Proposal: Princeton Companion to Physics

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I envision the Princeton Companion to Physics as a resource providing:

- Broad perspectives on physics as a cultural phenomenon, and its history
- Basic literacy in the concepts of physics in a widely accessible, attractive form
- Reliable accounts of our present state of knowledge in physics and its sister sciences
- Perspectives on the frontiers of knowledge, and visions of the future, from leading figures

It should be a book that people will find it pleasurable to turn to and browse – in other words, a pleasant companion.

I would like to reach several different audiences:

- *The educated public.* Physics is a central achievement of mankind, and an important part of modern culture. But the mathematical form of its theories can be intimidating, and the variety and strangeness of its experimental phenomena can be bewildering even to intelligent, sophisticated people. Many such people are intrigued by the spectacular results of physics that are all around us, or by exciting reports of new developments in the popular press, and would like to understand those things more deeply.
- *Students.* Many aspiring physicists, or potential users of physics, would like to get a real sense of "what's out there" in the subject before entering detailed studies.

- *Scientists and engineers, in general (including mathematicians).* Physics provides foundations for other parts of natural science and engineering. Many specialists in those other areas would like to deepen their understanding, and also to get in touch with new implications and possible applications of frontier physics.

- *Physicists.* Many physicists will enjoy learning about the history of their subject, getting oriented in physics outside their particular specialty, and sharing in the visions of leading experts.

Those thoughts about what we can realistically hope to provide, and who we are trying to reach, inform the choices of structures and topics that follow.

I propose to organize the Companion into an introductory essay and seven major sections, which I will now describe in turn. Of course, I anticipate that details of these proposals, and maybe even aspects of the overall plan, will evolve in response to suggestions from our referees, the associate editors, and the authors we approach.

1 Introductory Essay

Approximately 20 pages, drafted and finalized by me, vetted by associate editors and friendly volunteers.

The bulk of the introductory essay will be, in spirit, an expanded version of this proposal, explaining the goals and structure of the book. It will start with a very broad consideration of what physics has been and is, and also include an apology for what has been left out, specifically including most of "applied physics".

I'd also like to include a brief – 1 or 2 page – stand-alone *Reader's Guide*, wherein the relationships among the different sections, the (lack of) logical dependencies, and the differing levels of sophistication assumed at different places are set out.

2 Concepts

Approximately 150 pages, mainly from the editorial staff, including me.

This will be in the style of an "Encyclopedic Dictionary", with short (1-3 page) essays defining, elaborating and providing perspective on 50-60 central concepts in physics. The entries could include some history, some interpretation, and an occasional equation. The entries will also contain links to later parts of the book.

To get the discussion going, I have attached a tentative list of candidate concepts, in Appendix A.

3 Milestone Experiments

Approximately 150 pages, under the direction of an associate editor or special invitee who is a distinguished expert in the history of science.

Physics is an empirical science, and I feel it is very important to highlight the grounding of our concepts in concrete facts. Fortunately this can be done in an entertaining and informative way, by focusing on historic experiments that shaped physics. I'd shoot for 10-15 page descriptions of 15-20 experiments. A tentative list of suggestions appears as Appendix B.

4 Unifications

Approximately 100 pages, based on invited contributions, with detailed instructions from editors.

Unification of seemingly diverse ideas has been a major theme running through the history of physics, and is one of its great intellectual achievements. It is an ongoing process, and drives a lot of research activity today. It is also, I think, a very attractive way to present important ideas: The process of unification has elements of conflict, drama, and fulfillment that lend themselves naturally to story-telling. A tentative list of suggestions appears as Appendix C. Note that the unifications naturally fall into three classes – accomplished, ongoing, prospective – that could appear as separated pieces.

5 Great Equations

Approximately 100 pages, based on invited contributions, with detailed instructions from editors.

A special feature of physics, among the natural sciences, is the precision and power of its quantitative results, captured in great equations. They represent another kind of unification, for they assert the equality of *a priori* different things. The great equations give us another very attractive way to present important ideas. A tentative list of suggestions appears as Appendix D.

6 The State of the Art

Approximately 300 pages, based on invited contributions.

This section, and the following one, form the backbone of the book. For this section, I will solicit 15-25 page articles by leading figures in subject areas at the forefront of contemporary physics. A tentative list of such areas appears as Appendix E

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7 The Family of Physics: Sister Sciences

Approximately 150 pages, based on invited contributions.

This section continues the survey of contemporary physics, moving now to its horizontal (as opposed to vertical) frontiers, so to speak. Here I anticipate a broader range of page lengths, say 5-25 pages, depending on the area, since some of these cross-disciplinary intersections are more limited than others. The basic approach will be the same, though: Encourage leading figures to share their visions. A tentative list of candidate areas appears as Appendix F.

8 At the Frontier: Mysteries, Challenges, Prospects

Approximately 50 pages, including solicited contributions and a concluding essay by me.

Physics remains a dynamic subject, featuring deep unsolved mysteries, exciting challenges, and open opportunities. Many examples will have been touched upon at different points in the preceding sections. But it will be fitting, at the conclusion of this *Companion*, to address the future explicitly, in an organized way.

The format I'm leaning toward is the following. I'd propose to send questionnaires to 10-12 world leaders – most likely, a subset of our contributors – inviting them to comment, if they'd like to, on the issues raised in Appendix G, and to add any additional remarks they feel are appropriate. The associate editors and I will collect and edit the more interesting of these remarks, and present a digest associated with each topic. I will supply a brief introduction, connecting tissue, and a 15-20 page concluding essay.

A candidate list of topics appears as Appendix G.

Appendix A – Concepts: A Tentative List

- *Accelerators*
- *Anthropic argument / Anthropic principle*
- *Antiparticles*
- *Asymptotic freedom*
- *Atomic Structure*
- *Axion*
- *Big Bang*
- *Black Hole*
- *Boson / Fermion / Anyon*
- *Chaos*
- *Classical Mechanics*
- *Complementarity*
- *Conservation Laws*
- *Core theory / Standard Model*
- *Dark energy / Dark matter*
- *Electrodynamics / Quantum Electrodynamics*
- *Electromagnetic spectrum*
- *Elementary Particles*
- *Emergence*
- *Energy*
- *Entanglement*
- *Entropy*

- *Fractional Quantum Numbers*
- *Free Energy*
- *General relativity*
- *Geometric and Wave Optics*
- *Gravity waves*
- *Higgs field / Higgs fluid / Higgs mechanism / Higgs particle*
- *Inertial Frame*
- *Initial conditions*
- *Inflation*
- *Large Hadron Collider (LHC)*
- *Local Symmetry / Gauge Symmetry*
- *Magnetic Resonance*
- *Mass*
- *Microwave background radiation*
- *Neutron Star*
- *Nuclear Physics*
- *Parity / Parity transformation / Parity violation / Handedness*
- *Phase Transition*
- *Quantum chromodynamics (QCD)*
- *Quantum fluctuation / Virtual Particle / Vacuum Polarization / Zero point motion*
- *Quantum fluid / Quantum field*
- *Quantum theory / Quantum mechanics*
- *Renormalization / Renormalization group*
- *Resonance*

- *Special relativity*
- *Spectra (atomic, molecular, and other)*
- *Spin*
- *Spontaneous symmetry breaking*
- *String Theory*
- *Superconductivity / Superfluidity*
- *Supersymmetry (SUSY)*
- *Symmetry / Symmetry transformation / Symmetry group*
- *Thermodynamic Equilibrium / Thermodynamic State*
- *Turbulence*
- *Weak and Electroweak Interactions*

Appendix B – Historic Experiments: A Tentative List

- Free fall and pendula
- The gravitational force
- The mechanical equivalent of heat
- Phases and phase transitions
- The nature of color
- Spectral lines
- Trichromatic vision
- The speed of light
- Interference: light is waves
- The conservation of charge
- Coulomb's law
- Magnetic forces
- Induction
- Electromagnetic waves
- The nuclear atom
- Atomic number
- Quarks and Gluons: Jets
- The Higgs Particle
- Brownian motion
- Light Quanta
- Superconductivity and Superfluidity
- Lasers and Masers

- The expansion of the universe
- The existence of dark matter
- Bell's inequalities

Appendix C – Unifications: A Tentative List

Part 1: Accomplished Unifications

Note: The names attached here are for identification purposes, and should not be taken as exclusive attributions.

- space and number; geometry and algebra (Descartes)
- celestial and terrestrial law (Galileo, Newton)
- mechanics and ray optics (Hamilton)
- electricity, magnetism, and wave optics (Maxwell)
- space and time (Einstein, Minkowski)
- wave and particle (Einstein, de Broglie)

Part 2: Ongoing Unifications

- microphysics and cosmology
- entropy and information

Part 3: Prospective Unifications

- substances and forces (grand unification: quantum numbers)
- substance and force (quantitative unification, supersymmetry)
- space-time and substance and force (gravity coupling, string theory)

Appendix D – Great Equations: A Tentative List

- F= ma
- Newton's law of gravity
- The Maxwell equations
- The laws of thermodynamics
- Entropy and state-counting
- Black body formula
- Lorentz transformation
- Mass energy conversion
- Einstein's field law
- Expansion of the universe (homogeneous cosmology)
- Schrödinger equation
- Commutation relations and uncertainty principle
- Born rule
- Dirac equation
- Yang-Mills equation
- Renormalization group; running of couplings
- Band Structure
- Gap equation
- Josephson effects
- Bell's inequality
- Bekenstein-Hawking entropy formula

Appendix E – State of the Art Reviews: A Tentative List

- Quantum field theory (QCD emphasis)
- Numerical quantum field theory
- Simulation of Complex Systems
- Tests of fundamental symmetries
- Electroweak interactions
- Neutrino physics (including astrophysics and cosmology)
- Conformal field theory
- String theory
- Supersymmetry
- Astrophysics of black holes
- Quantum theory of black holes
- Gravitational waves
- The standard model of cosmology
- Cosmic microwave background
- Inflation + dark energy
- Quantum optics (including tests of QM)
- Quantum information / quantum computing
- Cold atoms
- Mesoscopic systems and "nanotechnology"
- Superconductivity / superfluidity
- Topology in condensed matter physics
- Dynamical systems (chaos, nonlinear dynamics)

Appendix F – Sister Sciences: A Tentative List

- Astrophysics: stars and neutron stars
- Astrophysics: tools
- Quantum chemistry
- Microscopy
- Biology: tools
- Biology: soft condensed matter
- Physics of mind (physics of perception, neural nets)
- Simulation and visualization in the service of physics
- Physics in the service of simulation and visualization (computer graphics, computer games)
- Physics and architecture (structural analysis, new possibilities opened by new materials)
- Energy technologies: batteries, solar, nuclear, ...
- Physically inspired mathematics (exactly soluble models, use of QFT and string theory in topology and algebraic geometry)

Appendix G – Frontiers: A Tentative List

Part 1: Mysteries

- Dark matter, dark energy
- Quantum gravity, including black hole quantum mechanics
- Origin of the universe (initial conditions)
- The quantum world (what is QM, axiomatically? Is its interpretation problematic? How do we reconcile its strangeness with our classical perception of the world?)
- Family problems

Part 2: Challenges

- Experimental frontiers: gravitational waves, relic neutrinos, proton decay, electric dipole moments and "semi-forbidden" processes
- Solving the equations! - chemistry, nuclear physics, materials design from first principles

Part 3: Prospects

- Dream materials (room temperature superconductors, ultra-strong substances, ultra-efficient solar cells)
- 3D, fault-tolerant, self-repairing computers
- Self-assembling and self-reproducing machines
- Quantum computers
- Expanding sensoria
- Physics in culture: new philosophies, new art forms