Opening Remarks
Trial and Error
A Quantum World
Generalised Probability
Closing Remarks

The Physic(al) Process

A tale of trial and error in a quantum world

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Abstract

We provide a brief introduction to the scientific method as applied to physics, emphasising the role of mathematical formalism in the construction and refinement of physical theories. Following this we discuss how physics on a small scale requires a new theory—quantum theory—presented through the lens of generalised probability. Though the application of quantum theory has been widely successful over the last century, certain pathologies cannot be ignored. We present three of these in order of increasing severity: the problems of limitation, interpretation, and existence.

Motivation

I'm a Theoretical Physicist[1], but what does that mean?

- Does it mean the work I do isn't real?
- Does it mean I make up extra dimensions when things don't work out?
- Does it mean I'm annoyingly pedantic about everything just like Sheldon?

Today I want to dispel some common misunderstandings

[1] \Computer Scientist\Theoretical Chemist

Structure

1. Foundations
    1. Trial and Error
    2. A Quantum World
    3. Generalised Probability
2. Problems
    1. Limitation
    2. Interpretation
    3. Existence

Trial and Error

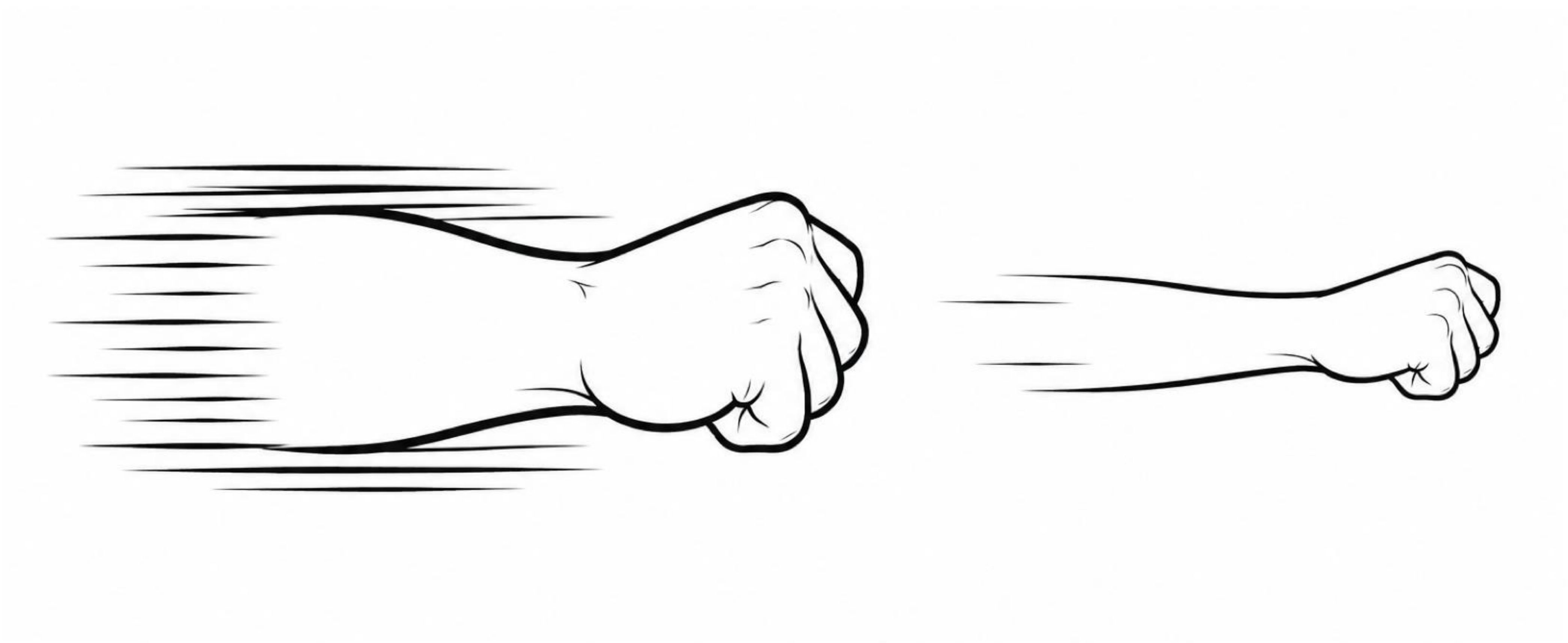
The ambition of every physicist is to understand how the universe works

- We want to describe a set of rules which everything in the universe (and the universe itself) obeys.
- These rules are written down in the language of mathematics[2]
- Ideally the universe is distilled into as few rules as possible (not always possible)

[2] See me after if you're interested in the many philosophical assumptions and implications of this statement

Trial and Error

We begin with some intuition: A fast and heavy punch hurts more than a slow and light punch



$$\text{force} = \text{mass} \times \text{velocity}$$

Trial and Error

Congratulations, you are now a Theoretical Physicist!

Trial and Error

But there is a problem with this rule

- It implies the follow through on the punch has no impact on how much the punch hurts
- Anyone who has been punched knows that is WRONG

Once a rule is written, we have to physically check that the universe actually obeys this rule. This is the job of an experimental physicist

Trial and Error

Going back to the drawing board, we account for the follow through by instead writing

$$\text{force} = \text{mass} \times \text{acceleration}$$

Again we experiment to verify that the rule holds and IT DOES

BUT EVERYTHING HAS ITS LIMIT

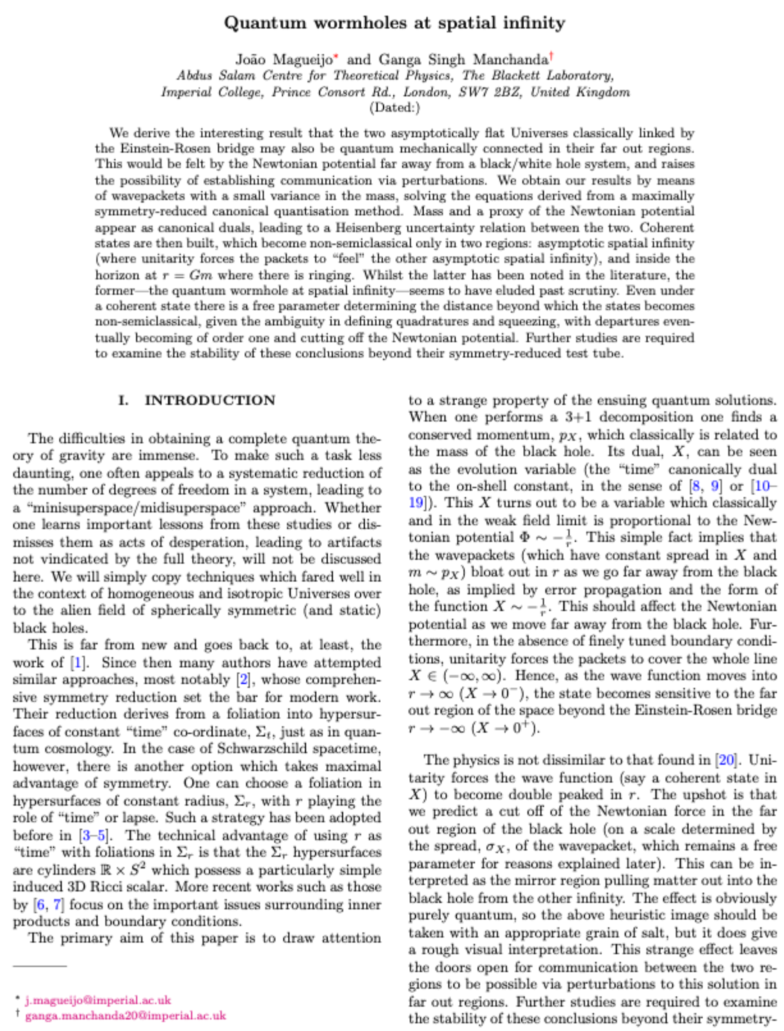
Trial and Error

- Every rule holds under certain conditions
- This rule fails when mass is variable, like in a rocket

By going back to the drawing board, we can develop a more general rule which is is applicable even when mass is variable[3]. This more general rule might have implications that extend past its current domain which we can investigate experimentally

[3] Modern physics builds rules based on symmetry, see me after to hear unnecessary details about this

Trial and Error



Quantum wormholes at spatial infinity

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(Dated:)

We derive the interesting result that the two asymptotically flat Universes classically linked by the Einstein-Rosen bridge may also be quantum mechanically connected in their far out regions. This would be felt by the Newtonian potential far away from a black/white hole system, and raises the possibility of establishing communication via perturbations. We obtain our results by means of wavepackets with a small variance in the mass, solving the equations derived from a maximally symmetry-reduced canonical quantisation method. Mass and a proxy of the Newtonian potential appear as canonical duals, leading to a Heisenberg uncertainty relation between the two. Coherent states are then built, which become non-semiclassical only in two regions: asymptotic spatial infinity (where unitarity forces the packets to "feel" the other asymptotic spatial infinity), and inside the horizon at $r = Gm$ where there is ringing. Whilst the latter has been noted in the literature, the former—the quantum wormhole at spatial infinity—seems to have eluded past scrutiny. Even under a coherent state there is a free parameter determining the distance beyond which the states becomes non-semiclassical, given the ambiguity in defining quadratures and squeezing, with departures eventually becoming of order one and cutting off the Newtonian potential. Further studies are required to examine the stability of these conclusions beyond their symmetry-reduced test tube.

I. INTRODUCTION

The difficulties in obtaining a complete quantum theory of gravity are immense. To make such a task less daunting, one often appeals to a systematic reduction of the number of degrees of freedom in a system, leading to a "minisuperspace/midisuperspace" approach. Whether one learns important lessons from these studies or dismisses them as acts of desperation, leading to artifacts not vindicated by the full theory, will not be discussed here. We will simply copy techniques which fared well in the context of homogeneous and isotropic Universes over to the alien field of spherically symmetric (and static) black holes.

This is far from new and goes back to, at least, the work of [1]. Since then many authors have attempted similar approaches, most notably [2], whose comprehensive symmetry reduction set the bar for modern work. Their reduction derives from a foliation into hypersurfaces of constant "time" co-ordinate, Σ_t, just as in quantum cosmology. In the case of Schwarzschild spacetime, however, there is another option which takes maximal advantage of symmetry. One can choose a foliation in hypersurfaces of constant radius, Σ_r, with r playing the role of "time" or lapse. Such a strategy has been adopted before in [3–5]. The technical advantage of using r as "time" with foliations in Σ_r is that the Σ_r hypersurfaces are cylinders $\mathbb{R} \times S^2$ which possess a particularly simple induced 3D Ricci scalar. More recent works such as those by [6, 7] focus on the important issues surrounding inner products and boundary conditions.

The primary aim of this paper is to draw attention to a strange property of the ensuing quantum solutions. When one performs a 3+1 decomposition one finds a conserved momentum, p_X, which classically is related to the mass of the black hole. Its dual, X, can be seen as the evolution variable (the "time" canonically dual to the on-shell constant, in the sense of [8, 9] or [10–19]). This X turns out to be a variable which classically and in the weak field limit is proportional to the Newtonian potential $\Phi \sim -\frac{1}{r}$. This simple fact implies that the wavepackets (which have constant spread in X and $m \sim p_X$) bloat out in r as we go far away from the black hole, as implied by error propagation and the form of the function $X \sim -\frac{1}{r}$. This should affect the Newtonian potential as we move far away from the black hole. Furthermore, in the absence of finely tuned boundary conditions, unitarity forces the packets to cover the whole line $X \in (-\infty, \infty)$. Hence, as the wave function moves into $r \to \infty$ $(X \to 0^-)$, the state becomes sensitive to the far out region of the space beyond the Einstein-Rosen bridge $r \to -\infty$ $(X \to 0^+)$.

The physics is not dissimilar to that found in [20]. Unitarity forces the wave function (say a coherent state in X) to become double peaked in r. The upshot is that we predict a cut off of the Newtonian force in the far out region of the black hole (on a scale determined by the spread, σ_X, of the wavepacket, which remains a free parameter for reasons explained later). This can be interpreted as the mirror region pulling matter out into the black hole from the other infinity. The effect is obviously purely quantum, so the above heuristic image should be taken with an appropriate grain of salt, but it does give a rough visual interpretation. This strange effect leaves the doors open for communication between the two regions to be possible via perturbations to this solution in far out regions. Further studies are required to examine the stability of these conclusions beyond their symmetry-

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A Quantum World

The physical process works very well

- Over the last century experimentalists have made observations on the scale of atoms and molecules
- On this small scale, the world is not as simple as force $=$ mass $\times$ acceleration
- We are forced to develop a new theory

Quantum Theory

The Physic(al) Process

Ganga Singh Manchanda

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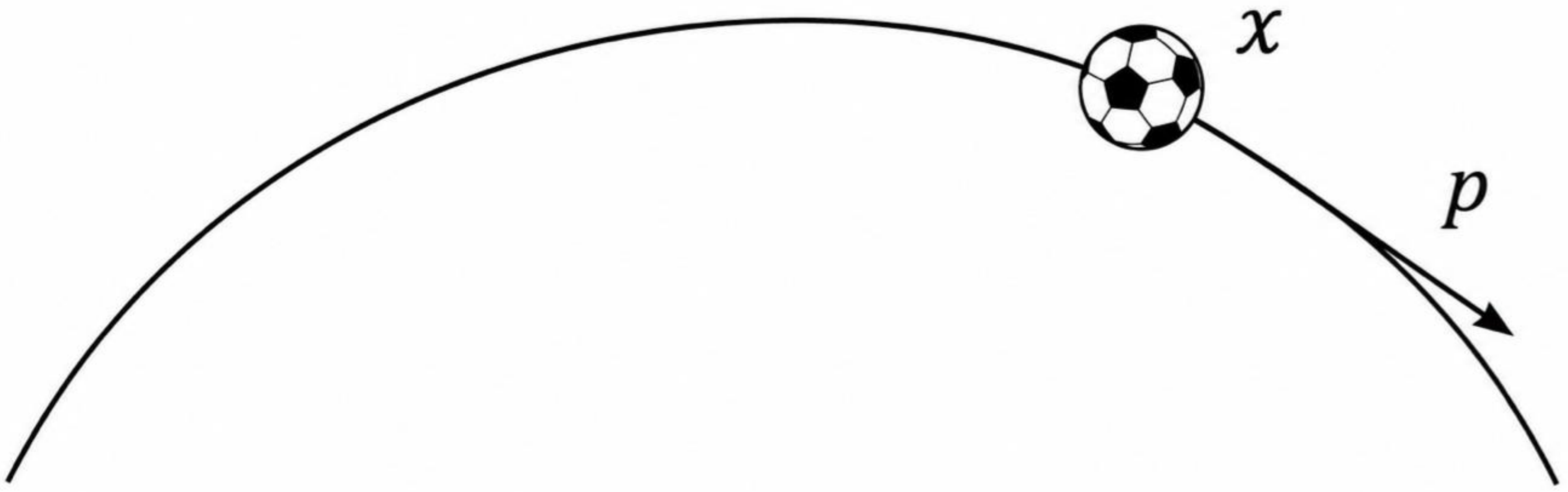
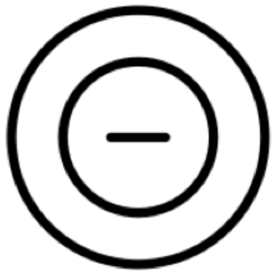
Imagine a ball

I can give it a kick



A Quantum World

Now imagine an electron



I can give it a ‘kick’

But I won’t see what I saw with the ball

In fact I won’t see much at all because observation and measurement works very differently in the quantum world

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A Quantum World

In quantum theory, it's all about possibility (and probability)

$\ominus$ The electron could be here

or it could be here $\ominus$

Until we peek and find out, it's in both. Our observation forces it to pick an option with probability determined by the theory

A Quantum World

- Our uncertainty in position and momentum is characterised by Δx and Δp, respectively
- With the ball, we can know its exact position and exact momentum at the same time such that $\Delta x = \Delta p = 0$

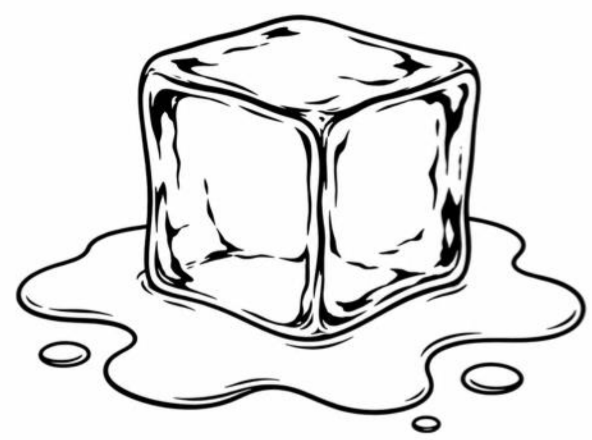
With an electron this is not possible. Quantum theory sets a fundamental limit on our knowledge of the universe

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

This is an information trade-off. The more I know about position, the less I know about momentum and vice versa

A Quantum World

Imagine an ice cube in the dark



- I can't see, so all I can do is grab to know its position
- It's really slippery, so as I grab it, it shoots out of my hand
- The more tightly I grab, the more quickly it shoots out
- The more accurately I can measure its position, the less certain I am of its momentum in the next moment

A Quantum World

Some comments are in order

- $\hbar$ is absurdly small, so this effect matters on the scale of an electron but not on the scale of a ball
- Quantum theory is not just academic curiosity
- Without these developments there would be no phones, computers, internet, medicine...

Quantum theory underpins the entire modern world

Generalised Probability

Now comes the interesting part

Claim

Quantum theory feels weird because the universe is based on a more general theory of probability than what humans intuitively understand

Generalised Probability

Consider a very human example: height and shoe size

- All humans have some height and some shoe size[4]
- Even before I check all 8 Billion of them, they exist

Person	Height	Shoe Size
1	185cm	29.5cm
⋮	⋮	⋮
8 Billion	172cm	23cm

This spreadsheet gives an underlying description of reality

[4] Assuming they have feet

Generalised Probability

In terms of the ball, this spreadsheet is called the state space and it's filled with the pairs (x, p) rather than $(\text{height}, \text{shoe size})$

Suppose the ball can exist in

- Two positions: LEFT or RIGHT
- Two momenta: FORWARDS or BACKWARDS

The state space is then

$$\Omega = \{(\mathsf{L}, \mathsf{F}), (\mathsf{L}, \mathsf{B}), (\mathsf{R}, \mathsf{F}), (\mathsf{R}, \mathsf{B})\}$$

Any one of these represents a complete specification of reality

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Knowledge of one variable can lead to knowledge of another

Suppose the state space is reduced to

$$\Omega = \{(\mathsf{L},\mathsf{F}),(\mathsf{L},\mathsf{B}),(\mathsf{R},\mathsf{F})\}$$

Then

$$\begin{aligned} x = \mathsf{L} &\implies P(\mathsf{L},\mathsf{F}) = P(\mathsf{L},\mathsf{B}) = \frac{1}{2} \\ x = \mathsf{R} &\implies P(\mathsf{R},\mathsf{F}) = 1 \end{aligned}$$

If I know that $x = \mathsf{R}$, I immediately know that $p = \mathsf{F}$ because the results are correlated through the joint distribution $P(x,p)$

Generalised Probability

The electron doesn't admit a joint distribution like the ball. Everything we know about an electron is encoded in a state ψ which replaces the (x, p) picture we have for a ball

We can interpret ψ through the lens of

$$\text{Position:} \quad P_{\psi}(x) = |\psi(x)|^2$$

or

$$\text{Momentum:} \quad P_{\tilde{\psi}}(p) = |\tilde{\psi}(p)|^2$$

but never as $P_{\psi\backslash\tilde{\psi}}(x, p)$ at the same time

Generalised Probability

There is no spreadsheet in quantum theory, no underlying complete description of reality. Instead we have

$$\psi + \text{choice of } x \text{ OR } p \longrightarrow \text{probabilities of } x \text{ OR } p$$

- If I choose position, quantum theory tells me the probabilities for position outcomes
- If I choose momentum, quantum theory tells me the probabilities for momentum outcomes
- The theory cannot describe probabilities for position and momentum outcomes at the same time

Generalised Probability

- This is more general than the ball
- The Heisenberg uncertainty principle forbids a situation where the position immediately tells me the momentum
- The state space (spreadsheet) picture allows these restrictive correlations, quantum theory doesn't

Over many electrons, these quantum effects average out resulting in the emergence of a ball that behaves like a ball rather than a ball that behaves like an electron

Conclusion

We've discussed some fundamental ideas in physics and looked at them through some interesting (unusual) lenses

I hope I made it through in time

I hope you understood

I hope you enjoyed

Thank you :)

Bibliography

The mathematics presented here is heuristic and makes many simplifications. For a complete treatment[5], see

R. F. Streater, "Classical and quantum probability", *J. Math. Phys.* **41**, 3556–3603 (2000).

[5] Not for the faint of heart