Is 'Quantum Darwinism' Really a Darwinism?

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Rough Guide

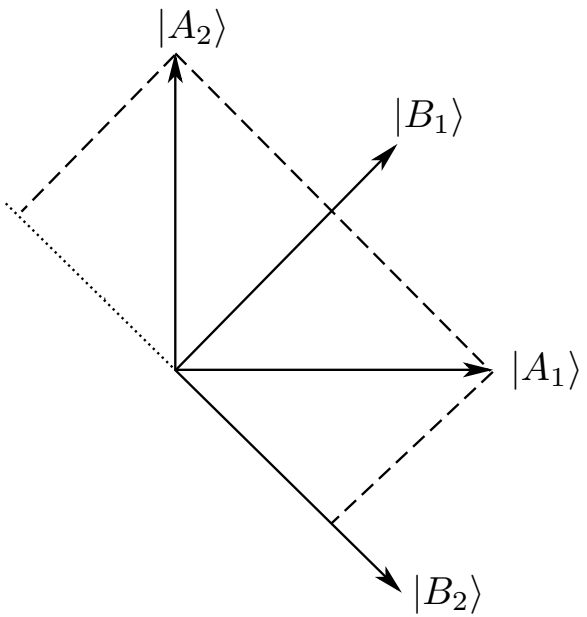
- QT in a nutshell
- decoherence and ‘Quantum Darwinism’
- three steps to dispute Darwinian character:
  - if interpretation neutral, no Darwinism because selection and reproduction apply at different levels
  - if this is fixed, tied to Everett interpretation
  - if Everett interpretation accepted, no Darwinism after all, due to lack of a resource

Quantum Theory in a Nutshell

- *state* $|\psi_S\rangle$ of system S is element of a *linear vector space* $\mathcal{H}$ over *complex numbers* $\mathbb{C}$
- 'observables' O represented by *self-adjoint* (linear) *operators* $\hat{O}$ acting on $\mathcal{H}$
- some *non-commuting*; e.g. $\hat{x}\hat{p} - \hat{p}\hat{x} = \imath\hbar \neq 0$
- *unitary* (linear, bijective, norm preserving) operators $\hat{U}$ represent *state transformations*
  - e.g. dynamics: $\hat{U}(t;t_f)\,|\psi_S(t)\rangle = |\psi_S(t_f)\rangle$ with $\hat{U}(t;t_f) = e^{-\frac{\imath}{\hbar}\hat{H}(t_f-t)}$ (simplest case)

Quantum Theory in a Nutshell

- 'ambiguity' 1: there can be *physical reasons* to write $|\psi_S\rangle = \alpha_1 |o_1\rangle + \alpha_2 |o_2\rangle + \alpha_3 |o_3\rangle + \ldots = \sum_j \alpha_j |o_j\rangle$, where $\hat{O} |o_j\rangle = o_j |o_j\rangle$, meaning that $\mathcal{S}$ has definite value o_j for O
- 'ambiguity' 2: a state from $\mathcal{H}$ can *always* be written as a superposition in *some arbitrary* basis of $\mathcal{H}$:



Quantum Theory in a Nutshell

- for $|\psi_S\rangle = \sum_j \alpha_j |o_j\rangle$ we have $\Pr_O^{\psi_S}(o_j) = |\alpha_j|^2$ (*Born's rule*)
- $\alpha_j = \langle o_j|\psi_S\rangle$ (*inner product*)
- $\langle o_i|o_j\rangle = \delta_{ij} = \begin{cases} 1 \text{ if } i = j \\ 0 \text{ else} \end{cases}$ (*orthonormal basis*; ONB)
- $|o_j\rangle$ vs. $|o_j\rangle\langle o_j|$, $|\psi_S\rangle$ vs. $|\psi_S\rangle\langle\psi_S|$ ('projectors', repres. *pure* states)
- *density operator* $\hat{\rho}_S = \sum_k p_k |\psi_S^{(k)}\rangle\langle\psi_S^{(k)}|$ (*mixed* state, so long as $p_k \neq 1$ for some k)
- $\hat{O} = \sum_j o_j |o_j\rangle\langle o_j|$

Interpretive Problems

- $|o_j\rangle\ |\mathcal{M}_0\rangle \overset{\hat{U}}{\mapsto} |o_k\rangle\ |\mathcal{M}_{o_j}\rangle$, where $\hat{U} = e^{\frac{\imath}{\hbar}\hat{H}_{\text{int}}\Delta t}$
- $\sum_j \alpha_j |o_j\rangle\ |\mathcal{M}_0\rangle \overset{\hat{U}}{\mapsto} \sum_{j,k} \alpha_{jk} |o_k\rangle\ |\mathcal{M}_{o_j}\rangle = \sum_j \tilde{\alpha}_j |\tilde{o}_j\rangle\ |\mathcal{M}_{o_j}\rangle =: |\psi_{\mathcal{SM}}\rangle$
- *entangled* state, i.e., cannot be written as $|\tilde{\tilde{o}}_j\rangle\ |\tilde{\mathcal{M}}_{o_j}\rangle$ in *any* basis of $\mathcal{H}_\mathcal{S} \otimes \mathcal{H}_\mathcal{M}$
- ambiguity 2 (again):
  - $|\psi_{\mathcal{SM}}\rangle = \frac{1}{\sqrt{2}} (|\uparrow_z\rangle + |\downarrow_z\rangle)\ |\mathcal{M}_0\rangle \mapsto |\psi^f_{\mathcal{SM}}\rangle = \frac{1}{\sqrt{2}} (|\uparrow_z\rangle|\mathcal{M}_{\uparrow_z}\rangle + |\downarrow_z\rangle|\mathcal{M}_{\downarrow_z}\rangle)$
  - $|\psi^f_{\mathcal{SM}}\rangle = \ldots = \frac{1}{\sqrt{2}} (|\uparrow_x\rangle|\mathcal{M}_{\uparrow_x}\rangle + |\downarrow_x\rangle|\mathcal{M}_{\downarrow_x}\rangle)$
- *projection postulate* (Dirac, 1958; von Neumann, 1932): $|\psi_{\mathcal{SM}}\rangle \mapsto |\tilde{o}_\ell\rangle\ |\mathcal{M}_{o_\ell}\rangle$
  - ad hoc: *how/when/where/why* does the change occur? What *causes* it? ("Heisenberg cut"; "Wigner's friend")

Decoherence Theory

- $\hat{U}_{\mathcal{SM},\mathcal{E}} |\psi_{\mathcal{SM}}\rangle |\mathcal{E}_0\rangle = \hat{U}_{\mathcal{SM},\mathcal{E}} \sum_j \alpha_j |\mathcal{S}_j\rangle |\mathcal{M}_j\rangle |\mathcal{E}_0\rangle = \sum_j \alpha_j |\tilde{\mathcal{S}}_j\rangle |\tilde{\mathcal{M}}_j\rangle |\mathcal{E}_j\rangle$
- *partial tracing*:
  - $\hat{\rho}_{\mathcal{SME}} = |\psi_{\mathcal{SME}}\rangle\langle\psi_{\mathcal{SME}}| = \sum_{i,j} \alpha_j \alpha_i^* |\mathcal{S}_j\rangle\langle\mathcal{S}_i| \otimes |\mathcal{M}_j\rangle\langle\mathcal{M}_i| \otimes |\mathcal{E}_j\rangle\langle\mathcal{E}_i|$
  - $\mathrm{Tr}_{\mathcal{E}}(\hat{\rho}_{\mathcal{SME}}) =: \hat{\rho}_{\mathcal{SM}} = \sum_{i,j} \alpha_j \alpha_i^* |\mathcal{S}_j\rangle\langle\mathcal{S}_i| \otimes |\mathcal{M}_j\rangle\langle\mathcal{M}_i| \langle\mathcal{E}_j|\mathcal{E}_i\rangle_t$
  - if $\langle\mathcal{E}_i|\mathcal{E}_j\rangle \approx 0$ for $i \neq j$, we obtain $\hat{\rho}_{\mathcal{SM}} \approx \sum_j |\alpha_j|^2 |\mathcal{S}_j\rangle\langle\mathcal{S}_j| \otimes |\mathcal{M}_j\rangle\langle\mathcal{M}_j|$
  - often perfectly valid for $t \to \infty$ and good approximation after a short *decoherence time* (e.g. Joos et al. 2003, p. 67; Schlosshauer 2007, pp. 70 ff.)

Decoherence Theory

$\hat{\rho}_{\mathcal{SM}} \approx \sum_j |\alpha_j|^2 \, |\mathcal{S}_j\rangle\langle\mathcal{S}_j| \otimes |\mathcal{M}_j\rangle\langle\mathcal{M}_j|$

- approximate & improper *mixture* of eigenstates ($|\mathcal{S}_j\rangle\langle\mathcal{S}_j| \otimes |\mathcal{M}_j\rangle\langle\mathcal{M}_j|$) of preferred observables $\hat{M} = \sum_j m_j \, |\mathcal{M}_j\rangle\langle\mathcal{M}_j|$, $\hat{S} = \sum_j s_j \, |\mathcal{S}_j\rangle\langle\mathcal{S}_j|$
- stable under influence of environment ('preferred basis')
- typically approximately localized states with approximately well-defined velocity/momentum (*quasi-classical*)
- *but*: no 'or' from an 'and' (Bell, 1990)

'Quantum Darwinism'

Zurek (2009, p. 182):

"Monitoring by the environment means that information about $\mathcal{S}$ is deposited in $\mathcal{E}$. [...] Decoherence theory ignores it [the information – FJB]. The environment is 'traced out'. [...] Quantum Darwinism recognizes that [...] observers eavesdrop on the environment. Most of our data come from fragments of $\mathcal{E}$."

'Quantum Darwinism'

- How much information?
  - Shannon entropy $H(X) = -\sum_x p_x \log_2(p_x)$ of a variable X with distribution p_x "as a measure of how much information we have gained *after* we learn the value of X" (Nielsen and Chuang, 2010, p. 500)
  - *von Neumann entropy* $S(\mathcal{S}) = -\operatorname{Tr}\left(\hat{\rho}_\mathcal{S} \log_2 \hat{\rho}_\mathcal{S}\right)$
  - if $\hat{\rho}_\mathcal{S} = \sum_x p_x |x\rangle\langle x|$ (perfect decoherence), the two will coincide
- how to exploit environment?
  - use *mutual information* $I(\mathcal{S} : \mathcal{F}) = H(\mathcal{S}) + H(\mathcal{F}) - H(\mathcal{S}, \mathcal{F})$, where $\mathcal{F}$ is a *fraction* of $\mathcal{E}$ (a set of subsystems of $\mathcal{E}$), and $H(\mathcal{S}, \mathcal{F})$ is evaluated w.r.t. $\hat{\rho}_{\mathcal{S}\mathcal{F}} = \operatorname{Tr}_{\mathcal{E}\setminus\mathcal{F}}(\hat{\rho}_{\mathcal{S}\mathcal{E}}) \approx \sum_x p_x |x\rangle\langle x| \otimes |\mathcal{F}_x\rangle\langle\mathcal{F}_x|$ after short decoherence time

‘Quantum Darwinism’

Diagram cf. Zurek (2009, p. 183)

Whence the Darwinism?

- three modules of generalized evolution (cf. Schurz 2011, p. 131; Lewontin 1970, p. 1):
  - *reproduction*: some entities will reproduce (in generations, w.r.t. certain traits)
  - *variation*: reproduced traits will vary; variation will get reproduced
  - *selection*: some entities/traits will reproduce faster than others, hence spreading and pushing other entities/traits aside in the long run

Whence the Darwinism?

Zurek (2009, p. 182):

"only states that produce multiple informational offspring—multiple imprints in the environment—can be found out from small fragments of $\mathcal{E}$ [variation – FJB]. The origin of the emergent classicality is then not just survival of the fittest states (the idea already captured by [decoherence]) [selection – FJB], but their ability to 'procreate', to deposit multiple [...]copies of themselves[...] throughout $\mathcal{E}$ [reproduction – FJB]."

Whence the Darwinism, Really? (Step 1)

- decoherence: $\sum_{i,j} \alpha_i \alpha_j^* \left|\mathcal{S}_i\right\rangle\!\left\langle\mathcal{S}_j\right| \otimes \left|\mathcal{M}_i\right\rangle\!\left\langle\mathcal{M}_j\right| \otimes \left|\mathcal{E}_i\right\rangle\!\left\langle\mathcal{E}_j\right| \xrightarrow{t\to\infty,\mathrm{Tr}_{\mathcal{E}}} \sum_i |\alpha_i|^2 \left|\mathcal{S}_i\right\rangle\!\left\langle\mathcal{S}_i\right| \otimes \left|\mathcal{M}_i\right\rangle\!\left\langle\mathcal{M}_i\right|$ (*selection* of the $\{\left|\mathcal{S}_i\right\rangle\!\left\langle\mathcal{S}_i\right|\}$ and $\{\left|\mathcal{M}_i\right\rangle\!\left\langle\mathcal{M}_i\right|\}$)
- before decoherence, there is a range of bases on equal footing (*variation*)
- 'multiple copies' in $\mathcal{E}$ of states stable under decoherence (*reproduction*):

$$\sum_j \alpha_j \left|\mathcal{S}_j\right\rangle \left|\varepsilon_0^{(1)}\right\rangle \overset{\hat{U}}{\longmapsto} \sum_j \alpha_j \left|\mathcal{S}_j\right\rangle \left|\varepsilon_j^{(1)}\right\rangle$$

$$\sum_j \alpha_j \left|\mathcal{S}_j\right\rangle \left|\varepsilon_j^{(1)}\right\rangle \left|\varepsilon_0^{(2)}\right\rangle \overset{\hat{U}}{\longmapsto} \sum_j \alpha_j \left|\mathcal{S}_j\right\rangle \left|\varepsilon_j^{(1)}\right\rangle \left|\varepsilon_j^{(2)}\right\rangle$$

$$\vdots$$

- observation: *selection* of *observable* (and associated *basis*) due to decoherence, but *reproduction* of *values* (and associated *states*)

Whence the Darwinism, Really? (Step 2)

- fix: let *all the* eigenstates / projectors of $\sum_j s_j \, |\mathcal{S}_j\rangle\langle\mathcal{S}_j|$ be selected!
- variations refer to variations of *states* of $\mathcal{S}$ due to prior interaction with $\mathcal{E}$
- corresponds to selection of the *values* s_k on a *set of 'branches'* $|\mathcal{S}_k\rangle \, |\varepsilon_k^{(1)}\rangle \, |\varepsilon_k^{(2)}\rangle \ldots |\varepsilon_k^{(N)}\rangle$ resolving $|\psi_{\mathcal{S}\mathcal{E}}\rangle = \sum_j \alpha_j \, |\mathcal{S}_j\rangle \, |\varepsilon_j^{(1)}\rangle \, |\varepsilon_j^{(2)}\rangle \ldots |\varepsilon_j^{(N)}\rangle$

Whence the Darwinism, Really? (Step 2)

Zurek (2009, p. 185)

the structure of the correlations within $|\psi_{\mathcal{S}\mathcal{E}}\rangle$ leaves no doubt as to what these branches are

ibid.

our discussion is interpretation free, and this is a virtue

- not true: applying selection & reproduction to same level presupposes *Everett / many worlds interpretation* (MWI)

Whence the Darwinism, Really? (Step 2)

- that "[i]ndividual states—one might say with Bohr—are mostly information, too fragile for objective existence" (Zurek, 2009, p. 185) by itself rather incomprehensible
- notable 'anti-realist' interpretations either try to dispense with decoherence altogether (cf. Fuchs and Schack, 2012) or do not interpret it as descriptive of anything (cf. Healey, 2012)
- other realist interpretations are hard to reconcile with decoherence (cf. Schlosshauer, 2004); introducing an explicit collapse would kill the (unitary/decoherence based) computations

Whence the Darwinism, Really? (Step 2)

Zurek (2003a, p. 718; emph. added)

Using Darwinian *analogy*, one might say that *pointer states* are the most "fit." They survive monitoring by the environment to leave "descendants" that inherit their properties.

Zurek (2009, p. 185; emph. added)

When $f = 0$, the observer is ignorant of *what branch he will find out*

- resonates well with MWI-based 'self locating'-versions (Carroll and Sebens, 2014) of Zurek's (2003b; 2005; 2009) proof of the Born rule

Whence the Darwinism, Really? (Step 3)

Wallace (2012, p. 120; orig. emph.)

there is actually no such thing as the number of branches. [...]the branching structure is given by decoherence, and decoherence does not deliver a structure with a well-defined notion of branch count.

Maudlin (2014, p. 798; emph. alt.)

Decoherence implies that the evolution of the *total wavefunction* [of the universe – FJB] can, at a *macroscopic and somewhat approximate level* of analysis, *we* [sic.] *treated as* a collection of wavefunctions, each of which evolves independently of the others.

Whence the Darwinism, Really? (Step 3)

Zeh (2000, p. 226)

The quantum world (described by a wave function) would correspond to *one* superposition of myriads of components representing *classically* different worlds. [...] It is not the real world (described by a wave funtion [sic.]) that branches in this picture, but [...] the *observed* (apparent) "world"

Whence the Darwinism, Really? (Step 3)

1. the global quantum state $|\Psi\rangle$ of the universe does not *literally* branch ('spawn off' independent components at certain points in time), according to decoherence
2. even if it would, that would not lead to a well-defined *number* of such branches
3. therefore, even in the MWI there is no sense in which the fittest states can be said to outnumber the less fit ones in the long run

Whence the Darwinism, Really? (Step 3)

- put differently: what would be the *resource* for which states compete *if not the total overall amount of branches occupied in the global state vector*?
- analogy: evolution of solar system
  - retention corresponds to recurrence of certain configurations in space over time / spread of these in spacetime
  - 'resource': physical space(time)
- for want of a well defined 'branch count' and proper separation of branches, there is no analogous resource in QT!

Conclusions

- 'Quantum Darwinism' is either not interpretation-neutral or no Darwinism since selection and reproduction apply to different things
- if rectified by supplying a suitable interpretation and re-interpreting some claims, it looses outnumbering less fit by fittest, for want of a proper resource
- therefore, it is no Darwinism properly so called

Thanks!

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