Perspectives

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M. Veltman (1980) -

Right now, theorists are in the driver's seat, and will be for the next 30 years, but then, we have no idea what comes next, and we'll absolutely need experimental guidance.

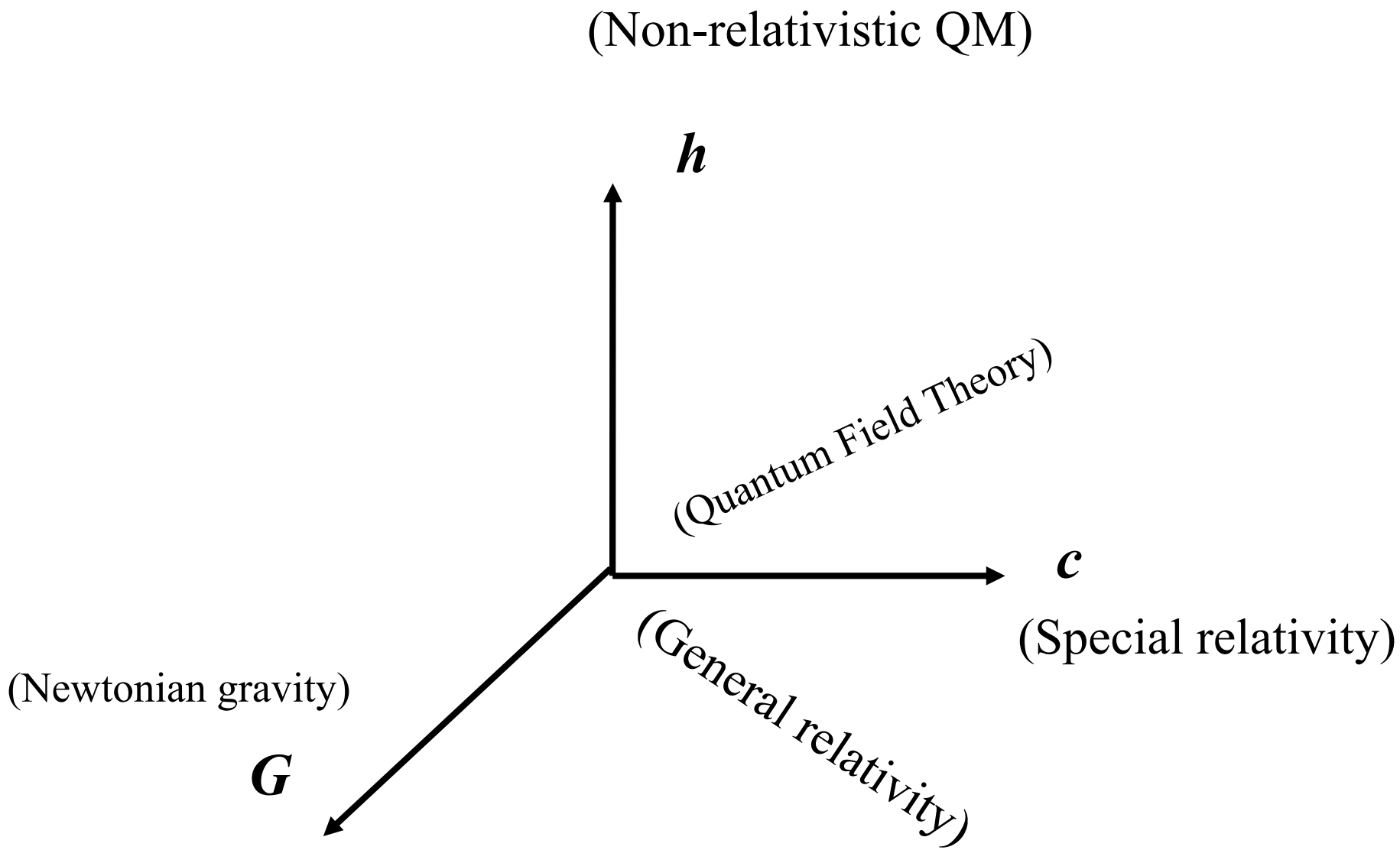
(SLAC Summer School)

Context - 1980

- QCD verified
  - Existence of jets
  - Scaling violations in deep inelastic scattering
- Electroweak theory well established
- Neutral currents seen
- Z, W bosons just around the corner
- 3 generations of quarks and leptons
- Nothing earth shaking in theory since
  - Footnote: neutrino mixing
- Concept of "World Accelerator"

Drivers of Particle Physics

- Emergence of fundamental particles
  - Experimentally driven
  - Masses, mixing angles
  - Are we really in the point-like era?
- Structure of forces
  - Theory driven
  - Unitary symmetry (spin-like descriptions)
  - Resolution of singularities
- Hints from cosmology


(Non-relativistic QM)
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(Quantum Field Theory)
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(Special relativity)
(General relativity)
(Newtonian gravity)
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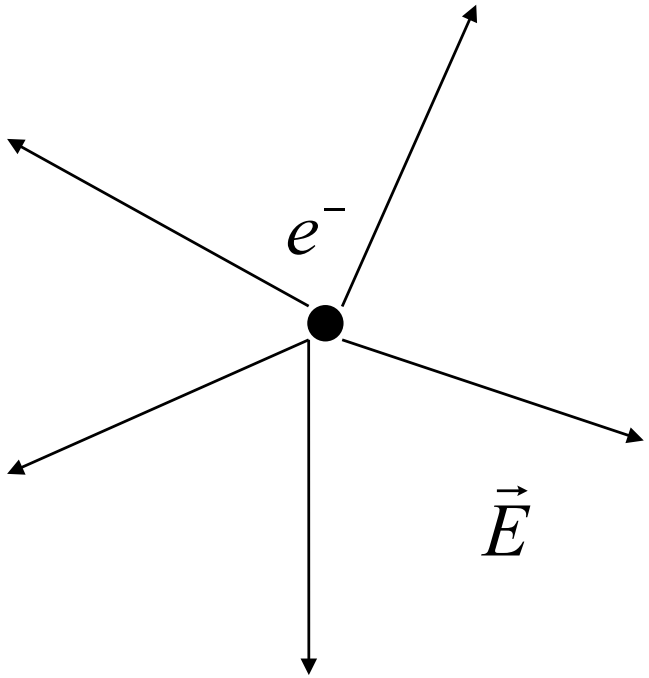
Self energies, renormalization

- Often times, we lose sight of the importance of singularities inherent in theories, and how they drive theoretical considerations

Energy in electric field - classical

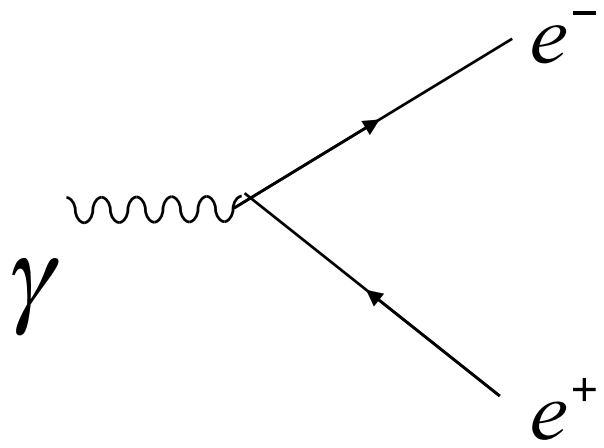
$$\vec{E}(\vec{r}) = \frac{kQ}{|\vec{r}|^2}$$

$$u = \frac{1}{8\pi}(\vec{E}^2 + \vec{B}^2)$$



Relativistic quantum mechanics -

New particles, new processes -
But still electrodynamics!



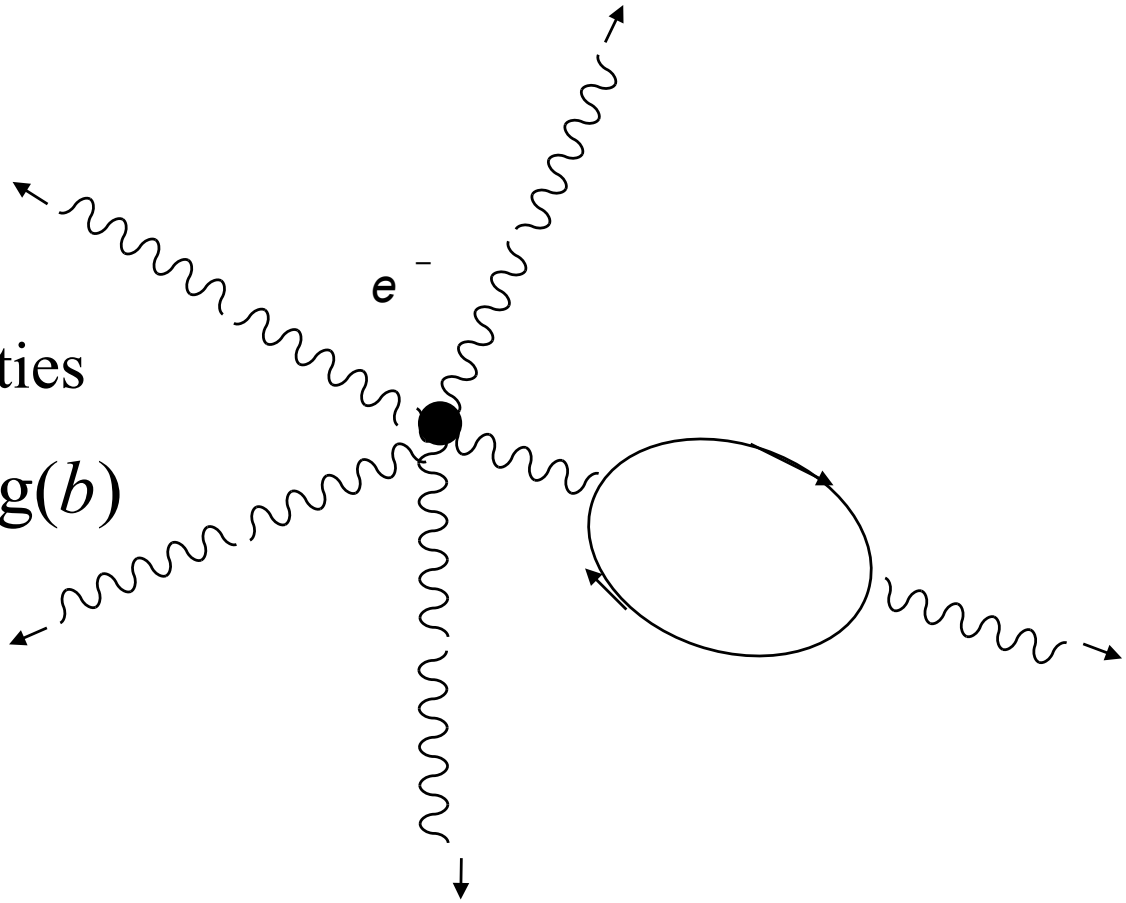
Added structure to fields/definition of charge

New structure of singularities

$\log(1/r^2)$

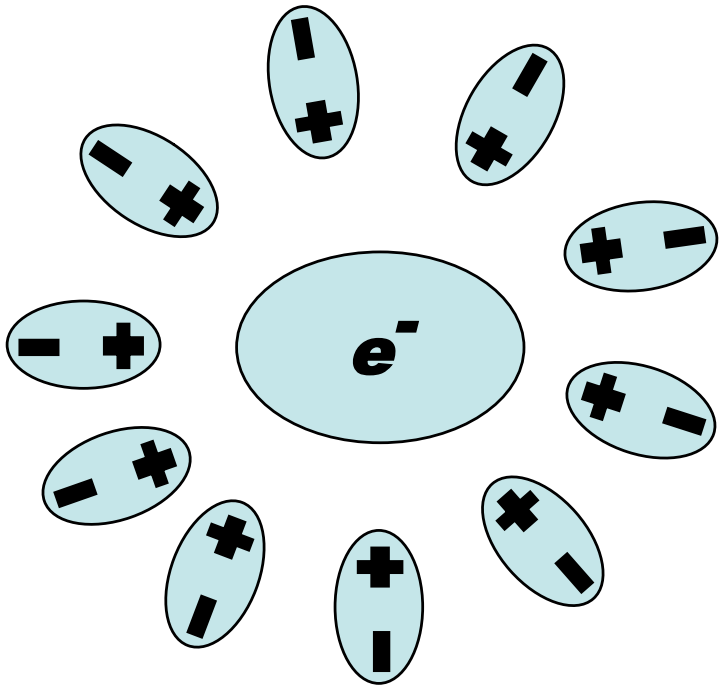
Factorization of infinities

$\log(ab) = \log(a) + \log(b)$



Screening (or anti-screening in QCD) - infinities factorized into redefinitions of charge/mass/other

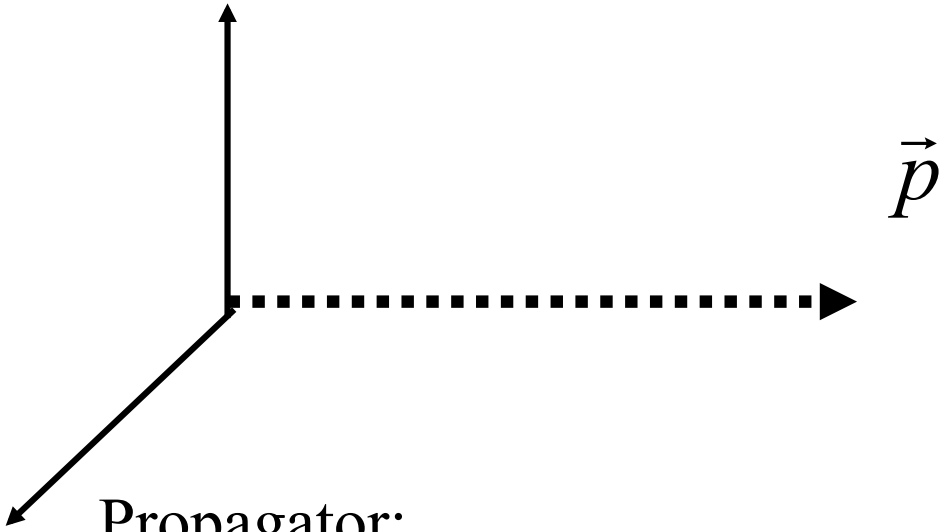
$$e = f(Q^2) + e_0$$



Why dwell on this?

- Renormalizability is a key feature of any viable theory.
- Much information gained from 1980 until the present was driven by the way the parameters of the electroweak theory were interwoven via loops (e.g. relation of the top quark mass to W/Z masses)
- Major motivation for supersymmetry (grand unification)

Just one problem: massive gauge boson polarization states



Propagator:

$$\frac{-i\left(g_{\mu\nu}-\frac{q_\mu q_\upsilon}{M^2}\right)}{q^2-M^2}$$

In high momentum limit, longitudinal polarization states grow arbitrarily large

The solution?

- Longitudinal degrees of freedom arise from interactions: Higgs? Dynamical?
- Tosses the problem "over the fence"
  - Non-zero vacuum expectation value
  - Invoked in two entirely different scales in cosmology
- Something must happen at the TeV scale
  - Otherwise the Standard Model violates unitarity
  - Renormalizability

Back to Veltman's comments

- 1980: A "fulcrum point" in the history of elementary particle physics
- 1950-1980: emergence of quarks, electromagnetism and weak interactions as SU(2)xU(1) theory, QCD
- 1980-2010: era of renormalization corrections predicting the physics accurately in accelerator experiments, AND
  - Filling in CKM matrix elements - confirm SM CP viol.
  - Neutrino oscillations
- 2010 and beyond - how are the longitudinal degrees of freedom of gauge bosons regulated?

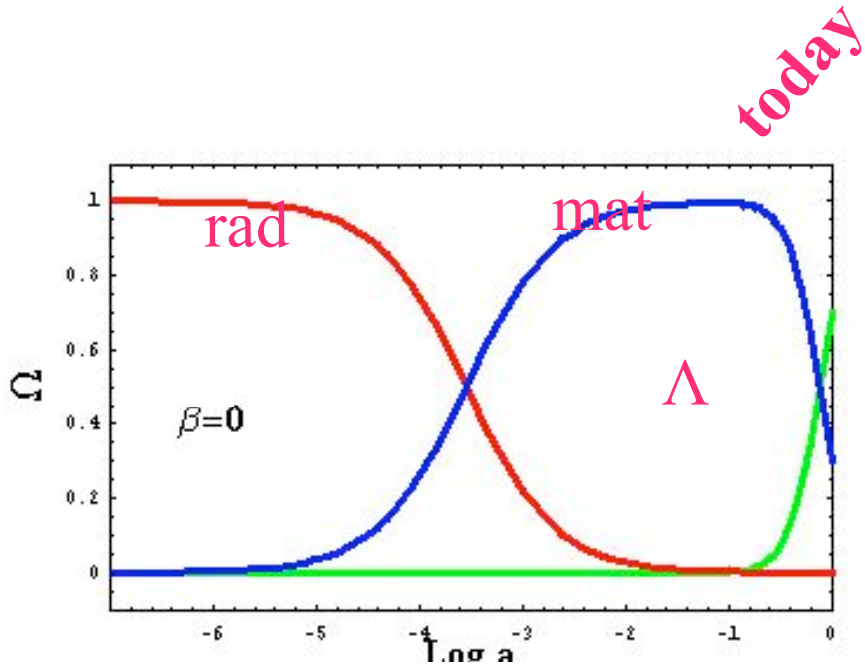
Cross-overs and surprises

- Vacuum energy invoked in very different energy scales
  - Cosmological inflation
    - At grand unification scale
      - Uniformity of CMB
  - Cosmic coincidence problem
    - Dark energy/dark matter roughly comparable in our era - present era - milli-eV scale
- Why is there no TeV scale inflation?
- Quantum field theory jumping over to explain puzzles in cosmology - scalar fields.

Why is Ω_Λ almost equal to Ω_M?

$\rho_M = a^{-3}$

$\rho_\Lambda = a^0$



Neutrino mixing

- Is this a surprise?
  - Unexpected, yes, but readily accommodated
    - Does not shake the foundations of the SM
  - More parameters for the SM
- Can the mixing matrices help us understand the fermion sector, beyond adding parameters?

Neutrino Mixing II

- N.B. FIRST major hint of mixing came from astrophysics
  - Solar neutrino problem
- Evidence from cosmic ray data
  - Kamiokande
- Current efforts: mine the mixing matrix
  - CP phase

Imperative questions and tools

- LHC!!!
  - Probing the EWK symmetry breaking scale
  - Space of theories and parameters daunting!
    - Standard Higgs
    - Supersymmetry
    - Dynamical symmetry breaking
    - Extra dimensions
  - Critical test - longitudinal W-W scattering will be very difficult (one of the factors driving the SSC energy) even with upgrades

LHC Physics

- Understand the Standard Model!!!
  - First on the menu
  - Calibrates important backgrounds - e.g. missing energy
    - Top quark production
    - Z decay into neutrinos
- Strongly coupled
  - Technicolor
  - Squarks, gluinos
- Higgs-like cross sections
- Longitudinal W-scattering

Tools

- ILC
  - Probably will be critical to understand the symmetry breaking sector
  - Major issue - what is the relevant scale?
    - LHC provides guidance
- Accelerator physics beyond LHC/ILC
  - Difficult - fundamental advances must be made on multiple fronts
    - Peak electric fields - slow improvement with freq.
    - Beam current/focusing - difficult with small scales
    - Magnet technology
    - Detector technology

Rare processes

- Motivation to explore flavor changing neutral currents still there
  - Cautionary notes from RSVP initiative
- Double beta decay
- Mining B physics at LHC

The Universe as Accelerator

- Highest energies accessible
- Interpretations more difficult
  - History
  - Thermal equilibrium
  - Structure formation
  - Unknowns - breakdown in gravity versus matter terms in GR
- Major cross-over success: neutrino mixing
  - Optimism for SUSY as dark matter or Higgs-like vacuum as dark energy?

Dark matter/dark energy

- Terrestrial experiments
  - Low rate
    - Solids - difficult to scale
    - Liquids - can scale, low backgrounds - directionality?
    - Gases - can scale, background?, directionality
  - Regardless of technology, definitive experiments will be large and expensive affairs

Observational side

- Gravitational lensing has the strongest potential on paper for dark energy studies
  - Large coverage of sky (10,000 sq. degrees)
  - Huge datasets
  - Lots of number crunching
  - Can systematics be controlled?
- Cluster formation
  - SZ effect, microwave, x-rays, optical
- Baryon oscillations

Observational II

- Z=0 Supernovae
  - Necessary to constrain Hubble curves
  - Near term
- Large Z
  - Onset of structure formation
- CMB - decades to go
  - B mode polarization as probes of inflation

Perspective

- History seems to progress in a slip-stick fashion - like earthquakes
- We have moved beyond the somewhat predictable era of Standard Model renormalization and standard cosmology into uncharted waters.
- Will the interplay between astrophysics and terrestrial particle physics continue to provide insights? Probably, yes, but what will we find? Stay tuned.