# Einstein's searches for a fundamental theory

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## introduction

It's fairly clear how SR and GR are related, but Brownian motion and the photoelectric effect seem disjoint. They were, however, part of a unified project which occupied Einstein for most of his life. I want to show how they fit fully and naturally into his place in intellectual history.

This also means giving the reasons why he was so reluctant to believe in QM as anything other than a provisional and effective theory.



## coverage

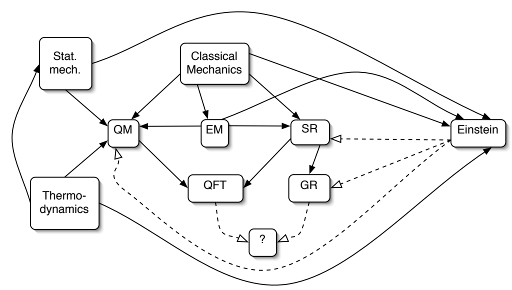
I'm going to cover a very broad range of physics – each one of the sections below counts as one or two courses in an undergraduate degree.

What I have to say today draws heavily on Einstein's *Autobiographical Notes*, in which he described his intellectual history, and in which he makes clear how the various things he has worked on hang together.

I'll talk about quantum mechanics in general, without talking very much at all about quantum mechanics in particular.



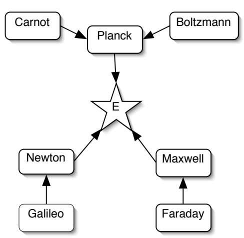
## einstein's intellectual network






## einstein's people network

- Newton: 'if I have seen a little further it is because I was standing on the shoulders of giants'
- Einstein stood on the shoulders of a *lot* of giants






## thermodynamics and statistical mechanics

> A theory is the more impressive the greater the simplicity of its premises, the more different kinds of things it relates, and the more extended its area of applicability. Hence the deep impression that classical thermodynamics made upon me. It is the only physical theory of universal content concerning which I am convinced that, within the framework of the applicability of its basic concepts, it will never be overthrown.
>
> – *Autobiographical Notes*

## the laws of thermodynamics

- Zeroth: if two bodies are in thermal equilibrium with a third, then they must also be in thermal equilibrium with each other (ie, there is such a thing as temperature).
- First: Energy is conserved, if heat is taken into account.
- Second: no process is possible whose sole effect is to transfer heat from a cooler to a warmer body; or, there are irreversible processes; or, there is such a thing as entropy, and it increases.



## the laws of thermodynamics

Or:

> The energy of the universe
> is constant, the entropy of the universe tends to a maximum.
> – *Carnot*

Thermodynamics has a completely staggering range of applicability, from steam engines to chemistry to black holes.



## mechanics: galileo and newton

Wonderfully simple theory.

- Galileo described the relativity principle – you can't tell if you're moving.
- Galileo implicitly describes 'inertial systems'; Newton describes absolute space and time, marking inertial systems as special; Mach wonders what's special about inertial frames.
- Galilean transformations



## mechanics: galileo and newton

Newton describes everything from gases to the motion of planets (with only minor corrections from GR, even now; in the precession of Mercury, Newton is wrong by 43 as/century)

Newton describes a 4-dimensional spacetime, but a special one, in which the time and space dimensions don't interact – everyone has the same time everywhere.

The newtonian concepts of mass, inertia, momentum, energy are so fundamental that we reason with them intuitively (and popularly), even now. They seem obvious.



## mechanics: newton and einstein

> Newton, forgive me: you found just about the only way possible in your age for a man of highest reasoning and creative power. The concepts that you created are even today still guiding our thinking in physics, although we now know that they will have to be replaced by others farther removed from the sphere of immediate experience, if we aim at a profounder understanding of relationships.
> – *Autobiographical Notes*



## statistical mechanics

Thermodynamics meets mechanics.

- Although mechanics is deterministic down to the smallest scales (it claims), you can't predict the motions of atoms in a gas, because (i) you can't know enough information, and (ii) there's too many of them.
- So use probability.
- Boltzmann did this, and. . . recovered thermodynamics!

Worlds collide.

## faraday, maxwell and electromagnetism

- At the end of the 19th century, electromagnetism was concerned with the properties of electricity and magnetism *and matter*.
- It was only at the turn of the century that Maxwell's equations, and Hertz's experiments, showed that electromagnetism was light.
- But it's *incompatible with Galilean relativity!* When you switch point of view, Maxwell's equations change in an odd way.
- . . . but let's not worry about that.



## einstein and em

Einstein: yes, let's worry about that!

Einstein took two important things from EM and its transformation:

- the transformation properties are important;
- Lorentz's insistence on the field having a separate existence in empty space, providing action at a distance: "at the time [. . . ] it was a surprising and audacious step".



## einstein and planck

- Einstein admired Planck's daring, even though Planck's reasoning was flawed (and Planck surely knew it)
- Planck used thermodynamic arguments to produce an argument for the experimental black-body distribution
- Packets of radiation spring out of Planck's hat



## einstein and quantum mechanics

> *On a heuristic viewpoint concerning the production and transformation of light:* "The undulatory theory of light, which operates with continuous three-dimensional functions, applies extremely well to the explanation of purely optical phenomena [. . . ]. However it should be kept in mind that optical observations refer to values averaged over time and not to instantaneous values. [I]t is conceivable that a theory of light operating with continuous three-dimensional functions will lead to conflicts with experience if it is applied to the phenomena of light generation and conversion."



## qm and thermodynamics (again)

Einstein shows that the *thermodynamic* properties of light (the black-body spectrum) can be explained by imagining that light is a 'gas' of energy packets.

> "The next obvious step is to investigate whether the laws of emission and transformation of light are also of such a nature that they can be interpreted or explained by considering light to consist of such energy quanta"

Explains (i) Stokes' rule for photoluminescence, (ii) the photoelectric effect, and (iii) photoionisation of gases.



## einstein, fields and symmetry

This goes against the grain of Einstein's other work:

- fields are crucial to EM, and particles aren't
- SR enlarges the symmetry group of mechanics to that of EM
- GR enlarges it still further, and makes the gravitational field central to spacetime

. . . but QM is just particles.

## qm isn't good enough

Einstein admired what others had achieved with QM:

> "That this insecure and contradictory foundation was sufficient to enable a man of Bohr's unique instinct and sensitivity [to explain atoms] appeared to me as a miracle. [. . . ] This is the highest form of musicality in the sphere of thought"

but

> "the basic concepts [of QM] have been taken from classical mechanics."



## einstein, podolsky, rosen

- QM says that the wavefunction, $\Psi$, contains all the information – is the thing that is 'real'
- But if two particles are physically separate but part of the same quantum system, and you measure one (non-deterministically), then 'there is an element of physical reality corresponding to the state of the other particle', contra QM
- So QM may 'work', but isn't complete, Einstein says, so that $\Psi$ doesn't contain all the information – isn't 'real'



## epr, john bell and alain aspect

- Einstein suggested 'hidden variables', which we can't measure, but which nonetheless govern the dynamics of particles deterministically
- Bell's theorem draws consequences of hidden variables
- The Aspect experiment shows there can be no hidden variables in QM

But Einstein wouldn't care.



## the problem with qm

EPR wasn't Einstein's real problem with QM, but "The basic concepts [of QM] have been taken from classical mechanics."

For Einstein, QM wasn't rich and simple enough: "one will judge a theory to be the more nearly perfect the simpler a 'structure' it postulates and the broader the group concerning which the field equations are invariant". QM is "a temporary expedient".

GR implies the way that masses move and interact; for QM, as with classical mechanics and EM, you have to add the laws of motion 'by hand', and sit them on top of GR.



## quantum field theory

- QED and QCD are very successful, and are compatible with SR
- They are field theories – no particles
- Mathematically ugly
- Too many free parameters (23 parameters in the Standard Model, which must simply be measured from nature, and which are not inevitable)



## einstein and realism

- "Physics is an attempt conceptually to grasp reality as something that is considered to be independent of its being observed". Only a problem in QM.
- Talked of "faith in the simplicity, ie, intelligibility, of nature: there are no *arbitrary* constants of this kind"

## . . . and theories

- Theories must not contradict experimental fact, but they are judged on “what may briefly but vaguely be characterised as the ‘naturalness’ or ‘logical simplicity’ of the premises”
- “there is no way from experience to the construction of a theory”



## future theories

- GR tells you something precise
- Seems to see QM as sterile. A future theory will contain more structure, and be invariant under a larger group
- Kaluza-Klein theory was one attempt which he briefly endorsed, and he worked on ideas in this area
- QFT doesn’t do this, but unified field theories make a start
- . . . and some string theories do precisely this – GR in 11 dimensions



## epitaphs

“I seem to have been like a small child playing at the seaside, diverting myself in now and again finding a smoother stone or a prettier shell than ordinary, while the great ocean of truth lay all undiscovered before me” – *Newton*

“This exposition has fulfilled its purpose if it shows the reader how the efforts of a life hang together and why they have led to expectations of a certain kind” – *Einstein*