“QBism” - the quantum Bayesian program of
C. M. Caves
R. Schack
D. M. Appleby
myself
See arXiv.org.

See also:
C. G. Timpson,
“Quantum Bayesianism: A Study”
and
pirsa.org/09080010
08080039
My Favorite Convex Set

(My Favorite Shape)

Christopher Fuchs
FI - Perimeter Inst.

Work with:

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A quantum state, being a summary of the observers' information about an individual physical system, changes both by dynamical laws and whenever the observer acquires new information about the system through the process of measurement. The existence of two laws for the evolution of the state vector becomes problematical only if it is believed that the state vector is an objective property of the system. If the state of a system is defined as a list of [experimental] propositions together with [their probabilities of occurrence], it is not surprising that after a measurement the state must be changed to be in accord with the new information. The "reduction of the wave packet" does take place in the consciousness of the observer, not because of any unique physical process which takes place there, but only because the state is a construct of the observer and not an objective property of the physical system.
The hypothesis that there is an external world, not dependent on human minds, made of something, is so obviously useful and so strongly confirmed by experience down through the ages that we can say without exaggerating that it is better confirmed than any other empirical hypothesis.

— Martin Gardner
A Single-User Theory

- probability theory
- quantum theory

“The Bayesian, subjectivist, or coherent, paradigm is egocentric. It is a tale of one person contemplating the world and not wishing to be stupid (technically incoherent). He realizes that to do this his statements of uncertainties must be probabilistic.”

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— D. V. Lindley
the consequence
= an experience, $E_k$

$\psi$ 

the catalyst
= quantum system,

$\Psi_d$

the action
= $\{ E : \mathcal{F} \}$, a POVM
the consequence
= an experience, $E_k$

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the action
= $\{E_i\}_i$, a POVM
the consequence
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the catalyst
= quantum system,

the action
= $\{E_i^j\}$, a POVM
Calculus 1

Calculus 2

Calculus 3

Character 1

Character 2

Character 3
the consequence
= an experience, $E_k$

the catalyst
= quantum system,

the action
= $\{E_i^\lambda\}$, a POVM
Calculus 1 → Character 1
Calculus 2 → Character 2
Calculus 3 → Character 3
the consequence
= an experience, $E_k$

the catalyst
= quantum system, $\Phi_d$

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the consequence
= an experience, $E_k$

the catalyst
= quantum system, $\rho_d$

the action
= $\{E_i\}_3$, a POVM
A satisfactory statement about the actual (objective) characteristics of the quantum world should contain no \( |\psi\rangle \)'s at all.

Really. None!
Density Operators

\[ \rho \in \mathcal{L}(\mathcal{H}_d) \]

- Linear operators
- Complex vector space
- Catalog of uncertainties

1. \( \rho^+ = \rho \)
2. \( \text{tr} \, \rho = 1 \)
3. \( \rho(x) > 0 \)

Convex hull of the set \( \{ \psi \langle \psi | \psi \rangle : \psi \in \mathcal{H}_d \} \)
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convex hull of the set \( \{ 1\psi\langle \psi | : |\psi\rangle \in \mathcal{H} \} \)
Quantum Probability Theory

classical probability theory

Classical probability is "just" the commutative case.
Probability Theory
formal structure of Quantum Mechanics

Probability Theory
The Born Rule

Given $\rho$ and $\{E_i\}$,

quantum state

POVM measurement

$p(i) = \text{tr} \rho E_i$

"The Born Rule"
formal structure of Quantum Mechanics

Probability Theory
The Born Rule

Given $\rho$ and $\{E_i\}$,

- quantum state
- POVM measurement

\[ p(i) = tr(\rho E_i) \]

"The Born Rule"
\[ p \leftrightarrow p(h) \]
Bureau of Standards

the "standard" quantum measurement
Bureau of Standards

the "standard" quantum measurement

\[ p(h) \]
Bureau of Standards

the "standard" quantum measurement

[Diagram of a vault with various symbols and arrows indicating a process involving p(h) and q(i).]
Bureau of Standards

the "standard" quantum measurement

\[ p(h) \rightarrow q(i) \]
von Neumann

Standard measurements not good enough for the bureau.

\[ H = \sum_i \alpha_i \Pi_i \quad , \quad \Pi_i = \left| i \right\rangle \left\langle i \right| \]

\[ p(i) = \text{tr}_\rho \Pi_i = \left\langle i | \rho | i \right\rangle \]

\[ \Rightarrow \begin{pmatrix} \rho_{ii} \\ \rho_{12} & \rho_{22} \\ \vdots & \ddots & \ddots \end{pmatrix} \]
<table>
<thead>
<tr>
<th>Standard Measurements</th>
<th>Generalized Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>${\pi_i}$</td>
<td>${E_b}$</td>
</tr>
<tr>
<td>$\langle \psi</td>
<td>\pi_i</td>
</tr>
<tr>
<td>$\sum_i \pi_i = I$</td>
<td>$\sum_b E_b = I$</td>
</tr>
<tr>
<td>$\rho(i) = tr \rho \pi_i$</td>
<td>$\rho(b) = tr \rho E_b$</td>
</tr>
<tr>
<td>$\pi_i \pi_j = \delta_{ij} \pi_i$</td>
<td></td>
</tr>
</tbody>
</table>
Informational Completeness

quantum states

\( \rho \in \mathcal{L}(\mathcal{H}_d) \) — \( D^2 \)-dimensional vector space

Choose POVM \( \{E_n\} \), \( h=1, \ldots, D^2 \), with \( E_h \) all \underline{linearly independent}. (Can be done.)

\( D^2 \) numbers \( \rho(h) = \text{tr} \rho E_h \) determine \( \rho \).

\[ \uparrow \text{projection of } \rho \text{ onto } E_h \]

Any \( \{E_n\} \) can be the \underline{standard} quantum measurement.

Because \( (A,B) = \text{tr} A^* B \) is an inner product.
Probability Simplex

\[ \vec{\rho} = \begin{bmatrix} \rho(0) \\ \rho(1) \\ \vdots \\ \rho(n) \end{bmatrix} \]

\[ \sum_h \rho(h) = 1 \]

\[ \rho(h) \geq 0 \quad \forall h \]
Informational Completeness

Quantum states
\[ \rho \in \mathcal{L}(\mathcal{H}_D) \quad \text{— D}^2\text{-dimensional vector space} \]

Choose POVM \( \{E_h\}, \ h = 1, \ldots, D^2, \) with \( E_h \) all linearly independent.
(Can be done.)

\( D^2 \) numbers \( \rho(h) = \text{tr} \rho E_h \) determine \( \rho \).

Any \( \{E_h\} \) can be the standard quantum measurement.

Because
\[ (A,B) = \text{tr} A^* B \]
is an inner product.

Projection of \( \rho \) onto \( E_h \).
Informational Completeness

quantum states

$\rho \in \mathcal{L}(\mathcal{H}_D) = D^2$-dimensional vector space

Choose POVM $\{E_n\}, \ h = 1, \ldots, D^2,$

with $E_n$ all linearly independent.

(Can be done.)

$D^2$ numbers $\rho(n) = \text{tr} \rho E_n$ determine $\rho$.

Because $(A,B) = \text{tr} A^* B$ is an inner product.

projection of $\rho$ onto $E_n$

Any $\{E_n\}$ can be the standard quantum measurement.
A Very Fundamental Mmt?

Suppose $d^2$ projectors $\Pi_i = |\psi_i\rangle \langle \psi_i|$

satisfying

$$\text{tr} \, \Pi_i \Pi_j = \frac{1}{d+1}, \quad i \neq j$$

exist.

Can prove:

1) the $\Pi_i$ linearly independent

2) $\sum_i \frac{1}{d} \Pi_i = I$

So good for Bureau of Standards.

Also

$$\rho(i) = \frac{1}{d} \text{tr} \rho \Pi_i$$

$$\rho = \sum_i \left[ (d+1) \rho(i) - \frac{1}{d} \right] \Pi_i$$
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But do such sets of states exist?
A Very Fundamental Mmt?  

Suppose $d^2$ projectors $\Pi_i = |\psi_i\rangle \langle \psi_i|$, satisfying

$$\text{tr} \, \Pi_i \Pi_j = \frac{1}{d+1}, \quad i \neq j$$

exist.

Can prove:

1) the $\Pi_i$ linearly independent
2) $\sum_i \frac{1}{d} \Pi_i = I$

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Also

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$$\rho = \sum_i [d+1 \rho(i) - \frac{1}{d}] \Pi_i$$
But do such sets of states EXIST?
?
Inequivalent SIC Sets

Let $d = 3$, $\omega = e^{\frac{2\pi i}{3}}$.

**Set 1**

\[
\begin{bmatrix}
0 \\
-1 \\
1 \\
\end{bmatrix}, \quad \begin{bmatrix}
0 \\
1 \\
i \\
\end{bmatrix}, \quad \begin{bmatrix}
io \\
\omega \\
\end{bmatrix}
\]

**Set 2**

\[
\begin{bmatrix}
-2 \\
1 \\
1 \\
\end{bmatrix}, \quad \begin{bmatrix}
-2 \\
1 \\
1 \\
\end{bmatrix}, \quad \begin{bmatrix}
-2 \\
1 \\
1 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
2 \\
1 \\
1 \\
\end{bmatrix}, \quad \begin{bmatrix}
-2 \\
1 \\
1 \\
\end{bmatrix}, \quad \begin{bmatrix}
-2 \\
1 \\
1 \\
\end{bmatrix}
\]

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\begin{bmatrix}
1 \\
-2 \\
1 \\
\end{bmatrix}, \quad \begin{bmatrix}
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\begin{bmatrix}
1 \\
1 \\
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\end{bmatrix}, \quad \begin{bmatrix}
1 \\
1 \\
-2 \\
\end{bmatrix}
\]
Inequivalent SIC Sets

Let $d = 3$, $\omega = e^{\frac{2\pi i}{3}}$.

Set 1

$\begin{bmatrix} 0 & 0 & 0 \\ -1 & -2 & 0 \\ 1 & 0 & 3 \end{bmatrix}$

$\begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 13 \\ -1 & -1 & 3 \end{bmatrix}$

Set 2

$\begin{bmatrix} -2 & -2 & -2 \\ 1 & 1 & 1 \\ -1 & -1 & -1 \end{bmatrix}$

$\begin{bmatrix} -2 & -2 & -2 \\ 1 & 1 & 1 \\ -1 & -1 & -1 \end{bmatrix}$
Evidence for Existence

Analytical Constructions
\[ d = 2 - 13 \setminus 15, 19 \]

Numerical \((\epsilon \leq 10^{-40})\) \(10^{-38}\)
\[ d = 2 - 4 \cdot 67 \]
Remarkable Theorem

Jones & Linden, PRA II (2005)
Flammia, (unpub, 2004)

Let $A$ be Hermitian, $A^\dagger = A$.

Then, $A = |\psi\rangle\langle\psi|$ if and only if

$$\text{tr} \ A^2 = \text{tr} \ A^3 = 1.$$
A Very Fundamental Mmt?  

Suppose $d^2$ projectors $\Pi_i = |\psi_i\rangle\langle\psi_i|$ satisfying

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$$\rho(i) = \frac{1}{d} \text{tr} \rho \Pi_i$$

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**Pure States in SIC Language**

Conditions

\[ \rho^+ = \rho, \quad \text{tr} \rho^2 = \text{tr} \rho^3 = 1 \]

translate to

\[ \sum_i \rho(i)^2 = \frac{2}{d(d+1)} \]

and

\[ \sum_{jke} c_{jke} \rho(j) \rho(k) \rho(l) = \frac{d+1}{(d+1)^2} \]

where

\[ c_{jke} = \text{Re} \; \text{tr} \, \Pi_j \Pi_k \Pi_l \]

Could these be independently motivatable physical constants?
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$$\text{tr} \ A^2 = \text{tr} \ A^3 = 1.$$
**Proof:**

$a_i$ - eigenvalues of $A$

$\text{tr} A^2 = \sum_i a_i^2 = 1 \quad \Rightarrow \quad |a_i| \leq 1$

$1 - a_i \geq 0$

$0 = \text{tr} A^2 - \text{tr} A^3 = \sum_i a_i^2 (1 - a_i)$

$\Rightarrow \quad a_i = 0 \quad \text{or} \quad 1 - a_i = 0$

$\text{tr} A^2 = 1 \quad \Rightarrow \quad a_i = 1 \quad \text{for one and only one } i.$

QED
Given $p(H_i)$

Any SIC

But really going to do this.

Given $p(D_i|H_i)$

Any von Neumann

Imaginary

Imaginary
Laws of Probability

\( H_i \) - various hypotheses one might have

\( D_j \) - data values one might gather

**Given:**

- \( p(D_j | H_i) \) \( \leftrightarrow \) expectations for data given hypothesis
- \( p(H_i) \) \( \leftrightarrow \) expectations for hypotheses themselves

**Question:** What expectations should one have for the \( D_j \)?

**Answer:**

\[
P(D_j) = \sum_i p(H_i) p(D_j | H_i)
\]
Given $p(H_i)$

Any SIC

Imaginary

Given $p(O|H_i)$

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$p(H_i)$ \leftarrow expectations for hypotheses themselves

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Answer: $P(D_i) = \sum_i p(H_i) p(D_j | H_i)$
In this case,

\[ p(D_j) \neq \sum_i p(H_i) p(D_j | H_i). \]

As Ballentine (1986) points out, there are hidden conditionals

\[ p(D_j) \quad \text{really} \quad p(D_j | C_1) \]
\[ p(H_i) \quad \text{really} \quad p(H_i | C_2) \]
\[ p(D_j | H_i) \quad \text{really} \quad p(D_j | H_i, C_2) \]
But really going to do this.
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Given $p(D; I | H_i)$

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\[ p(D_j | H_i) \text{ really } p(D_j | H_i, C_2) \]
\[ p(D_j) = (d+1) \sum_i p(H_i) p(D_j|H_i) - 1 \]

Quantum  \rightarrow  (Usual) Bayesian  \rightarrow  Magic!
Given \( p(H_i) \)

Any SIC

Given \( p(D_j | H_i) \)

But really going to do this.
**Laws of Probability**

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\[ D_j \] - data values one might gather

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P(D_i) = \sum \ p(H_i) \ p(D_j | H_i)
\]
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Any SIC

Imaginary

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(Usual) Bayesian

Magic!
Given $p(H_i)$

Any SIC

Given $p(D_i|H_i)$

But really going to do this. Any von Neumann
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- $p(H_i)$ \(\leftarrow\) expectations for hypotheses themselves

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**Answer:**

$$P(D_j) = \sum_i p(H_i) p(D_j|H_i)$$
\[ q(j) = (d+1) \sum_{i} p(i) r(j|i) - \frac{1}{2} \sum_{i} r(j|i) \]

\[ q(j) = f(\overline{p}, \{ \overline{r} \}) \]
Examples

1) Take $\vec{\xi} = \vec{p}$. Consequently must have

$$\vec{p} \cdot \vec{p} \leq \frac{2}{d(d+1)}$$

Same as quantum.

2) Consider a subset \{\vec{p}_k\} \subseteq S with $k = 1, \ldots, m$ such that

$$\vec{p}_k \cdot \vec{p}_k = \frac{2}{d(d+1)}$$

$$\vec{p}_k \cdot \vec{p}_\ell = \frac{1}{d(d+1)} \quad k \neq \ell.$$  

How large can $m$ be?

Answer: $d$, same as quantum.
Think SIC thoughts!

... and maybe by way of it we'll come to understand quantum mechanics a little better.
Bayesian Perspective

No logical reason why situation with conditional lotteries should be commensurate with situation without conditional lotteries.

\[ p(D_j) \neq \sum_i p(H_i) p(D_j | H_i) \]

(Need better notation, though.)

Quantum Perspective

Nonetheless, there may be

\[ p(D_j) = (d+1) \sum_i p(H_i) p(D_j | H_i) - \frac{1}{d} \sum_i p(D_j | H_i) \]
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\sum_{h} \rho(h) = 1 \\
\rho(h) \geq 0 \quad \forall h
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Bureau of Standards

the "standard" quantum measurement
Bureau of Standards

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$P(n) \rightarrow q(i)$
Bureau of Standards

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Density Operators

\[ \rho \in L(\mathcal{H}_d) \]

- linear operators
- complex vector space
- catalog of uncertainties

1) \( \rho^* = \rho \)
A Single-User Theory

- probability theory
- quantum theory

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Am. J. Phys. 36, 704-712 (1968)

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