Building flat space-time from information exchange between quantum fluctuations

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Abstract

We consider a hypothesis in which classical space-time emerges from information exchange (interactions) between quantum fluctuations in the gravity theory. In this picture, a line element would arise as a statistical average of how frequently particles interact, through an individual rate $dt \sim 1/f_t$ and spatially interconnecting rates $dl \sim c/f$. The question is if space-time can be modelled consistently in this way. The ansatz would be opposite to the standard treatment of space-time as insensitive to altered physics at event horizons (disrupted propagation of information) but by extension relate to the connection of space-time to entanglement (interactions) through the gauge/gravity duality. We make a first, rough analysis of the implications this type of quantization would have on the classical structure of flat space-time, and of what would be required of the interactions. Seeing no obvious reason for why the origin would be unrealistic, we comment on expected effects in the presence of curvature.
1 Introduction

A motivation for making the following analysis is to consider an alternative scenario to when the Einstein field equations (EFE) in general relativity break down. The standard concept of space-time is that it constitutes a background, with definite singularities only at points of high curvature. At an event horizon, new physics is not required to be experienced by an infalling observer due to the EFE, but is a matter related to the information paradox [1], black hole complementarity [2,3] and the firewall paradox [4], where the concern is the entanglement structure between Hawking radiation and interior modes. The central issue might be fundamentally different. In extending space-time past an event horizon by means of the equivalence principle, an important assumption is made: that space-time exists independently of information exchange. If this is false, space-time structure would undergo a change near event horizons, where information ‘output’ (such as signals sent out) undergoes a change, and eventually is randomized. To our knowledge, this type of scenario has not been analysed.

A key question is if space-time can be modelled consistently as a phenomenon emergent from information exchange — interactions — between quantum particles, or if a background picture is required. While an interaction origin would be exotic, the persistent difficulties with quantizing gravity merits looking beyond standard considerations, e.g. by examining the assumption mentioned above. We look at what would define a scenario where space-time arises on a macroscopic scale from interactions at the quantum level, in terms of the physics involved at the quantum and classical levels. Since this analysis concerns quantum space-time rather than quantum gravity, a first issue is flat space-time (as we will get to shortly), which therefore is the focus of the present text. Within this setting, there is no evidence that an interaction scenario is more physical than a background, but neither do we find immediate reason to rule it out, leaving it a hypothesis of interest for further analysis.
At the quantum level, the basic suggestion is to replace the metric tensor of general relativity (in its role of giving rise to $ds^2$) with rates of information exchange between pairs of quantum particles, including (and heavily reliant on) vacuum fluctuations. This amounts to describing a connectivity between quantum particles in terms of a frequency, with length through $dl \sim c/f$, and relative passage of time for each quantum particle through its total rate of interaction, with $dt \sim 1/f_t$. An equilibrating process is assumed so that gradients are suppressed, and to begin with the points of reference can be thought of as on a lattice. We discuss this ansatz further in §3. Right here the argument is that an average over interactions such as these can give rise to an effective metric tensor while the quantum physics is decidedly different from a background scenario. A rough likeness can be made with how temperature arises from kinetic energy.

A few reasons to look into a quantum interaction origin of space-time begins with that in focussing only on background models, relevant physics might be bypassed. Secondly, for space-time concepts (distance, relative angles, time evolution) to arise from interactions, the connections must concern entanglement\(^1\) as mentioned in [5], and entanglement has been shown to be important to space-time [6] through the gauge/gravity duality [7]. A space-time upheld by dynamic entanglement would be upheld by interactions, and a logical question is if that origin is restricted to the dual gauge theory. The presented hypothesis could represent a new take on how to model an entanglement origin, although we do not discuss entanglement structures here. Thirdly, some immediate effects of an underlying information exchange structure are supported by a standard phenomenon which is well-understood but paradoxal: wave-particle duality in particle diffraction. The two last points are suggestive at best, but still interesting.

A first, direct consequence of an information exchange origin would appear in settings away from vacuum where flat space-time is a good approximation. In such settings, information propagation typically is restricted due to matter in the shape of e.g. apertures and edges, and the shortest path is around rather than across an obstacle. This property of information exchange implies non-trivial structure of the associated flat space-times, relative to the asymptotic vacuum (rather than with a very special choice of coordinates). We will call this relative geometry, and model it on the connectivity of flat space-time, leaving $dt$ constant. As it constitutes a first deviation from the properties of a standard background, we begin with analysing this effect, its consistency and subsequent restrictions on the quantum interactions. Note that the concept, an illustration of which can be found in figure[11] fits within flat space-time. That an observer comparing one region with a reference frame based on the vacuum might see non-trivial geometry is in agreement with diffeomorphism invariance.

We model relative geometry on the observed distortion of light rays near apertures and edges. The general effect of wave-particle duality is in agreement with what relative geometry could give rise to, and warrants a closer look at the concept rather than the opposite. The object of interest is not a description of the diffraction phenomenon, but if an information origin could be plausible. The suggested scenario is not a pilot wave theory, but is rather similar to a path integral approach in that it relies on probabilities of path deviations dependent on the relative geometry. In our approach, a qualitative model of relative geometry in agreement with the wave-particle duality provides a way

\(^{1}\)For example, an interaction origin of a scalar product would require pairwise spin 1/2 entanglement.
to assess the logic of an underlying structure of space-time based on information exchange, through what it implies for the quantum interactions.

The quantum interactions is the final object of investigation: how they are restricted by properties of flat space-time and the metric tensor. We give some comments on what to expect with curvature, and in the near-horizon region, but restrictions from and quantum effects associated with curvature require analyses beyond those given in the present text.

Below, we begin with a rough analysis of the implications an interaction exchange origin would have on flat space-time, in §2. This includes a qualitative outline of effects of relative geometry on particle paths, two examples of relative geometry in slit and edge diffraction, and some general comments on the effective (very classical) structure that relative geometry would represent. Here, §2.1 merely illustrates the concept whereas the first paragraph in §2 and §3 detail the physics of the hypothesis. In §3 we describe the quantum interactions, as well as possible effects of curvature.

2 Flat space-time effects

In setting up a first, crude model of relative geometry, suitable for a comparison with light diffraction, it is reasonable to restrict to static, flat space-time with geometry obstructing information flow surrounded by an asymptotic vacuum. $dt$ is constant. The scale of the geometry (introduced by various obstacles) as well as any other relevant physics is assumed to be such that no quantum effects of fluctuations belonging to the space-time structure are relevant to leading order. The stress-energy tensor is disregarded (particles passing through are assumed to have a negligible effect on the configuration) as well as any cosmological constant. Without relative geometry, the setting is trivial.

With relative geometry, two points of reference are used: the asymptotic vacuum, and the obstacles setting the geometry. A flow of information is assumed to delineate geodesics through or past apertures or edges. In this sense the Minkowski space appears in a very special set of coordinates compared to the asymptotic vacuum, and is dependent on the symmetries of the geometry. As is discussed in more detail in §2.1.3, an intuitive origin would lie in how information spreads out from a constriction and in that sense sets a connectivity of a tension structure that would make up space-time. How tightly the tension structure is bound together would describe how quickly information passes through different regions. Effectively, the flat frame is a boundary value problem.

More than the configuration (apart from if relative geometries can be fit within flat space-time) the quantum effects of how particles pass through the space-time are of central importance. Unlike in a background, with an information origin of space-time a particle cannot simply ‘pass through space-time’, following geodesics set by curvature. A quantum particle would interact with the quantum constituents underlying the tension structure which defines e.g. what is ‘forward’. This must be imparted on the particle, which cannot have knowledge of the local structure in each region prior to encountering it. Any such communication will be imperfect, and restricted by the way the particle interacts with the structure.

The process of particle propagation must be modelled on the wave-particle duality, which provides the only flat space-time effect that can be consistent with a relative geometry scenario. The key properties of such particle diffraction is scale invariance in particle wavelength ($\lambda$) vs scale of the geometry ($D$), interference, end particle paths of straight lines in accord with the symmetry of
the geometry, and nested intensity patterns from nested geometry configurations. A naive protocol can be outlined in terms of a series of steps, where a particle samples the local tension structure of a region or along a line of $O(\lambda)$ in comparison with its previous reference frame, gets an estimate of how the path bends ($\sim D$), generates a shift in angle of progress according to some probability distribution and then resets its reference frame in agreement with the last sampled region. Here, the only relevant scale would be $\lambda$ vs how sharply the space bends over the sampled region, giving an effective scale invariance in $\lambda/D$. In the absence of curvature, the probability distribution for how angle deviations are generated need to be assumed to fall off quickly away from zero, so that particles with $\lambda \gg D$ remain insensitive to the structure. In addition, a reasonable quantum feature is a preference for certain quantum steps, here in terms of angular deviations instead of energy levels, creating periodic resonances within the diffraction intensity distributions.

The above picture may well be too simplistic to reproduce particle diffraction faithfully, but the principle is made clear. With a reference structure deviating from the vacuum configuration and in accord with the flow of information through the geometry, it is possible to obtain the properties of particle diffraction through a protocol similar to a path integral formalism, with particle wavelength $\lambda$ setting sensitivity to the reference structure\footnote{Effects dependent on $\lambda$ would have to arise from interactions between the particle and the reference structure.}— at least provided that interference effects can be accommodated. We see no immediate objection to this (especially as preference for specific quanta is a characteristic of quantum physics) but a more thorough analysis would be required to fully verify that the correct diffraction can be captured. If not, the hypothesis of an interaction origin clearly fails.

Another concern is light diffraction with selection on polarization. We briefly comment on how this might be fitted into the picture after analysing the implications for the quantum interactions in §3.1. With a scenario building on information exchange, however, properties directly connected to information propagation (such as light) turn into defining qualities (in this case of space-time) rather than limitations on what is physical. Therefore polarization concerns, relating to characteristics of information without impact on most particles, are not among the most pressing matters at hand, and are deferred until a later point.

Lastly, the present analysis is of static relative geometries for simplicity, and generic relative geometries must include time dependence. With changes in geometry consistent with approximately flat space-time, causality should limit the propagation of the subsequent effects (classical or quantum).

We now proceed with illustrating two types of relative geometries that are central to diffraction patterns, the case of a single/double slit and that of a sharp edge, to illustrate the concept of relative geometry. It is classical in the same sense that general relativity is, with the difference that there is structure from information connectivity in the absence of curvature. The actual quantum constituents and their interactions, giving rise to the effective tension structure, is another matter entirely. In discussing relative geometry, we have merely assumed such a quantum level structure based on information exchange to exist, and restricted the discussion to a region and scale where it is valid to disregard them in every sense except for their average impact. An interesting feature is that quantum effects must be present anyway, through particle interaction with the relative geometry.
2.1 Relative geometry in flat space-time

As described above, relative geometry would be present already in flat space-time and occur due to obstacles to information flow. It would introduce extra structure at changes in information connectivity, and so be non-trivial near e.g. apertures and edges. For a pair of simple key illustrations in static, flat space-time with constant $\frac{dt}{\sqrt{g}}$, we restrict to $2d$ slices,

$$ds^2 = -dt^2 + dz^2 + dl^2_{d=2} = g_{ij}(x)dx^idx^j, \quad dl^2_{d=2}\big|_{\text{vacuum}} = dx^2 + dy^2,$$

(1)

with $g_{ij}(x)$ smooth and where the added geometry is assumed to be constant in $z$ for a sufficient distance, such as for a long slit. The condition for the Riemann curvature tensor to vanish e.g. is

$$dl^2_{d=2} = f^2(u,v)du^2 + h^2(u,v)dv^2 : \left(\frac{f'}{h}\right)'_v + \left(\frac{h'}{f}\right)'_u = 0,$$

(2)

and relative geometry simply refers to a flat space-time which does not have a metric equal to the identity matrix in the vacuum reference frame $(x,y)$. However, that extra structure needs to approach the asymptotic vacuum quickly, likely exponentially fast.

The key to a relative geometry is the symmetry of the set-up, and for that we now proceed with two illustrations: slit and edge diffraction. Afterwards, we discuss an information connectivity interpretation of the concept.

2.1.1 Single- and double-slit diffraction

For single or double slits, the symmetry of the light diffraction is that of an elliptic cylindrical coordinate system, since the wave pattern describes hyperbolae. The maxima and/or minima follow lines of constant length difference to the two foci, embodied by either the edges of the one slit, or by the two slits. A large part of the appropriate geometry hence is elliptic.

The full picture is quite intricate. For a double-slit, there are single slits at the foci, and for a single slit, there are edges at the foci. In addition, an elliptic transformation does not give a diffeomorphism for the line between the foci. However, we will assume a decent separation of scales between the various effects, so that the different structures can be considered to be nested within each other and dealt with separately. We begin with the elliptic symmetry, and come back to the validity of the overall configuration afterwards.

With the slit(s) extending in the $xz$-plane, symmetrically around $x = 0$, we let the elliptical coordinates $(a, \phi)$ be

$$\begin{cases} x = L \cosh a \sin \phi \\ y = L \sinh a \cos \phi \end{cases}, \quad a \geq 0, \quad \phi \in [0, 2\pi],$$

(3)

and from now on restrict to $2d$. $D = 2L$ defines the distance between the foci, and we have

$$dx^2 + dy^2 = L^2 \cosh 2a + \cos 2\phi \left(\frac{da^2 + d\phi^2}{2}\right).$$

(4)

In the elliptic coordinate system, the hyperbolae describe geodesics for

$$dl^2_{d=2} = L^2 \frac{e^{2a}}{4} \left(da^2 + d\phi^2\right).$$

(5)

$3\dddot{x} + \Gamma_{jk}^{i} \dddot{x}^j \dot{x}^k = 0$ with only $\dot{a} \neq 0$ gives $\dot{a}(t) = C e^{-a(t)}$, with some constant $C$. 

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Figure 1: 2d illustration of how flat space-time can support relative geometry from the reference point of an asymptotic vacuum. Boundary conditions around geometrical objects (apertures, edges etc.) may cause local coordinate redefinitions of the actual flat frame. The mesh delineates a (2d cut-out of) flat space-time that causes hyperbolic geodesics in the vacuum reference frame. Further adjustments need to be made along the slit opening ($|x| < 1, y = 0$) for smoothness and edge effects.

This is flat and has the vacuum as an asymptote at $a >> 1$. (5) obeys (2) and approaches (4) exponentially fast in $a$. It can be recast into

$$\begin{equation}
\begin{bmatrix}
\xi = e^a \sin \phi \times L/2 \\
\eta = e^a \cos \phi \times L/2
\end{bmatrix} = d\xi^2 + d\eta^2, \quad \xi^2 + \eta^2 \geq \frac{L^2}{4},
\end{equation}
\tag{6}
$$

with

$$\begin{cases}
x = \left(1 + \frac{L^2/4}{\xi^2 + \eta^2}\right) \xi \\
y = \left(1 - \frac{L^2/4}{\xi^2 + \eta^2}\right) \eta.
\end{cases}
\tag{7}
$$

The lines of constant $(\xi, \eta)$ are depicted in the xy-plane in figure 1.

The upshot of the above is that through the symmetry, it is possible to identify a flat geometry where hyperbolae are geodesics. Figure 1 illustrates this relative geometry, which is to be compared with the trivial background structure typically assumed for approximately flat space-time. This figure is intended to serve as a simple, explicit example of relative geometry, to make it easier to grasp that new concept.

However, figure 1 clearly is not the full relative geometry even for a single slit: the true $g_{ij}(x, y)$ needs to be both smooth and include edge diffraction. In the case of the single slit, these corrections are not difficult to picture. The edge modulation (discussed in the next section) can be added to the foci, and for smoothness a local modulation along $a = 0$ (of the elliptic frame) can be introduced. It need not change the qualitative features of the relative geometry overly much.

The double-slit relative geometry is more complicated. A brief speculation on how one might solve for that geometry can be found in §2.1.3, which indicates a nested set-up with modifications mostly around the foci, provided a clear separation of scales. A key question is how the different
single- and double-slit intensity distributions, with the latter periodic in $\lambda/D$ throughout and the former with a centralised peak of width $2\lambda/D$, could possibly be a product of the same type of geometry, that of figure 1. However, there is a decided difference in that the path through a single slit is not centred through a foci, but along the line in-between. Likely the experienced geometry can account for the dissimilarity of the single- and the double-slit diffraction periodicities. A conclusive statement would require a more thorough analysis of how the particle paths evolve.

At the present level of analysis, the relative geometry of figure 1 (with suitable modifications) implies little new for the paths of particles passing through. The geometry scales linearly with $D$, which fits with a a scale invariance of $\lambda/D$ and implies that quantum resonances occur at multiples of $C\lambda/D$ for some constant $C$. The symmetry sets the main peak to be at no angular deviation, and the path deviations are restricted to occur within some distance $\sim D$ of the foci, since the relative geometry quickly approaches the asymptotic vacuum. In addition, slits and gratings would give similar results, with particle paths going through the half-plane relative geometry twice in both settings.

The conclusion from this merely is that it likely is possible to fashion a structure within flat space-time and endow particle interactions with overall properties in relation to it, with an end result in rough agreement with light diffraction. The slit illustration is an explicit example of how that structure would appear. We now turn to an example that straightforwardly gives a smooth relative geometry, and has implications for the quantum interactions.

2.1.2 Edge diffraction vs Gaussian apertures

The symmetry of a sharp edge is not obvious. Assuming that relative geometry occurs at changes in information connectivity, a circular symmetric, smooth modulation with an exponential convergence to the asymptotic vacuum is implied. The simplest example is a Gaussian, but the deduction of that shape can be made more precise. The inverse of what relative geometry a sharp edge causes is when the asymptotic vacuum is a good reference frame across an aperture. Such apertures give intensity distributions directly corresponding to the transmission profile of the aperture, which holds precisely for Gaussian profiles. Hence the relative geometry around a sharp edge indeed should be described by a Gaussian modulation.

In polar coordinates $(r, \theta)$ set relative to the asymptotic vacuum and centred on the tip of the edge, we then have geodesics curving around the edge with

$$dl^2_{d=2} = d\xi^2 + d\eta^2,$$

$$\begin{align*}
\xi &= \left(1 - e^{-r^2/2\sigma^2}\right) r \cos \theta \\
\eta &= \left(1 - e^{-r^2/2\sigma^2}\right) r \sin \theta
\end{align*},$$

(8)

where the standard deviation $\sigma$ represents a length scale of the underlying structure.

The above proposed relative geometry has definite similarities to actual edge diffraction. The Fresnel integrals used for describing the diffraction pattern are reminiscent of $e^{ir^2}$, and for quantum effects in terms of path deviations, the Gaussian profile suggest a periodicity in something close to or approaching $x^2$ rather than $x$, as is the case for the slit periodicities of $n \times \lambda/D$ with the linear exponent in $n$. The $\sim x^2$ periodicity is also a property of edge diffraction, depicted in figure 2.
While far from conclusive, these similarities are non-trivial and in line with a correlation between the diffraction pattern and the relative geometry.

### 2.1.3 The impact of information connectivity on flat space-time

An emergence of relative geometry from information connectivity can be examined at the macroscopic level, before a closer look at what would be required of the quantum interactions. Here, the space-time description simply is that of general relativity, but with the assumption of an underlying structure in information exchange between particles (vacuum fluctuations): to what degree they are entangled and how quickly a deviation is communicated from one point to another. The simplest illustration of the subsequent effect is in flat space-time, where the density of vacuum fluctuations can be assumed to be constant compared to the vacuum frame, and the intuitive picture is that of figure [5]. At any constriction formed by matter, information will be more quickly communicated through the empty space, i.e. the openings or connecting regions. For simplicity we assume the boundaries set by matter to be comparatively insulating, in the same sense that they block photons, which ought to be a good first order approximation. When a connecting region opens up, the rate of interaction is diluted among the increased amount of available points of interaction. The vacuum fluctuations cannot be equally tightly bound together throughout. The result is a reference frame for length and directions which describes flat space-time, but carries relative geometry compared to the vacuum. Effectively, it should be possible to think of the equilibrating process as a flow of information, although the static case does not contain an actual flow through the space-time, but represents how

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**Figure 2:** The qualitative features of single-slit and edge diffraction. The only comparison intended is a note on the periodicity, which is linear for a slit but approaches quadratic for a sharp edge.

**Figure 3:** Illustration of (left) how a higher number of degrees of freedom are available on each side of a constriction, to a flow passing through, and (right) the suggested elliptic (one-sided) solution to the geodesics, disregarding smoothness and edge effects at the connecting line.
the structure is upheld by continuous equilibration of connections between the particles. This is our qualitative interpretation of the underlying process. The subsequently required, suitable interactions at the quantum level are discussed in §3.

When identifying a relative geometry, i.e. the macroscopic structure, a useful approach seems to be to use diffeomorphism invariance to render the geometry into straight lines at right angles, with parallel lines denoting the same type of boundary condition (connecting vs insulating), as illustrated in figure 4. In these settings the geodesics are trivial (up to edge effects and smoothness across connecting lines) and the diffeomorphism to get to the linear setting is the key to the relative geometry. The linear configuration is easily obtained for each half-plane of the single slit in terms of elliptic coordinates, but to find the appropriate diffeomorphism for e.g. the double slit is more difficult.

In considering an information origin of space-time, the flat space-time structure turns into a boundary value problem, modulus Gaussian profiles. A resemblance to temperature in figure 4 is easy to see in solutions to the heat equation in the absence of sources ($\nabla^2 T = 0$), but where temperature originates in linear interactions, the information structure is characterized by something else. With energy $E \propto r^{-2}$ (instead of $E \propto T$), curvature definitely should represent non-linear dynamics at the quantum level. The qualitative macroscopic picture is of a tension structure. The flatness condition, in $2d$ simply (2), is diffeomorphism invariant and only compatible with linear interactions when the boundary conditions are linearized, as in figure 4. Meanwhile, the diffeomorphism invariance amounts to a purely relative description, a self-consistent theory without external points of reference (parameterization invariant).

3 The quantum nature of the interactions

At the quantum level, the ansatz of an origin of space-time in information exchange means that we model a line element $ds^2$ as arising from interactions between quantum particles in the vacuum: mostly vacuum fluctuations, but any other particles as well. With a qualitative separation $ds^2 = -c^2 dt^2 + dl^2$, the space-like distance $dl$ can be substituted with an effective interaction rate ($f$) through assuming information to be communicated at the speed of light, $c$: $dl = c/f$. $f$ is in turn given by an average over the individual interaction rates between quantum particles in a region. $dt$ is also connected to an interaction rate: that of the total interaction rate for each quantum particle, which provides a relative measure of the passage of time for each particle. This way of modelling
time is intuitive from the nature of atom clocks and effects on them from gravity.

As a starting point, the points of reference can be thought of as on a lattice, and an equilibrating process is assumed to be present so that differences in interaction rates are suppressed. In the classical, static and flat model analysed in §2, effects of quantum fluctuations, gravity, time-dependence and diffeomorphisms changing the weight of \( dt \) are disregarded. The only relevant interaction rate for a quantum particle then is how frequently it interacts with different particles. By causality the (static) interactions must be consistent with a lattice distribution, so that interaction between two particles, where one is connected to a third party, implies direct interactions between all of the tree particles in consistency with the mathematical definition of a neighbourhood.

However, while a lattice picture is helpful, it is both misleading and strictly not necessary. To begin with, there is a redundant degree of freedom in the choice of coordinate frame, appearing to give rise to diffeomorphism invariance, since all that matters is the relative total rate and connections between the quantum particles rather than the way those are presented. In addition, in the flat case it is tempting to give preference to the equidistant lattice with identical fall-off in interaction rate, corresponding to a unitary \( g_{\mu\nu} \). This picture is misleading since the quantum particles representing vacuum fluctuations neither appear at set points nor last indefinitely, and the density (of vacuum fluctuations) is expected to be translation invariant in the reference vacuum frame rather than in the diagonalised representation, if it fills any physical function at all. In the presently analysed hypothesis of space-time emergence, the equivalence class that is diffeomorphism invariance makes interaction rate the only invariant, definitely physical property.

In a classical limit, a space-time originating in interactions must have the properties of a tension structure, built on non-linear interactions. The boundary conditions alone need to set the static, flat configuration, as illustrated in §2.1.3. At the quantum level, the interactions must be compatible with giving rise to such a macroscopic, flat structure, and with the EFE in general, in a limit where quantum fluctuations are suppressed to the point when they can be disregarded. These classical theories should be good descriptions across macroscopic times and distances (where quantum distances are at the Planck scale) in regions where the lifetime of the vacuum fluctuations (\( \tau_f \)) is large enough for the structure to equilibrate (\( \tau_f \gg \tau_{eq} \)).

### 3.1 Restrictions from flat, static space-time

It is unclear if restrictions on the quantum interactions can be deduced directly from the effective tension structure discussed in §2.1.3. A complicating circumstance is that the setting is macroscopic.

As to the profile of the quantum interaction rates (in equilibrium), the fall-off of the profile is implied by several properties of the static, flat space-time. (1) As analysed in §2.1.2, the fall-off of relative geometry away from geometry without an imposed scale is Gaussian, and relative geometry is sensitive to boundary conditions modulo Gaussian profiles. (2) By smoothness of \( g_{\mu\nu} \), the functional basis ought to be Gaussian. (3) Gaussians interactions give rise to Euclidean geometry. Relations such as Pythagoras’ theorem (and relations with angles in general) can be

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4A model where regions near matter are characterized by less frequent interactions (by gravity) also justifies the assumption in §2 that geometry in approximately flat space-times can be modelled as insulating boundaries to information flow. There, it is reasonable to treat lines/areas of slower information exchange as insulating, in some simplifying limit.
recovered from that consecutive interactions, by necessity products, add up in terms of lengths. The
interactions e.g. must fulfil
\[ f(a)f(b) = f(c) \quad \text{as in} \quad e^{a^2}e^{b^2} = e^{c^2} \quad (9) \]
for some special directions \((\vec{a} \perp \vec{b})\), presumably in a unitary representation. All of this implies
a consistent ansatz to be that each quantum particle is associated with a Gaussian interaction rate
profile,
\[ f_t \times \prod_i \sigma_i e^{-\sum_i \frac{x_i^2}{2\sigma_i^2}}, \quad i \in \{1, 2, \ldots, d\}. \quad (10) \]
Here, the standard deviations \(\sigma_i\) set a reference for length through describing how quickly the in-
teraction frequency decreases away from the one-to-one correlation at \(x = 0\). We will assume this
reference length to be naturally unitary in vacuum: \(\sigma_{0,i} = 1\). \(f_t\) gives a measure of the individual,
total interaction rate, and we will let \(f_t \leq f_{t,0} = 1\).

In this picture, deviations from the vacuum values should be due to acceleration or fall under the
equivalence class of diffeomorphisms. A deviation from the Gaussian profile itself is expected in a
pre-equilibration state of the vacuum fluctuations, and perhaps even due to acceleration. The profile
is an idealization in the sense that its spread must be limited by causality. Note that the suggested
interaction profile is derived only from classical structures: the static, flat scenario analysed in \(\S2\)
and properties of Euclidean space and the metric. While these properties seem to be internally
consistent and in agreement with an information origin of space-time, they say nothing of the nature
of quantum fluctuations, or of restrictions from properties of curvature on a macroscopic scale.
For example, in the static, flat case all quantum particles have \(f_t \equiv 1\) and are identical save for the perceived distance between them, and so the analysis only concerns interaction rates between
points, as in \(\sigma\), while omitting relations concerning \(f_t\). It is a decoupled set-up, in need of more
analysis to be made precise.

Although the analysis decouples properties related to time from those of space and only probe
the latter, a statistical average is implied:
\[ ds^2 \sim \left\langle -c^2 f_t^2(x) dt^2 + \sum_i \sigma_i^{-2}(x) dx_i^2 \right\rangle \quad (11) \]
in the coordinates of the asymptotic vacuum, where the configuration \((\sigma_i)\) needs to be shaped by
some flatness condition. Invariance under a change of inertial frame does not give more details on the
static, flat interactions — what goes beyond a rephrasing of how the interactions appear rather
falls under effects of acceleration (such as a slower passage of time) and quantum effects at speeds \(v \sim c\).

A final comment that can be made about the interactions based on the static and flat analysis
is that the presence of a set \(\{\sigma_i\}\) implies multiple separate and orthogonal interaction channels
for each particle, as is characteristic for spin 1/2 entanglement. Such a basis has the potential of
capturing effects of polarization, typical for interference of light, with separate, co-existing reference
structures. In addition, this would give \([S_x, S'_y] \propto e^{-\sum_i (x_i - x_i')^2/(2\sigma_i^2)}\) for two separate particles,
provided that the entanglement is proportional to the interaction. In this sense, interaction rates
possibly may be interpreted in terms of entanglement entropy.
3.2 Comments on effects of curvature

The hypothesis of an interaction origin of space-time needs an analysis with respect to curvature and effects at the quantum level, beyond the scope of this text. The flat, static case discussed above must have additional restrictions from curvature/acceleration and time-dependence, including quantum fluctuations. Some immediate observations can however be made. The effect of acceleration on local, relative time is visible in the weights of \( dt^2 \) in terms of the Lorentz factor and the Schwarzschild metric (with \( c = 1 \))

\[
(1 - v^2) dt^2, \quad \left( 1 - \frac{2MG}{r} \right) dt^2,
\]

relatable to kinetic \( (mv^2/2) \) and potential energy \( (mMG/r) \), indicating that the weights should be possible to attribute to the force a (virtual) particle has been subjected to. One question is if this can be connected to the quantum physics of the interaction rates, e.g. in terms of complementarity of \( (E,t) \). Invariance of \( f_i / \prod_i \sigma_i \) under a change of energy would set length contraction and the inverse of time dilation (i.e. the frequency counterpart) to be identical.

A more direct feature is that there for gravity is a non-linear equilibrium tension configuration, visible e.g. in the \( r^{-1} \) of the \( g_{tt} \) of the Schwarzschild metric, which the interactions must capture on a macroscopic scale, in addition to compatibility with the EFE and properties of curved space. The non-linear profile suggests a dependence on both \( f_i \) and \( \{ \sigma_i \} \) in the near vicinity, which would be compatible with changes propagating through space-time as waves, in a description where a local equilibration of fast modes (non-classical) has been projected out. Considering this and the previous analysis of flat space-time, it would not be surprising if general relativity can be modelled consistently as emergent from information exchange. The question is if the quantum effects are realistic.

Another aspect of the quantum particle scheme is that vacuum fluctuations and particles separate from the vacuum are put on an equal footing in terms of upholding the interactions giving rise to space-time — with the difference that non-fluctuations remain present, retain their properties and ought to have a set total interaction rate relative to the surroundings, so that they define the structure rather than carry it. In a full consistency check of the hypothesis, it is necessary to examine if this equal treatment of quantum particles can be compatible with how the stress-energy tensor shows in the EFE.

Even with a full analysis of what general relativity would specify for the quantum interactions (if compatible) most of the quantum features would still be undetermined. For a full picture not only the quantum interactions themselves would have to be identified, but also the manner in which they equilibrate: how changes propagate etc. The equilibration protocol at the quantum level would be especially relevant for the quantum properties of gravity, and would define the physics near event horizons. In the present hypothesis, event horizons occur at \( \tau_f \sim \tau_{eq} \), where the frequency of interaction between vacuum fluctuations is not large enough to allow information (including light) to propagate away and have the connections equilibrate to the classical limit, before the fluctuations cease to exist. Here, quantum fluctuations of space-time (not captured by the EFE) would dominate.

A breakdown of the effective, macroscopic theory described by general relativity close to event horizons would be of central interest in a final analysis, representing the main reason to consider an
interaction origin of space-time to begin with. Based on the assumption of an origin of propagation in information exchange between quantum particles, a region with $\tau_f \sim \tau_{eq}$ can be expected to be characterized by a randomization of propagation. This might give rise to a shell-like structure around black holes, with a sharp fall-off of probability of particle occurrence in the radial direction, and a random output of ‘interior’ particles as they reconnect with the equilibrated space-time. This is however pure speculation. It is difficult to say what could be the result of a scheme where the existence of a particle would have as much impact as anything in the surroundings on the near vicinity ‘space-time’. A random walk scenario with a shell-like structure (where the interior of a black hole is left as outside of/a sparse area of space-time) however has similarities to the fuzzball proposal [8] and suggestions that the event horizon of a black hole represent a quantum phase transition [9].

4 Summary

Quantizations of gravity typically build on that space-time constitutes a background insensitive to changes in physics above the Planck scale. This assumption of insensitivity is especially important at event horizons, where physics crucial to quantum gravity is expected and light propagation is disrupted. Motivated by the elusive nature of quantum gravity, its connection to entanglement (i.e. interactions, if dynamic), and to exhaust all possibilities, we have looked at what would come out of a scenario where space-time is not insensitive to disrupted propagation of information, such as light. We have initiated a study of a hypothesis in which classical space-time arises as an effective tension structure for how information propagates, upheld in the vacuum by information exchange (interactions) between quantum fluctuations. In this picture, a line element would arise as a statistical average of how frequently particles interact, through an individual rate $dt \sim 1/f$, and interconnecting rates $dl \sim c/f$.

We have analysed if this type of quantization can be modelled in a way consistent with emergence of flat space-time, and illustrated the effects it would have on the emergent, classical structure as well as what would be required of the quantum interactions. In addition to curvature, a space-time originating in information exchange would be shaped by how matter provides boundary conditions to propagation of information, a scenario which could be compatible with wave-particle duality in particle diffraction. However, our only non-trivial result is that equilibrated interactions must have a Gaussian fall-off to capture the relations of Euclidean geometry, which coincides with trivial particle diffraction for Gaussian apertures. More thorough analyses of quantum effects, and curvature, are necessary to determine whether the hypothesis is realistic or not. Apart from quantum properties of the space-time structure, a second type of quantum effect is present through how particles interact with the space-time. If the interference effects of particle diffraction cannot fit with the scenario of relative geometry, the hypothesis fails.

Our focus has been on a rough, qualitative analysis of what would be required for consistency rather than on counterexamples, which constitutes a limited scrutiny of the hypothesis, but we feel enough internal consistency is observed to warrant further interest in this ansatz for quantizing space-time.
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