are enumerated, then overcome. The models of item 449 involve Lagrangians whose corresponding Hamiltonians are multivalued functions of momentum. It is not entirely obvious how to quantize such Hamiltonians, but a consistent, well-motivated procedure is proposed in item 457. In some cases, an amendment to the Heisenberg commutation relations is required. It is also demonstrated, in item 457, that the sorts of models studied in 449 can arise naturally from conventional, widely used quantum field theories.*

- 449. Classical Time Crystals (with A. Shapere) cond-mat.other 1202.2537 v 2 *Phys. Rev. Lett.* **109** (2012) 160402 (February 2012) [MIT-CTP 4347].

- 450. Quantum Time Crystals quant-ph 1202.2539 v 2, *Phys Rev. Lett.* **109** (2012) 160401 (February 2012) MIT-CTP [4348].
- 457. Branched Quantization (with A. Shapere) (June 2012), quant-ph 1207.2677 [MIT-CTP 4381].

Quantum Mechanics and Topology Change

Item 462 shows how quantum theories may be continuously deformed, in such a way that they start as models based on one space and end up as models on a topologically distinct space.

- 462. Models of Topology Change (with Alfred Shapere and Zhaoxi Xiong) hep-th 1210.3545, [MIT-CTP 4397] (October 2012)

Mathematics of Gauge Theory

On a few occasions I have published exploratory mathematical ideas that seemed to me especially pretty or naturally connected to physics, without any immediate sense of how they might be applied. Item 26 presented an ansatz for instanton solutions, which in a generalized form became quite influential. Item 137 is foundational. Item 254 is a heterodox but I think extremely intriguing approach to construction of gravity as a gauge theory. One aspect of this, which requires less radical departures than the full program, is a connection between the meaning of the cosmological term (initial value versus microscopically determinate) and the question whether one should require invariance under volume-changing transformations.

- 18. Non-Uniqueness of Gauge Field Potentials (with S. Deser), *Phys. Lett.* **65B**, 391 (1976).
- 19. Inequivalent Embeddings of SU(2) and Instanton Interactions, *Phys. Lett.* **65B**, 160 (1976).
- 26. Geometry and Interaction of Instantons, Quark Confinement and Field Theory: Proceedings of a Conference at the University of Rochester, Rochester, NY, June 14-18, 1976, Stump and Weingarten, eds. (Wiley-Interscience, NY, 1977), pp. 211-219.

- 137. Discrete Gauge Symmetry in Continuum Theories (with L.M. Krauss), Phys. Rev. Lett. 62, 1221 (1989).
- 151. Infrared Behavior at Negative Curvature (with C. Callan), Nucl. Phys. B340, 366 (1990). [90/4]
- 244. Mass Splittings from Symmetry Obstruction (with L. Cornalba), Phys. Lett. B 411, 112-116, (1997). hep-th/9706014 [97-48]
- 245. Some Examples in the Realization of Symmetry, Nucl. Phys. B 68 (Proc. Suppl.), 367, (1998). hep-th/9710135 [97/116]
- 254. Riemann-Einstein Structure from Volume and Gauge Symmetry, Phys. Rev. Lett., 80, 4851, (1998). hep-th/9801184 [97-142]

Geometric Phase in Dynamics

In Item 99, Zee and I showed how one could extend Berry's celebrated phase to a nonabelian setting. Item 112 presents a simple, natural example. Items 120, 123, 124, and 128 demonstrate the use of gauge theory concepts to describe two problems in the mechanics of deformable bodies: self-orientation (say of divers or falling cats) at zero angular momentum, and self-propulsion (say of bacteria) at low Reynolds number. Item 130 has become the standard reference on its subject matter. In the technical part of item 453 I returned to the analysis of level crossings in the presence of symmetry, and found some beautiful universal structure.

- 99. Appearance of Gauge Structures in Simple Dynamical Systems (with A. Zee), Phys. Rev. Lett. 52, 2111 (1984).
- 112. Simple Realizations of Magnetic Monopole Gauge Fields: Diatoms and Spin Precession (with J. Moody and A. Shapere), Phys. Rev. Lett. 56, 893 (1986).
- 120. Geometry of Self Propulsion at Low Reynolds Number (with A. Shapere), Jour. Fluid Mech. 198, 557 (1989).
- 124. Self-Propulsion at Low Reynolds Number (with A. Shapere), Phys. Rev. Lett. 58, 2051 (1987).

- 128. Gauge Kinematics of Deformable Bodies (with A. Shapere), *Am. J. Phys.* **57**, 514 (1989).
- 130. Geometric Phases in Physics (a text and reprint volume, edited with A. Shapere) (World Scientific, 1989).
- 453. Introduction to *Quantum Matter* Nobel Symposium 148: Graphene and Quantum Matter, eds. A Niemi, F. Wilczek, E. Ardonne, H. Hansson, <http://iopscience.iop.org/1402-4896/2012/T146/010101> (2012).

Entanglement (Geometric) Entropy

Item 194 defined the entanglement (originally “geometric”) entropy in quantum field theory, and computed for an interval in 1+1 dimensional conformal field theory. Interest in entanglement entropy has swelled over the years, due to its connections with quantum information theory, the characterization of quantum critical points, and (through holography) to quantum gravity. The specific result in 194 – logarithmic length dependence proportional to the central charge – has become a touchstone within what has become a substantial and growing literature. Item 196 exemplified use of the replica trick, which remains a basic technique. Item 204 spelled out some subtleties that arise for fermion fields, and gave a vastly simplified derivation for free massless fields. Item 440 identified and calculated some new universal coefficients for massive fields.

- 194. Geometric and Renormalized Entropy in Conformal Field Theory, (with C. Holzhey and F. Larsen), *Nucl. Phys.* **B 424** (1994) 443. hep-th/9403108 [93/88]
- 198. On Geometric Entropy, (with Curtis Callan), *Phys. Lett.* **B333**, (1994) 55-61. hep-th/9401072 [93/87]
- 204. Geometric Entropy, Wave Functionals, and Fermions (with F. Larsen), *Annals of Physics*, **243**, 280, (1995). hep-th/9408089 [94/51]
- 440. Some Calculable Contributions to Entanglement Entropy, (with M. Hertzberg), (July 2010) hep-th/1007.0993 *Phys. Rev. Lett.* **106** (2011) 050404 [MIT-CTP 4110].

Black Holes

This is a cluster of papers concerned with the quantum theory of black holes. Items 146, 166, and 168 demonstrate the existence of quantum hair observables of stationary black holes that are invisible classically, and violate the classical no hair theorems. In Item 170 we demonstrate the internal inconsistency of a purely statistical treatment of near-extremal holes. In Item 177 Holzhey and I discussed a class of dilaton black holes that behave much like elementary particles; it later developed, that in certain cases these solutions in fact do correspond to elementary objects in string theory. In Items 203 and 205 we show, by tough concrete calculations, how the worst aspects of the inconsistency can be relieved by enforcing full energy conservation (including gravitational self-energy). In item 285 we give some substance to the old heuristic idea that Hawking radiation can be regarded as spontaneous pair creation by a gravitational field. A line element that is regular through the horizon and particular well adapted to such calculations, and has other features of interest, was introduced in Item 202 (the mathematics, though not the quantum physics, of this line element has a prehistory). In item 372 Robinson and I found a nice connection between Hawking radiation and gravitational anomalies: the radiation cancels the anomaly in the effective theory of the black hole exterior. In items 395 and 399 the analysis was successfully extended to charged and rotating black holes.

- 146. Discrete Quantum Hair on Black Holes and the Nonabelian Aharonov-Bohm Effect, (with M. Alford and J. March-Russell), Nucl. Phys. B337, 695 (1990).
- 166. Dynamical Effect of Quantum Hair (with S. Coleman and J. Preskill), Intl. Jour. Mod. Phys. Lett. A6, 1631 (1991). [91/17]
- 168. Growing Hair on Black Holes (with J. Preskill and S. Coleman), Phys. Rev. Lett. 67, 1975 (1991). [91/32]
- 170. Limitations on the Statistical Description of Black Holes (with P. Schwarz, A. Shapere and S. Trivedi), Mod. Phys. Lett. A6, 2353 (1991). [91/34]
- 173. Quantum Hair on Black Holes (with S. Coleman and J. Preskill), Nucl. Phys. B378, 175 (1992). hep-th/9201059 [91/64]
- 177. Black Holes as Elementary Particles (with C.F.E. Holzhey), Nucl. Phys. B380, 447 (1992). hep-th/9202014 [91/71]
- 202. Some Applications of a Simple Stationary Line Element for the Schwarzschild Geometry, (with P. Kraus), Mod. Phys. Lett. A 9, 3713, (1994). gr-qc/9406042 [94/46]

- 203. Self-Interaction Correction to Black Hole Radiance, (with P. Kraus), Nucl. Phys. B 433, (1995) 403. gr-qc/9408003 [94/61]
- 205. Effect of Self-Interaction on Charged Black Hole Radiance (P. Kraus), Nucl. Phys. B437 (1995) 231. hep-th/9411219 [94/101]
- 265. Global Structure of Evaporating Black Holes (with M. Parikh), Phys. Lett. B449, 24-29, (1999). gr-qc/9807031 [98-57]
- 285. Hawking Radiation as Tunneling (with M. Parikh) *Phys. Rev. Lett.* **85** 5042-5045 (2000).
- 372. A Relationship Between Hawking Radiation and Gravitational Anomalies (with S. Robinson) *Phys. Rev. Lett.* **95** 011303 (2005).
- 395. Hawking Radiation of Charged Black Hole through Gauge and Gravitational Anomaly (with S. Iso and H. Umetsu) *Phys. Rev. Lett.* **96** 151302 (2006).
- 399. Anomalies, Hawking Radiation and Regularity in Rotating Black Holes (with S. Iso and H. Umetsu) *Phys. Rev.* **D74** 044017 (2006).

String Theory

Item 119 is one of the earliest papers on T-duality. In Item 169 we studied black holes in supergravity, and demonstrated their dual spectrum. In Item 220 we pointed out the non-zero horizon area of extremal black holes with several charges, showed that this area is independent of various moduli (consistent with its interpretation as an entropy) and argued from duality that something very close to the Bekenstein-Hawking formula must be valid. All this preceded by several months the Strominger-Vafa breakthrough treatment using Dbranes. In Item 236 Larsen and I made a first attempt to apply the improved understanding of string black holes to cosmology. Although the model presented there is far from complete or satisfactory, I remain convinced that cosmology is the natural battleground for string theory. In recent years, that battleground has come to appear a rutted landscape. Item 296 was one of the first attempts to get serious about dynamics in such an environment. Item 391 is my take on the issues around universe-selection and the anthropic principle. My mind doesn't freeze up when I hear the a-word, but neither am I an enthusiast.

- 119. Compactification of the Twisted Heterotic String (with V. Nair, A. Shapere and A. Strominger), Nucl. Phys. B287, 402 (1987).
- 169. Dual Dilaton Dyons (with A. Shapere and S. Trivedi), Mod. Phys. Lett. A6, 2677 (1991). [91/33]
- 220. Internal Structure of Black Holes (with F. Larsen), Phys. Lett B 375, 37, 1996. hep-th/9511064 [95/92]
- 236. Resolution of Cosmological Singularities (with Finn Larsen), Phys. Rev. D 55, 4591, (1997). hep-th/9610252 [96-108]
- 296. Saltatory Relaxation of the Cosmological Term in String Theory (with J. Feng, J. March-Russell, and S. Sethi) *Nucl. Phys.* **B602** 307-328 (2001).
- 391. Enlightenment, Knowledge, Ignorance, Temptation *Universe or Multiverse?* ed. B. Carr xx (full reference to follow) (2007)

Popular and Semi-Popular Pieces

I have long been interested in communicating results from the frontiers of physics to the scientific (and, ideally, the general) public. In recent years I have been asked to do this on a regular basis for both Nature and Physics Today. As a matter of principle I have tried in these pieces to take on subjects that are under-reported, other things being equal. Many choice pieces are collected in item 396. I've classified and annotated the items listed in this subsection in a separate file. Here I will only mention a few highlights. Items 115 and 423 are full-scale popular books, that have reached large audiences. Items 430 and 460 are special to me. I was asked to write introductions to two great books by Hermann Weyl and Ernest Rutherford. I accepted with pleasure, worked hard on them, and am proud of the results. Item 416 is, in my opinion, a significant elucidation of the concept "fundamental constant". Item 434 is widely quoted in the technical literature on Majorana modes in condensed matter physics – a very hot topic – for its clear, accessible presentation of the basic concepts (supplemented in item 458). Item 405 is a big think.

- 115. Longing for the Harmonies [a book] W.W. Norton (January, 1988).
- 116. Virtual Particles [a sonnet] Norton Anthology of Light Verse, ed. Baker, 1986.

- 164. Anyons, *Scientific American* 264, #5, p. 58 (May, 1991).
- 193. 10^{12} Degrees in the Shade (preprinted as Hot Stuff: The High Temperature Frontier), *The Sciences*, January/February 1994, 22. [93/50]
- 226. A crack in the Standard Model?, *Nature* Vol. 380, 19-20, (7 March 1996).
- 246. Panning for Gold at the K Stream, *Nature* 389, 671 (16 Oct. 1997).
- 250. Colour Takes The Field, *Nature* 390, 659 (18/25 Dec. 1998).
- 251. Neutrino Deficit Challenges Conservation Laws, *Nature* 391, 123 (8 Jan. 1998).
- 252. Why are there Analogies between Condensed Matter and Particle Theory?, *Physics Today*, 11 (Jan. 1998).
- 255. Liberating Quarks and Gluons, *Nature*, 391, 330-331, (22 Jan. 1998).
- 256. Back to Basics at High Temperature, *Physics Today*, 11 (April 1998).
- 264. Particle Physics: The Standard Model Transcended, *Nature* 394, 13-15, (2 July 1998).
- 267. Nuclear and Subnuclear Boiling, *Nature* 395, 220-221 (17 September 1998).
- 272. The Persistence of Ether, *Physics Today*, 52, 11-13, (January 1999).
- 277. Cosmic Molasses for Particle Masses, *New Scientist*, (April 1999).
- 281. And you're glue *Nature* **400**, 21-23. (1 July 1999).
- 288. Mass Without Mass I: Most of Matter *Physics Today* **52N11** (1999).
- 291. Mass Without Mass II: The Medium is the Mass-age *Physics Today* **53N1** 13-14 (2000).
- 289. Maxwell's Other Demon, *Nature* **402**, 22-23, (4 November 1999).
- 305. Precision Precession *Nature* **410** 28-20 (2001).
- 306. When Words Fail *Nature* **410** 149 (2001).
- 307. A Piece of Magic: The Dirac Equation *It Must be Beautiful* ed. G. Farmelo 102-130 (Granta, 2002).
- 312. Scaling Mount Planck 1: A View from the Bottom *Physics Today* **54N6** 12-13 (2001).
- 321. Scaling Mount Planck 2: Base Camp *Physics Today* **54N11** 12-13 (2001).

- 328. Scaling Mount Planck 3: Is That All There Is? *Physics Today* **55N8** 10-11 (2002).
- 317. What is Quantum Theory?, *Physics Today* , **53N6** 11-12, (2000) [MIT-CTP-3159].
- 319. The World's Numerical Recipe *Daedalus* **131-1** 142-147 (2001).
- 344. The World's Numerical Recipe *Best American Science Writing 2003* ed. O. Sacks 96-101 (Harper-Collins 2003).
- 324. Fermi and the Elucidation of Matter *Fermi Remembered* ed. J. Cronin (U. of Chicago Press 2004).
- 326. Four Good Questions With Pretty Good Answers *Fundamental Physics: Heisenberg and Beyond* ed. G. Buschhorn and J. Wess (Springer 2004).
- 327. The Social Benefit of High-Energy Physics *Macmillan Encyclopedia of Physics, Supplement: Elementary Particle Physics* (2002).
- 335. Life's Parameters *Physics Today* **56N2** 10-11 (2003).
- 339. Analysis and Synthesis 1: What Matters for Matter *Physics Today* **56N5** 10-11 (2003).
- 340. Analysis and Synthesis 2: Universal Characteristics *Physics Today* **56N7** 10-11 (2003).
- 345. Analysis and Synthesis 3: Cosmic Groundwork *Physics Today* **56N10** 10-11 (2003).
- 352. Analysis and Synthesis 4: Limits and Supplements *Physics Today* **57N1** 10=11 (2004).
- 342. The Origin of Mass *Physics@MIT* 24-35 (2003).
- 378. The Origin of Mass [modified from 342] *Frontline* **22N10** (2005); *Mod. Phys. Lett. A* **21** 701-720 (2005).
- 355. From "Not Wrong" to (Maybe) Right *Nature* **428** 261 (2004).
- 356. Total Relativity: Mach 2004, *Physics Today*, **57N4**10-11 (2004) [MIT-CTP 3482].
- 362. Whence the Force of $F=ma$? 1: Culture Shock *Physics Today* **57N10** 11-12 (2004).
- 369. Whence the Force of $F=ma$? 2: Rationalizations *Physics Today* **57N12** 10-11 (2004).
- 371. Whence the Force of $F=ma$? 3: Cultural Diversity *Physics Today* **58N7** 10-11 (2004).
- 366. In Search of Symmetry Lost *Nature* **433** 239-247 (2004).

- 388. On Absolute Units 1: Choices *Physics Today* **58N10** 12-13 (2005).
- 393. On Absolute Units 2: Challenges and Responses *Physics Today* **59N1** 10-11 (2005).
- 400. On Absolute Units 3: Absolutely Not *Physics Today* **59N5** 10-11 (2006).
- 387. Journal Club: Promise that Anyon Particles Hold for Quantum Computing Excites the Physicist Who Named Them *Nature* **437** 299 (2005).
- 389. An Explorer and Surveyor [on Hermann Weyl] *Nature* **437** 1095 (2005).
- 390. The Universe is a Strange Place *Lepton-Photon Interactions at High Energies, International Symposium XXII* 447-461 (2005).
- 396. Fantastic Realities: 49 Mind Journeys and a Trip to Stockholm (World Scientific, 2006).
- 402. My Favorites [discussion of favorite books] *New York Academy of Sciences Update* **19** (May/June 2006).
- 404. On Magic Moments *Seed* Nov. 2006 39.
- 405. Archaeopteryx Looks Up *New York Academy of Sciences Update* **20** (Sept./Oct. 2006).
- 406. Reasonably Effective 1: Deconstructing a Miracle *Physics Today* **59N11** 8-9 (2006).
- 414. Reasonably Effective 2: Devil's Advocate *Physics Today* **60N5** 8-9 (2007).
- 416. Fundamental Constants, pp. 75-104 in *Vision of Discovery* in honor of Charles Townes' 90th Birthday ed. R. Chiao, physics.gen-ph/0708.4361 [MIT-CTP 3847]. (2007)
- 417. Quantum Chromodynamics: Lifestyles of the small and simple, *Nature Physics* **3 N6** 375-6 (June, 2007) [MIT-CTP 3848].
- 422. My Wizard, Reference Frame Column, *Physics Today* **61 N1**[MIT-CTP 3866] (2008).
- 423. *The Lightness of Being: Mass, Ether and the Unification of Forces*, (Basic/Perseus, August 2008).
- 429. Mass by Numbers, (2008) *Nature* **456** 449 [MIT-CTP 4002]
- 430. Introduction to *Philosophy of Mathematics and Natural Science*, Hermann Weyl author, (Princeton University Press, 2008) [MIT-CTP 4005]
- 434. Majorana Returns, *Nature Physics* **5** 614-618 (2009) [MIT-CTP 4016]

- 458. Quantum physics: Majorana modes materialize *Nature* **486** 195-197 (June 2012) [MIT-CTP 4376]
- 460. Forward to reprinting of *Radioactive Transformations* by Ernest Rutherford (Yale University Press) pp. ix-xli(September, 2012).

Miscellaneous

These are three papers that dont fit naturally anywhere else. Item 89 arose out of discussions of the annihilation of magnetic monopoles and antimonopoles in the early Universe, but quickly took on a different flavor. We discussed how a proper treatment of spatial fluctuations can invalidate the usual treatment of chemical kinetics, which implicitly assumes homogeneity. Later authors including Cardy developed a very pretty renormalization group analysis of the phenomena we found here, and generalizations. Item 214 is the only observable tip of a much larger iceberg representing my interest in quantum computing. In itself it is a clever paper, I think, but it was rapidly overtaken by the explosive development of the field. In Item 278 we discuss how some extremely simple, symmetric potentials can be shown both analytically and numerically to develop an exponential set of inequivalent local minima. In special relativity two space-like separated events will appear, to different inertial observers, to occur in either time order. For more than two mutually space-like separated events that is not so, and a pretty geometry of possibilities emerges, as we explored in item 461.

- 89. Particle-Antiparticle Annihilation in Diffuse Motion (with D. Toussaint), Jour. Chem. Phys. 78, 2642 (1983).
- 214. Realization of the Fredkin Gate Using A Series of One- And Two-body Operators, (with H.F. Chau), Phys. Rev. Lett 75 748 (1995). quant-ph/9503005 [95/15]
- 278. Minimal Potentials with Very Many Minima (with Marin Soljagic). cond-mat/9904190 [99-39]
- 461. Constraints on Chronologies, (with Alfred Shapere), gr-qc 1208.3841 [MIT-CTP 4389] (Aug. 2012).

Special

These are six papers I prepared for special occasions. I put a lot of thought into them, and I am generally pleased with how they came out. Implicitly, and in part explicitly, they present my vision of physics. Item 238 was prepared as part of the celebration of the 250th anniversary of Princeton University. Item 259 was prepared as part of the American Physical Society Centennial volume. Item 274 was prepared as a special News and Views Feature for Nature. Finally, Item 279 was prepared for a special supplement issue of Nature, also designed to celebrate the century in physics. It is brief, but of very broad scope. I had the honor to present the rapporteur's talk on high energy physics at the 100th Anniversary Solvay Conference; this is item 455. Item 459 is a review and deep meditation on the mass concept in modern physics.

- 238. The Future of Particle Physics as a Natural Science, Published in Critical Problems in Physics in celebration of the 250th Anniversary of Princeton University, November 1996, eds. Fitch, Marlow, and Dementi, Princeton University Press; also in Int. Jour. Mod. Phys. A 13, 863, (1998); also in Magazine of Physics, Science & Ideas Vol. 1 No. 2) 12-25, (Dec. 1996). hep-ph/9702371 [97-11]
- 259. Quantum Field Theory, in the American Physical Society Centenary issue of Rev. Mod. Phys. 71, S85-S95, (1999); More Things in Heaven and Earth A celebration of Physics at the Millennium, ed. B. Bederson, (Springer-Verlag, New York), (1999). hep-th/9803075 [98-20]
- 274. Getting Its from Bits Nature 397, 303-306 (28 Jan. 1999).
- 279. Reaching Bottom, Laying Foundations, Nature, special issue A Celebration of Physics, for American Physical Society 100th anniversary, 4-5, (April 1999).
- 455. A Long View of Particle Physics, in Solvay Conference "The Quantum World", to appear in the Proceedings. hep-th 1204.4683, [MIT-CTP 4358] (April 2012).
- 459. Origins of Mass, hep-ph 1206.7114 *CEJP* **D12-00144** (June 2012) [MIT-CTP 4379].