Title: The nature of the wave function in de Broglie's pilot-wave theory

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Abstract: TBA

The nature of the wave function in de Broglie's pilot-wave theory

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The 1927 Solvay Conference

Louis de Broglie presented a new, many-body dynamics.

“Pilot-wave theory”.

Velocity is determined by a wave in configuration space.

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Widespread mythology about this conference:

-- dominated by Bohr-Einstein debate

-- de Broglie's pilot-wave theory "hardly discussed at all"

-- de Broglie presented only the one-body pilot-wave theory

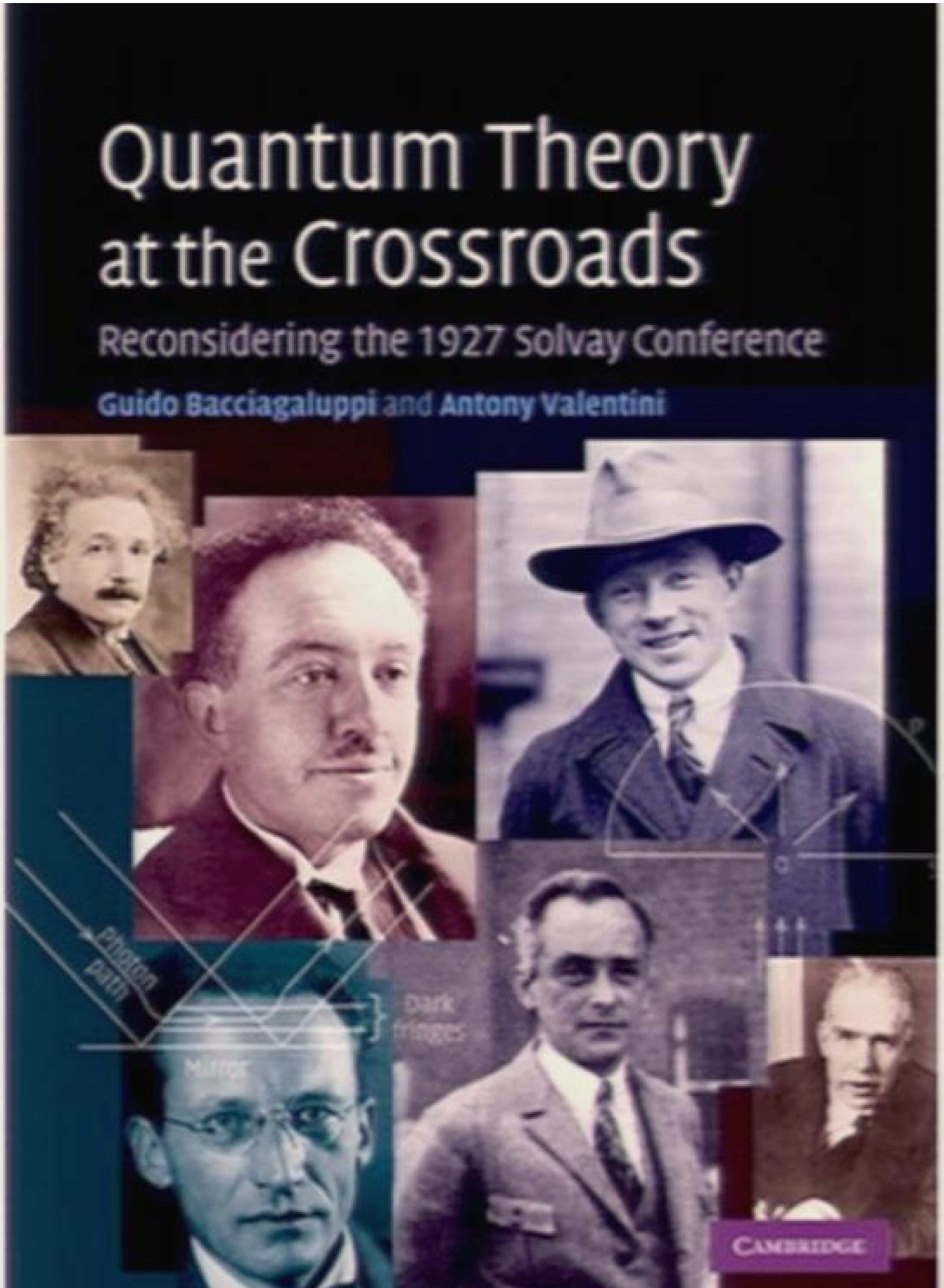
-- de Broglie unable to reply to Pauli's objection (eventually clarified by Bohm)

All completely wrong!

Extensive discussions of all three versions of QM.

De Broglie's reply to Pauli was essentially correct.

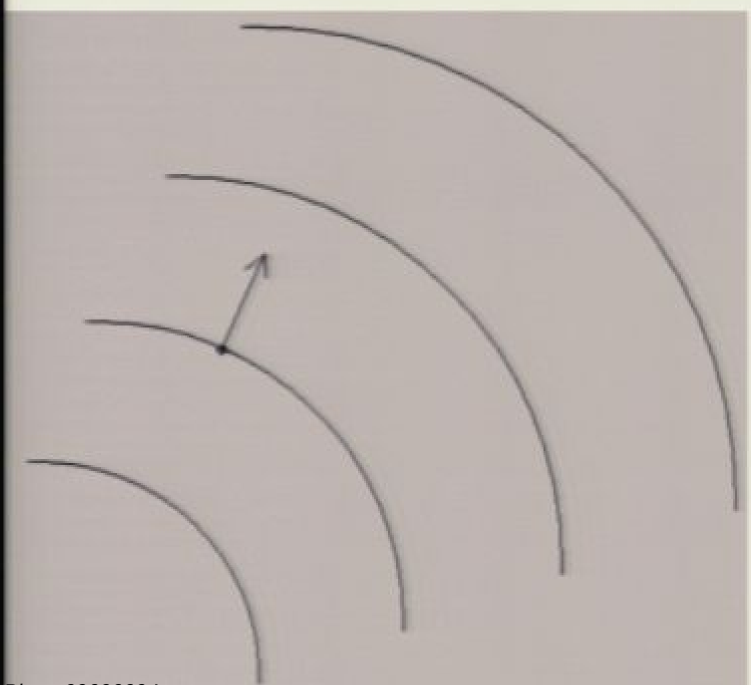
Bohm misunderstood Pauli's (misleading) example.


Quantum Theory
at the Crossroads
Reconsidering the 1927 Solvay Conference
Guido Bacciagaluppi and Antony Valentini
Photon path
Dark fringes
Mirror
CAMBRIDGE

De Broglie's Pilot-Wave Dynamics (1927)

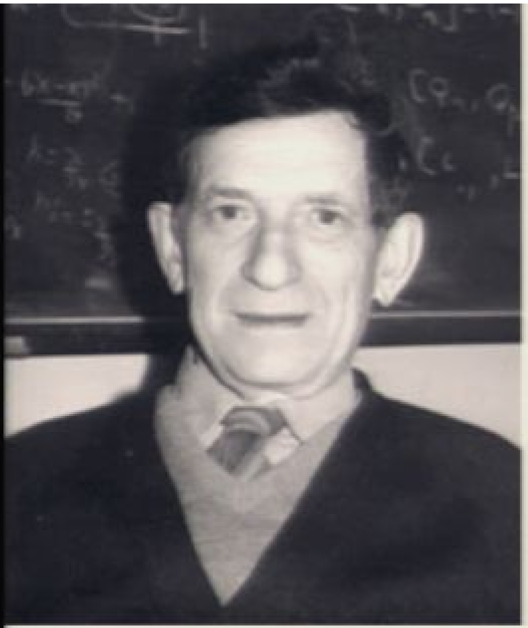
$$m_i \frac{d\mathbf{x}_i}{dt} = \nabla_i S$$

$$i \frac{\partial \Psi}{\partial t} = \sum_{i=1}^{N} -\frac{1}{2m_i} \nabla_i^2 \Psi + V \Psi$$



Get QM if assume initial $P = |\Psi|$

(shown fully by Bohm in 1952; apply dynamics to apparatus)



Bohm's Newtonian version (1952)

$$m_i \frac{d^2\mathbf{x}_i}{dt^2} = -\nabla_i (V + Q)$$

$$Q \equiv -\sum_{i=1}^{N} \frac{1}{2m_i} \frac{\nabla_i^2 |\Psi|}{|\Psi|}$$

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For Bohm, $\mathbf{p}_i = \nabla_i S$ is an initial condition; can be relaxe

For de Broglie, $\mathbf{p}_i = \nabla_i S$ is the law of motion.

De Broglie's dynamics and Bohm's dynamics are differen

"Bohmian mechanics" is a misnomer for de Broglie's dynamic

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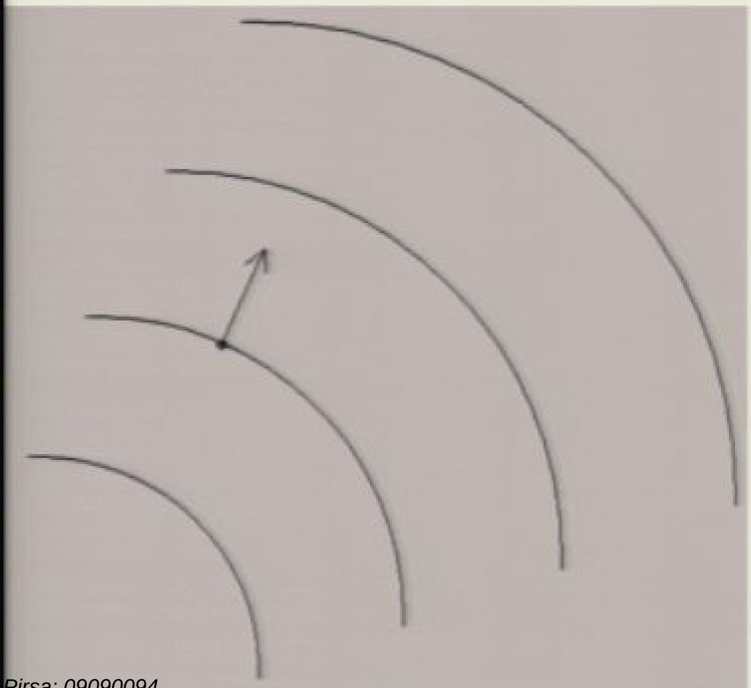

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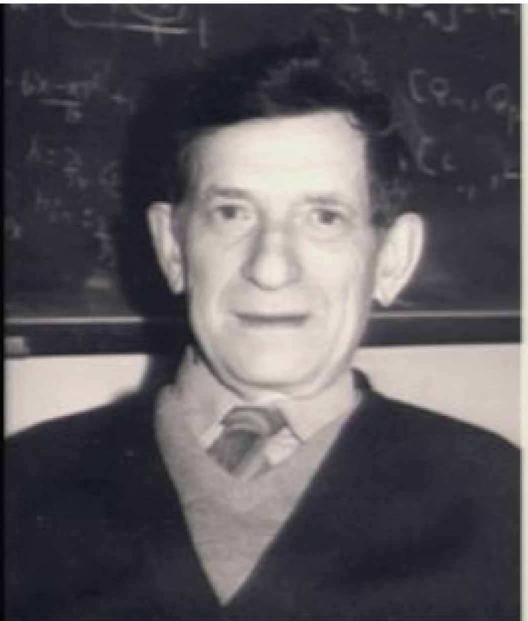

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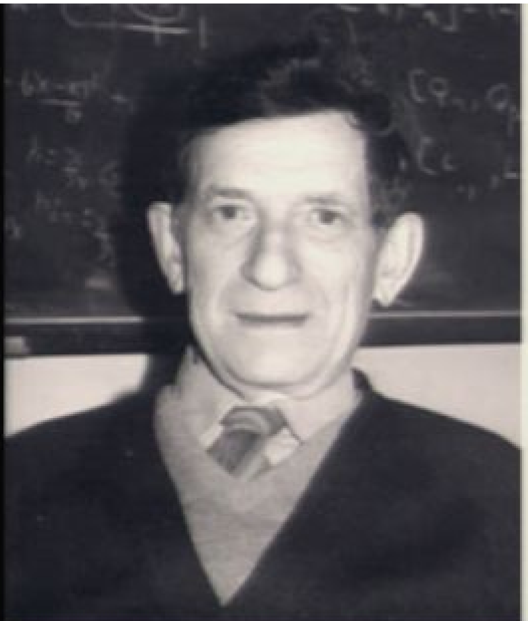

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“Catching up” with de Broglie’s 1927 dynamics

*Bohm 1952: explains full quantum theory of measurement

* Bell 1964: nonlocality is a general feature

* Bell--KS 1966--7: contextuality is a general feature

* Valentini 1991, 2002: nonequilibrium superluminal
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* Montina 2007: exponentially large number of degrees of
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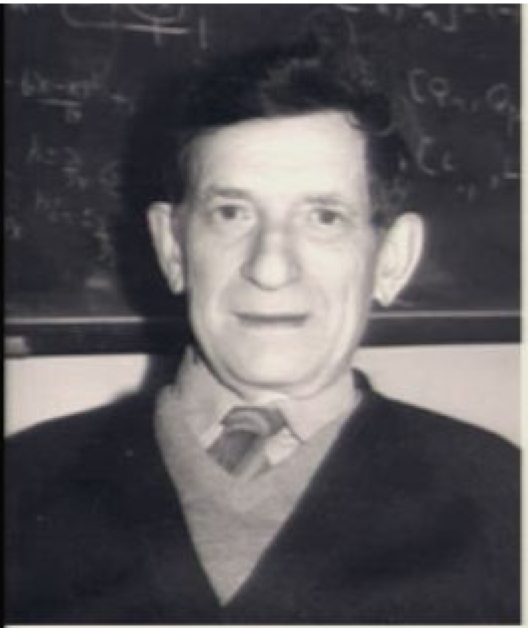

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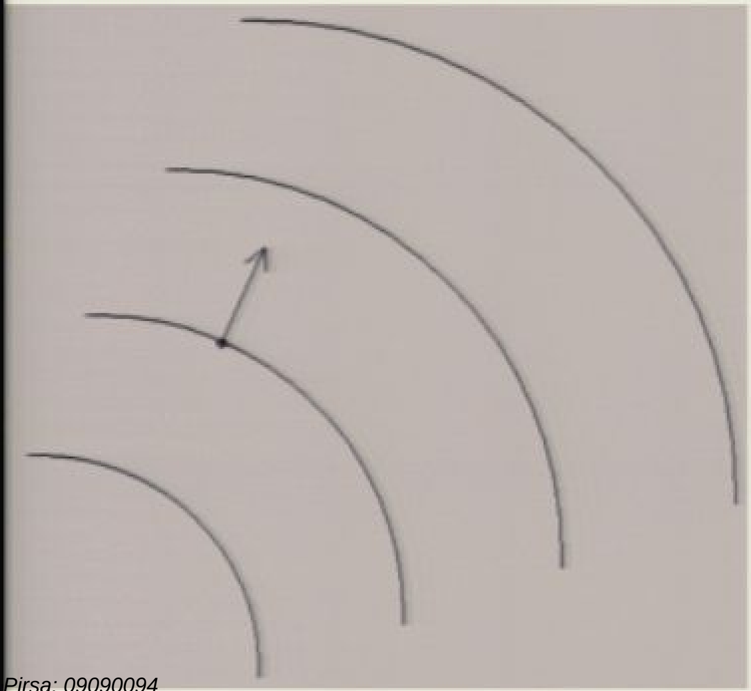

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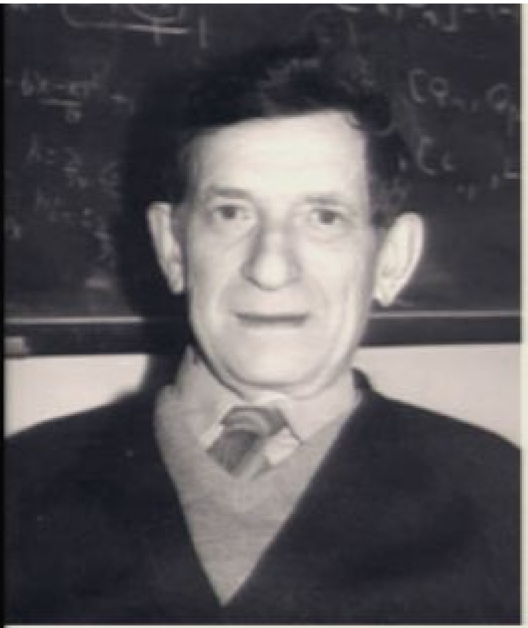

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What is Psi?

Three unconvincing ideas:

1. Ψ is comparable to the electromagnetic field (Bohm 1952)

2. The existence of "only one universe" implies that the universal Ψ cannot be contingent

3. The universal Ψ is lawlike (nomological)

1. Ψ is comparable to the electromagnetic field (Bohm 195

No, because (among other reasons):

There is no notion of "test particle".

If we introduce a test particle to probe psi, we increase th dimension of the space on which psi is defined.

(At the 1927 Solvay conference, Schroedinger claimed that psi was comparable to the EM field, and de Broglie criticised this claim by pointing out that the space in which psi propagates depends on the number of degrees of freedom of the system.)

Very bad comparison.

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2. The existence of "only one universe" implies that the universal Ψ cannot be contingent

(E.g. Goldstein 2009: universal Ψ "is not controllable: it is what it is".)

But cf.

-- spacetime geometry at a cosmological level (flat, expanding, etc)

-- the intergalactic magnetic field

There is only one spacetime geometry for the universe, and only one intergalactic magnetic field.

And yet, the precise form of both objects is a contingency (not determined by physical law).

By the way ...

Beware of statements that "there is only one universe" (except in trivial tautological sense):

Current cosmological theories make it quite plausible that ou observed universe is in fact merely one element of a huge an possibly infinite ensemble.

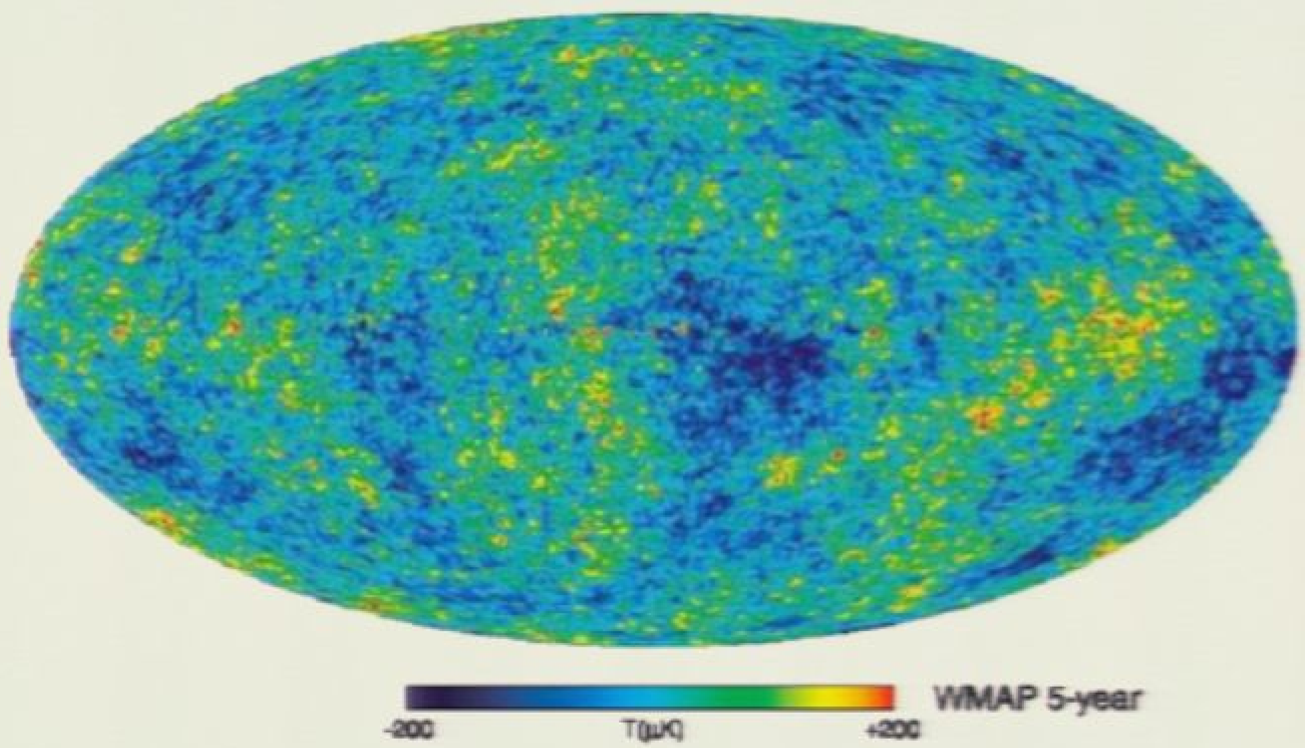
-- one small patch in an infinite flat space (standard model

-- eternal inflation (infinity of pocket universes)

-- multiverse theories (string theory, inflation)

And: practising cosmologists are unconcerned about applying probability theory to "the universe":

E.g. statistical analysis of the cosmic microwave background "only one sky" (assume statistical rotational invariance)



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Duerr, Goldstein and Zanghi 1996:

"This fundamental wave function Ψ, the universal wave function, is static, stationary, and, in the view of many physicists, unique."

Not true:

-- in canonical quantum gravity, solutions for Ψ (satisfying the Wheeler-DeWitt equation and other constraints) are far from unique

-- same kind of contingency we are used to for quantum states elsewhere in physics (Rovelli 2004) (for example in cosmological models, Bojowald, Ashtekar, et al.)

Well, then, what *is* Psi?

A new type of causal agent

More abstract than forces or conventional fields

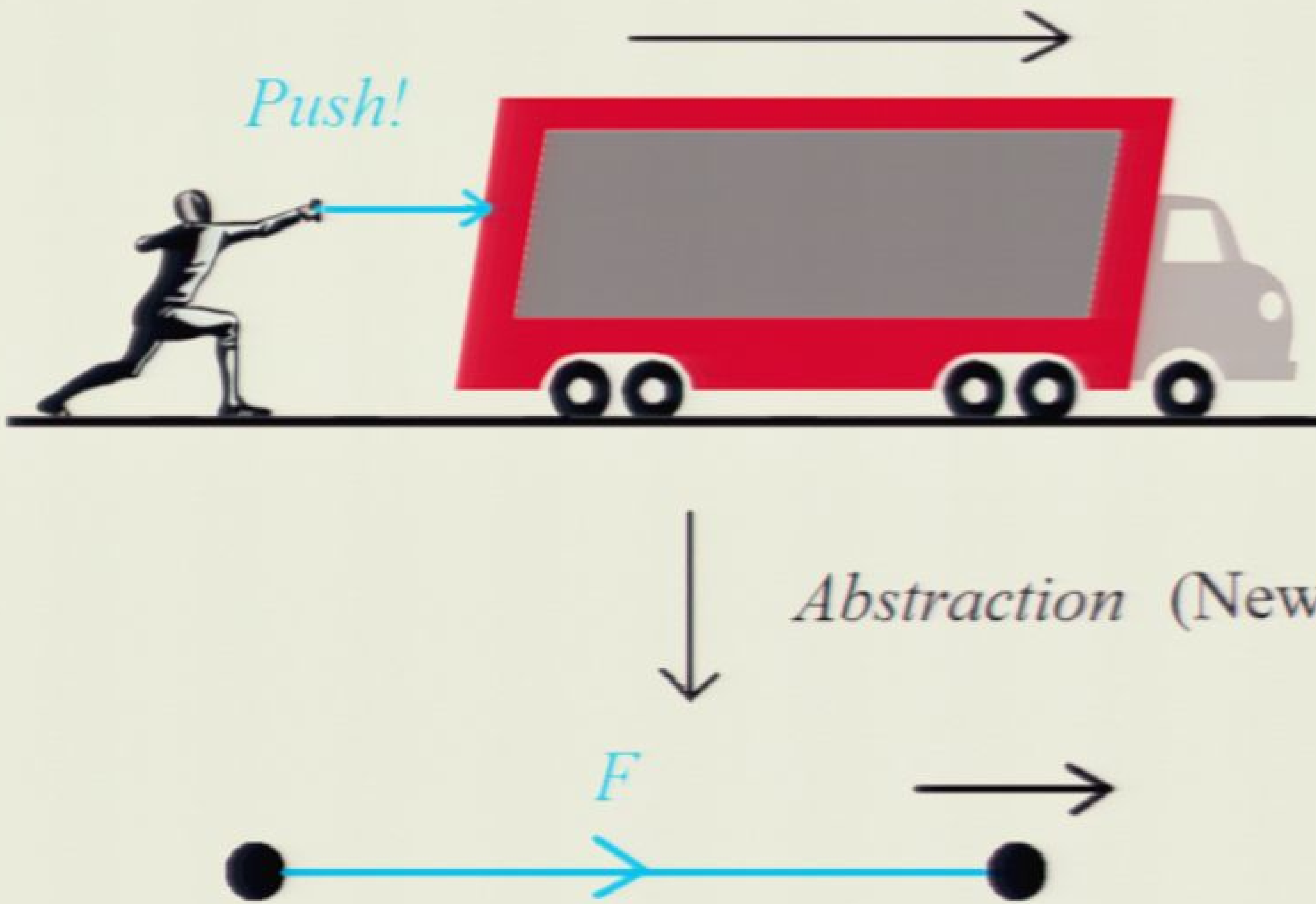
Brief history of causal agents in physics:

-- Forces (Newton, 17^{th} century)

-- Fields (Faraday, Maxwell, 19^{th} century)

-- Pilot waves (de Broglie, 20^{th} century, unrecognised)

Forces



mass × *acceleration* = *force*

Forces cause acceleration of masses

Even at a distance, across empty space:

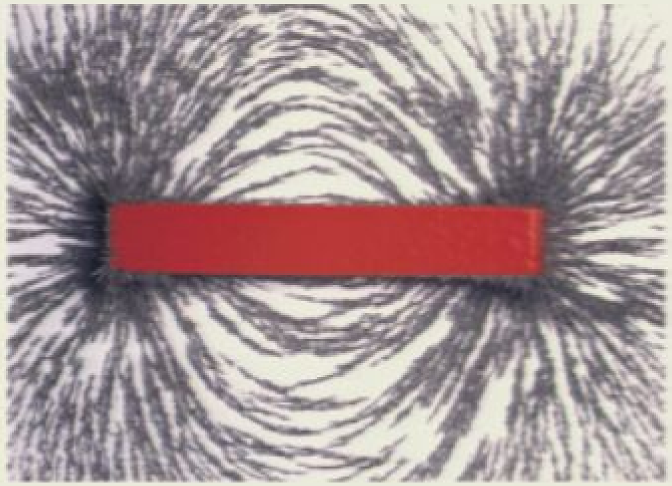
The Moon is "attracted" to the Earth (Newton, 17th century)

Newton never believed it. Provisional theory only.
Wanted a "deeper" explanation (aether, action by contact).

Even so, Newtonian gravitation is usually understood in term
of action-at-a-distance (an irreducible concept).

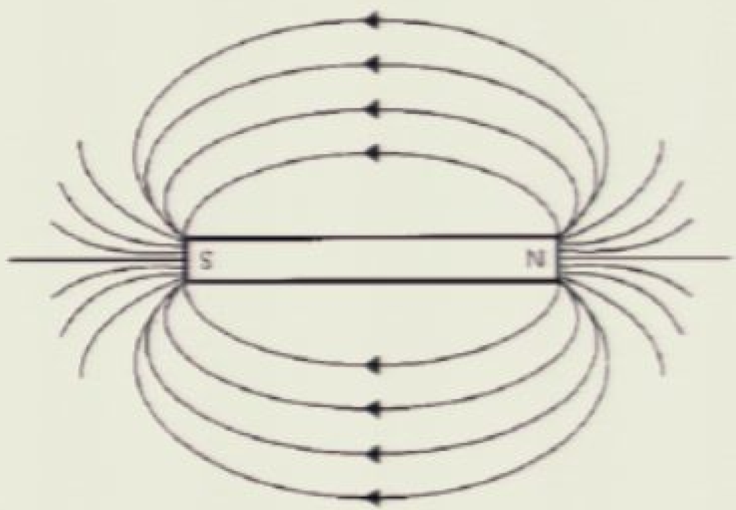
Fields

Iron filings around a bar magnet



Abstraction (Michael Faraday

"Lines of force" around a bar magnet



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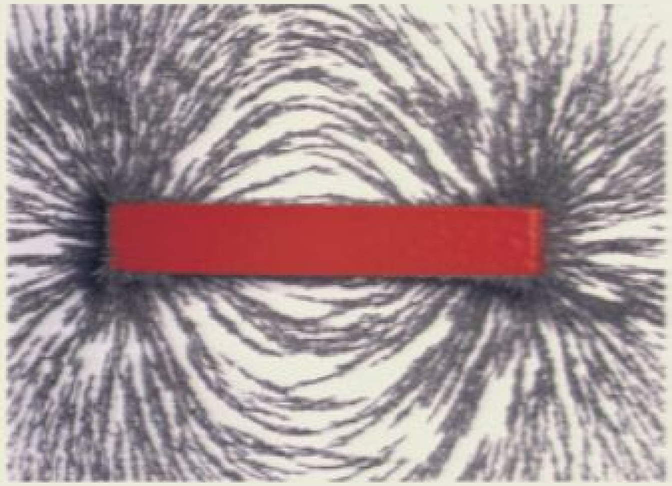

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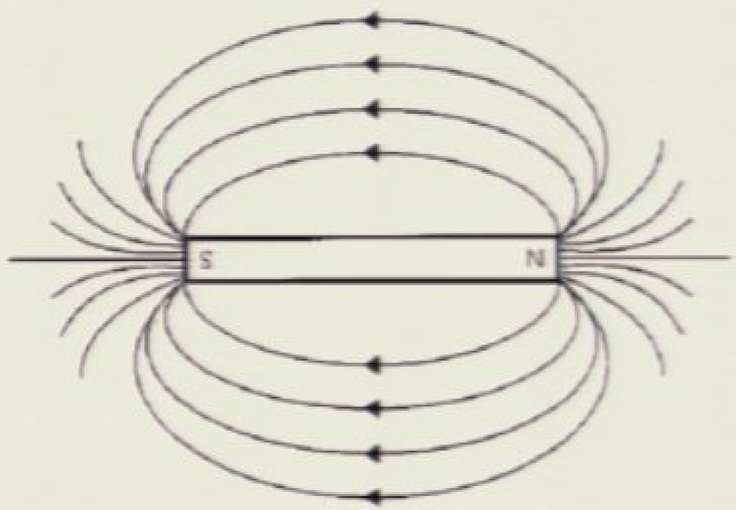
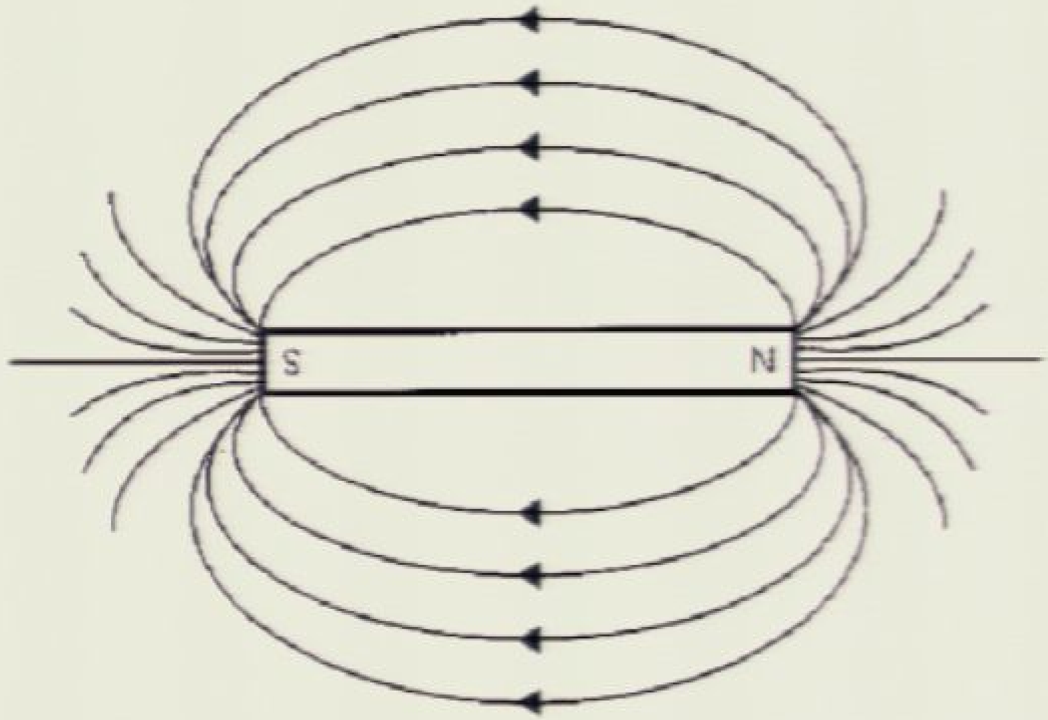


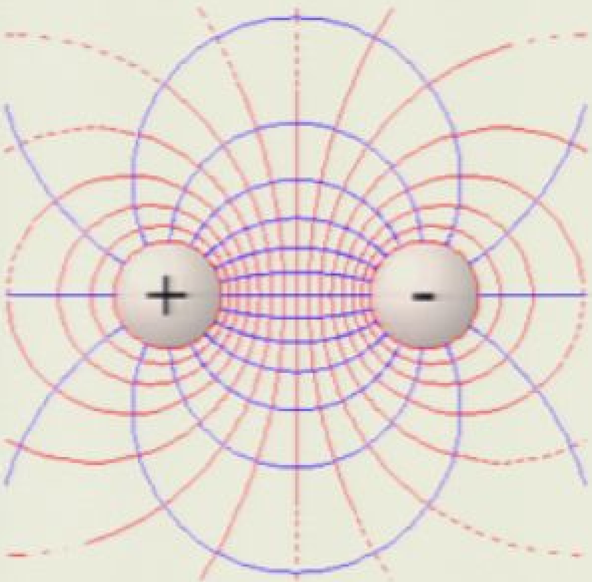
The "force field" exists even in empty space:



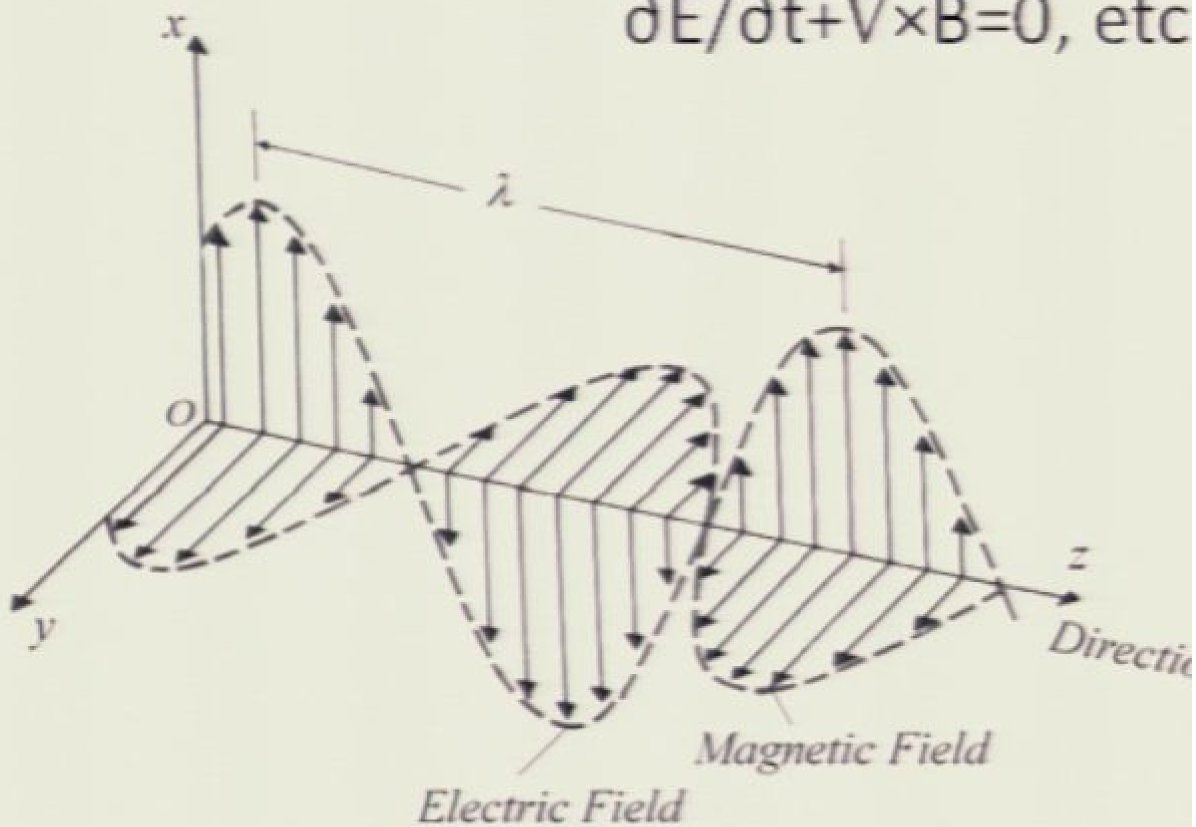
Faraday's ideas seemed nonsensical at the time.

How can a force be present in empty space, where there is no accelerating massive body?

Put in mathematical form by Maxwell:

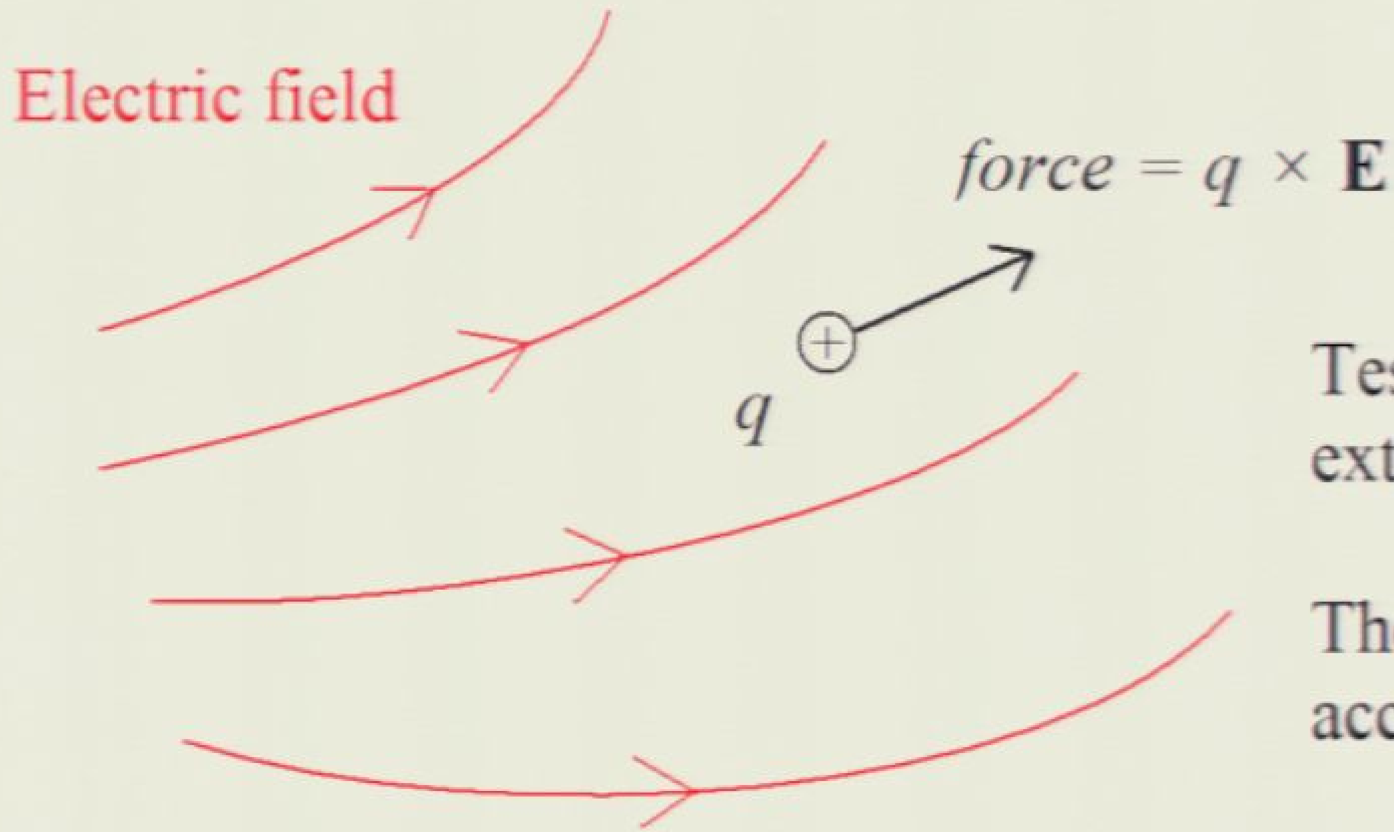


$\partial E/\partial t+\nabla\times B=0$, etc



The success of electromagnetic theory led to the eventual acceptance of Faraday's concept of "field".

What once seemed nonsensical now seems clear:



Test charge in an external field.

The charge is accelerated.

There are fields *even where there are no charges*.

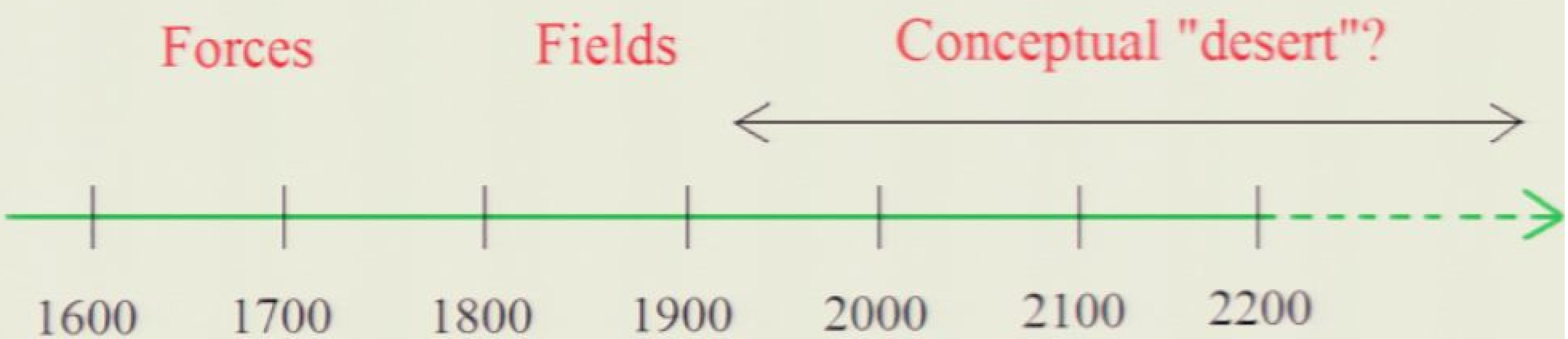
"Inactive" field elements EXIST.

They can propagate alone in empty space.

Is that all?

No new types of causal agent?

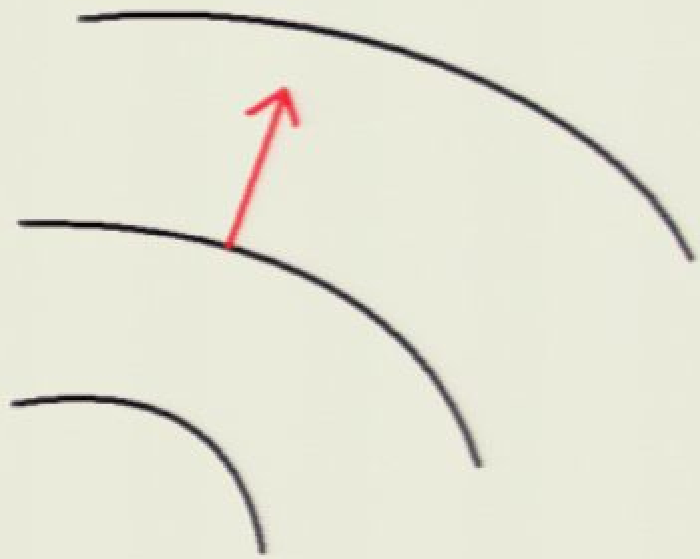
For the rest of physics history?



Actually, in the 1920s ..., de Broglie proposed ..

Pilot Waves

Pilot wave in configuration space



$$m_i \frac{d\mathbf{x}_i}{dt} = \nabla_i S$$

Brief history ...

Pilot Waves

1923--24: de Broglie proposed $m\, d\mathbf{x}/dt = \nabla S$ as a new law of motion (one particle).

-- Unify Maupertuis and Fermat principles

-- Abandon classical dynamics (diffraction in free space)

1926: Schroedinger found the correct wave equation for de Broglie's waves

1925--27: de Broglie tried to *derive* his law of motion $m_i\, d\mathbf{x}_i/dt = \nabla_i S$ (for many particles) from a deeper theory

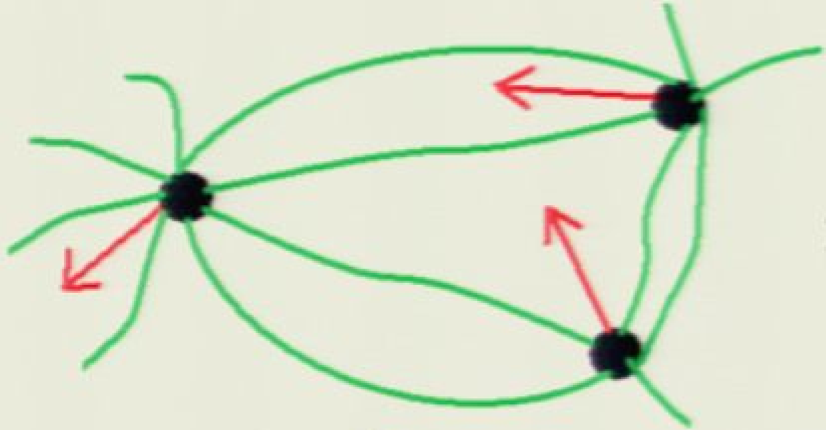
1927: de Broglie gives up, and proposes pilot-wave dynamics in configuration space as a *provisional theory* (cf. Newton, and early attitudes to EM theory)

What kind of deeper theory did de Broglie have in mind?

Pilot-wave theory abstracted from "double solution" theory:

Singular waves in 3-space

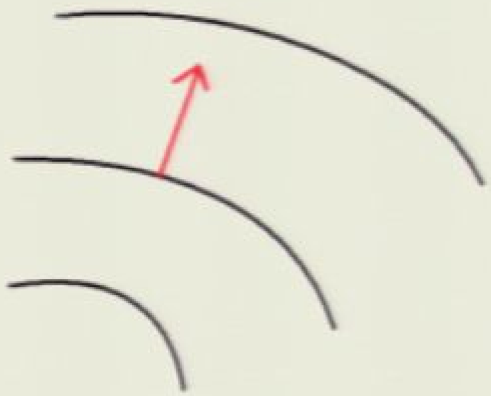
Coupled partial differential equations



$\Rightarrow \quad m_i \frac{d\mathbf{x}_i}{dt} = \nabla_i$ ...

$\downarrow$ *Abstraction* (de Broglie 192...

Pilot wave in configuration space



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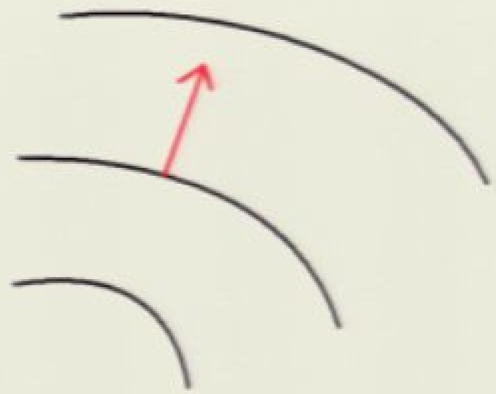
Solve Schrödinger equation in configuration space. Obtain motion of singularities *without having to solve the coupled partial differential equations in 3-space*

Pilot wave in configuration space



$$m_i \frac{d\mathbf{x}_i}{dt} = \nabla_i S$$

What is this thing called Psi? A new type of causal agent ...

-- exists in configuration space, even where there is no configuration ("inactive" elements/packets EXIST)

-- obtained by abstracting away conventional 3-space interaction (fixed interactions between parts)

-- resulting theory is "non-mechanical": interactions between particles are not given by fixed functions of, say, distance; other particles are not the "origin" of forces (Bohm)

Pilot-wave theory abstracted from "double solution" theory:

Singular waves in 3-space

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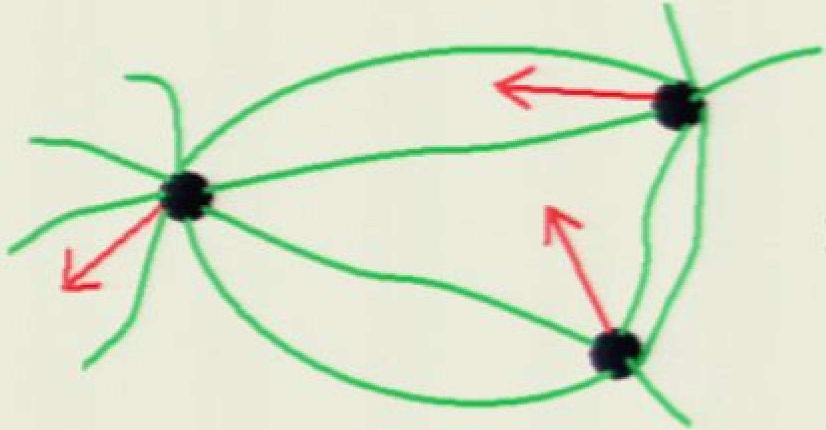
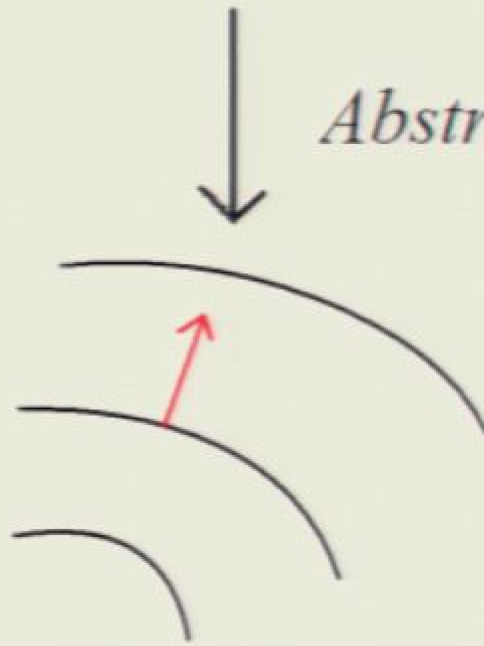


$\Longrightarrow \quad m_i \frac{d\mathbf{x}_i}{dt} = \nabla_i$

Abstraction (de Broglie 192

Pilot wave in configuration space



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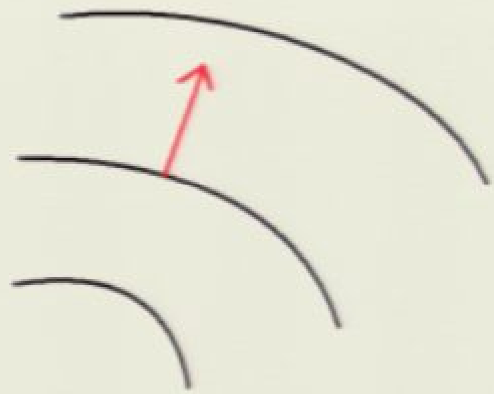

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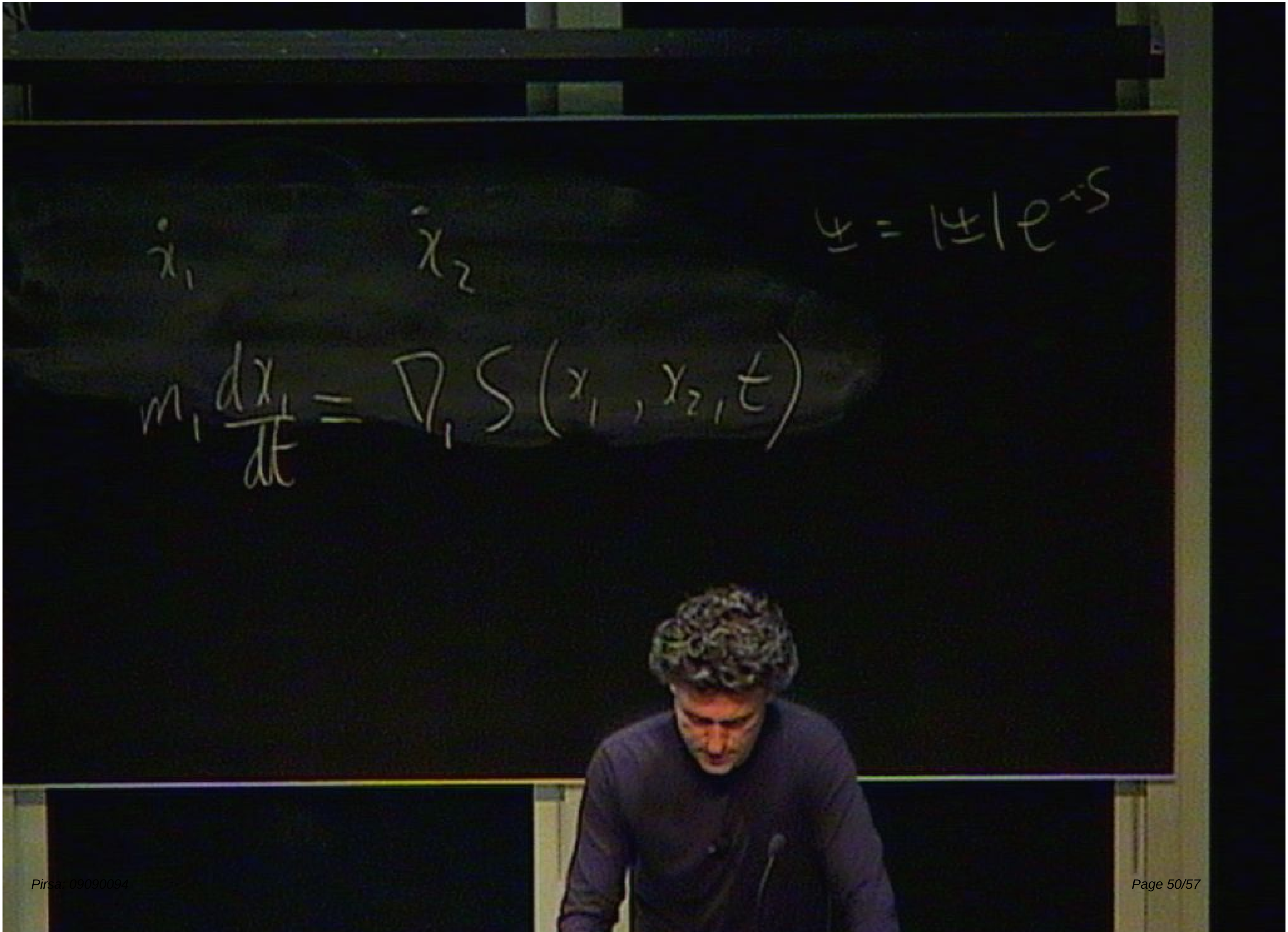

$\dot{x}_1$
$\dot{x}_2$
$\Psi = |\Psi| e^{iS}$
$m_1 \frac{dx_1}{dt} = \nabla_1 S(x_1, x_2, t)$

The dynamics is grounded in configuration space

For example:

-- Lagrangian density $\mathcal{L}$ for field Ψ

-- global phase symmetry $\Psi \longrightarrow \Psi\, e^{i\theta}$

-- Noether current coincides with deBB current (for an arbitrary Hamiltonian given by a differential operator, Struyve and Valentini 2008).

Spacetime symmetries are not central
(natural current in one frame)

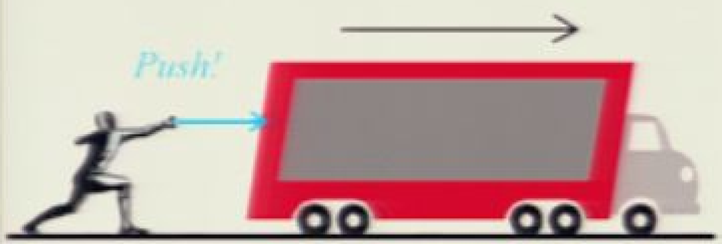
We should learn to think in terms of configuration space

Wave in configuration space provides a natural account of non-locality in 3-space

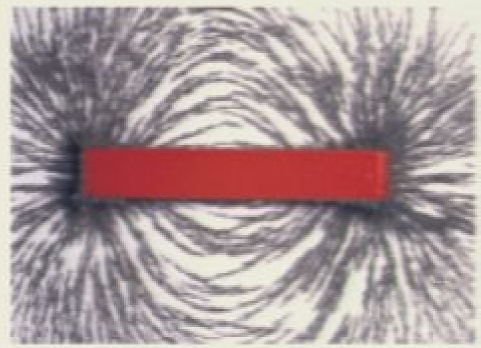
Completely independent of spatial separation

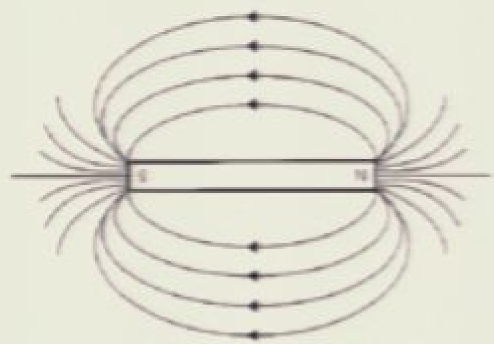
Completely unaffected by matter in between

Forces
17th century

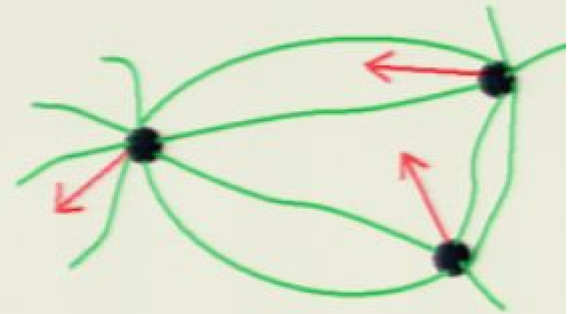


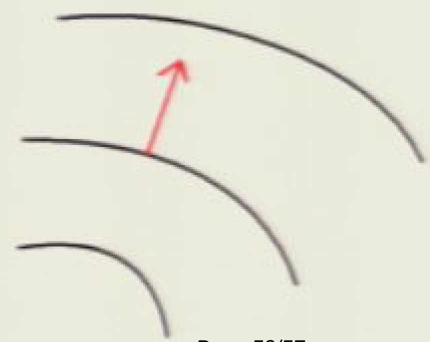
Fields
19th century





Pilot waves
20th /21st century



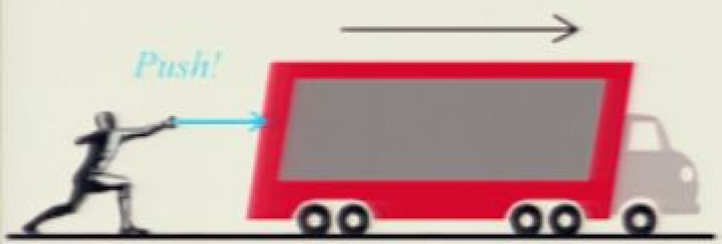


Wave in configuration space provides a natural account of non-locality in 3-space

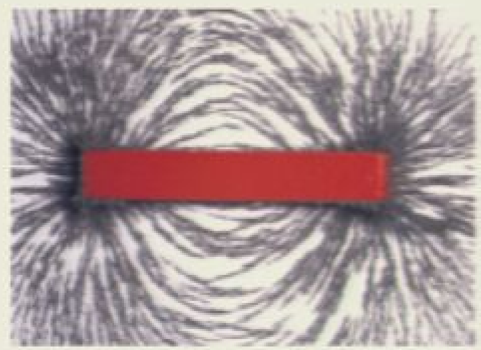
Completely independent of spatial separation

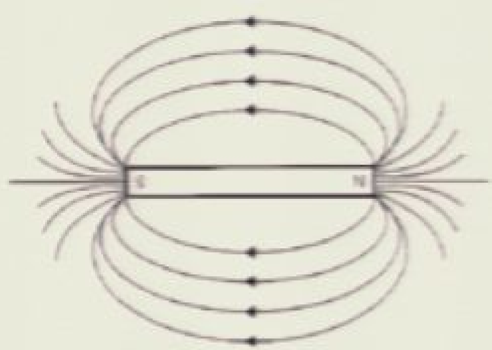
Completely unaffected by matter in between

Forces
17th century

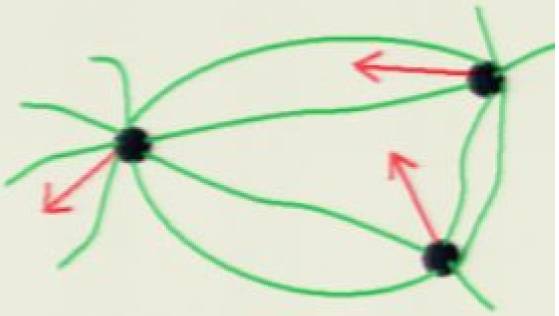


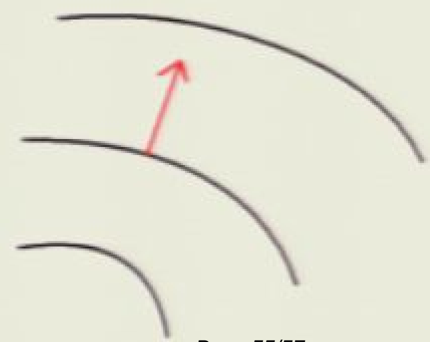
Fields
19th century





Pilot waves
20th /21st century





Important perspective: not the "ultimate theory"

-- Cf. Newtonian gravity, classical EM theory

-- Could try now to go beyond it (cf. general relativity); but perhaps premature

-- Or, to make progress, perhaps (for a while) we must accept this idea and develop its consequences (cf. 18^{th} cent.)

-- Will pilot-wave theory go the way of Newtonian gravity (useful but wrong), or the way of the EM field (an indispensible new concept)?

We'll see!

Forces
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Fields
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Pilot waves
20th/21st century