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Inter-theory relations in quantum gravity: Correspondence, reduction, and emergence

Karen Crowther

Department of Philosophy, University of Geneva, Switzerland

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ABSTRACT

Relationships between current theories, and relationships between current theories and the sought theory of quantum gravity (QG), play an essential role in motivating the need for QG, aiding the search for QG, and defining what would count as QG. *Correspondence* is the broad class of inter-theory relationships intended to demonstrate the necessary compatibility of two theories whose domains of validity overlap, in the overlap regions. The variety of roles that correspondence plays in the search for QG are illustrated, using examples from specific QG approaches. *Reduction* is argued to be a special case of correspondence, and to form part of the definition of QG. Finally, the appropriate account of *emergence* in the context of QG is presented, and compared to conceptions of emergence in the broader philosophy literature. It is argued that, while emergence is likely to hold between QG and general relativity, emergence is not part of the definition of QG, and nor can it serve usefully in the development and justification of the new theory.

1. Introduction

The search for a theory of quantum gravity (QG) is one of the biggest open problems in physics.[1] The theory must describe the domains where both general relativity (GR) and quantum (field) theory are supposed to be required. It is generally expected to replace GR, in the sense of being a *more fundamental* theory that describes the "high-energy" or "micro" degrees of freedom that "underlie" gravitational phenomena.[2] Exploring the relationships between QG and current physical theories is interesting in itself, but is important also for myriad other reasons, including better understanding the nature and implications of current theories; investigating scientific theory-change and theory construction; and gaining insight into the nature and structure of QG. In fact, understanding these relationships serves crucially in the development and justification of QG. In regards to theory development, for instance, the links between current theories play a role in indicating the domain where QG is necessary, and act as stepping-stones towards finding the new theory. And, in regards to theory justification, the requirement that the new theory link back to current theories is especially significant in the case of QG, given the lack of novel empirical data that QG is required to explain, and the extreme regimes where QG is expected to be needed—it seems like this link back to established physics may be the surest way (currently known) for QG to make contact with the empirical realm.

Additionally, there is an even stronger sense in which understanding these relationships is crucial to theory development and justification in QG—they play a role in determining what would count as a theory, i.e., in *defining what QG is*. Here, QG is understood as any theory that satisfies the set of criteria that are taken to define QG. Currently, there is no well-established, generally agreed-upon set; however, some of the criteria whose *inclusion* is the least controversial across all the approaches to QG concern the relationships to, and between, current theories. For instance, I take it

E-mail address: karen.crowther@unige.ch.

[1] "QG" can refer to either the collective research program, or the theory being sought. Here, it is usually the *theory* that is being referred to; I endeavour to be explicit when context demands it.

[2] Here, "micro" is used purely in a figurative sense, as a means of distinguishing the degrees of freedom described by QG from those ("macro" degrees of freedom) of current physics. "High-energy scales" and "short-length scales" are used interchangeably, and are also used to signify the domain expected to be described by QG. The scare quotes indicate that this may not literally be true, because the idea of length (and, correspondingly, energy) may cease to be meaningful at some scale, and QG may describe this very regime. Please keep this in mind, as I will drop the scare quotes.

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that the set includes at least the following criteria: that the theory describe the domains where both GR and quantum theory are necessary[3]; that the theory "recover" GR in the regimes where GR is known to be successful; and that the theory take into account quantum theory (by being quantum itself, in some sense, or by also relating to the framework of quantum field theory, or recovering particular quantum field theories—or a combination of these methods).[4]

As I show in this paper, the inter-theory relationships that serve in the roles concerning the development and justification of QG (including, for instance, expounding and refining the relevant notion of "recovery" that features in the definition of QG, and demonstrating the relative fundamentality of the theory) are those that are broadly classifiable as *correspondence* and *reduction*.[5] Yet, so far, the literature on the philosophy of QG has not looked at these relationships. Instead, however, there has been a lot of work considering the idea of *emergence* in the context of QG. This literature typically makes little attempt to explicate its connection to the main accounts of emergence in more general literature,[6] and often either works with a deliberately minimal characterisation of "emergence", as a generic asymmetric inter-theory relation (involving one theory being more fundamental than another),[7] or construes "emergence" as something akin to (but perhaps running in the opposite direction to) reduction—being a relation, or relations, illustrating (broadly) the dependence, derivability, or "recovery" of GR (or aspects/structures of GR, including spacetime) from QG.[8] The best way of understanding emergence in the context of QG, however, is as a relationship where a less-fundamental theory is novel and autonomous (or "robust") compared to QG, whose physics it nevertheless depends upon in some sense.[9] I find that this conception of emergence is likely to hold (between QG and GR, for instance), but that it does not (and cannot) play a useful role in the development and justification of the new theory.

In this paper, I investigate the ideas of (relative) fundamentality, correspondence, reduction and emergence. Primarily, I consider these relationships as they apply between QG and GR, but I also touch upon the relationships between QG and the framework of quantum theory, and between QG and the quantum field theories of the standard model of particle physics.[10] I have five aims in doing so:

1. To better understand the nature of the relationships between QG and current physics;
2. To articulate and distinguish these four types of inter-theory relations (relative fundamentality, correspondence, reduction, and emergence), and the connections between them;
3. To (begin to) expound the variety of roles that these four relations play in the context of QG, and demonstrate their utility for investigating different questions in the context of QG;
4. To encourage interest in the investigation of correspondence and reduction in the context of QG, especially in regards their roles in theory-development and justification;
5. To clarify the discussion of emergence in the QG literature, and to show how the conception of emergence applicable in QG relates to the general ideas of *strong emergence* and *weak emergence*, familiar from general philosophy of science.

The structure of the paper is as follows: §2 explores what it means for a theory to be more fundamental than another, arguing that it involves an asymmetrical notion of dependence; §2.1 outlines how QG may be understood as more fundamental than GR. §3 presents the idea of correspondence as the broad class of inter-theory relationships intended to demonstrate that two theories whose domains of validity overlap are compatible in these domains—i.e., that the theories (approximately) share the same results in the overlap regions; this section also provides some indication of the wide variety of roles played by correspondence relations in theory development and justification. §3.1 provides examples of correspondence relations, and their roles, in the context of QG. §4 explores the idea of reduction, arguing that it is a special case of correspondence that applies when the region of overlap in the domains of two theories is the entire domain[11] of one of these theories; but, unlike correspondence generally, it also aims at evidencing deducibility, and thus relative fundamentality. §4.1 shows how reduction is taken as a criterion of theory success in QG. Finally, §5 explores the conception of emergence as the novelty and robustness of a less-fundamental theory compared to a more-fundamental theory of the same system; §5.1 explains how it applies in the context of QG; and §5.2 explores its relationship to the notions of weak emergence and strong emergence in the more general philosophy literature, arguing that while some accounts of weak emergence may be applicable, strong emergence should not hold in the case of QG/GR, given the role of reduction in the definition of the theory.

2. Fundamentality

Here, I just speak about *relative* fundamentality[12]: a *more fundamental* theory, *M*, of a given system, *S*, or phenomenon, *P*, provides a *more basic* description of *S* or *P* than a *less fundamental* theory, *L*, does. There is only one condition for relative fundamentality: that the laws of *L* somehow depend (at least partly) upon the physics described by *M*, *and not vice-versa*. Note three points of clarification, however, in regards to *M*, *L*, *S* and *P*. Firstly, *M* will typically describe the system, *S* at a different range of energy scales than *L*, or perhaps under different conditions. Secondly, *M* might not actually describe the phenomenon, *P*, that *L* does, but rather (some of) the physics underlying *P* (i.e., part of the more-basic physics responsible for the appearance of *P*).

Thirdly, due to the way that theories are designated and differentiated, the more fundamental physics that is responsible for the laws of *L*, might not be described by a single more-fundamental

[3] Note that gravity is a universal force, and, technically, quantum theory is also universal: its domain of applicability includes all physical systems. Yet, we do not *need* to use GR and quantum theory to describe all systems.

[4] I have been purposely vague in framing each of these criteria, because even though this list represents part of the minimal agreed upon set, the *interpretations* of these criteria vary from approach to approach.

[5] Some of the various other ways in which these relationships are used in the search for QG are outlined and illustrated in the relevant sections below (§3–4.1).

[6] There are exceptions, e.g., Bain (2013).

[7] This is not a criticism of the individual papers, however, since the minimal characterisation may be sufficient for these authors' arguments, e.g., Knox (2013); Teh (2013); Rickles (2013); Seiberg (2007).

[8] E.g., Berenstein (2006); Butterfield and Isham (1999); Wüthrich (2017); Yang (2009).

[9] E.g., Crowther (2016); de Haro (2017); Oriti (2014), following Butterfield (2011a,b); Crowther (2015).

[10] Exploring the relationships between QG and quantum theory is a task that requires, and deserves, much more attention than I can devote here. There are many interesting questions regarding how quantum mechanics, and its interpretation, may be modified in the context of QG.

[11] I use "domain", "domain of success" and "domain of applicability" interchangeably to refer to the complete set of systems/phenomena successfully described by the theory in question. I take it that we are only speaking of actual, successful theories of physics, and only speaking of them as they actually apply in our world (in the case of QG, this is the theory once it is actual).

[12] While QG must be more fundamental than GR, QG need not be a fundamental theory; i.e., it is not necessary to include the criterion of (absolute) fundamentality in the definition of QG (Crowther & Linnemann, 2017).

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