Introduction: Individuality, Distinguishability, and (Non-)Entanglement

Cord Friebe[*], Kian Salimkhani[†], and Tina Wachter[‡§]

June 16, 2021[¶]

Elementary particles appear in different ways. Particles of the same kind (similar particles) share all state-*independent* properties like mass, charge, and spin quantum number; there are many similar particles, but they are indistinguishable with respect to a certain class of properties. However, the case might even be stronger: similar particles apparently share all state-*dependent* properties, like spatial location and spin projection. This threatens the validity of Leibniz's famous *Principle of the Identity of Indiscernibles* (PII; see Rodriguez-Pereyra (2014) for a historical reconstruction).

As it is usually understood, quantum mechanics requires for similar particles to be in permutation invariant states. Take the following state, for example:

$$|\psi\rangle = \frac{1}{\sqrt{2}}\big[|R\rangle_1|\uparrow_z\rangle_1|L\rangle_2|\downarrow_z\rangle_2 - |L\rangle_1|\downarrow_z\rangle_1|R\rangle_2|\uparrow_z\rangle_2\big] \ , \tag{1}$$

with properties of spatial location L and R and spin properties $\uparrow_z$ and $\downarrow_z$. According to the standard reading, both particles are in the same state, namely in the same two-particle state or, if preferred, in the same reduced mixed state:

$$\hat{\rho}_{1;2} = \frac{1}{2}\big(|R,\uparrow_z\rangle\langle\uparrow_z,R| + |L,\downarrow_z\rangle\langle\downarrow_z,L|\big) \ . \tag{2}$$

Philosophically, one hence concluded (as per the standard) that similar quantum particles, regardless of their state, violate every interesting version of the PII;

[*]Philosophical Seminar, University of Siegen, Adolf-Reichwein-Str. 2, 57076 Siegen, Germany; Cord.Friebe@uni-siegen.de

[†]Philosophical Seminar, University of Cologne, Albertus-Magnus-Platz 1, 50923 Cologne, Germany; k.salimkhani@uni-koeln.de

[‡]Institute for Philosophy, University of Hannover, Im Moore 21, 30167 Hannover, Germany

[§]Philosophical Seminar, University of Siegen, Adolf-Reichwein-Str. 2, 57076 Siegen, Germany; Tina.Wachter@uni-siegen.de

[¶]The published version of this introduction is available online at: https://doi.org/10.1007/s10838-021-09568-0.

the quantum particles are utterly indistinguishable in every physically possible situation, no matter how many such particles are being considered.

Since Saunders (2006), some authors have applied the discerning defence of the PII in the following way: they argue that (at least for fermions) there is always an overlooked physical relation that discerns the particles weakly. This relation is not asymmetrical, as previously expected, but irreflexive, which is allegedly sufficient to save the PII. In the case at hand, proponents of Weak Discernibility (WD) would say that, although no particle has a definite spin projection property, both particles are physically discerned by having *opposite* spin. Thus, until recently, the state of the art was that the PII can either be saved by WD, or is lost.

Recently, however, Ghirardi et al. (2002) pointed out that one has to carefully distinguish purely permutation invariant states, such as the above, from states that are also physically entangled, such as the following:

$$|\mathrm{EPR}\rangle = \frac{1}{\sqrt{2}}\big[|\uparrow\rangle_1|\downarrow\rangle_2 - |\downarrow\rangle_1|\uparrow\rangle_2\big] \otimes \big[|R\rangle_1|L\rangle_2 + |L\rangle_1|R\rangle_2\big] \ . \tag{3}$$

In this state, the properties of spatial location are no longer coupled with the spin properties. In addition, one can now violate Bell-inequalities. Consequently, the requirement of permutation invariance can be satisfied in different ways, with robust physical consequences or without them. This distinction is the physical grounds for a new iteration of the philosophical debate.

Firstly, the basic physical notions of permutation symmetry and entanglement are newly under philosophical consideration. Then, secondly, some authors have argued that a stronger version of the PII can be satisfied by similar quantum particles, at least in purely permutation invariant states. For example, therein there apparently is a particle located at R with spin-up and another particle located at L with spin-down; two (not merely weakly) distinguishable particles apparently emerge within such states.

Still, these distinguishable particles cannot be those that are labelled by the tensor product indices "1" and "2", since both particle 1 and particle 2—if there is any such particle—would be in the same mixed state. Therefore, connected with the new discerning defense of the PII, the so-called labelling problem arises (or rather returns in a new way): what Caulton and Butterfield dubbed "factorism", i.e., the view that the tensor indices refer to physical particles, is under pressure. This philosophy of language aspect is the second main issue of this special subject matter.

In particular, the four papers address the following issues.

In his paper 'How to justify the symmetrization postulate in quantum mechanics', Tomasz Bigaj examines the question of how quantum mechanics justifies the Symmetrisation Postulate—mainly with respect to many particle systems. Furthermore, he addresses the issue of how to properly interpret labels that are

present in the formal representation of the physical states of same-type particles.

The joint paper 'Identical Quantum Particles as Distinguishable Objects' by Dennis Dieks and Andrea Lubberdink argues against the factorist approach. They charge both the former standard view as well as the WD approach with tacitly assumed indistinguishability of similar particles, and offer an alternative conception of quantum particles, which understands such particles as emergent, non-fundamental, and always absolutely distinguishable based on their physically grounded identity.

In 'Leibniz, Kant, and Referring in the Quantum Domain', Cord Friebe also advocates an anti-factorist perspective. He presents two alternative strategies of referring to similar particles: the Leibnizian strategy of referring with the help of (newly introduced) descriptive proper names, and the Kantian strategy of referring via intuition and demonstratives.

Lastly, F. A. Muller and Gijs Leegwater defend factorism against several anti-factorist arguments in their paper 'The Case against Factorism'. They show how with the construction of 'snapshot Hilbert space' and 'Schrödinger-movie' the QM formalism could offer labels that refer descriptively. In this way, similar particles become absolutely discernible, even from a factorist perspective.

The special issue follows up on the international workshop *Individuality, Distinguishability, and (Non-)Entanglement* that took place at the University of Bonn in March 2018. The invited lectures have been recorded and are available online.[1] The workshop was organised as an event of the research project (FR 1461/6) funded by the German Research Foundation (DFG).

We would like to thank all speakers—namely Tomasz Bigaj, Jeremy Butterfield, Adam Caulton, James Ladyman, Andrea Lubberdink, F. A. Muller, Simon Saunders, Lev Vaidman, and Tina Wachter—and all participants—in particular, Matthias Kleinmann, Christina Ritz, and Gijs Leegwater—for truly memorable and stimulating discussions as well as a great atmosphere. Furthermore, we are especially grateful to Maren Bräutigam and Lina Theiß for their great assistance and help during the workshop. We also would like to thank Anne Hoffsümmer, Martina Richtberg, and Alexander Schubert for their help with preparing the workshop.

Lastly, a big thank you to the 12 anonymous reviewers, all of whom are renowned scholars who have previously worked on these issues and were not participants of the workshop themselves, for dedicating their time and expertise.

Grants: KS is supported by the DFG grant FOR 2495 (research group *Inductive Metaphysics*); TW is supported by the DFG grant FR 1461/6-2 (research project *Individualität, Unterscheidbarkeit und Verschränkung*).

[1] See https://www.philosophie.uni-bonn.de/de/aktuelles/tagung-distinguishability.

References

Ghirardi, G., Marinatto, L. and Weber, T. (2002), 'Entanglement and properties of composite quantum systems: A conceptual and mathematical analysis', *Journal of Statistical Physics* **108**(1/2), 49–122. DOI: 10.1023/A:1015439502289.

Rodriguez-Pereyra, G. (2014), *Leibniz's Principle of Identity of Indiscernibles*, Oxford University Press, Oxford.

Saunders, S. (2006), 'Are quantum particles objects?', *Analysis* **66**(1), 52–63. DOI: 10.1093/analys/66.1.52.