Studies in History and Philosophy of Modern Physics 46 (2014) 170–178

Contents lists available at ScienceDirect

Studies in History and Philosophy of Modern Physics

journal homepage: www.elsevier.com/locate/shpsb

Holography as a principle in quantum gravity?—Some historical and systematic observations

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ARTICLE INFO

Article history:
Received 18 December 2012
Received in revised form
17 November 2013
Accepted 2 December 2013
Available online 18 January 2014

Keywords:
Holography
History of physics
Black holes
AdS/CFT correspondence
Topological QFT
Hermann Weyl
Leibniz

ABSTRACT

Holography is a fruitful concept in modern physics. However, there is no generally accepted definition of the term, and its significance, especially as a guiding principle in quantum gravity, is rather uncertain. The present paper critically evaluates variants of the holographic principle from two perspectives: (i) their relevance in contemporary approaches to quantum gravity and in closely related areas; (ii) their historical forerunners in the early twentieth century and the role played by past and present concepts of holography in attempts to unify physics. By combining these two perspectives a certain depth of focus is gained which allows us to draw some tentative conclusions about what might be reasonable aspirations and prospects for holography in quantum gravity. By the same token, we will have a brief and critical look at wider philosophical interpretations of the term.

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When citing this paper, please use the full journal title *Studies in History and Philosophy of Modern Physics*

1. Introduction

Over the last two decades much research has been done on the challenging concept of holography. Especially within the context of quantum gravity (QG), this concept has gained considerable interest and was even claimed to be the guiding principle for all QG.[1] Indeed the interest has become rather widespread and holography has made it repeatedly into journals likes *Science* and the *Scientific American* (Bekenstein, 2003; Cho, 2012; Moyer, 2012); most recently because of an experimental setup at Fermilab which is claimed to allow for an empirical test of the existence of holography.[2]

The aim of this paper is to provide a critical overview and assessment of holographic principles as they occur in contemporary quantum gravity and insofar as they are meant to relate to important aspects of relativistic spacetime and of quantized matter. Apart from contemporary physics, we will discuss some aspects and aspirations from early twentieth century approaches towards a unified physics, for this is where important forerunners of modern holography have originated. This combination of systematic and historical considerations will help to determine what might be reasonable prospects to be set on holography.

To begin with, let us briefly remind the reader that the modern term "holography" stems from optics. When trying to improve electron microscopy, Dennis Gábor (Nobel prize 1971) developed a new recording technique, which makes crucial use of light's phase information. More specifically, in an optical hologram, the interference pattern of coherent light with its reflection from a

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[1] We use the term "quantum gravity" (QG) to encompass all approaches or frameworks which encompass a quantized theory of gravitation. Thus, "QG" refers not only to approaches which aim for a quantization of gravitation in particular (such as canonical and perturbative approaches, loop quantum gravity, supergravity, spin foams, group field theories and dynamical triangulations) but also to approaches which aim for a unification of the whole of physics (such as string theory, M-theory, and Kaluza–Klein theories).

[2] The experiment at Fermilab consists of two Michelson interferometers placed on top of each other and is intended to investigate a possible jitter in one spatial direction due to an "informational shortage" based on holography, i.e., based on the fact that information only increases with the surface instead of volume. However, theoretical physicists such as Susskind and Bousso have claimed that this experiment is off-target. According to Bousso, this can already be seen from the fact that the holographic principle, as usually understood in QG, maintains Lorentz invariance, whereas the generalized "uncertainty relation" on which the Fermilab experiment is based fails to be Lorentz invariant.

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http://dx.doi.org/10.1016/j.shpsb.2013.12.003

three-dimensional object is registered on a photographical plate. If shined on by the same kind of light, the two-dimensional plate partially encodes the three-dimensional information of the original object. In more general terms, the fascinating thing about holography is that it allows us to encode or register a $(d+1)$-dimensional object on a d-dimensional screen or surface.

Hence, the most general notion of holography has to do with the complete reduction of a bulk description of a physical system (in particular spacetime physics) to a description of the same purely in terms of boundary data and dynamics. Over the last 30 years this conceptual idea has gained much interest in QG, that is, in the exceedingly difficult context of reconciling quantum physics and general relativity (GR). There are intimate relations between certain $(d+1)$-dimensional theories describing gravity and some d-dimensional nongravitational quantum gauge field theories and a bulk-boundary correspondence is "holographic" insofar as the d-dimensional space of the latter theory can be understood as being the boundary of some $(d+1)$-dimensional space described by the former theory.[3]

The holographic relation that has raised most interest in this context is the AdS/CFT correspondence, or Maldacena conjecture, arising from string theory. It maintains an equivalence relation between a non-Euclidean five-dimensional theory of gravitation and a four-dimensional quantum gauge theory. Since, technically speaking, the one-to-one equivalence relation involved here is a duality, people also speak about "gauge–gravity duality". Even though the AdS/CFT correspondence is still neither proven mathematically nor empirically suggested, it enjoys popularity not only within string theoretic approaches towards quantum gravity but also as a heuristic tool or toy model in certain contexts of quantum field theory. We will treat the AdS/CFT correspondence in more detail in Section 3.

However, our focus will not remain on string theory. In the same section, we will also discuss attempts for a manifest implementation of a holographic principle as suggested by Smolin. This will reveal some close relationships between general relativity and constrained topological field theories. Notably, given the specific (finite) nature of the latter, a better understanding of this relationship may lead towards an asymptotically safe theory of quantum gravity.

After showing the different ambitions going along with the concept of holography in contemporary QG, we will investigate what can be classed as the "prehistory" of the concept in Section 4. Here we will have a look at approaches from around 1920 which also sought for a kind of dual description of general relativity and (quantum) theories of subatomic matter. Hermann Weyl's work on field physics as being a "surface aspect" of something which is not itself in our four-dimensional spacetime will be particularly revealing in this context, both for physical and for philosophical reasons. Since Weyl takes his own work to be an accomplishment of the programmatic framework of the then "new physics" outlined by Leibniz, we will very briefly sketch some of the striking parallels between this early modern framework and the central characteristics of modern holography.

On the basis of these systematic and historical observations, our paper ends by comprehending the general physical and philosophical aspirations set on holography and drawing some tentative conclusions about the prospective limits of its systematic use (Section 5).

[3] In the following, the term "boundary" denotes the $n-1$ dimensional hypersurface of an n dimensional manifold $\mathcal{M}$. This may be indicated by the formula $B=\partial\mathcal{M}$ which, for closed boundaries, fulfils the Cartan identity $\partial B=\partial\partial\mathcal{M}\equiv 0$ (the boundary of a boundary is zero). The term "surface", when used in its technical sense, will refer to any two-dimensional boundary. Notably, four-dimensional manifolds are rather special because—other than lower and higher-dimensional manifolds—there are many differential structures of the same topological manifold. This is expressed by their Donaldson invariants related to Yang–Mills instantons (Atiyah, Dijkgraaf, & Hitchin, 2010).

2. The contemporary history of holography

2.1. Black hole physics and (surface) information

In the early 1970s Stephen Hawking and others tried to reconcile the physics describing black holes with the laws of thermodynamics (Bardeen, Carter, & Hawking, 1973). Based on an idea by J. M. Greif, Jacob Bekenstein suggested attributing an entropy to black holes (BH) since, otherwise, the entropy of, for example, a hot gas crossing the event horizon of a black hole would simply disappear and the second law of thermodynamics would be violated (Bekenstein, 1973, 1981). Black holes were argued to be objects with maximal entropy, the numerical value being

$$S_{\mathrm{BH}}=\frac{A}{4}, \tag{1}$$

where A is the area of the event horizon given in Planck units ($l_{\mathrm{P}}^2=2.59\times 10^{-66}\ \mathrm{cm}^2$).

Arguably, this value also marks an upper bound for the entropy of a bounded system. Bekenstein suggested that any isolated mass m which fits inside a closed surface area and which is not itself a black hole must have an entropy $S_m<A/4$. Thus, entropy was suggested to depend on some surface area rather than on the volume and this then gave way to expressions like "area law" and "holography" to describe the situation.

However, here some slight reservations have to be added since the Hawking–Bekenstein associations of geometrical quantities with thermodynamical variables have not been left undisputed. Indeed, the full reconciliation of thermodynamics with relativity (both special and general) appears to be an open problem. For instance, a non-local formulation of relativistic thermodynamics based on the backward light cone of an event has been recently proposed (Dunkel, Hänggi, & Hilbert, 2009).[4] Moreover, the existence of event horizons as understood by Hawking and Bekenstein has also been questioned. Laughlin (2003), in view of the unproven formal extrapolation from the regular spacetime of a neutron star to the singular mathematical construction of a black hole, has suggested that a phase transition in spacetime occurs rendering the resulting "dark star" completely regular without the need of a horizon.

Returning to the historical development, the next important step was the employment of Shannon's definition according to which the amount of information of a system is equivalent to its entropy. This allowed calculation of the maximum number of "bits" encoded in a certain spacetime region by reference only to its surface (Lloyd, 2002). This area law of maximum information is sometimes also called "Bekenstein bound". Besides, the recourse to the concept of information also reinforces the usage of the term "holography". For now the situation is even more similar to the case of an optical hologram where three-dimensional information content gets encoded on a two-dimensional "screen".[5] On the other hand, one may challenge the physical meaningfulness of such a recourse to the concept of information. The fact that thermodynamical entropy and Shannon entropy are given in different units—energy divided by temperature and bits, respectively—is sometimes viewed as a mere

[4] But again this might be problematic since, generally speaking, the mere reformulation of thermodynamics in "covariant" form may not resolve the issue. An infamous example is Cartan's reformulation of Newton's theory of gravity in terms of a degenerate connection and Riemannian curvature tensor. This reformulation does not change the physical content and leads, for example, to only one-half of the observed gravitational light deflection. Arguably, concepts like entropy and temperature should rather be based on a relativistic Boltzmann equation (Strain, 2010b) involving Lorentz *invariant* variables, like the $s:=g_{\mu\nu}(p_1+p_2)^\mu(p_1+p_2)^\nu$ of Mandelstam.

[5] In simplicial quantum gravity, the spectral dimension of (Lorentzian, or after Wick rotation, Euclidean) space appears not to be fixed. For example, Euclidean dynamical triangulations show that it can run from a value of 3/2 at short distance to 4 at large distance scales (Reuter & Saueressig, 2011).

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