What is Quantum Field Theory ?

Who "needs" Quantum Field Theory ?

These days, one doesn't even need to know quantum mechanics to be a professor of theoretical physics.

(I do not speak of experimental physicists, for whom I have only admiration since they can do things I cannot do.)

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"clouds & smoke passing in front of our eyes"

Chapter I.1 of a ~~forthcoming~~ just published textbook on quantum field theory 3

WHO NEEDS IT ?

Quantum field theory arose out of our need to describe the ephemeral nature of life.

No, seriously, quantum field theory is needed when we confront simultaneously the two great physics innovations of the last century of the previous millenium: special relativity and quantum mechanics.

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	big	small
fast	rocketship near light speed no need for QM	the marriage of quantum mechanics & special relativity
slow	classical physics	slow moving electron scattering off a proton, no need for special relativity

In the peculiar confluence of special relativity & quantum mechanics a new set of phenomena arises: particles can be born & particles can die

A new subject in physics, quantum field theory, is needed to describe birth & death, & some kind of life in between.

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QM: uncertainty principle

$$\Delta E \sim \frac{1}{\Delta t}$$

Special relativity: energy = matter

$$E = mc^2$$

But no matter what you do to the Schrödinger equation of one electron, always one electron.

Concept of field goes back to Faraday

Maxwell's theory of the electromagnetic field contains two hidden symmetries that will rock 20th century physics (relativistic & gauge)

Is it conceivable that present theory also contains hidden structure?

In hindsight, the Terrible notation of 19th century physics

(magnetic field = H ?)

But now also, Yang-Mills theory Terrible notation: redundancy in description

Already, in non-relativistic QM, photon (electromagnetic field) treated as a field but not the electron => Jordan, Heisenberg Dirac, ...

All particles are excitations in some field

(graviton just a particle like any other, an excitation in the gravitational field (e.g. S. Weinberg's Text on gravity)

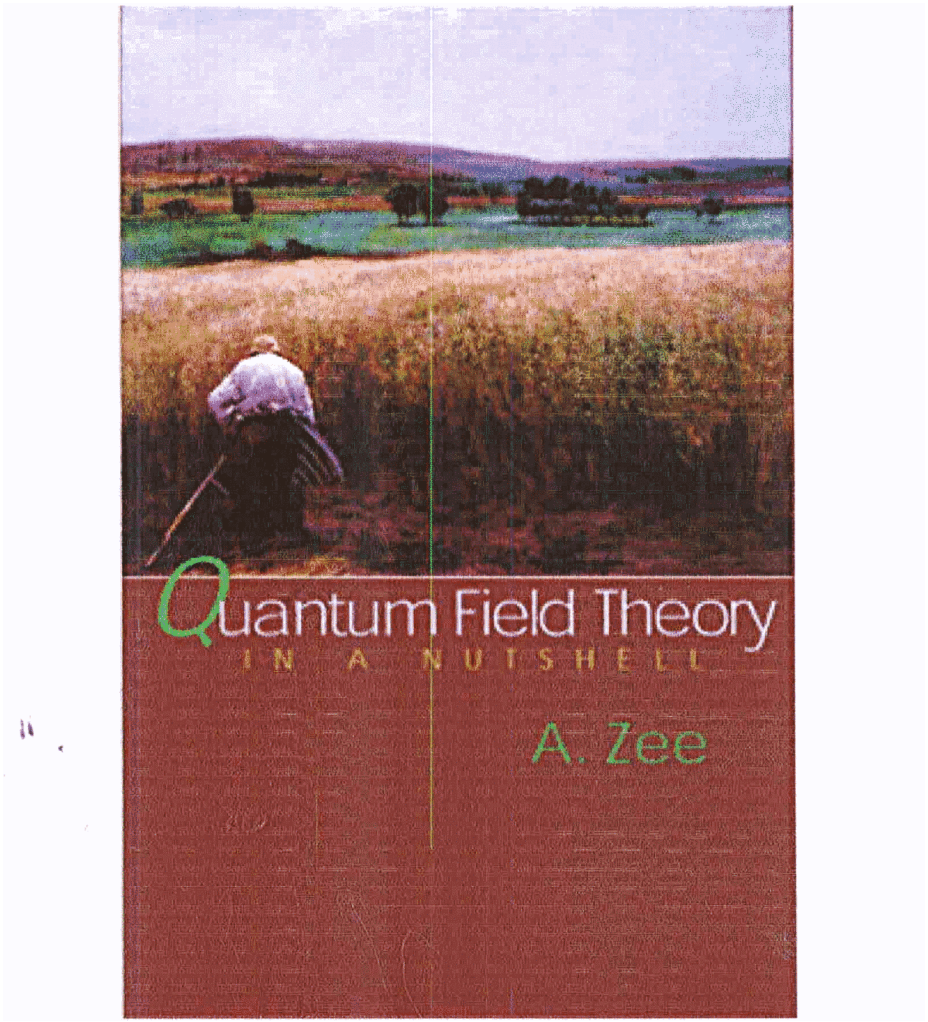
but somehow also responsible for the spacetime arena in which all fields work & play —

it is somehow different?

quantum gravity?

cosmological constant?

)



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- the rise of field theory in condensed matter physics

(as distinct from earlier use of perturbative field theory, e.g. Fetter & Walecka, Abrikosov et al)

e.g. quantum Hall fluid
microscopic degrees of freedom = electrons
but long distance physics = Chern-Simons gauge field
with fractionally charged excitations

e.g. surface growth & renormalization group

e.g. replica & supersymmetry

- gravity introduced as early as possible

- try to be much lighter in formalism
stories, jokes, fictitious characters (Confusio) à la Galileo
- Eight Parts of the Celestial Dragon
itp.ucsb.edu/~zee/JingYong.html

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Quantum field theory has had two near-death experiences

late 1940's : inability to produce covariant (Lorentz) results & divergences

The young people were the (revolutionary) conservatives

late 1960's : S-matrix school, inability to deal with the strong interaction

The triumph of field theory = "a victory parade" that made "the spectator gasp with awe & laugh with joy"

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quantum mechanics = (0+1)-dimensional field theory

string theory = (1+1)-dimensional field theory

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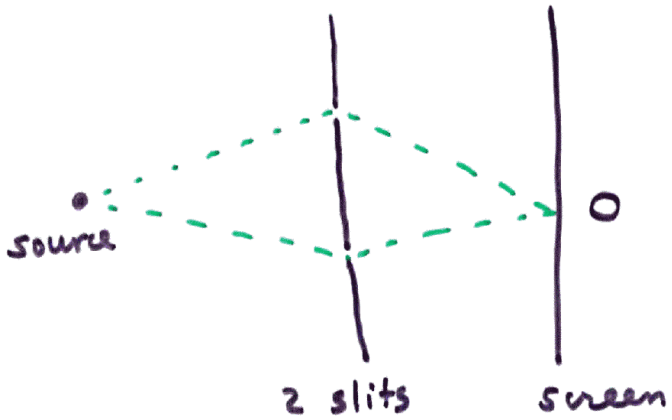
When we teach (or learn) QM Schrödinger or Heisenberg formalism

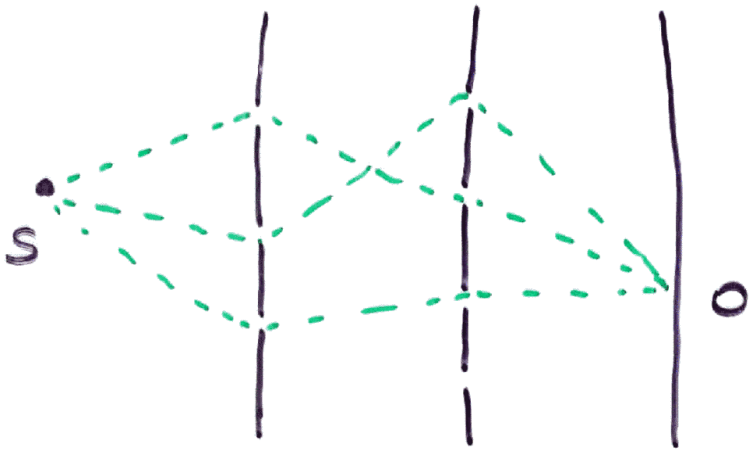
Conceptually more profound (& leading naturally to QFT) : Dirac-Feynman path integral or Schwinger functional integral formalism



add amplitudes

Students almost never ask : What if 3 holes?

"



add amplitudes

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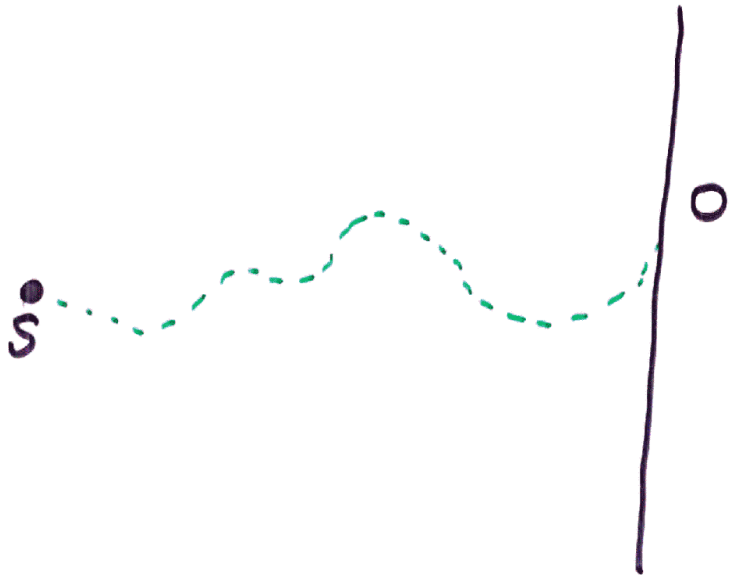
The most Zen of all :
add ∞ number of screens &
drill ∞ number of holes in each screen



add amplitudes over all paths
Integral over all paths

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Quantum field theory
one great big fancy sum (integral)

$\int D\phi\, e^{-S(\phi)}$ field $\phi(\vec{x}, t)$ ↑D dimension

Quantum mechanics

$\int D\phi\, e^{-S(\phi)}$ call it coordinate or position $\phi(t) \equiv q$

0+1 dimensional field theory

Random matrix theory

$\int d\phi\, e^{-S(\phi)}$ a matrix ϕ

0+0 dimensional

"Ordinary" integral in calculus

e.g. $\int d\phi\, e^{-\frac{1}{2}m^2\phi^2 - g\phi^4}$ a real number ϕ

~ 50 years of QFT finding methods or tricks to do the (functional) integral

e.g. lattice gauge theory, replace $\int$ by Σ & use computer

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Simplest method

Expand $\int d\phi\, e^{-\frac{1}{2}m^2\phi^2 - g\phi^4}$

$= \sum_{n=0}^{\infty} \frac{(-g)^n}{n!} \int d\phi\, e^{-\frac{1}{2}m^2\phi^2} \phi^{4n}$

Draw little diagrams to keep track of the terms

When I was a student, I was really eager to learn about Feynman diagrams which I had heard so much about.

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Schwinger: "Feynman brought quantum field theory to the masses."

"In the dark recesses of the sub-basement of Lyman, where theoretical students retired to decipher their tablets, and where the ritual taboo on pagan pictures could be safely ignored, and ...."

Paul Martin
Physica 96 (1979) p70.

The influence of Feynman diagrams on quantum field theory

For many years

QFT = $\sum$ Feynman diagrams

"Breaking the shackles of Feynman diagrams"

mid 1970's 't Hooft Polyakov + ...

- Structures (such as magnetic monopoles) that cannot be seen by Feynman diagrams ... $e^{-\frac{1}{g^2}}$
- duality ....
- .....

The purpose of physics is to understand Nature

Intellectual completeness

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of different areas of physics

For example,

Pauli exclusion & the spin-statistics connection (integer spin = Bosons
$\frac{1}{2}$ integer spin = Fermions)

"there is no one fact in the physical world which has a greater impact on the way things are" Duck + Sudarshan

from atoms to neutron stars to lasers
much of condensed matter physics
e.g. band structure, superconductivity
etc etc

Just a rule in non-relativistic quantum mechanics

Quantum field theory is more complete than quantum mechanics

Pauli exclusion can be derived

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How do you know that all the electrons are identical?

Many could have been made in a factory somewhere ....

we need QFT to explain this

Why is the electron charge exactly equal in magnitude to the proton charge?

Quantum electrodynamics less complete than grand unified theory

Why is spacetime (3+1)-dimensional?

Quantum field theory (can be written in any spacetime dimension) less complete than string theory

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One of the deepest mysteries of physics :

Dynamical evolution in the quantum world

$$e^{-\frac{i}{\hbar}Ht}$$

&

Boltzmann factor $e^{-\beta H}$

Imaginary time & inverse temperature

Just a coincidence or deeper ?

In any case, can be applied, e.g.
Hawking Temperature of a black hole

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Partition function
$Tr\, e^{-\beta H}$

represented as Euclidean field theory
(in contrast to Minkowskian field theory)

Many other problems in physics
can be represented as field theories

20th century Two Great Marriages 24

quantum physics + special relativity

→ quantum field theory

Late 20th century - early 21st century

quantum physics + general relativity

→ string theory or ?