Origin of probabilities and their application to the multiverse

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Center for Quantum Mathematics and Physics (QMAP)
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NBI
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Ways to experience this talk:

Have you thought about the “multiverse”, “eternal inflation” cosmological “measure problems” etc?
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Yes

You are prepared to fully appreciate the context.
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No worries, I will introduce many of these concepts at an introductory level
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Based on undergrad physics only
My history with this topic

AA: All randomness/probabilities are quantum (coin flip, card choice etc)
My history with this topic
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Hartle, Srednicki, Aguirre, Tegmark, ...
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A potential issue even for finite models
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(Or not)
Outline

1) Quantum vs non-quantum probabilities (toy model/multiverse)

2) Everyday probabilities

3) Be careful about counting!

4) Implications for multiverse/eternal inflation
Outline

1) Quantum vs non-quantum probabilities (toy model/multiverse)

2) Everyday probabilities

3) Be careful about counting!

4) Implications for multiverse/eternal inflation
Planck Data

---

Cosmic Inflation theory
Slow rolling of inflaton

Observable physics generated here
Slow rolling of inflaton

Observable physics generated here

Extrapolating back
Slow rolling of inflaton

“Self-reproducing regime”
(dominated by quantum fluctuations): Eternal inflation/Multiverse

Observable physics generated here

Extrapolating back

Steinhardt 1982, Linde 1982, Vilenkin 1983, and (then) many others
Slow rolling of inflaton

“Self-reproducing regime” (dominated by quantum fluctuations): Eternal inflation/Multiverse

Observable physics generated here

Alternatively, perhaps something (such as holography) cuts off this extrapolation back

Steinhardt 1982, Linde 1982, Vilenkin 1983, and (then) many others
Slow rolling of inflaton

“Self-reproducing regime” (dominated by quantum fluctuations): Eternal inflation/Multiverse

Observable physics generated here

Extrapolating back

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The multiverse of eternal inflation with multiple classical rolling directions

Self-reproduction regime

Where are we? (Young universe, old universe, curvature, physical properties A, B, C, D, etc)
The multiverse of eternal inflation with multiple classical rolling directions.

Where are we? (Young universe, old universe, curvature, physical properties A, B, C, D, etc)

"Where are we?" ➔ Expect the theory to give you a probability distribution in this space... hopefully with some sharp predictions.
The multiverse of eternal inflation with multiple classical rolling directions

Where are we? (Young universe, old universe, curvature, physical properties A, B, C, D, etc)

“Anything that can happen will happen infinitely many times” (A. Guth)

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String theory landscape even more complicated (e.g. many types of eternal inflation)

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Where are we? (Young universe, old universe, curvature, physical properties A, B, C, D, etc)

Classically Rolling

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Slow rolling of inflaton

“Self-reproducing regime” (dominated by quantum fluctuations): Eternal inflation/Multiverse

 observable physics generated here

Extrapolating back

Steinhardt 1982, Linde 1982, Vilenkin 1983, and (then) many others
Quantum vs Non-Quantum probabilities

Non-Quantum probabilities in a toy model:

\[ U = A \otimes B \quad A: \{ |1\rangle^A, |2\rangle^A \} \quad B: \{ |1\rangle^B, |2\rangle^B \} \]

\[ U: \{ |11\rangle, |12\rangle, |21\rangle, |22\rangle \} \quad |ij\rangle \equiv |i\rangle^A |j\rangle^B \]

Page, 2009; These slides follow AA & Phillips 2014
Quantum vs Non-Quantum probabilities

Non-Quantum probabilities in a toy model:

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\[ U: \{ |11\rangle, |12\rangle, |21\rangle, |22\rangle \} \quad |ij\rangle \equiv |i^A\rangle |j^B\rangle \]

Possible Measurements \(\leftrightarrow\) Projection operators:

Measure A only:

\[ \hat{P}_i^A = \left( |i^A\rangle A \langle i| \right) \otimes 1^B = \left[ |i1\rangle \langle i1| + |i2\rangle \langle i2| \right] \]

Measure B only:

\[ \hat{P}_i^B = \left( |i^B\rangle B \langle i| \right) \otimes 1^A = \left[ |1i\rangle \langle 1i| + |2i\rangle \langle 2i| \right] \]

Measure entire \(U\):

\[ \hat{P}_{ij} = |ij\rangle \langle ij| \]
Quantum vs Non-Quantum probabilities

\[ (\hat{A}^{1} \hat{A}^{2})_{ij} = \sum_{i} P_{ij} \]

Non-Quantum probabilities in a toy model:

\[ U = A \bigotimes B \]

Possible Measurements ↔ Projection operators:

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\[ \hat{P}_{i}^{A} = (|i\rangle^{A} \langle A |i\rangle) \bigotimes 1^{B} = [|i1\rangle\langle i1| + |i2\rangle\langle i2|] \]

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Measure entire U:

\[ \hat{P}_{ij} = |ij\rangle\langle ij| \]

BUT: It is impossible to construct a projection operator for the case where you do not know whether it is A or B that is being measured.
Quantum vs Non-Quantum probabilities

\[ \hat{P}_i = p_A \hat{P}^A_i + p_B \hat{P}^B_i \]

Possible Measurements ↔ Projection operators:

Measure A only: \[ \hat{P}^A_i = (|i\rangle^A \langle i|) \otimes 1^B = [|i1\rangle\langle i1| + |i2\rangle\langle i2|] \]

Measure B only: \[ \hat{P}^B_i = (|i\rangle^B \langle i|) \otimes 1^A = [|1i\rangle\langle 1i| + |2i\rangle\langle 2i|] \]

Measure entire U: \[ \hat{P}_{ij} = |ij\rangle\langle ij| \]

BUT: It is impossible to construct a projection operator for the case where you do not know whether it is A or B that is being measured.
Quantum vs Non-Quantum probabilities

Non-Quantum probabilities in a toy model:

\[ U = A \odot \]

Possible Measurements \( \iff \) Projection operators:

Measure A only: \( \hat{P}_i^A = \left( |i\rangle^A \langle i| \right) \otimes 1^B = \left[ |i1\rangle \langle i1| + |i2\rangle \langle i2| \right] \)

Measure B only: \( \hat{P}_i^B = \left( |i\rangle^B \langle i| \right) \otimes 1^A = \left[ |1i\rangle \langle 1i| + |2i\rangle \langle 2i| \right] \)

Measure entire U: \( \hat{P}_{ij} = \left| ij\right\rangle \langle ij \right| \)

BUT: It is impossible to construct a projection operator for the case where you do not know whether it is A or B that is being measured.

Could Write

Classical Probabilities to measure A, B

Albrecht @ NBI 11/1/2019
Quantum vs Non-Quantum probabilities

Non-Quantum probabilities in a toy model:

Possible Measurements
- Measure A only
- Measure B only
- Measure entire U

Measure entire U:
\[
\hat{P}_{ij} = |ij\rangle\langle ij|
\]

BUT: It is impossible to construct a projection operator for the case where you do not know whether it is A or B that is being measured.

Could Write
\[
\hat{P}_i = p_A \hat{P}_i^A + p_B \hat{P}_i^B
\]

\[
\hat{P}_i \hat{P}_j \neq \delta_{ij} \hat{P}_j
\]

\[
\hat{P}_i^A = (|i\rangle^A \langle i|) \otimes 1^B = [|i1\rangle\langle i1| + |i2\rangle\langle i2|]
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\]

Classical Probabilities to measure A, B

\[
|j\rangle^B
\]

\[
\{ : 1, 2, 11, 12, 21, 22 \}
\]

\[
\{ : 1, 2 \}
\]

\[
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Quantum vs Non-Quantum probabilities

\[
\hat{P}_i = p_A \hat{P}_i^A + p_B \hat{P}_i^B
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\[
\hat{P}_i^A = | i \rangle^A \langle i |
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\hat{P}_i^B = | i \rangle^B \langle i |
\]

\[
\hat{P}_{ij} \equiv |ij\rangle \langle ij|
\]

Non-Quantum probabilities in a toy model:

\[
U = A \otimes B
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Possible Measurements

Measure \( A \) only:

Measure \( B \) only:

Measure entire \( U \):

BUT: It is impossible to construct a projection operator for the case where you do not know whether it is \( A \) or \( B \) that is being measured.

Could Write

\[
\hat{P}_i^A \hat{P}_j^B
\]

Does not represent a quantum measurement

Page: The multiverse requires this (are you in pocket universe \( A \) or \( B \)?)
Quantum vs Non-Quantum probabilities

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BUT: It is impossible to construct a projection operator for the case where you do not know whether it is A or B that is being measured.

Could Write

\[ \hat{P}_i^A = \left| i \right>^A \left< i \right| \]

\[ \hat{P}_i^B = \left| i \right>^B \left< i \right| \]

\[ \hat{P}_{ij} = \left| ij \right> \left< ij \right| \]

Measure entire \( U \):

Page: The multiverse requires this (are you in pocket universe A or B?)

Does not represent a quantum measurement

Classical Probabilities to measure A, B

Measures \( \Leftrightarrow \) Projected measurements
• All everyday probabilities are quantum probabilities
• All everyday probabilities are quantum probabilities

Our *only* experiences with successful practical applications of probabilities are with quantum probabilities

AA & D. Phillips 2014
• All everyday probabilities are quantum probabilities

• One should not use ideas from everyday probabilities to justify probabilities that have been proven to have no quantum origin
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• One should not use ideas from everyday probabilities to justify probabilities that have been proven to have no quantum origin.

A problem for many multiverse theories (as practiced)

AA & D. Phillips 2014
Quantum vs Non-Quantum probabilities

Non-Quantum probabilities in a toy model:

\[ U = A \]

Possible Measurements

\[ \hat{\mathbb{P}}_i = p_A \hat{\mathbb{P}}_i^A + p_B \hat{\mathbb{P}}_i^B \]

\[ \hat{\mathbb{P}}_i \hat{\mathbb{P}}_j \neq \delta_{ij} \hat{\mathbb{P}}_j \]

Classical Probabilities to measure \( A, B \)

\[ \hat{\mathbb{P}}^A_i = (|i\rangle^A) \]

\[ \hat{\mathbb{P}}^B_i = (|i\rangle^B) \]

\[ \hat{\mathbb{P}}_{ij} = |ij\rangle \langle ij| \]

BUT: It is impossible to construct a projection operator for the case where you do not know whether it is \( A \) or \( B \) that is being measured.

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Measure entire \( U \):

Does not represent a quantum measurement.
Quantum vs Non-Quantum probabilities

Non-Quantum probabilities in a toy model:

$$U = A \otimes B$$

Measure entire $$U$$:

$$\hat{P}_{ij} = |ij\rangle \langle ij|$$

Measure $$A$$ only:

$$\hat{P}^A_i = |i^A\rangle \langle i^A|$$

Measure $$B$$ only:

$$\hat{P}^B_i = |i^B\rangle \langle i^B|$$

Classical Probabilities to measure $$A, B$$:

Where do these come from anyway?

Does not represent a quantum measurement.

BUT: It is impossible to construct a projection operator for the case where you do not know whether it is $$A$$ or $$B$$ that is being measured.

Could Write

$$\hat{P}_i = p^A_i \hat{P}^A_i + p^B_i \hat{P}^B_i$$

$$\hat{P}_i \hat{P}_j \neq \delta_{ij} \hat{P}_j$$

Page: The multiverse requires this (are you in pocket universe $$A$$ or $$B$$?)
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4) Implications for multiverse/eternal inflation
Outline

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4) Implications for multiverse/eternal inflation
Quantum effects in a billiard gas
Quantum effects in a billiard gas
Quantum effects in a billiard gas

\[ \Delta b = \delta x_\perp + \frac{\delta p_\perp}{m} \Delta t \]
Quantum effects in a billiard gas

\[ \Delta b = \delta x_\perp + \frac{\delta p_\perp}{m} \Delta t = \sqrt{2} \left( a + \frac{\hbar}{2a m \bar{v}} \right) \]

\[ \psi \propto \exp \left( \frac{-x^2}{2a^2} \right) \]
Quantum effects in a billiard gas

\[ \Delta b = \delta x_{\perp} + \frac{\delta p_{\perp}}{m} \Delta t = \sqrt{2} \left( a + \frac{\hbar}{2a} \frac{l}{m\overline{v}} \right) \]

\[ \psi \propto \exp \left( \frac{-x^2}{2a^2} \right) \]

\[ \text{min} \, 2^{3/2} \left( \frac{\hbar l}{2m\overline{v}} \right) \equiv \sqrt{\frac{l \chi_{dB}}{2}} \]

Albrecht @ NBI 11/1/2019
Quantum effects in a billiard gas

Minimizing \( \Delta b \rightarrow \) conservative estimates for my purposes (also motivated by decoherence in some cases)

\[ \Delta b = \delta x_1 \]

\[ \min \left( 2^{3/2} \left( \frac{\hbar l}{2m \bar{v}} \right) \right) \equiv \sqrt{\frac{l \lambda_{dB}}{2}} \]
Quantum effects in a billiard gas

Subsequent collisions amplify the initial uncertainty (treat later collisions classically ➔ additional conservatism)
Quantum effects in a billiard gas

After $n$ collisions:

$$\Delta b_n = \Delta b \left( 1 + \frac{2l}{r} \right)^n$$
Quantum effects in a billiard gas

\( n_Q \) is the number of collisions so that \( \Delta b_{n_Q} = r \)

(full quantum uncertainty as to which is the next collision)

\[
n_Q = - \frac{\log \left( \frac{\Delta b}{r} \right)}{\log \left( 1 + \frac{2l}{r} \right)}
\]
\( n_Q \) for a number of physical systems

(All units MKS)

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\( n_Q \) for a number of physical systems (all units MKS)

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<td>1</td>
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<td>Water</td>
<td>$3.0 \times 10^{-10}$</td>
<td>$5.4 \times 10^{-10}$</td>
<td>$3 \times 10^{-26}$</td>
<td>460</td>
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<td>$1.3 \times 10^{-10}$</td>
<td>0.6</td>
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<td>$3.4 \times 10^{-7}$</td>
<td>$4.7 \times 10^{-26}$</td>
<td>360</td>
<td>$6.2 \times 10^{-12}$</td>
<td>$2.9 \times 10^{-9}$</td>
<td>$-0.3$</td>
</tr>
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<td>$6.6 \times 10^{-34}$</td>
<td>$5.1 \times 10^{-17}$</td>
<td>8</td>
</tr>
<tr>
<td>Bumper Car</td>
<td>1</td>
<td>2</td>
<td>150</td>
<td>0.5</td>
<td>$1.4 \times 10^{-36}$</td>
<td>$3.4 \times 10^{-18}$</td>
<td>25</td>
</tr>
</tbody>
</table>
\( n_Q \) for a number of physical systems

(all units MKS)

<table>
<thead>
<tr>
<th></th>
<th>( r )</th>
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<td>460</td>
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<td>0.6</td>
</tr>
<tr>
<td>Billiards</td>
<td>0.029</td>
<td>1</td>
<td>0.16</td>
<td>1</td>
<td>6.6\times10^{-34}</td>
<td>5.1</td>
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Quantum at every collision

Albrecht @ NBI 11/1/2019
\( n_Q \) for a number of physical systems (all units MKS)

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Quantum at every collision

\((n_Q < 1 \rightarrow \text{breakdown of formula, but conclusion robust})\)
\( n_Q \) for a number of physical systems (all units MKS)

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Quantum at every collision
Every Brownian Motion is a “Schrödinger Cat”
$n_Q$ for a number of physical systems

(all units MKS)

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<tr>
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<th>$r$</th>
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</tr>
<tr>
<td>Bumper Car</td>
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<td>1.12</td>
<td>2.5</td>
<td>183</td>
<td>1.4</td>
<td>$3.4 \times 10^{-26}$</td>
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Quantum at every collision

Every Brownian Motion is a “Schrödinger Cat”

(independent of “interpretation”)

1,000,000,000,000
\( n_Q \) for a number of physical systems

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<td>8.16 ( \times 10^{-26} )</td>
<td>12 ( \times 10^{3} )</td>
<td>6.6 ( \times 10^{-34} )</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>Bumper Car</td>
<td>12 ( \times 10^{0} )</td>
<td>150</td>
<td>150</td>
<td>1025</td>
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This result is at the root of our claim that all everyday probabilities are quantum.

Every Brownian Motion is a “Schrödinger Cat”

Quantum at every collision
An important role for Brownian motion: Uncertainty in neuron transmission times

Brownian motion of polypeptides determines exactly how many of them are blocking ion channels in neurons at any given time. This is believed to be the dominant source of neuron transmission time uncertainties $\delta t_n \approx 1ms$.
Analysis of coin flip

\[ \delta t_f = \delta t_n \times \left( \frac{v_h}{v_h + v_f} \right) \]

\[ \delta t_t = \sqrt{2} \delta t_f \]

\[ f = \frac{4v_f}{\pi d} \]

\[ \delta N = f \delta t_t = 0.5 \]

Using:

\[ \delta t_n \approx 1 \text{ms} \quad v_h = v_f = 5 \text{m/s} \]

\[ d = 0.01 \text{m} \]
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50-50 coin flip probabilities are a derivable quantum result
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Without reference to “principle of indifference” etc. etc.
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50-50 coin flip probabilities are a derivable quantum result

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Using: Albrecht @ NBI 11/1/2019
Analysis of coin flip

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NB: Coin flip is “at the margin” of deterministic vs random: Increasing \(d\) or deceasing \(v_h\) can reduce \(\delta N\) substantially

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\[ \text{Coin diameter} = d \]

Still, this is a good illustration of how quantum uncertainties can filter up into the macroscopic world, for systems that *are* random.
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Still, this is a good illustration of how quantum uncertainties can filter up into the macroscopic world, for systems that *are* random.
Physical randomness vs “probabilities of belief”

Bayes:

\[
P(\text{Theory} | \text{Data}) = \frac{P(\text{Data} | \text{Theory})}{P(\text{Data})} P(\text{Theory})
\]

Physical randomness: To do with physical properties of detector etc.
Physical randomness vs “probabilities of belief”

Bayes:

\[ P(\text{Theory} \mid \text{Data}) = \frac{P(\text{Data} \mid \text{Theory})}{P(\text{Data})} \cdot P(\text{Theory}) \]

Proportions of belief:

- Which data you trust most
- Which theory you like best
Physical randomness vs “probabilities of belief”

Bayes:

\[
P(Theory \mid Data) = \frac{P(Data \mid Theory) \cdot P(Theory)}{P(Data)}
\]

This talk is about physical randomness only
Physical randomness vs “probabilities of belief”

Bayes:

\[ P(\text{Theory} \mid \text{Data}) = \frac{P(\text{Data} \mid \text{Theory})}{P(\text{Data})} P(\text{Theory}) \]

NB: The goal of science is to get sufficiently good data that probabilities of belief are inconsequential.
Physical randomness vs “probabilities of belief”

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Physical randomness vs “probabilities of belief”

Adding new data (theory priors can include earlier data sets):

\[ P_4(T \mid D_4) = \frac{P(D_4 \mid T)}{P(D_4)} P_3(T) \]

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Physical randomness vs “probabilities of belief”

Adding new data (theory priors can include earlier data sets):

\[ P_1(T | D_1) = \frac{P(D_1 | T)}{P(D_1)} P_0(T) \]

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This initial “model uncertainty” prior is the only \( P(T) \) that is a pure probability of belief.

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This talk is only about \(P(D \mid T)\) wherever it appears.
Physical randomness vs “probabilities of belief”

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Physical randomness vs “probabilities of belief”

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This is the only part of the formula where physical randomness appears.

This talk is only about \( P(D | T) \) appears.

NB: The goal of science is to get sufficiently good data that probabilities of belief are inconsequential.
All everyday probabilities are quantum probabilities

- Proof by exhaustion not realistic
All everyday probabilities are quantum probabilities

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- One counterexample (practical utility of non-quantum probabilities) will undermine our entire argument.
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- Which theories really do “require” classical probabilities not yet resolved rigorously.
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All everyday probabilities are quantum probabilities

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- Not a problem for many finite theories (AA, Banks & Fischler)
- Which theories really do “require” classical probabilities not yet resolved rigorously (symmetry?... simplicity? See below)

Some further thoughts:
Some further thoughts:

- Special relationship to cosmic structure from inflation: “(cosmic) probability censorship”
- A counterexample: Betting on the digits of Pi (Not!)
- Compare with classical computer
- Compare with color:
Outline

1) Quantum vs non-quantum probabilities (toy model/multiverse)

2) Everyday probabilities

3) Be careful about counting!

4) Implications for multiverse/eternal inflation
Outline

1) Quantum vs non-quantum probabilities (toy model/multiverse)

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4) Implications for multiverse/eternal inflation
Central message:

• “Randomness is (quantum) physics”
• Counting may or MAY NOT have a role in inferring or representing physical randomness
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- Example: Flip a coin and choose a ball:
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Counts of red & green balls here can be related in very concrete terms to the probability of heads vs tails
Central message:

• “Randomness is (quantum) physics”
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• Example: Flip a coin and choose a ball:

Counts of red & green balls here can be related in very concrete terms to the probability of heads vs tails
Now ask: What is the probability that a ball drawn from the “Results” bowl is red?
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• Different physical “completions” of this question are possible which give different answers. (≈ measures)
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• Different physical “completions” of this question are possible which give different answers. ($\approx$ measures)

• Counting is NOT enough.
Now ask: What is the probability that a ball drawn from the “Results” bowl is red?

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NB: “Sleeping Beauty problem”
Now ask: What is the probability that a ball drawn from the “Results” bowl is red?

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In a multiverse with many copies of you, there simply is *no* physical completion for the question “which observer am I?”. Future data may address this, but not in time to make predictions.
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This is where things go wrong in the standard treatment of the multiverse.
Now ask: What is the probability that a ball drawn from the “Results” bowl is red?
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In many cases counting observers has no predictive value.
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This is where things go wrong in the standard treatment of the multiverse. In many cases, counting observers has no predictive value. No point in counting for these cases.
Now ask: What is the probability that a ball drawn from the “Results” bowl is red?

- Different physical “completions” of this question are possible which give different answers. (≈ measures)
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In a multiverse with many copies of you, there apparently is *no* physical completion for the question “which observer am I?”. Future data may address this, but not in time to make predictions.

This is where things go wrong in the standard treatment of the multiverse.

No point in counting for these cases.

In many cases counting observers has no predictive value.
Outline

1) Quantum vs non-quantum probabilities (toy model/multiverse)

2) Everyday probabilities

3) Be careful about counting!

4) Implications for multiverse/eternal inflation
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1) Quantum vs non-quantum probabilities (toy model/multiverse)

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4) Implications for multiverse/eternal inflation
Implications for eternal inflation

1) No “volume factors”
2) Boltzmann Brain problem reduced
3) No “younerness/end of time” problem
Implications for eternal inflation

1) No "volume factors"
2) Boltzmann Brain problem reduced
3) No "youngness/end of time" problem

Pocket $A$ with $p_A$ (from quantum branching ratio)
Pocket $B$ with $p_B$
One semiclassical universe having many more possible observers in it than another (often counted by volume), does *not* give that universe greater statistical weight. Quantum branching ratio into one vs the other \( \frac{p_A}{p_B} \) does count.
Implications for eternal inflation

1) No “volume factors”
2) Boltzmann Brain problem reduced
3) No “youngness/end of time” problem
Implications for eternal inflation

1) No “volume factors”
2) Boltzmann Brain problem reduced
3) No “youness/end of time” problem

Pocket A with \( p_A \)

Pocket B with \( p_B \)
Implications for eternal inflation

1) No “volume factors”
2) This model has no “Boltzmann Brain” problem as long as $p_A / p_B$
   is “not too small”
Implications for eternal inflation

1) No “volume factors”

2) Boltzmann Brain problem reduced

This model has no “Boltzmann Brain” problem as long as \( \frac{p_A}{p_B} \) is not too small

Pocket A with \( p_A \)

Pocket B with \( p_B \)

Boltzmann brains are observers which look good vs current data but which quickly go bad
Implications for eternal inflation

1) No “volume factors”
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Pocket A with $p_A$

Pocket B with $p_B$
Implications for eternal inflation

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More pocket universes produced later vs earlier (due to more inflation)
Implications for eternal inflation

1) No “volume factors”
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More pocket universes produced later vs earlier (due to more inflation) & experience any time cutoff

Time cutoff regulator
Implications for eternal inflation

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More pocket universes produced later vs earlier (due to more inflation) & experience any time cutoff.

- Wavefunction cannot give probabilities for which pocket you are in.
- Time cutoff only there as (wrong) attempt to determine which pocket.
- The youngness/end of time problem is asking a question the theory cannot answer.
1) All practically applicable probabilities are of physics (quantum) origin.

2) Counting of objects may or MAY NOT be a way of accessing legitimate quantum probabilities.

3) Standard discussions of probabilities in cosmology often make errors re 2).

4) The “principle of indifference” has only ever been a phenomenology of point 1), nothing deeper. (Thus it should not form the basis of a “derivation of the Born rule”.)

5) 1) and care about 2) allow us to introduce better discipline into cosmological discussions (just say “no”). Implications so far:
   a) No (counting based) volume factors
   b) Reduced Boltzmann Brain problem
   c) No youngness/end of time problem
   d) Measure problems apparently resolved?

6) More rigorous treatment of eternal inflation (etc) needed to determine full implications.
Conclusions

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In a systematic treatment of the multiverse the classical probabilities will reappear as “priors”. Same math but very different role.

Also related to “Boltzmann Brains”
Conclusions

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Additional Slides
Cosmic structure

A note on “probability censorship”

Cosmic structure originates “superhorizon” in Standard Big Bag (why would they be quantum?)

Cosmic length scale

$\log(\frac{R_H}{R_{H0}})$

$\frac{\delta \rho}{\rho}$

Here

Observable Structure

Scale factor (measures expansion, time)

Today

Cosmic structure originates “superhorizon” in Standard Big Bag (why would they be quantum?)
Cosmic structure originates in quantum ground state in inflationary cosmology.

Cosmic structure originates "superhorizon" in Standard Big Bag (why would they be quantum?)

Scale factor (measures expansion, time)
• Proof by exhaustion not realistic
• One counterexample (practical utility of non-quantum probabilities) will undermine our entire argument
• Can still invent classical probabilities just to do multiverse cosmology
• Not a problem for many finite theories (AA, Banks & Fischler)
• Which theories really do require classical probabilities not yet resolved rigorously (symmetry?.. simplicity? See Cooperman 2011)

All everyday probabilities are quantum probabilities

Compare with identical particle statistics
Further discussion

Bet on the millionth digit of $\pi$

3.141592653589793238462643383279502884197169399375105820974944592307816406286

2089986280348253242117067982148086513282306647093844609550582231725359408128481
1174502841027019385211055596464622948954930381964428810975665933446128475648233
786783165271201909145648566923460348610454326648213393607260249141273724587006
606315588174881520920962829254091715364367892590360011330530548820466521384146
9519411160943305727036575959195309218611738193261179313051118548074462379962749
567351885752724891227938183011949129833636244065664308602139494695224737190
702179860943702770539217176293176752384674818467669405132000568127145263560827
78571342757789609176371782146840901224953430146549585371050792279689258923
54201995611212902196086403441815981362977477130996051870721134999998372978049
95105973173281606931859502445955346903803026425230825344685035261931188171010
003137838752886587533208381420617177691473035982535490428755468731159562863882
3537875937519577818577805323171226806613001927876611195909216420198938095257201
0654858632788659361553381827968230301952035301852968995773622599413891249721775
2834791315155748572424541506959508295331168617285588907509838175463746939319
255060400927701671139009848824012858361603563707660104710181942955596198946767
8374494482553797747264874104047534646246280466842590949129331367702889152104752
162069660240580381501935112533824030035876402474964732639141199272604269292796
782354781636009341721641219924586315030286182974555706749838505494588586926995
690927210797509302955321165344987202755960236480665499119881834797753566369807
426524527862558151884175746728909772793800081647060016145249192173217214772350
14144197356854816136115735255213347574184946843852323907394143334547762416862
518983569485562099219222184272550254256887671790494601653466804988627232791786
08578438327967976681451400953883873630950680064225125205117392984896084128488
626945604241965285022210661186306744278622039194950471237137836960956364371917
2874677646575739624138908658326459958113390478027590099465764078951269468398352
595709825822620522489407726719478268482601476990902640136934374355305068203496
Further discussion

Bet on the millionth digit of $\pi$

- The *only* thing random is the choice of digit to bet on
Further discussion

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• Fairness is about lack of correlation between digit choice and digit value
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Bet on the millionth digit of \( \pi \)

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- Fairness is about lack of correlation between digit choice and digit value
- Choice of digit comes from
  - Brain (neurons with quantum uncertainties)
  - Random number generator \( \rightarrow \) seed \( \rightarrow \) time stamp (when you press ENTER) \( \rightarrow \) brain
  - Etc
Further discussion

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Payout:

$$ P_\pi = \lim_{N_{tot} \to \infty} \frac{1}{N_{tot}} \sum_{\{i\}} (N^i_\pi - 4.5) = 0 $$
Classical Computer: The “computational degrees of freedom” of a classical computer are very classical: Engineered to be well isolated from the quantum fluctuations that are everywhere.

- Computations are deterministic
- “Random” is artificial
- Model a classical billiard gas on a computer:
  ➢ All “random” fluctuations are determined by (or “readings of”) the initial state.
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Further discussion

Std. thinking about classical probabilities
Our ideas about probability are like our ideas about color:

- Quantum physics gives the correct foundation to our understanding.
- Our “classical” intuition predates our knowledge of QM by a long long time, and works just fine for most things.
- Fundamental quantum understanding needed to fix classical misunderstandings in certain cases.
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