# Hacking the Quantum Revolution

Seven Pines

May 15-17, 2014

- Mid 1960s:
- Condensed matter physics
  - phase transitions
    mean field theory
  - Kadanoff
- High energy physics
  - deep inelastic scattering
  - Bjorken
- **scaling**

- 1. The 1930s
- 2. Hacking type revolution
- 3. Post WW II: QFT
- BCS, Phase transitions,
- Kadanoff, Wilson,
- Mathematical Physics
- Computers and Computing
- 4. Lepage
- 5. Coda

# Quantum Mechanics
# Stability of Matter

In a dynamical system, it is *not* the interacting entities that participate *as objects* in the formal constitution of "the system”, but rather their quantitative properties

and couplings. As a consequence, interaction is understood as the temporal or spatial change in the numerical value of variables. This change is captured

By  a set of (deterministic or stochastic) differential (or difference) equations.    Fontana and Buss

- During the 1930s:
- QFT  demonstration that the electromagnetic interactions between charged particles could
- be explained as due to photon exchanges,
- Fermi’s formulation of a field theory of β-decay,
- Yukawa’s suggestion that in analogy to electromagnetic forces the short range nuclear forces between nucleons could be generated
- by the exchanges of a hitherto unobserved massive particle
- Solid state ; nuclear physics

- Physics and Mathematics
- Physics and Computers

- Hacking type revolutions transform a wide range of scientific practices and are multidisciplinary, with new institutions being formed that epitomize the new directions. The time scale of Hacking-type revolutions
- is the *longue durée*, but the *durées* have become
- shorter as the scientific community has increased. Hacking-type revolutions are linked with substantial social change, and after a Hacking-type revolution
- there is a different feel to the world.

Styles of reasoning are the constructs that specify what counts as scientific knowledge

and constitute the cognitive conditions of possibility of science. They are made concrete through the specification of models. A style of reasoning must introduce new types of

"objects, evidence, sentences (new ways of being a candidate for truth or falsehood), laws, or any rate modalities, [and most importantly, ] possibilities."

The style of reasoning I associate with the Hacking-type quantum revolution is characterized by the hierarchization of the inanimate microscopic world.

**And quantum field theory is its language.**

# Post World War II

- Tomonaga, Schwinger, Feynman, Dyson all defined QED in terms of a Lagrangian wherein appears the parameters $m_o$ and $e_o$, the bare mass and bare charge of the electron.
- Anachronistically: To make the pertubative calculations well defined one introduces into
- the theory a large cut-off momentum $\Lambda$. One then calculates two physical processes which, determine the value of the observable mass,
- $m$, and that of the charge, $e$, of the electron.

$$e^2 = e_o^2 - \beta\, e_o^2 \ln(\Lambda / m_0)$$

$$m = m_0 - \gamma m_o (e_o^2 / \hbar c) \ln(\Lambda / m_0)$$

$$e_0{}^2 = e^2 + \beta_2 e^2 \ln(\Lambda / m)$$

$$m_0 = m + \gamma_1 m \; (e^2 / \hbar c) \ln(\Lambda / m)$$

- Dyson formalized this procedure of "renormalization" in terms of graphs ( Feynman diagrams) and proved that for QED the thus "renormalized" *S*-matrix scattering amplitudes are finite to all orders of perturbation theory. Furthermore, he indicated that only certain relativistic quantum field theories yielded finite results by this procedure. Renormalizability became an important selection principle for allowable field theories.

# QFT and Solid State Physics

- In 1947 Bogoliubov: liquid $^4$He. The use of creation
- and annihilation operators was a key element in the approximation method Bogoliubov introduced.
- Bogoliubov used the fact that in zeroth approximation the ground state of liquid $^4$He is macroscopically occupied by zero momentum particles and showed
- that when interactions are taken into account, a justifiable approximation is obtained by replacing the creation and annihilation operator for the zero momentum one particle state by classical, “c”,
- numbers. The resulting theory did not conserve particle numbers and broke the gauge symmetry of the original formulation.

- The incorporation of the field theoretic language by Bardeen, Cooper, and Schrieffer (BCS) in their theory of superconductivity was a landmark event (1957). The key insight of the BCS theory was the recognition of the consequences of the existence of an attractive force between electrons near the Fermi surface, stemming from their interactions with the lattice vibrations, i.e. with phonons. That interaction  gives rise to the formation of bound pairs of electrons of opposite momentum and opposite spin, Cooper pairs, and destabilizes the Fermi surface.

The simplified model BCS adopted is defined by the Hamiltonian

$$H = \sum_{\boldsymbol{k}\sigma} \varepsilon_{\boldsymbol{k}} c^{*}_{\boldsymbol{k}\sigma} c_{\boldsymbol{k}\sigma} - \frac{g}{V} \sum_{\boldsymbol{k},\boldsymbol{k}',\boldsymbol{q}} c^{*}_{\boldsymbol{k}+\boldsymbol{q}\uparrow} c^{*}_{-\boldsymbol{k}\downarrow} c_{-\boldsymbol{k}'+\boldsymbol{q}\downarrow} c_{\boldsymbol{k}'\uparrow}$$

which is to describe the physics of the set of states centered around the Fermi surface with energies between $\epsilon_F$ +($\omega_D$/2)and $\epsilon_F$ -($\omega_D$/2). A net attraction operates when g is a positive constant.

$$\frac{g}{V}\sum_{\boldsymbol{k}}\left\langle\Omega_S\left|c_{\boldsymbol{-k}\downarrow}\,c_{\boldsymbol{k}\uparrow}\right|\Omega_S\right\rangle=\Delta$$

$$\frac{g}{V}\sum_{\boldsymbol{k}}\left\langle\Omega_S\left|c^{*}_{\boldsymbol{k}\uparrow}\,c^{*}_{\boldsymbol{-k}\downarrow}\right|\Omega_S\right\rangle=\overline{\Delta}$$

In an influential paper published in 1959, Nambu suggested that the masses of elementary particles might arise in a similar way as in BCS: the vacuum state might likewise not respect the symmetries of the theory, and like the quasiparticles of the BCS theory elementary particles, might acquire mass. Nambu and Jona-Lasinio went on to construct a model that of a massless fermion field $\psi(x)$ that exhibited these characteristics.

$$\mathcal{L} = \mathrm{i}\overline{\psi}(x)\gamma^{\mu}\partial_{\mu}\psi(x) + g\left[\overline{(\psi}(x)\psi(x))^{2} - (\overline{\psi}(x)\gamma_{5}\psi(x))^{2}\right]$$

$\psi(x) \rightarrow e^{i\alpha}\,\psi(x)$ and $\psi(x) \rightarrow e^{i\beta\gamma_5}\,\psi(x)$

Two separate research lines can be discerned as stemming from BCS. One, principally located in high energy physics, leads from spontaneously broken symmetries to Yang-Mills gauge theories, to electroweak theory, to Gell-Mann-Low-Callan-Symanzik renormalization group methods, to asymptotic freedom and the standard model, and the award of the Nobel prize in Physics in 2004 to David J. Gross, H. David Politzer and Frank Wilczek *"for the discovery of asymptotic freedom in the theory of the strong interaction"*.

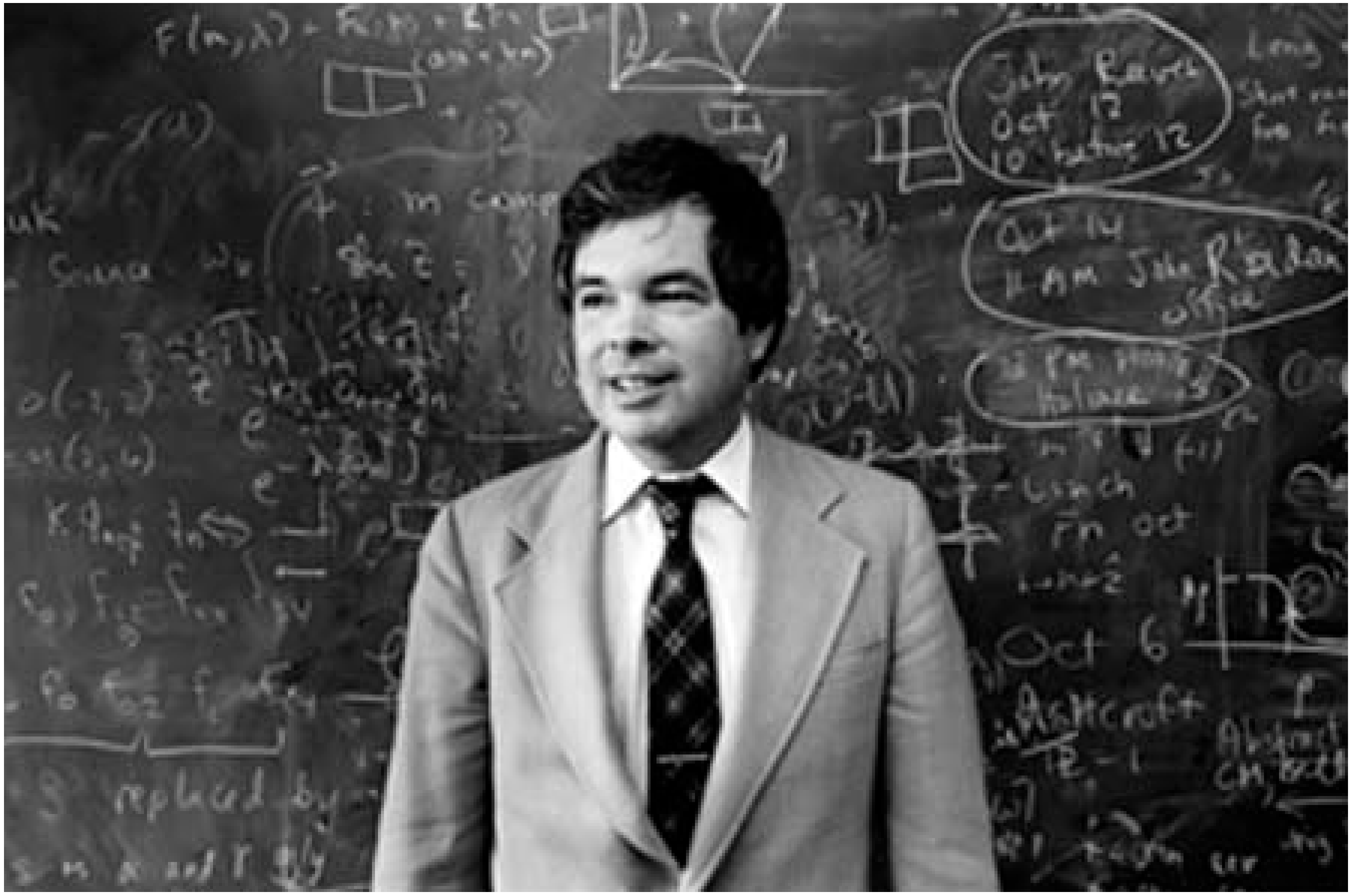
I refer you to David Gross's remarkable 1974 Les Houches lectures on "Applications of the Renormalization Group to High-Energy Physics" and to Frank Wilczek's article on "Quantum Field Theory" in the Centenary issue of the Reviews of Modern Physics, March 1999. in which the general principles underlying quantum field theory are analyzed -- such as locality, and the number of degrees of freedom invoked to implement locality --, and its impressive successes in establishing the standard model are insightfully presented.

The other research line stemming from BCS leads from it back to Onsager and Ising models, to phase transitions more generality, to universality in phase transitions, correlation lengths, critical exponents, and running coupling constants, and Wilson renormalization group methods. Ken Wilson's Nobel lecture and his review article with Kogut summarize these developments.

**Mathematical Physics**: Wightman, Jost, van Hove, Haag → Jaffe,….Hepp, (→Eckmann, Froehlich…),Ruelle,…, Hugenholtz,..Shroer,

**Computers and Computing**

**Experimental Physics**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Abstract

In thinking and trying out ideas about 'what is a field theory,' I found it very helpful to demand that a correctly formulated field theory be soluble by computer, the same way an ordinary differential equation can be solved on a computer, namely with arbitrary accuracy in return for sufficient computing power."

The transformation wrought by Ken Wilson's viewpoint is beautifully conveyed in Lepage's lectures on "What is renormalization?" and illustrated with QED. QED is defined by the Lagrangian density

$$\mathcal{L} = -\frac{1}{2} F^{\mu\nu}(x) F_{\mu\nu}(x) + \overline{\psi(x)} (i\gamma^{\mu}\partial_{\mu} - e_0 \gamma^{\mu} A_{\mu}(x) - m_0) \psi(x)$$

- The effect of the removal from the theory of all states with energies between $\Lambda_0$ and some new cut off $\Lambda$ ($\Lambda_0 >> \Lambda$) for processes at energies much lower than $\Lambda$ can be compensated by the addition to the Lagrangian the correction
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$$\delta \mathcal{L}_0 = -e_0\, c_0 \left( \frac{\Lambda}{\Lambda_o} \right) \overline{\psi}(x) \gamma^\mu \psi(x) A_\mu(x)$$

-
- where $c_0(\Lambda/\Lambda_0)$ is dimensionless constant equal to
-

$$c_0 \left( \frac{\Lambda}{\Lambda_o} \right) = \frac{e_0^2}{6\pi\hbar c} \log \left( \frac{\Lambda}{\Lambda_o} \right)$$

- $$\delta\mathcal{L}_m = -m_0\,\tilde{c}\left(\Lambda/\Lambda_o\right)\,\bar{\psi}(x)\psi(x)$$
- theory with Lagrangian

$$\mathcal{L} = -\frac{1}{2}F^{\mu\nu}(x)F_{\mu\nu}(x) + \overline{\psi(x)}\left(i\gamma^{\mu}\partial_{\mu} - e_{\Lambda}\gamma^{\mu}A_{\mu}(x) - m_{\Lambda}\right)\psi(x)$$

and coupling parameters

$$e_{\Lambda} = e_0\left(1 + c_0(\Lambda/\Lambda_0)\right)$$

$$m_{\Lambda} = m_0\left(1 + \tilde{c}_0(\Lambda/\Lambda_0)\right)$$

QFTs are somewhat temporary, but robust and very effective, constructions. The quantum revolution interpreted as a Hacking type revolution is the preliminary, ongoing account of these temporary, constructions.