On the origin of Gravity

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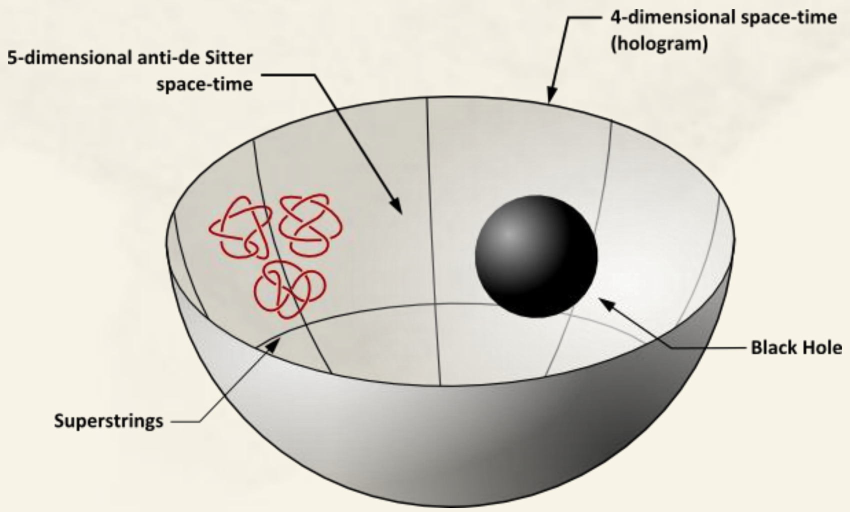
About Gravity

- Of all forces of Nature gravity is clearly the most universal. Gravity influences and is influenced by everything that carries an energy, and is intimately connected with the structure of space-time.
- Gravity dominates at large distances, but is very weak at small scales. In fact, its basic laws have only been tested up to distances of the order of a millimeter. Gravity is also considerably harder to combine with quantum mechanics than all the other forces.
- Many physicists believe that gravity, and space-time geometry are emergent.
- The universality of gravity suggests that its emergence should be understood from general principles that are independent of the specific details of the underlying microscopic theory.

1. Gravity is the amount of information associated with matter and its location, in whatever form the microscopic theory likes to have it, measured in terms of entropy.
2. Changes in this entropy when matter is displaced leads to an entropic force, which as we will show takes the form of gravity.
3. Its origin therefore lies in the tendency of the microscopic theory to maximize its entropy.
4. The information associated with a part of space obeys the holographic principle.



Holographic Principle suggests that the description of a volume of space can be encoded on a lower-dimensional boundary to that volume. Essentially, it posits that our three-dimensional universe can be described by information encoded on a two-dimensional surface, much like a hologram.

Entropic Force

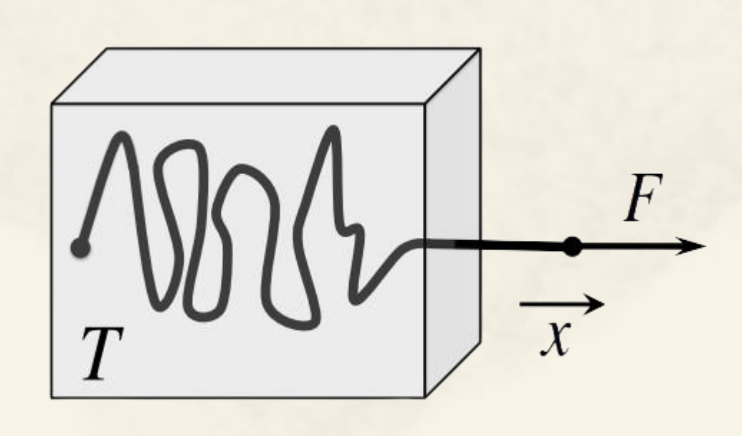
- An entropic force is an effective macroscopic force that originates in a system with many degrees of freedom by the statistical tendency to increase its entropy.
- The force equation is expressed in terms of entropy differences, and is independent of the details of the microscopic dynamics.
- When the polymer molecule is immersed into a heat bath, it likes to put itself into a randomly coiled configuration since these are entropically favored. The statistical tendency to return to a maximal entropy state translates into a macroscopic force, in this case the elastic force.
- The entropy :

$$S(E,x) = k_B \log \Omega(E,x)$$

- k_B is Boltzmann's constant and $\Omega(E,x)$ denotes the volume of the configuration space for the entire system as a function of the total energy E of the heat bath and the position x of the second endpoint. The x dependence is entirely a configurational effect: there is no microscopic contribution to the energy E that depends on x.
- Partition function:

$$Z(T,F) = \int dE\, dx\, \Omega(E,x) e^{-(E+Fx)/k_B T}$$

- By the balance of forces, the external force F should be equal to the entropic force, that tries to restore the polymer to its equilibrium position.



A free jointed polymer is immersed in a heat bath with temperature T and pulled out of its equilibrium state by an external force F. The entropic force points the other way.

- Specifically, one considers the micro canonical ensemble given by Ω(E +F x, x), and imposes that the entropy is extremal. This gives

$$\frac{d}{dx} S(E + Fx, x) = 0 \;\rightarrow$$

$$\rightarrow\; \frac{1}{T} = \frac{\partial S}{\partial E} \qquad \frac{F}{T} = \frac{\partial S}{\partial x}$$

Emergence of the Laws of Newton

- Bekenstein : when a particle is one Compton wavelength from the horizon, it is considered to be part of the black hole. Therefore, it increases the mass and horizon area by a small amount, which he identified with one bit of information. This lead him to his area law for the black hole entropy.
- We want to mimic this reasoning not near a black hole horizon, but in flat non-relativistic space. So we consider a small piece of an holographic screen, and a particle of mass m that approaches it from the side at which space time has already emerged. Eventually the particle merge with the microscopic degrees of freedom on the screen, but before it does so, it already influences the amount of information that is stored on the screen. The situation is depicted in figure.
- Motivated by Bekenstein's argument, let us postulate that the change of entropy associated with the information on the boundary equals:

$$\Delta S = 2\pi k_B \quad when \quad \Delta x = \frac{\hbar}{mc}$$

- More general, by assuming that the change in entropy near the screen is linear in the displacement Δx :

$$\Delta S = 2\pi k_B \frac{mc}{\hbar} \Delta x$$

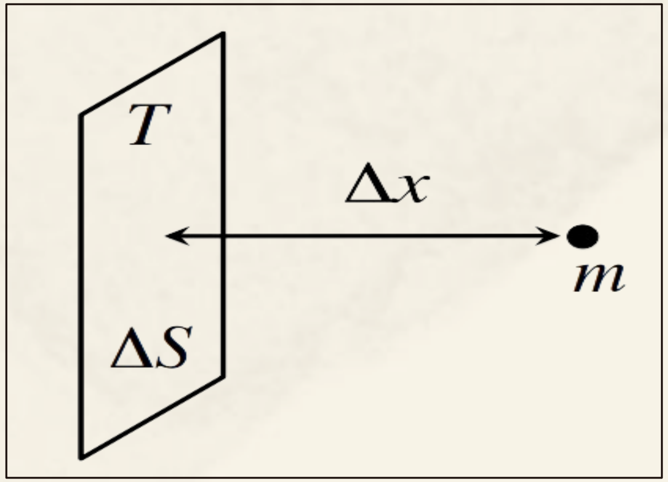
- Force arising : The basic idea is to use the analogy with osmosis across a semi-permeable membrane. When a particle has an entropic reason to be on one side of the membrane and the membrane carries a temperature, it will experience an effective force equal to :

$$F\Delta x = T\Delta S \text{ (Entropic Force)}$$

- Unruh showed, an observer in an accelerated frame experiences a temperature:

$$k_B T = \frac{1}{2\pi}\frac{\hbar a}{c}$$

- This equation should be read as a formula for the temperature T that is required to cause an acceleration equal to a. And not as usual, as the temperature caused by an acceleration.



A particle with mass approaches a part of the holographic screen. The screen bounds the emerged part of space, which contains the particle, and stores data that describe the part of space that has not yet emerged, as well as some part of the emerged space.

Newton's law of gravity

- Now suppose our boundary is not infinitely extended, but forms a closed surface. More specifically, let us assume it is a sphere. The key statement is simply that we need to have a temperature in order to have a force. Since we want to understand the origin of the force, we need to know where the temperature comes from.
- One can think about the boundary as a storage device for information. Assuming that the holographic principle holds, the maximal storage space, or total number of bits, is proportional to the area A. In fact, in an theory of emergent space this how area may be defined: each fundamental bit occupies by definition one unit cell.
- Let us denote the number of used bits by N. It is natural to assume that this number will be proportional to the area. So we write:

$$N = \frac{Ac^3}{G\hbar}$$

- Suppose there is a total energy E present in the system. Let us now just make the simple assumption that the energy is divided evenly over the bits N. The temperature is then determined by the equipartition rule:

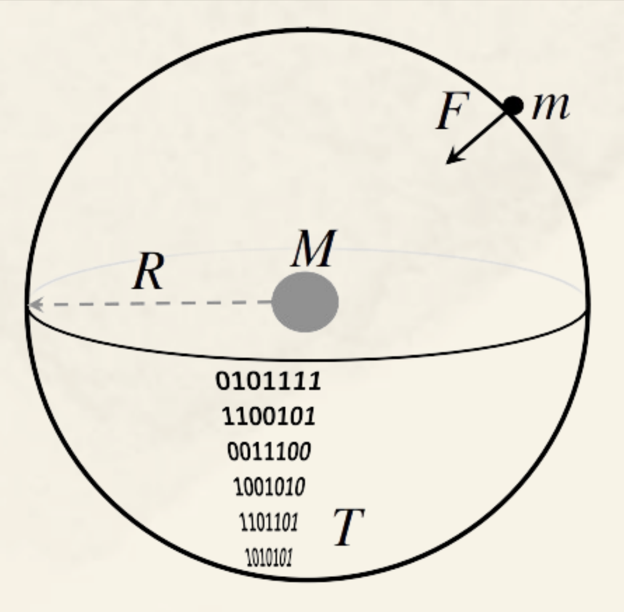
$$E = \frac{1}{2} N k_B T \text{ (average energy per bit)}$$

- Also we have equation:

$$E = Mc^2$$

- Here M represents the mass that would emerge in the part of space enclosed by the screen, see figure. Even though the mass is not directly visible in the emerged space, its presence is noticed though its energy.
- We left with :

$$A = \pi R^2 \rightarrow F = G\frac{Mm}{R^2}$$



A particle with mass m near a spherical holographic screen. The energy is evenly distributed over the occupied bits, and is equivalent to the mass M that would emerge in the part of space surrounded by the screen.