# An Armchair Guide:

## To Quantum Mechanics

Jonathan Allday

# Session 6:

## Bohm & Hiley

Being An Outsider Is Better

For Being Original

# David Bohm

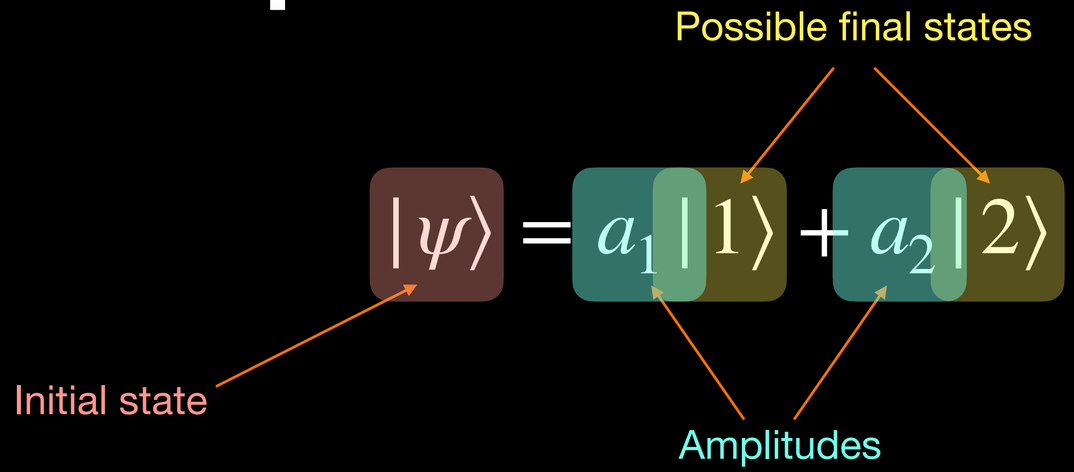
The usual interpretation of the quantum theory is self-consistent, but it involves an assumption that cannot be tested experimentally, viz., that the most complete possible specification of an individual system is in terms of a wave function that determines only probable results of actual measurement processes.

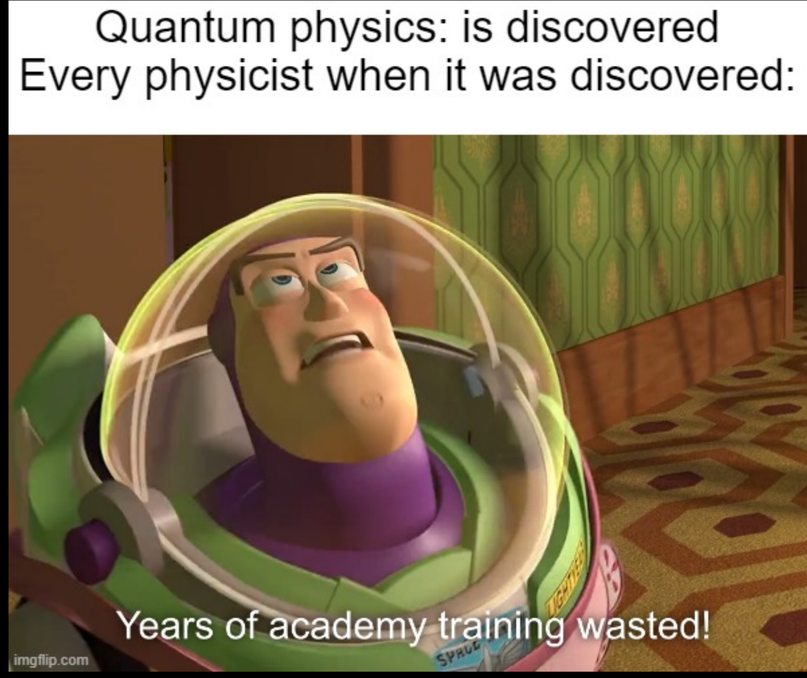
The only way of investigating the truth of this assumption is by trying to find some other interpretation of the quantum theory in terms of at present "hidden" variables, which in principle determine the precise behaviour of an individual system, but which are in practice averaged over in measurements of the types that can now be carried out.

At this stage … the author's principal purpose had not been to propose a definitive new theory, but was rather mainly to show, with the aid of a concrete example, that alternative interpretations of the quantum theory were in fact possible. Indeed, the theory in its original form, although completely consistent in a logical way, had many aspects which seemed quite artificial and unsatisfactory. Nevertheless, as artificial as some of these aspects were, it did seem that the theory could serve as a useful starting-point for further developments, which it was hoped could modify and enrich it sufficiently to remove these unsatisfactory features.

Bohm, D. (1957) Causality and Chance in Modern Physics. London: Routledge & Kegan Paul, Chapter 4

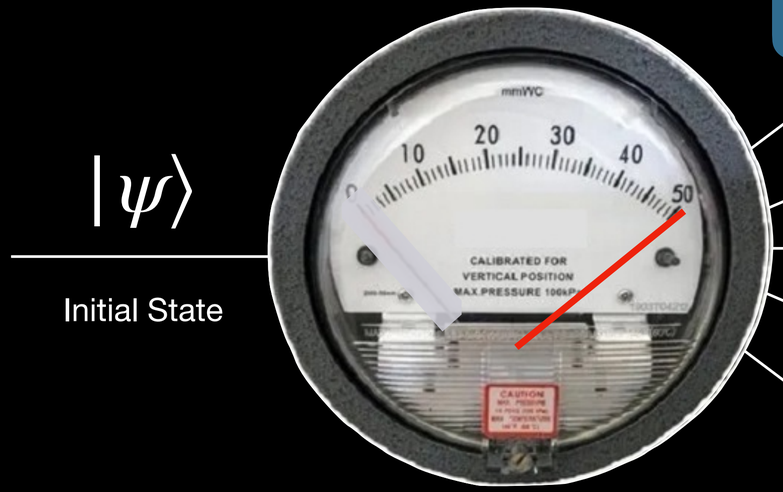
# Quantum Amplitudes




- The amplitude is where the physics lies
  - Amplitudes determine the probability of a result
  - Equations (e.g. Schrödinger's equation) help us calculate the amplitudes in different situations

# Measurement: Collapse of state




$|\psi\rangle$

Initial State

$a_1^2$ $|1\rangle$ Value 1 of property

$a_2^2$ $|2\rangle$ Value 2 of property

$|3\rangle$ Value 3 of property

$a_5^2$ $|4\rangle$ Value 4 of property

$|5\rangle$ Value 5 of property

$$|\psi\rangle = a_1|1\rangle + a_2|2\rangle + a_3|3\rangle + a_4|4\rangle + a_5|5\rangle$$

$|3\rangle$

Whatever is happening there is no calculation that allows us to predict exactly, it is only a probability

# Quantum Ontology

- Often said that quantum mechanics
  - Describes what things are in terms of what they become
  - Seems a fair characterisation
    - The state is a collection of amplitudes for becoming other states
  - Potentially an important clue
    - Should be thinking more of ‘processes’ not ‘things’?

the possibility or 'tendency' for an event to take place has a kind of reality—a certain intermediate layer of reality, halfway between the massive reality of matter and the intellectual reality of the idea or the image—this concept plays a decisive role in Aristotle's philosophy.

In modern quantum theory this concept takes on a new form; it is formulated quantitatively as probability and subjected to mathematically expressible laws of nature.

Wrong Heisenberg

# Basil Hiley

it is well known that Heisenberg favoured the use of potentialities. What is well less known is that Bohm also proposed that the wave function should be thought of in terms of potentialities.

Wrong Basil…

Bohm argued that the potentialities were latent in the particle and that they could only be brought out more fully through interaction with a classical measuring apparatus.

This of course is essentially the conventional view, so why did Bohm bother to make alternative proposals?

It was the complete absence of any account of the actual that troubled him.

In the quantum formalism nothing seemed to happen unless and until there was an interaction with a measuring apparatus. There was no actualisation until some form of instrument was triggered.

Surely something triggered the instrument?

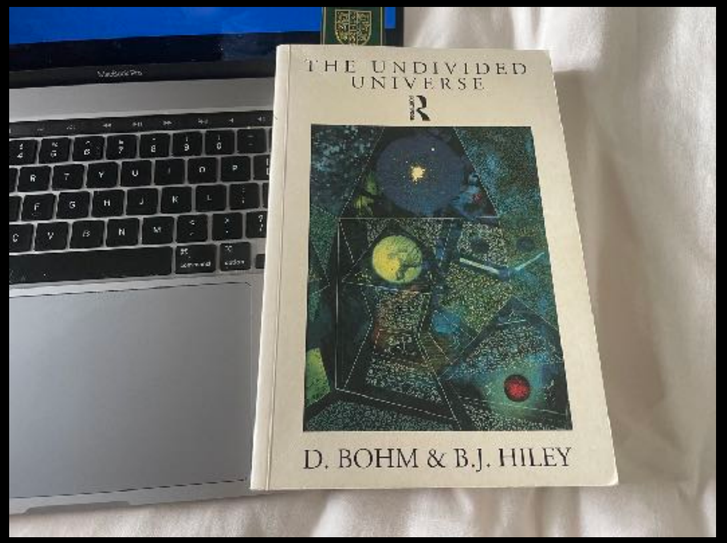
Why was the measuring instrument so different?

Isn't it just another collection of physical processes governed by the same laws of physics?

# Outstanding problems

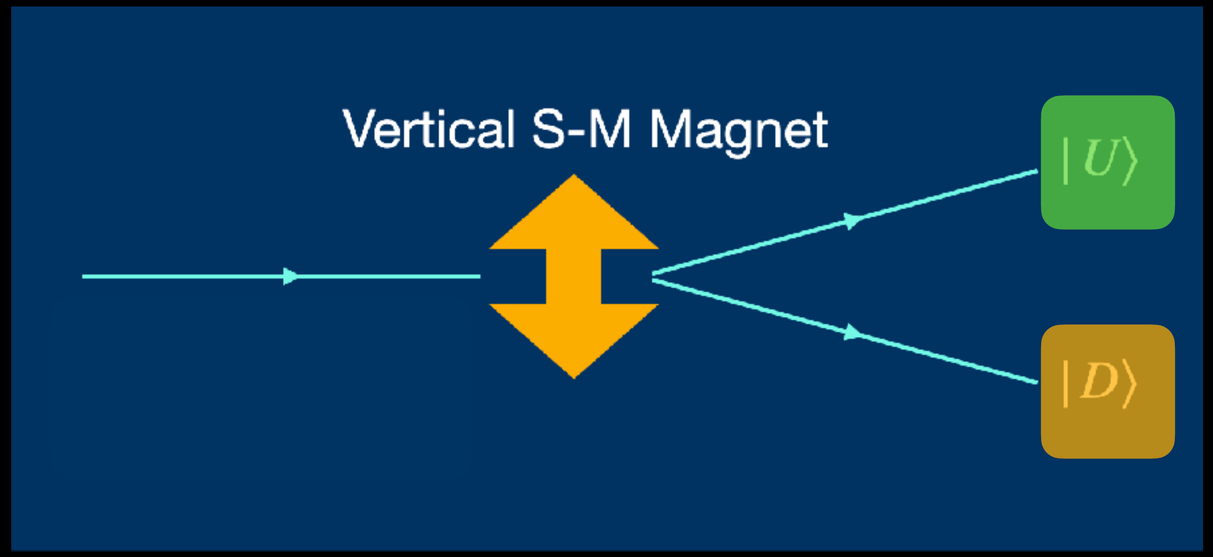
1. What is the wave function?
2. How does measurement trigger the collapse of state?
   - Not predicted or contained in the equations
3. Why is measurement different to any other process?

# Ontological ‘Interpretation’




- More a different way to do quantum theory
  - There is always a particle
    - It does not manifest or pop into existence
  - Each particle is accompanied by its own quantum field - $\psi$
    - This determines a new form of potential energy - the quantum potential
      - Which in turn guides / cajoles (not forces) the behaviour of the particle
  - Probability comes in:
    - As we cannot state the exact initial properties (position / momentum) of each particle
    - This is not a quantum probability - it is the more familiar ‘probability due to ignorance’

# More on superpositions

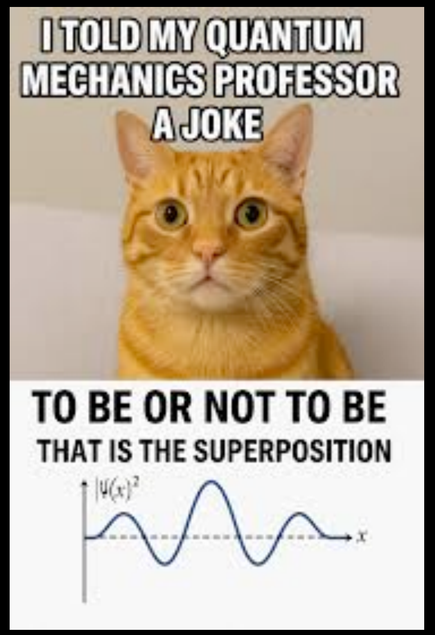



$\frac{2}{3}$

$\frac{1}{3}$

Amplitudes

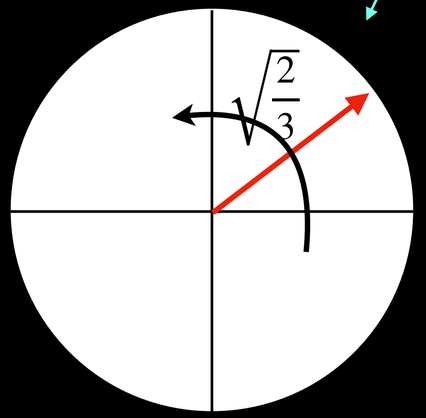
$$\Psi = \sqrt{\frac{2}{3}}|U\rangle + \sqrt{\frac{1}{3}}|D\rangle$$

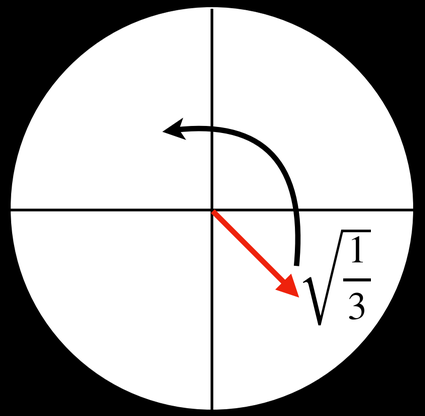


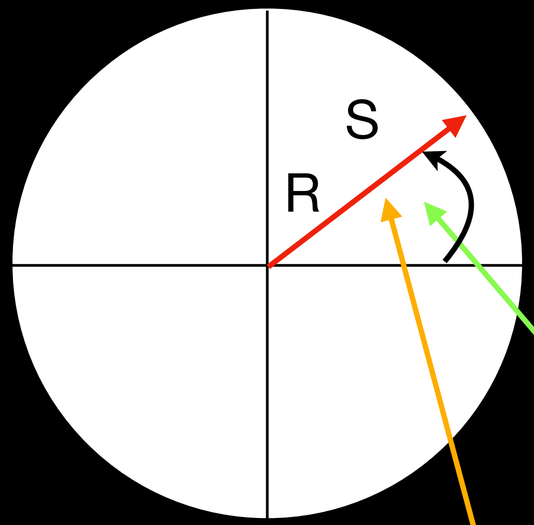

Each amplitude has a ‘phase’

Changes with time

At a rate that depends on energy…






$$\psi = Re^{iS/\hbar}$$

# The Flip

Schrödinger's Equation

$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial^2 x} + V\psi = i\hbar\frac{\partial\psi}{\partial t}$$

Kinetic Energy

Classical Potential Energy

Total Energy

Now, insert

$$\psi = Re^{iS/\hbar}$$

# Get two equations…

$$-\frac{\partial\left(R^2 v\right)}{\partial x}=\frac{\partial R^2}{\partial t}$$

$$P = R^2$$

Conservation of probability…

$$\frac{1}{2m}\left(\frac{\partial S}{\partial x}\right)^2 - \frac{\hbar^2}{2m}\frac{1}{R}\frac{\partial^2 R}{\partial x^2} + V = -\frac{\partial S}{\partial t}$$

Kinetic Energy

¿Que?

Classical Potential Energy

$$\text{momentum} = \frac{\partial S}{\partial x}$$

$$\text{energy} = -\frac{\partial S}{\partial t}$$

$$\frac{1}{2m}\left(\frac{\partial S}{\partial x}\right)^2 - \frac{\hbar^2}{2m}\frac{1}{R}\frac{\partial^2 R}{\partial x^2} + V = -\frac{\partial S}{\partial t}$$

¿~~Que~~? Not ‘Que’ - Q

This equation can be regarded as a generalised expression for the conservation of energy provided we regard Q as a new form of potential energy which is negligible in the classical world and is apparent only in quantum systems.

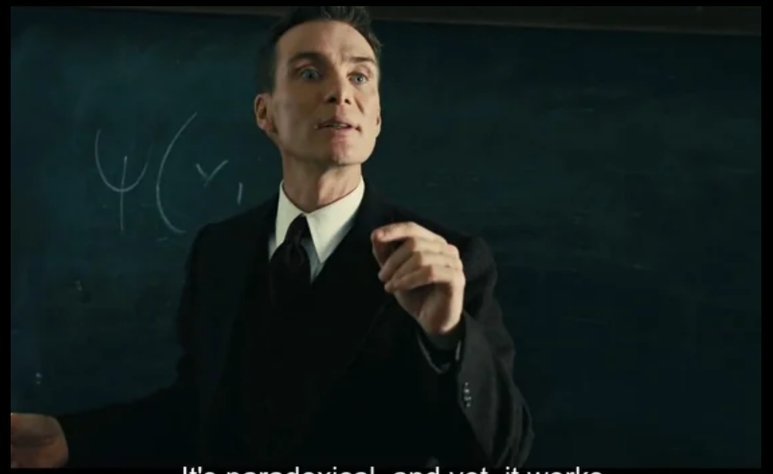
This energy has traditionally been called the quantum potential energy.

It should not be thought as the source of some mysterious new force to be put into the Newtonian equations of motion

# Its quantum potential time…

$$-\frac{\hbar^2}{2m}\frac{1}{R}\frac{\partial^2 R}{\partial x^2}$$

Depends on ‘hbar’ - sets the ‘quantum scale’



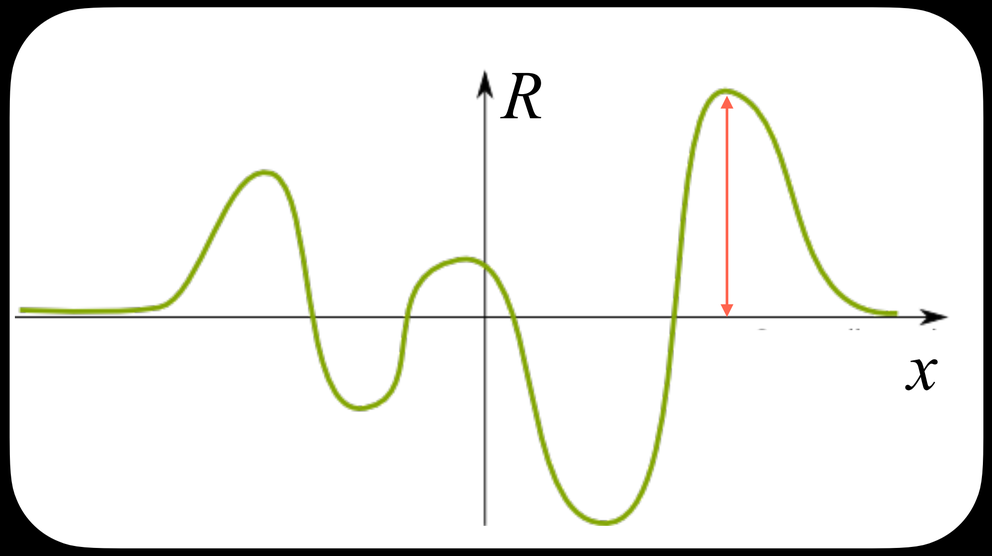

Cillian Murphy

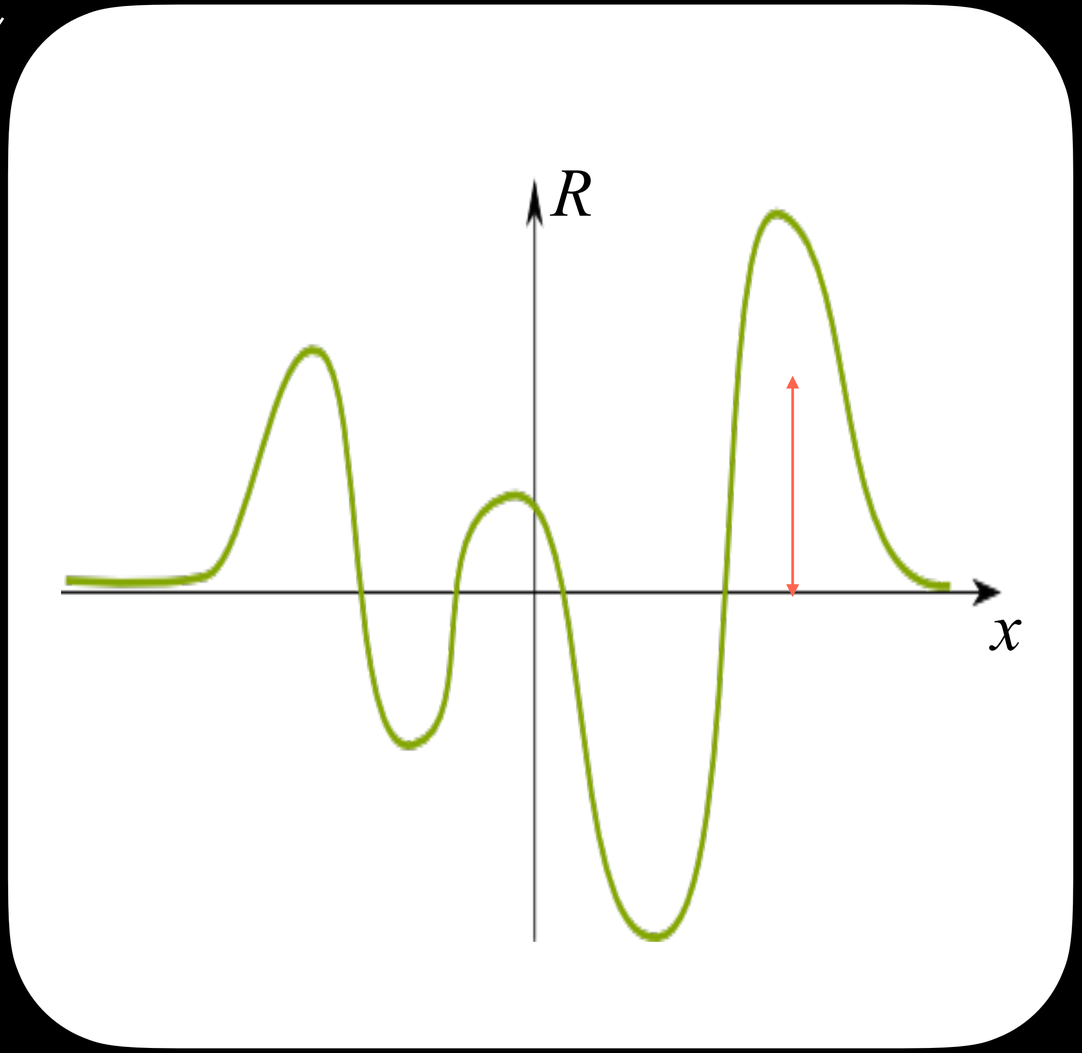
Oppenheimer

Classical physics folds in when the quantum potential is too small to worry about

$$Q = -\frac{\hbar^2}{2m}\frac{1}{R}\frac{\partial^2 R}{\partial x^2} = Q$$

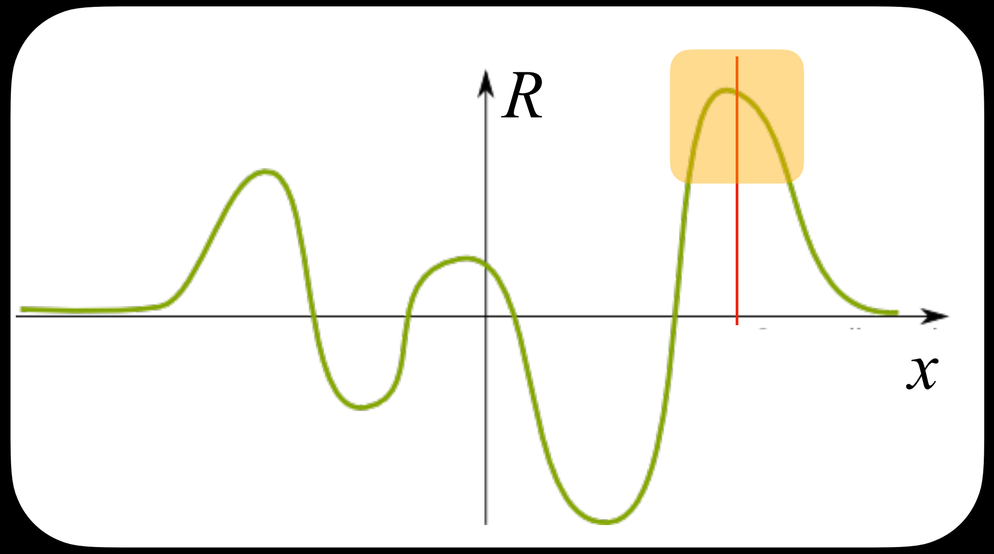
replace $R$ by $2R$



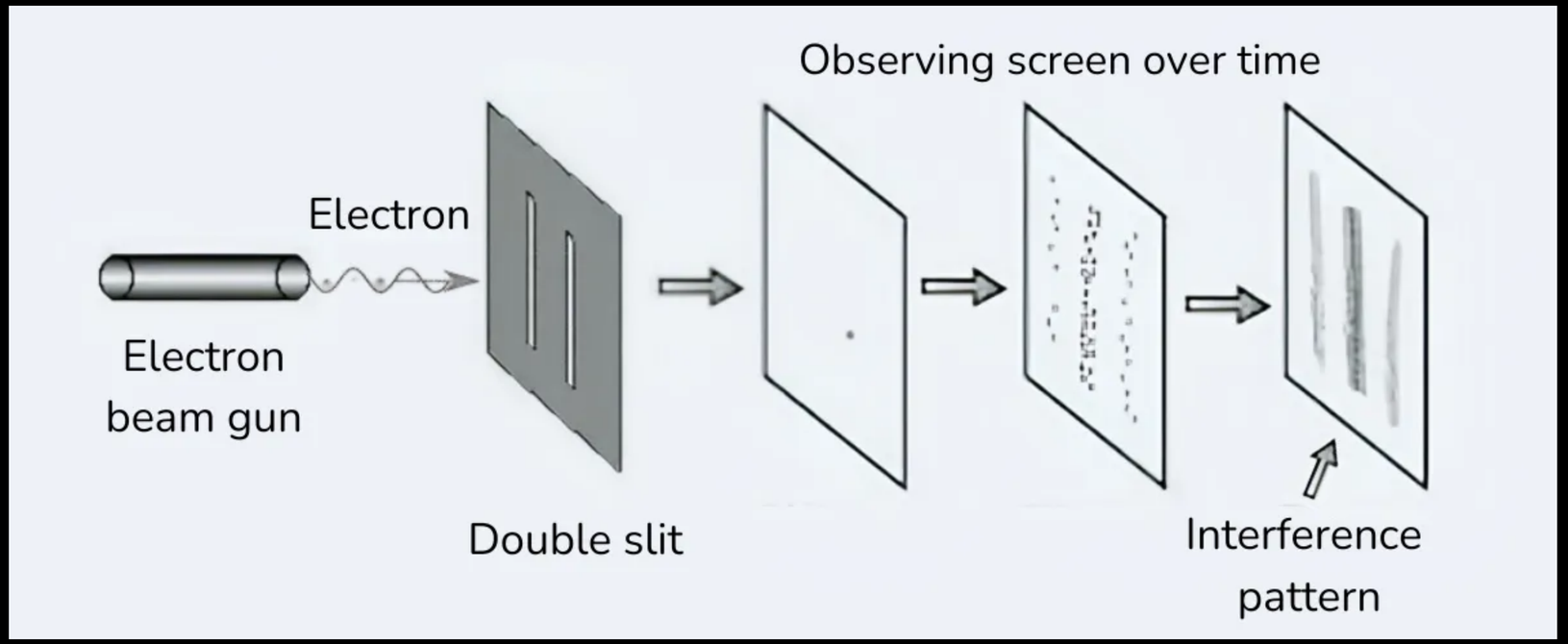
$$Q \equiv -\frac{\hbar^2}{2m}\frac{1}{R}\frac{\partial^2 R}{\partial x^2}$$

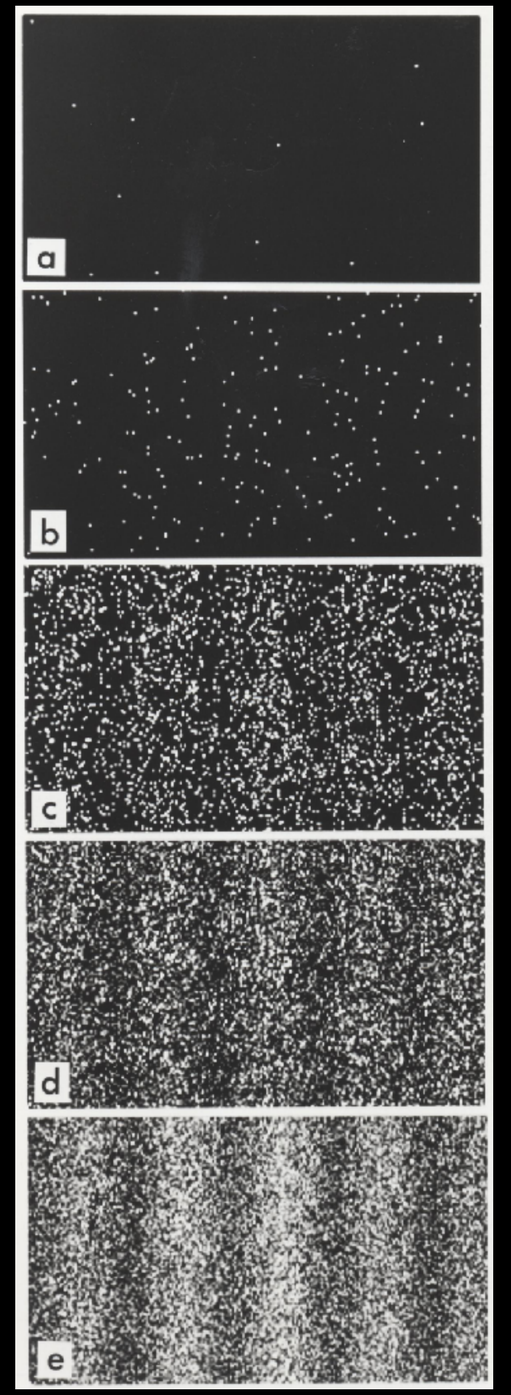
Its the *shape* of $R$, not the scale…




- Like overlapping waves:
  - The shape in a region
  - Determined by everywhere else
  - The full experimental arrangement

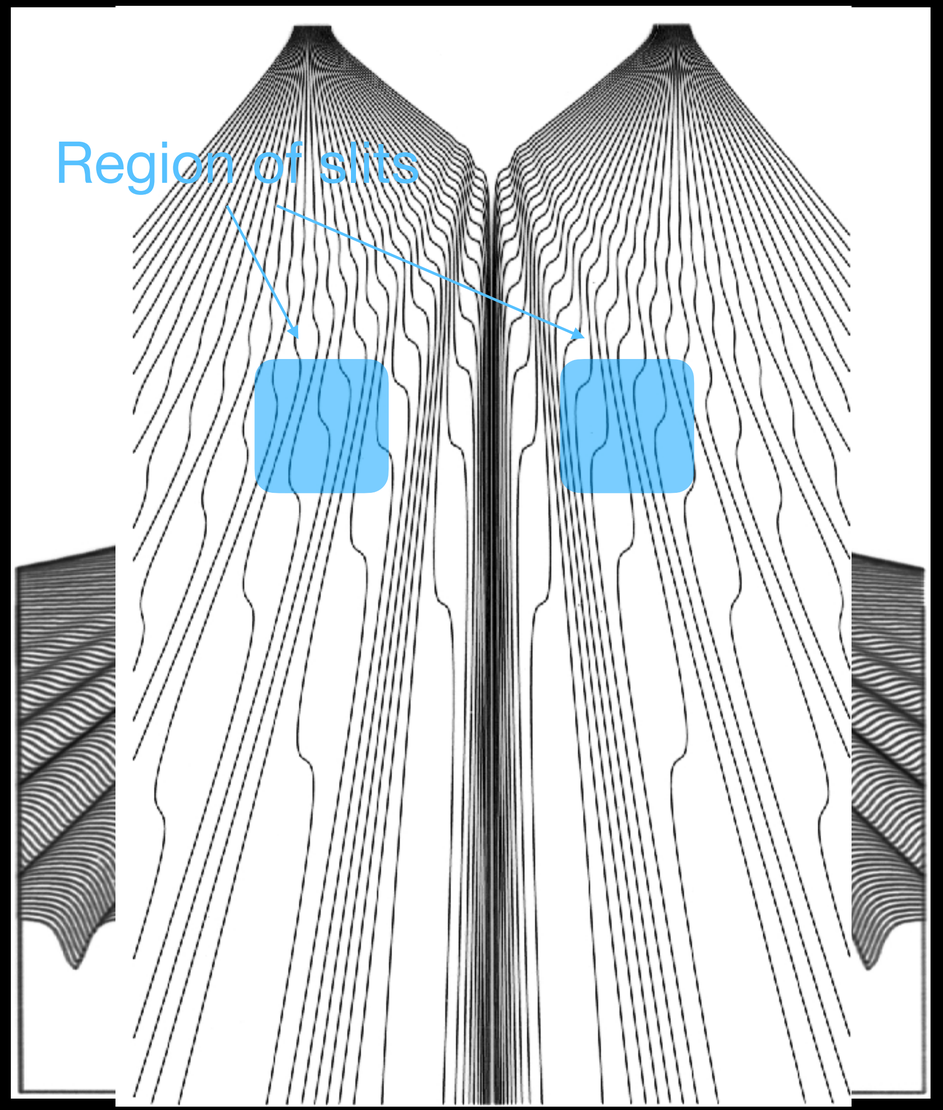
# Double slit


Observing screen over time
Electron
Electron
beam gun
Double slit
Interference
pattern


a
b
c
d
e

# Ontological view…

- The electron is always a particle
- Both the electron and the $\psi$ wave arrive at the slits
- The shape of the $\psi$ wave after the slits
  - (Hence the quantum potential, $Q$)
  - Is in-formed by the whole experimental arrangement
    - $\psi$ ‘passes through’ both slits - interference
    - *$Q$ guides the electron through one slit or the other*
      - depending on its starting point
  - Arrives at the screen
  - Very non-classical trajectories - not straight even in free space…




The Bohm trajectories for a double slit experiment

Electron trajectories under influence of $Q$

i.e. each one has a field, but they look the same…

While all the electrons … have essentially the same form of the quantum field and therefore of the quantum potential, they will all approach the slit system from different starting points. …we may expect an essentially random distribution of such incident electrons. The resulting trajectories … are then bunched into a series of dense and rare regions. These evidently constitute what are commonly called interference fringes.

This introduces several new features into the movement.

First of all, it means that particles moving in empty space under the action of no classical forces need not travel uniformly in straight lines.

This is a radical departure from classical Newtonian theory.

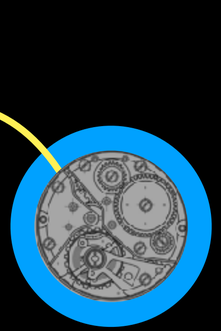
Moreover, since the effect of the wave does not necessarily fall off with the distance, even remote features of the environment can profoundly affect the movement.

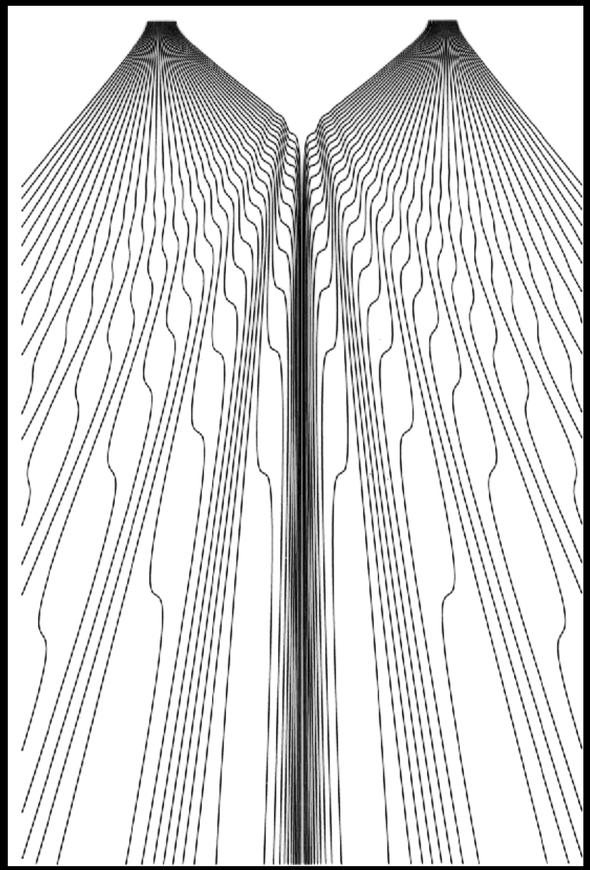
# Important!

- $Q$ is not creating a force on the electron
- The electron has some ‘internal mechanism’
  - Governing its self-movement
  - Influenced by $Q$
  - $Q$ contains active information

… while the Newtonian potential drives the particle along the trajectory, the quantum potential organises the form of the trajectories in response to the experimental conditions

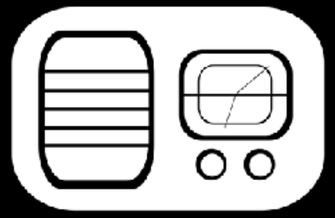
Self-motion of electron

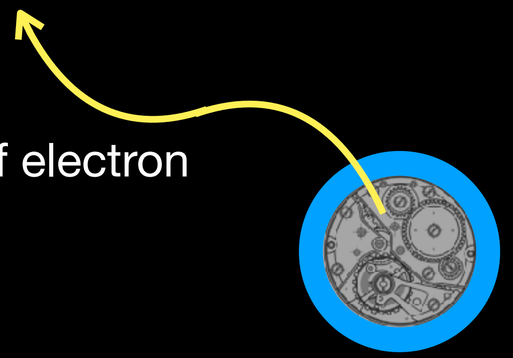




Electron trajectories under influence of $Q$

# Radio analogy….





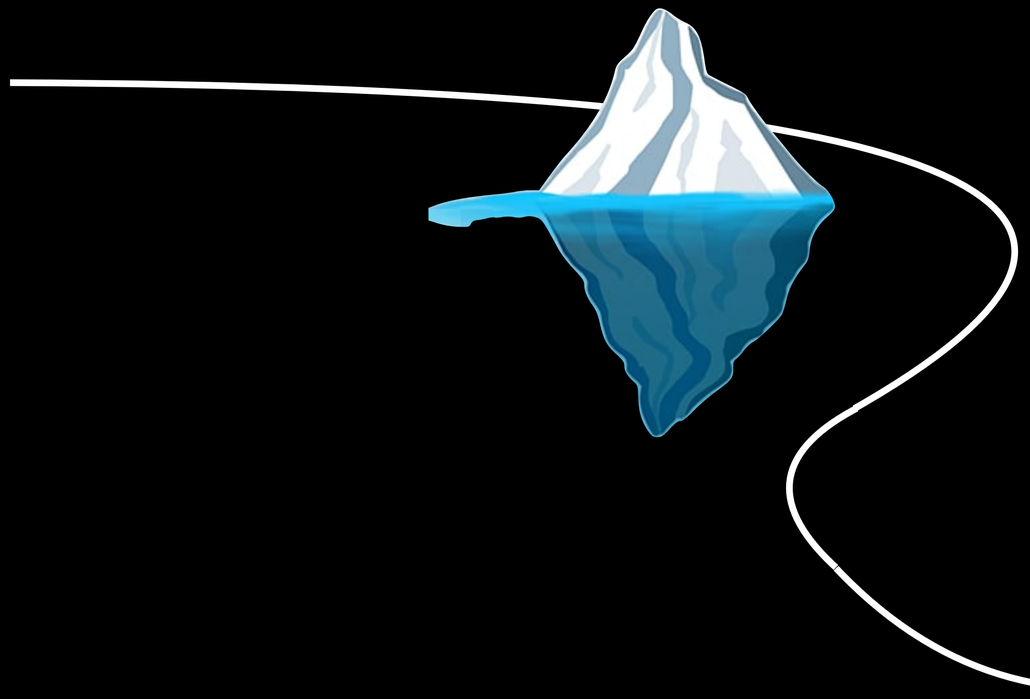

- The signal is the pattern of the radio wave
- In-forms the energy flowing through the radio
  - To make the sound….
- So the electron is in-formed to produce self-motion

Here, too, the effect of the radio waves is independent of their intensity and depends only on their form.

The essential point is that the ship is moving with its own energy, and that the form of the radio waves is taken up to direct the much greater energy of the ship.

We may therefore propose that an electron too moves under its own energy, and that the form of the quantum wave directs the energy of the electron.

# Ship Navigation



Form of the radio

waves directs the ship

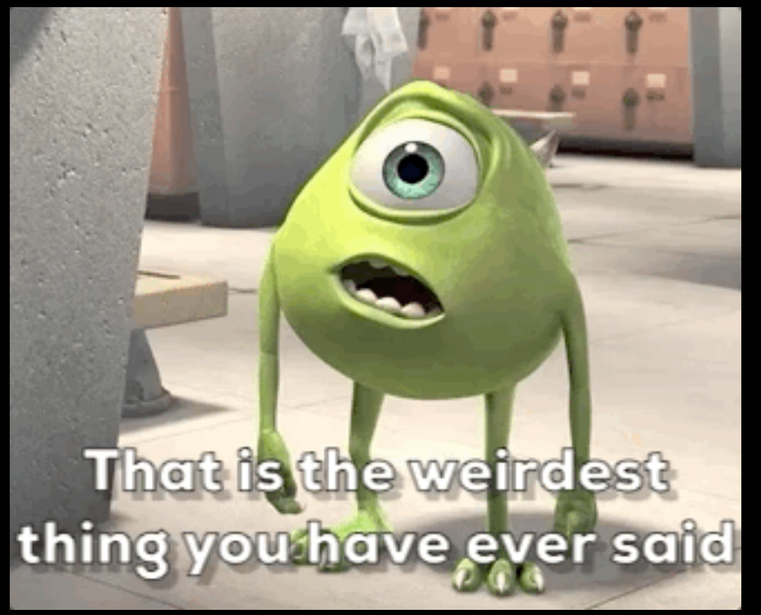
Small energy (radio) in-forms large energy (ship)

… we do not attempt to explain the guidance relation in a simple mechanical way …. Instead we are appealing to the notion that a particle has a rich and complex inner structure which can respond to information and direct its self-motion

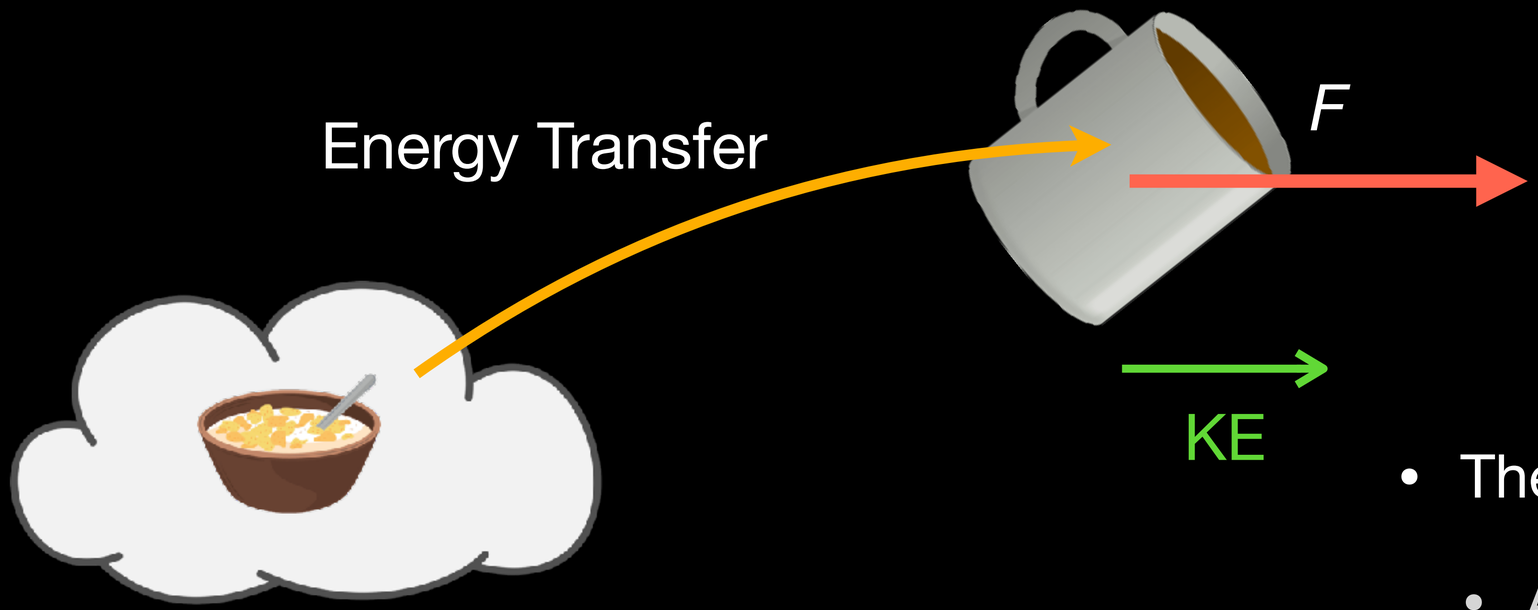
…between the shortest distances now measurable in physics (of the order of $10^{-16}$ cm) and the shortest distances in which current notions of space time probably have meaning which is of the order of $10^{-33}$ cm, there is a vast range of scale in which an immense amount of yet undiscovered structure could be contained. …Moreover, since the vacuum is generally regarded as full … with an immense energy of fluctuation…it may be further suggested that ultimately the energy of this particle comes from this source. (Some of it may also come from the rest mass of the particle)

# Q is a weird thing…

- Not like classical potential energy
  - No source…
    - Gravity ⇒ mass
    - Electromagnetism ⇒ current / charge
  - As no source, nothing to ‘push back against’
    - There is no energy flow
    - Energy in Q is small compared with other energies in the system
  - Effect scale independent
    - Q influenced by the whole experimental configuration
      - No matter how distant…



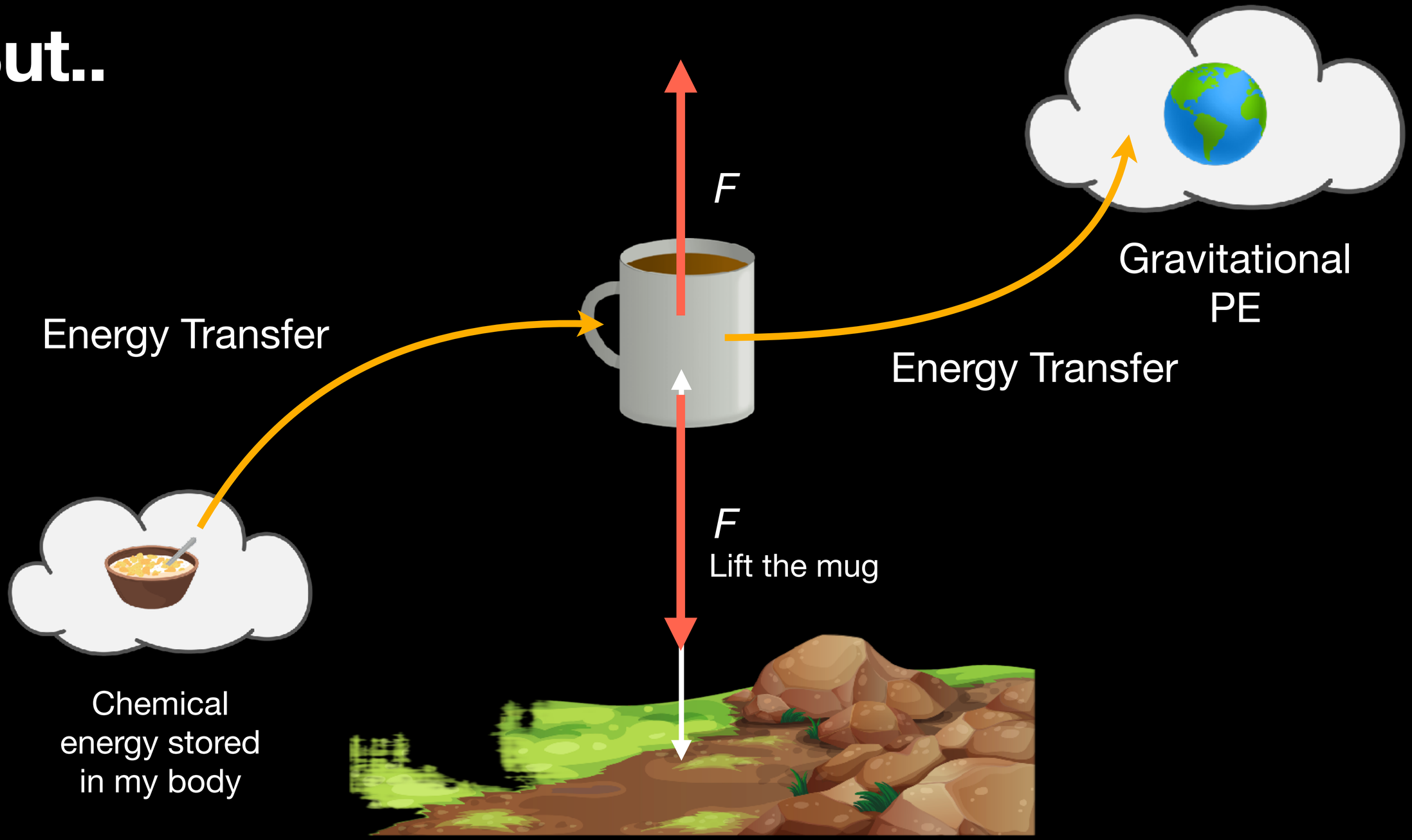
# How do potential energies behave…



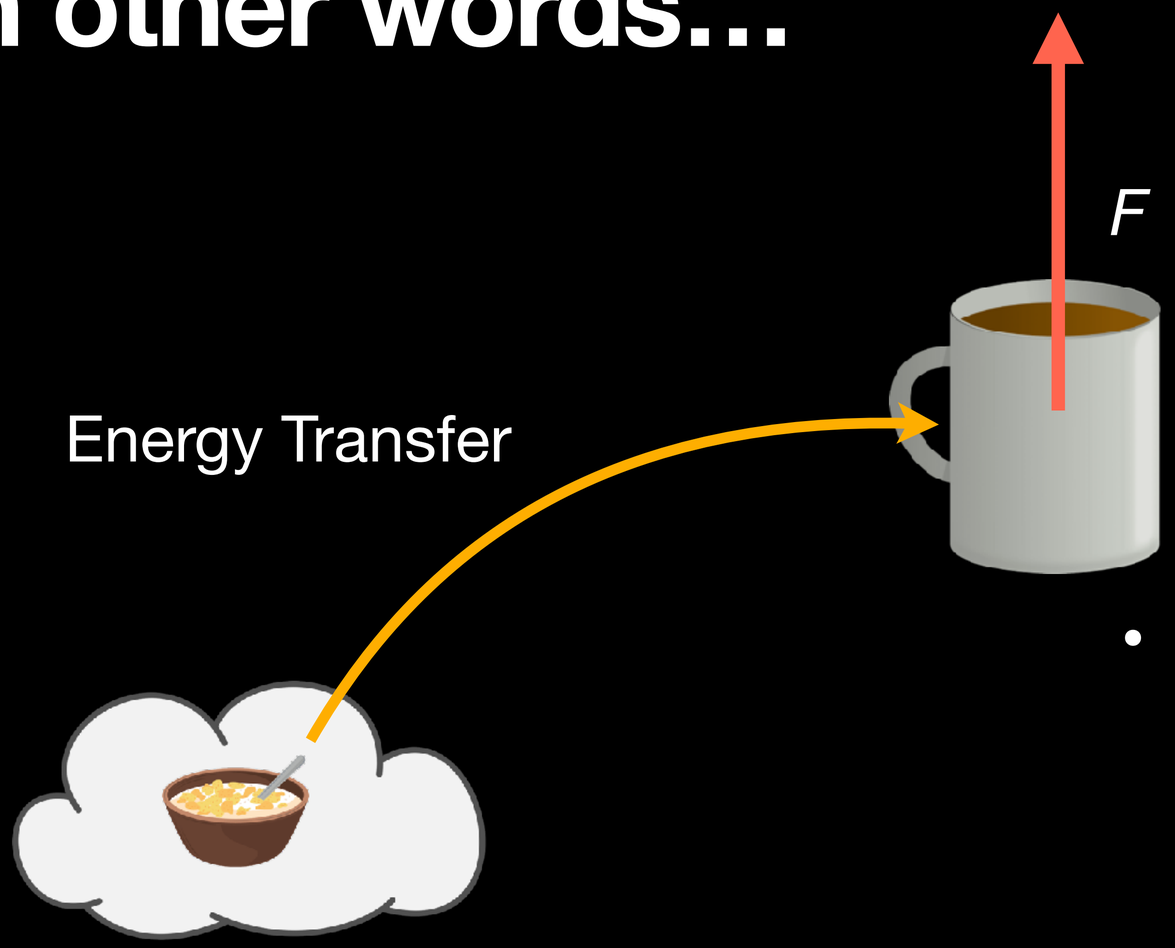
Someone call?

- The force
  - Acting like an energy conduit
    - Energy flow from me to the mug
  - ‘Action equals reaction’

# But..


F
Energy Transfer
Gravitational
PE
Energy Transfer
F
Lift the mug
Chemical
energy stored
in my body

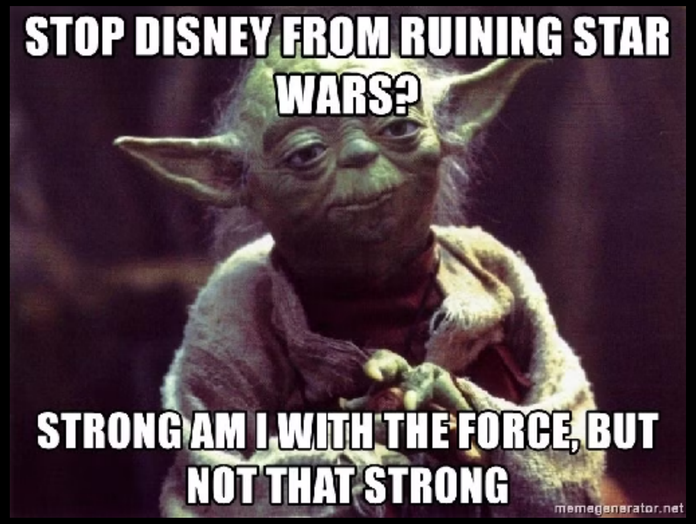
# In other words…



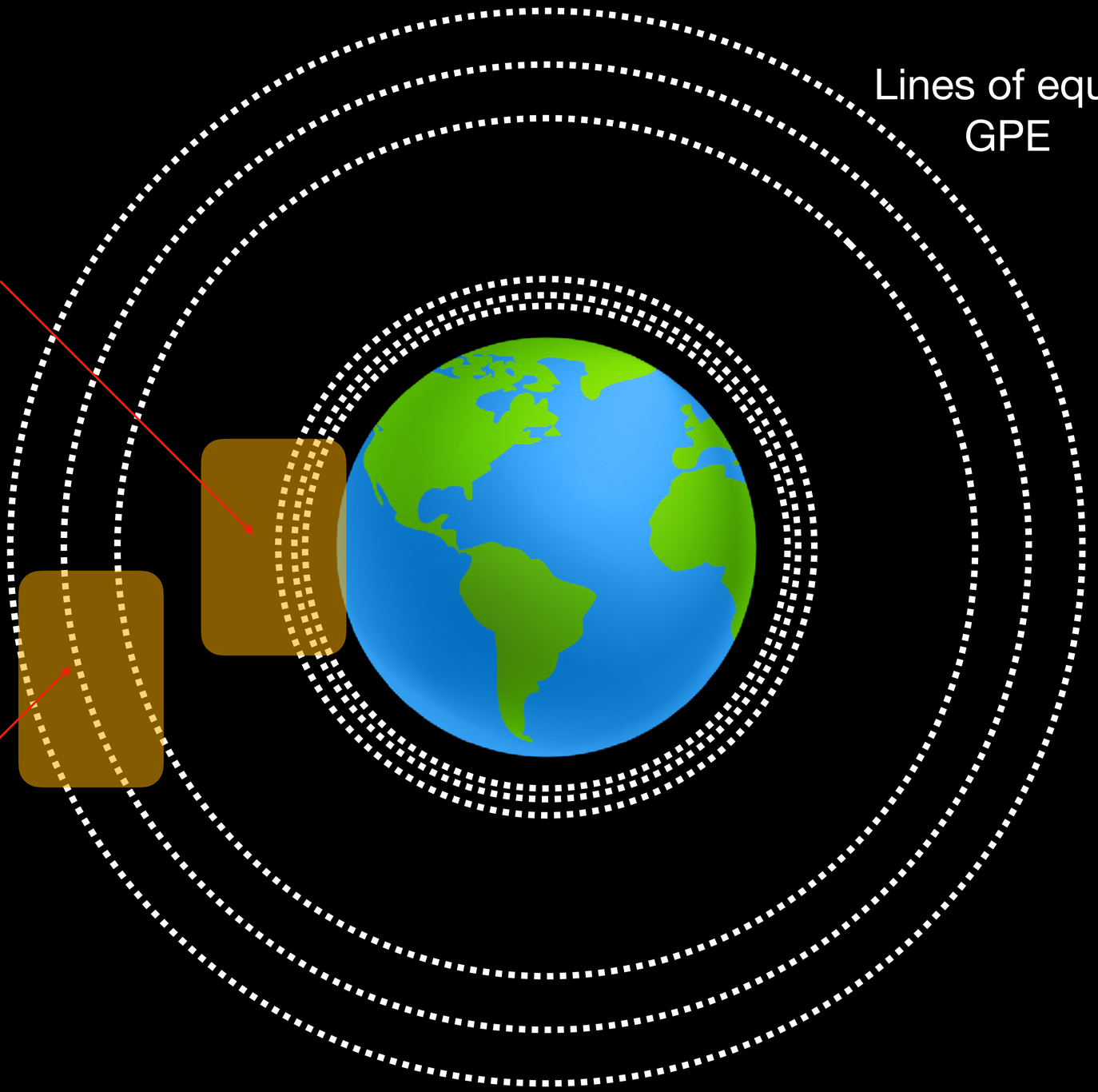

- We can think of forces as
  - Conduits for energy flow
  - Potential energies
    - Stored forms of energy inside fields

# GPE falls off with distance

Region where the force is strong

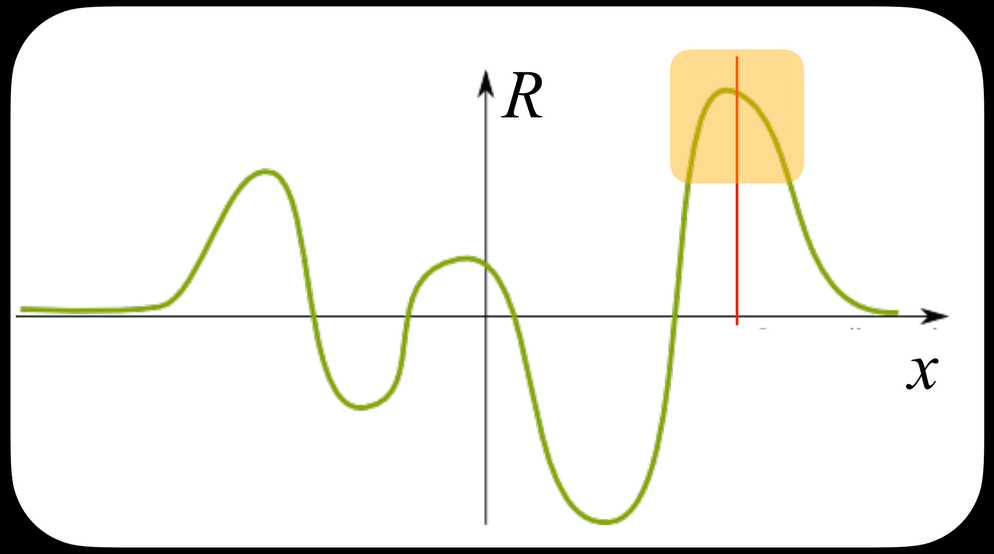



Region where the force is weak



$$Q \equiv -\frac{\hbar^2}{2m}\frac{1}{R}\frac{\partial^2 R}{\partial x^2}$$

Its the *shape* of $R$, not the scale…




- Like overlapping waves:
  - The shape in a region
  - Determined by everywhere else
  - The full experimental arrangement

# 2-particles

$$\psi = R\left[cos(S/\hbar) + isin(S/\hbar)\right]$$

- The wave function involves the location of both particles
  - So…
  - The quantum potential becomes

$$R = R(x_1, x_2, t)$$

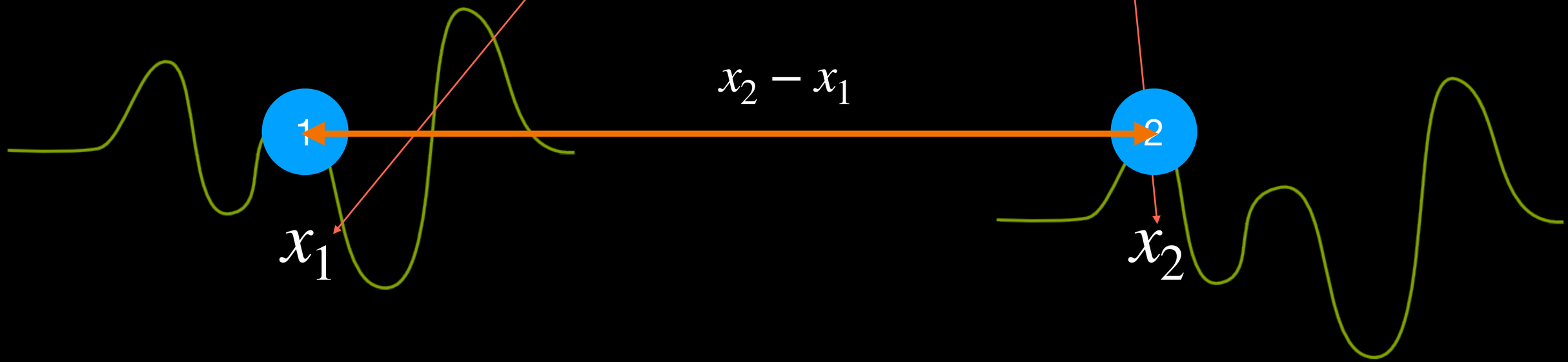
$$S = S(x_1, x_2, t)$$

$$Q = -\frac{\hbar^2}{2mR(x_1, x_2)}\left[\frac{\partial^2 R(x_1, x_2, t)}{\partial x_1^2} + \frac{\partial^2 R(x_1, x_2, t)}{\partial x_2^2}\right]$$

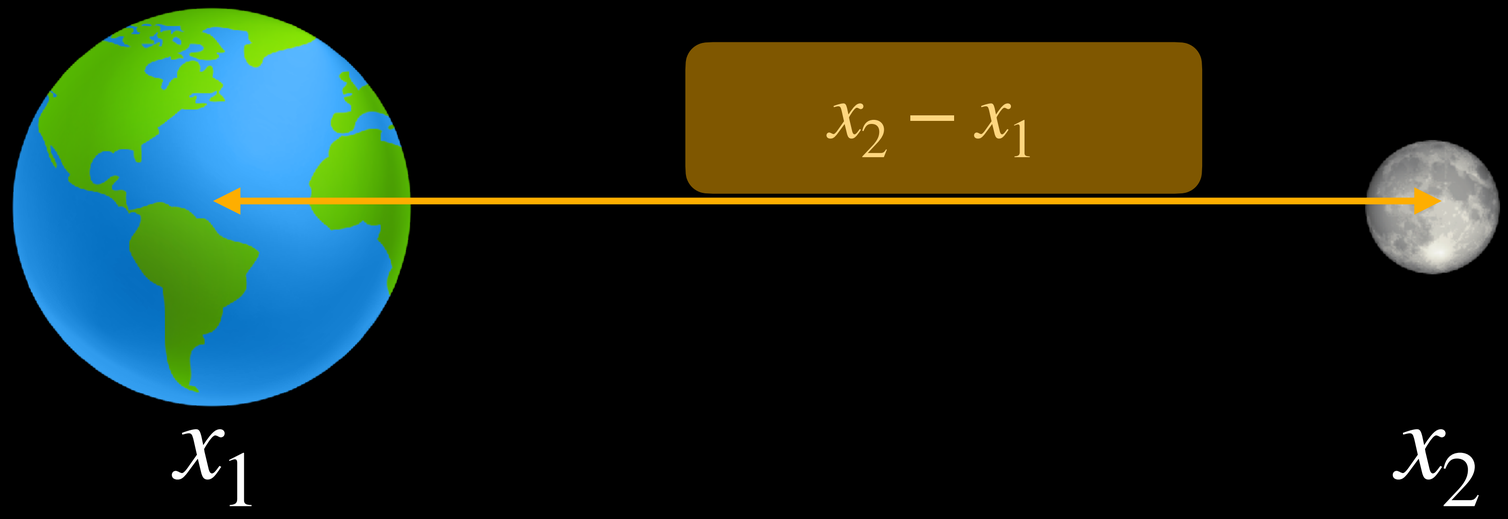
Nasty looking matheses

# Very important…

$$Q = -\frac{\hbar^2}{2mR(x_1, x_2)}\left[\frac{\partial^2 R(x_1, x_2, t)}{\partial x_1^2} + \frac{\partial^2 R(x_1, x_2, t)}{\partial x_2^2}\right]$$



# Contrast….



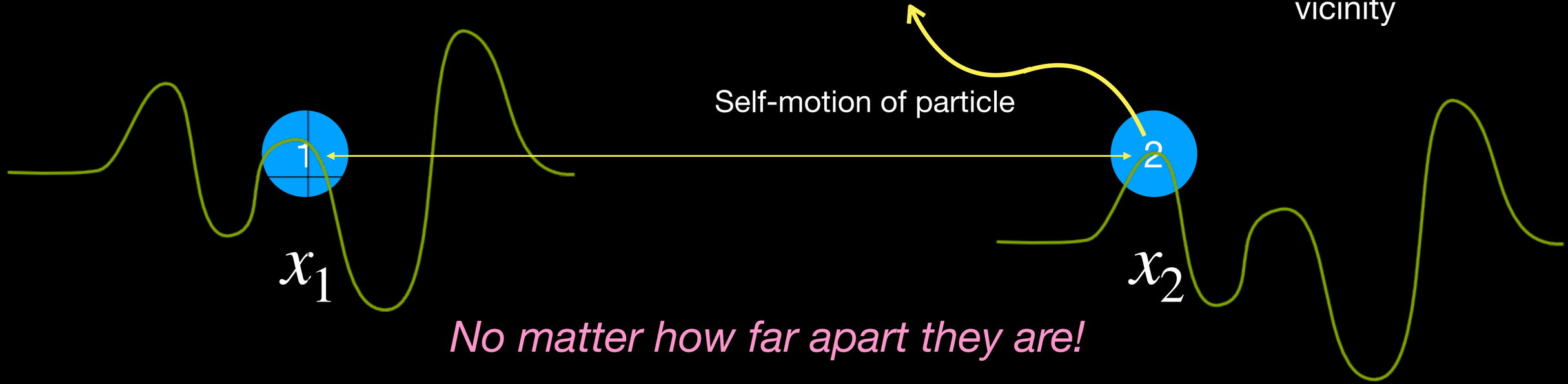

$$U = -\frac{GM_E M_m}{(x_2 - x_1)^2}$$

# QM is non-local

$$Q = -\frac{\hbar^2}{2mR(x_1, x_2)}\left[\frac{\partial^2 R(x_1, x_2, t)}{\partial x_1^2} + \frac{\partial^2 R(x_1, x_2, t)}{\partial x_2^2}\right]$$

As well as the shape of the wave function in other particle's vicinity

In-formed by the shape of the wave function in its vicinity




*No matter how far apart they are!*

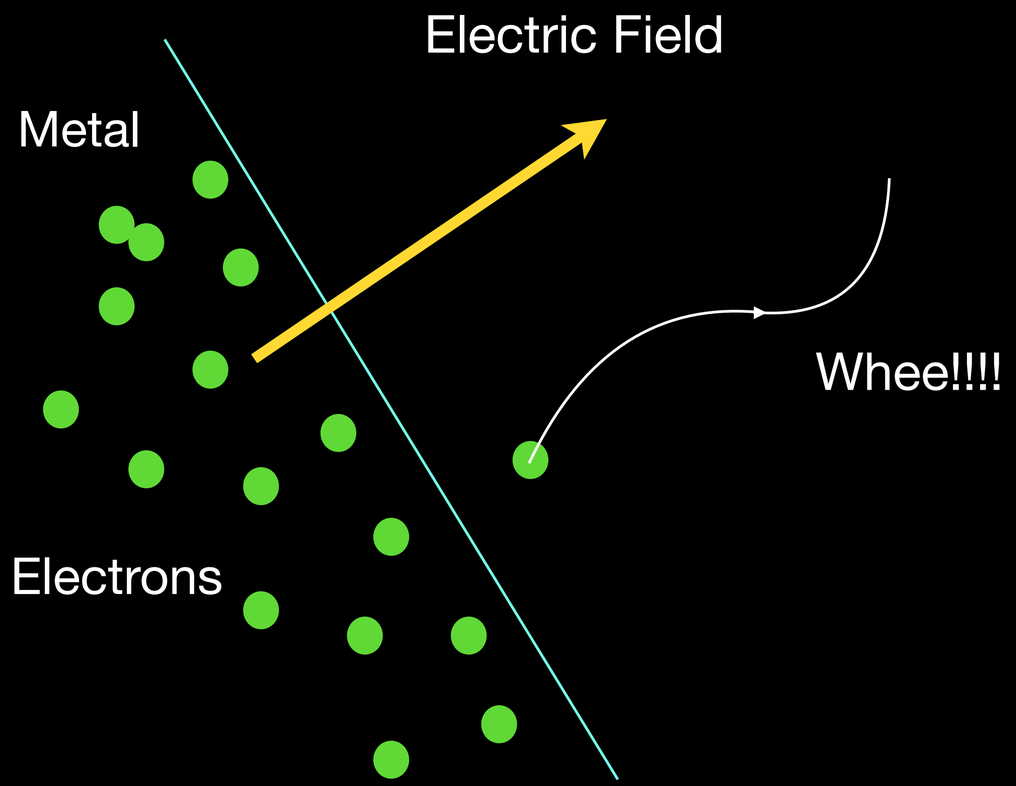
In our interpretation of the quantum theory, we see that the interaction of parts is determined by something that cannot be described solely in terms of these parts and their reassigned interrelationships.

Rather it depends on the many-body wave function. This many- body wave function evolves according to Schrödinger's equation. Something with this kind of dynamical significance that refers directly to the whole system is thus playing a key role in the theory

The relationship between parts of a system described above implies a new quality of wholeness of the entire system going beyond anything that can be specified solely in terms of the actual spatial relationship of all the particles.

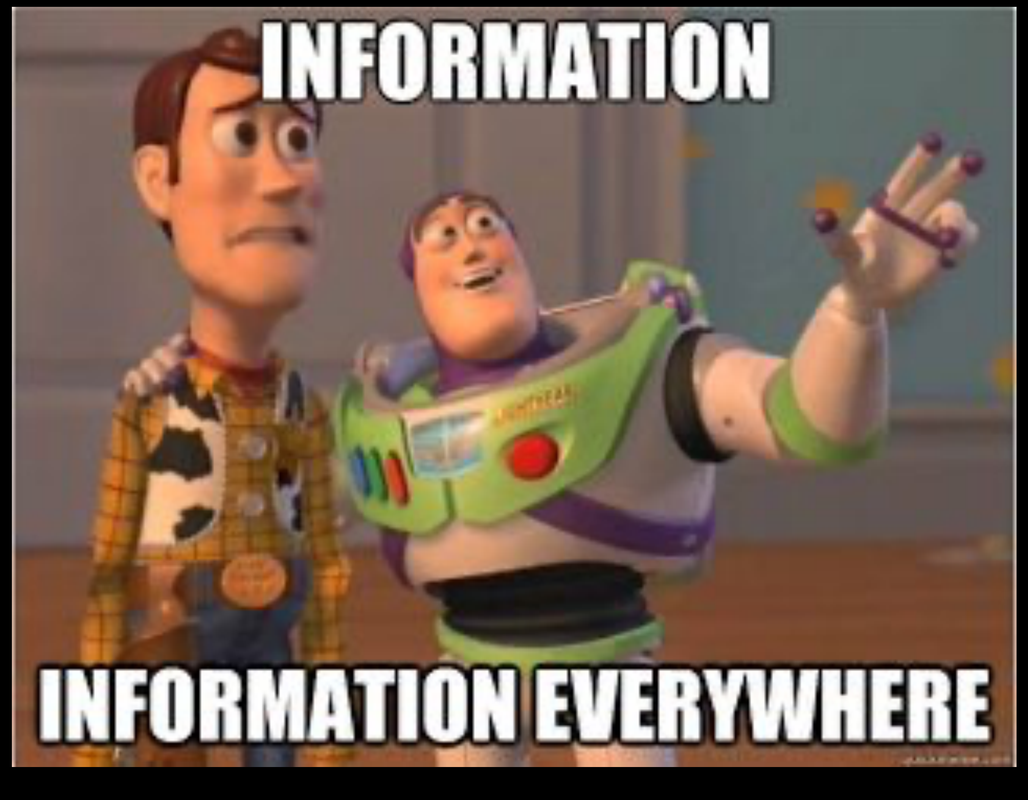
This is indeed the feature which makes the quantum theory go beyond mechanism of any kind.

# Crucial (subtle) point…

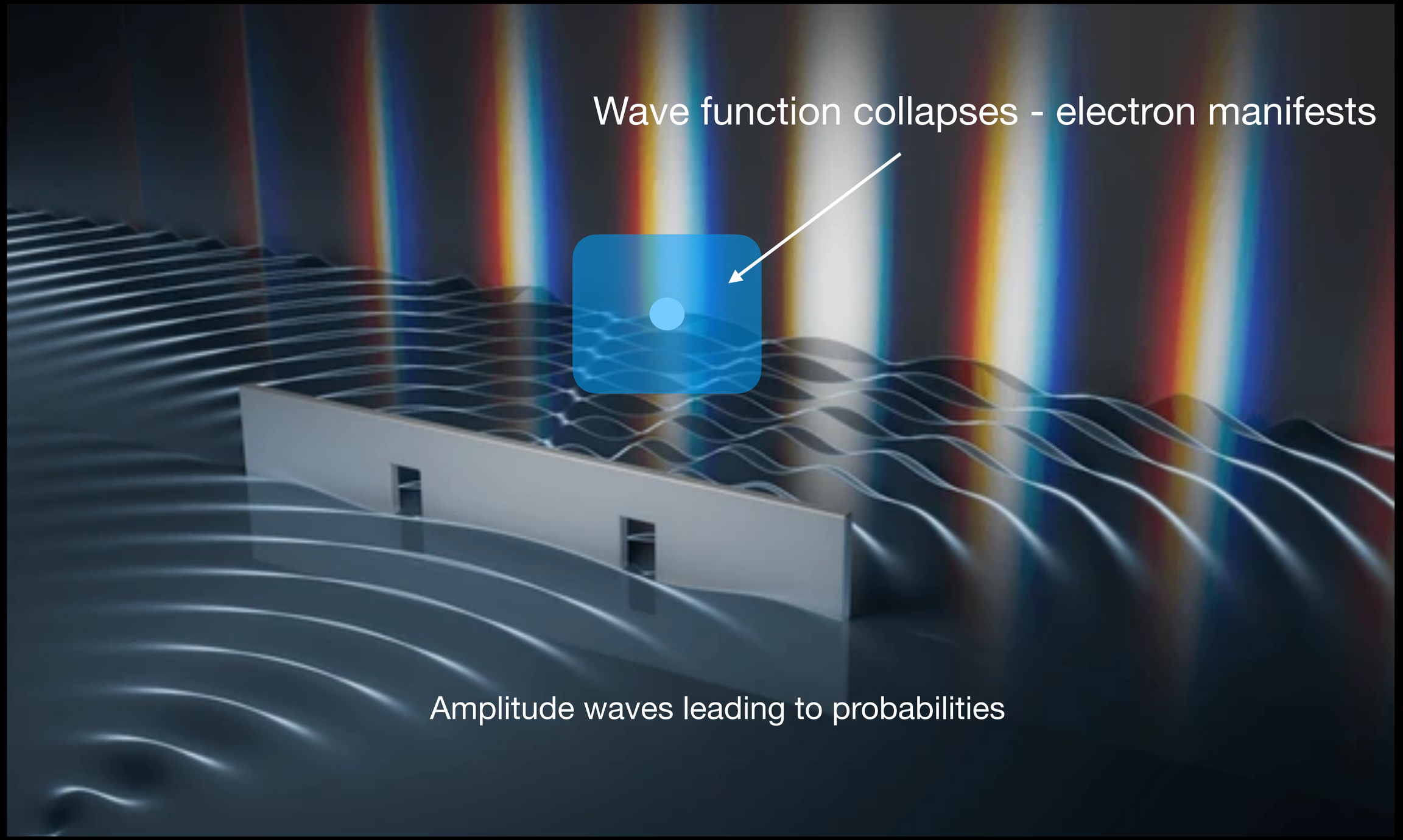


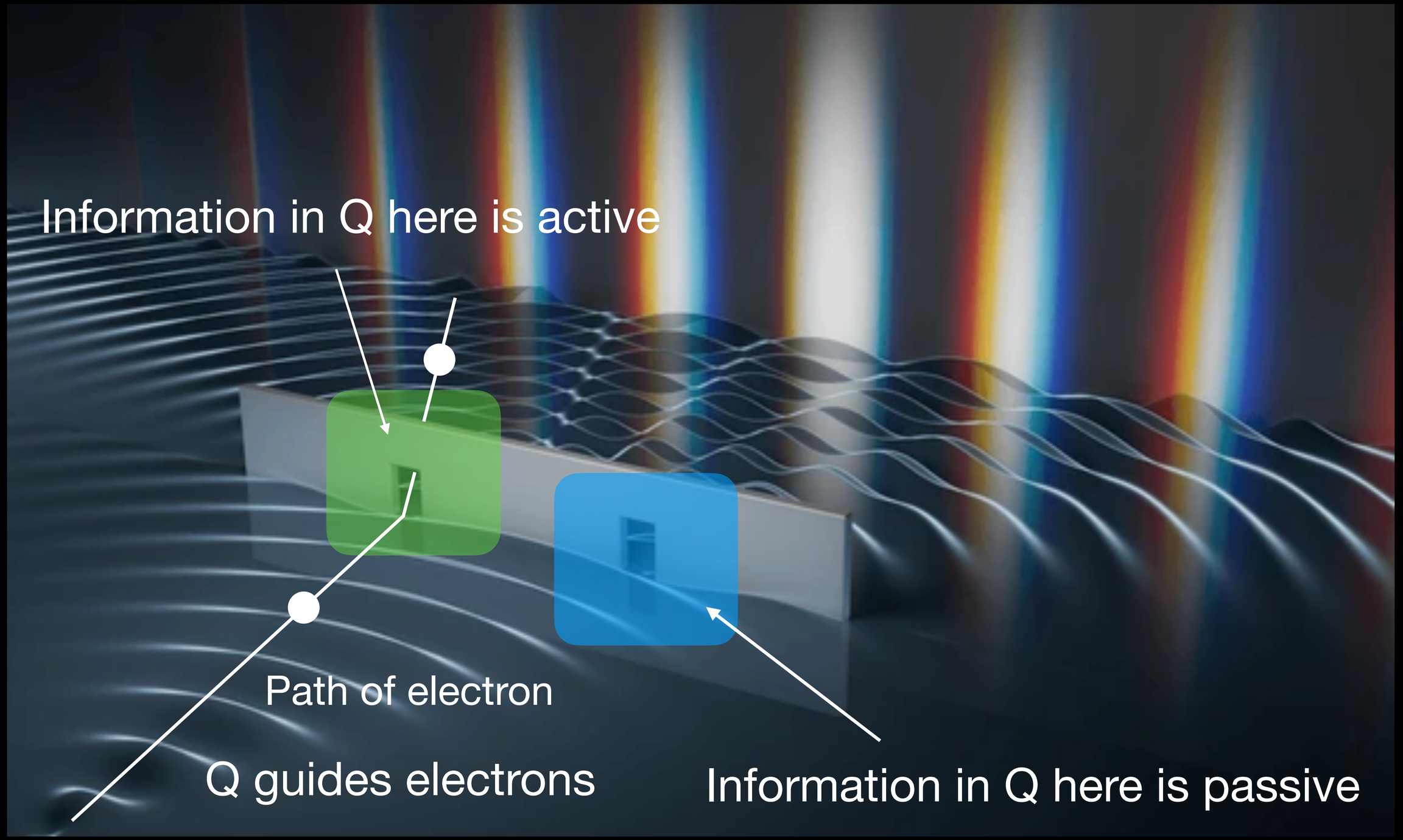

- Use an electric field
  - Strip electron from a metal
  - Take part in double slit…
- Position and momentum of the electron as it leaves the metal
  - Governed by Q
  - Influenced by millions of others (non-locally)
  - Effectively random
  - When electron tunnels out of metal
    - Wave function factorises
      - Electron proceeds independently of metal

# Active Information



In effect we have in this way introduced a concept that is new in the context of physics—a concept that we shall call active information. The basic idea of active information is that a form having very little energy enters into and directs a much greater energy. The activity of the latter is in this way given a form similar to that of the smaller energy.


Wave function collapses - electron manifests
Amplitude waves leading to probabilities


Information in Q here is active
Path of electron
Q guides electrons
Information in Q here is passive

As I have said above and will repeat again, quantum phenomena require us to think in a radical new way, a way in which we will have to ultimately give up both the notion of particles and fields.

Nevertheless, as we explained in our book, Bohm and Hiley (1993), by adopting the simplifying assumption of a particle with a well-defined position and momentum, we can obtain a consistent interpretation of the quantum formalism that does not contain many of the perplexing paradoxes that one faces daily in the standard approach

I want to make it absolutely clear here that I am not concluding from these arguments that the quantum particle actually is a ‘small lump of substance’ changing mechanically as the process develops in time. Something much subtler is involved. Nevertheless as I have remarked above, we can think of this process as being represented as a particle to within a certain approximation without arriving at a contradiction. When we go deeper and use field theory, a more complex process is revealed and clearly the simple particle picture must be modified in some radically new way.