The Phantom Glass Mystery: a transition from dry to lubricated friction

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The phantom glass is a spectacular phenomenon that occurs when a warm glass placed upside down on a wet surface starts moving on its own, as if propelled by an invisible force. We show that this spontaneous motion is the result of a transition between solid and liquid friction regimes due to a pressure increase in the glass. We reveal the existence of three phases in the dynamics of the system when the temperature of the glass is increased: Firstly, we observe an expulsion of liquid trapped inside the glass followed by a lift-off of the glass that eventually floats over a capillary bridge preventing air from escaping. Finally, when pressure is increased even further, the bridge breaks up and solid friction is restored.

FIG. 1. Warm glass moving spontaneously from right to left after being put on a glass surface . The surface initially coated with a thin layer of soap water and was intentionally tilted by $\simeq 1$ degree to drive the motion. The width of the field of view is $\simeq 50$ cm and the time between shots is $\simeq 0.5$ s

I. INTRODUCTION

There are two main types of frictions between solids. Dry solid friction, when the two solids are directly in contact, and liquid-mediated friction, also known as lubrication[1], when they are separated by a liquid layer[2]. Transition between the two regimes can be important in many practical situations, with both negative or positive practical consequences. On the one hand, in hydroplaning[3], the loss of adhesion can provoke skidding and dangerous car accidents, while on the other hand this type of transition is harnessed for recreational purpose in ice-skating or ski[4]. The interplay between solid and liquid friction also plays an important role in the understanding of the avalanche of wet granular materials[5].

This transition is illustrated in a so-called 'phantom glass phenomenon', which can be observed when putting a warm hand-washed glass upside down on a wet surface (see Fig. 1) When the proper conditions are met, the glass can start moving on its own as if pulled by an invisible force. Many videos illustrating this phenomenon can be found online by simply typing "glass moving by itself" in a search engine. Several explanations have been proposed and suggest that the motion of the glass is due to a suppression of solid friction and that the glass skids on a liquid layer. The Phantom glass phenomenon would then be a liquid version of the Leidenfrost effect where the adhesion of a liquid to a surface due to capillary hysteresis is suppressed by heating the droplet and creating a vapor cushion that isolates the liquid from the substrate[6,7], However, there is currently no quantitative or experimental confirmation of this hypothesis.

In this article we study quantitatively this phenomenon in a simple setup, sketched in Fig.2. We immerse a glass funnel in a shallow layer of water and the temperature of the system is varied vessel using a heating resistor. Our observations reveal a three step process as the glass is heated up, see Fig. 3. During the first phase, the pressure build-up due to the heating of the air inside the vessel expels the liquid from the glass. Direct solid-on-solid contact is however maintained during this phase and the glass motion is hindered. However when the liquid layer inside the glass is fully removed, the glass starts to hover over a sub-millimeter-high capillary bridge preventing the air from escaping and maintaining the internal excess-pressure. This capillary bridge forms a lubricating layer that allows the motion of the glass under the smallest external perturbation, for instance a slight tilt of the table. Finally when the temperature is increased even further, the capillary bridge breaks and the air can

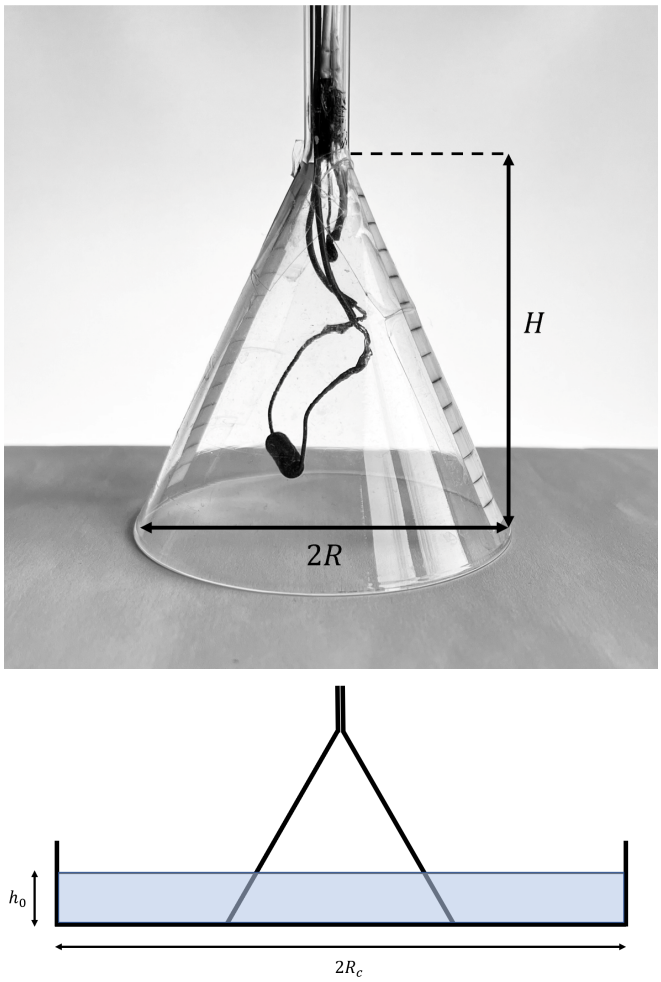

FIG. 2. Sketch of the experimental setup. Upper panel: the funnel height and diameters are equal and we have $H = 2R = 7$ cm. The inner temperature is controlled by a heating resistance and the temperature is measured using a 10K thermistor located close to the top of the tapered section of the funnel the heating resistance. Lowe panel: the funnel is placed upside-down in a glass crystallizer of radius $R_c = 8.3$ cm that we fill with a layer of water of variable height h_0.

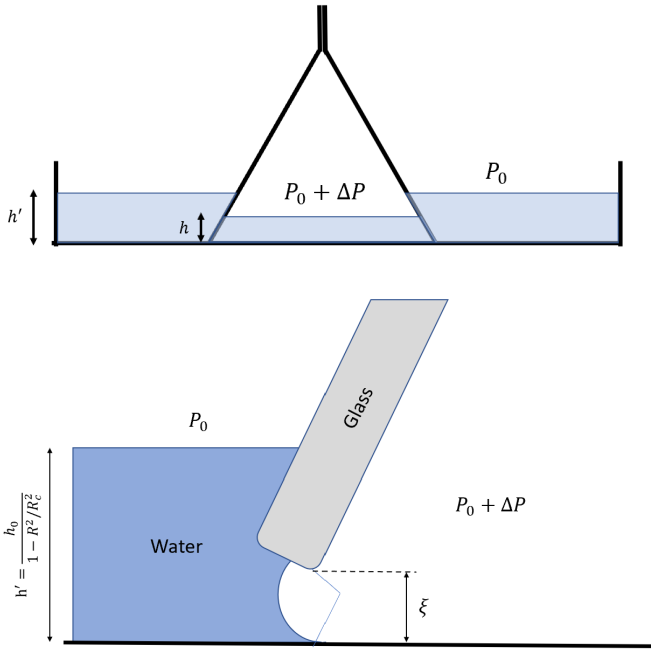

FIG. 3. Three-step route to levitation. Upper panel: During the first stage the pressure increase expels the inner water film through the cracks between the bottom edge of the funnel and the crystallizer. The increased inner-volume mitigates the pressure excess and prevents lift-off. Lower panel (close-up): When the water is fully expelled, the glass takes off but air is still trapped inside by a capillary bridge connecting the glass to the bottom of the crystallizer. The bridge ruptures when the geometric constraint $\xi \leq 2r$ is no longer met.

finally escape, as evidenced by the formation of bubbles at the basis of the glass.

II. EXPERIMENTAL SETUP AND OBSERVATIONS

The experimental setup is depicted in Fig. 2. As a vessel we use an upside-down glass funnel. The inner temperature is controlled by a 2 kΩ heating resistance and it is probed using a 10K thermistor. The end of the funnel through which we feed the wires connecting the electric components is sealed using Patafix®. The mass m of the funnel is $m = 40$ g and we change it by sliding brass bolts along its neck.

The funnel is placed in a glass crystallizer that we fill with thin layer of a solution of SDS (Sodium dodecyl Sulfate) in water of controlled thickness h_0. Unless explicitly stated, we work with a concentration of SDS $c = 10$ mM slightly above the critical micelle concentration (cmc) $c_{\rm cmc} \simeq 8.3$ mM[8] and for which the surface tension is $\gamma \simeq 34$ mN/m.

When heating slowly the air inside the funnel, we observe first that the level of water inside the glass decreases, signaling that the film is expelled from the vessel under the increased pressure. We confirmed the existence of this outwards flow by adding a few drops of dye to the water inside the funnel: when heating is turned on, we observe that the dye indeed leaves the funnel. However, during this phase, the friction between the glass and the surface remains high, suggesting that the glass undergoes a direct solid-on-solid contact with the surface, friction is high and the glass cannot move.

However, once the liquid film inside the vessel has been fully expelled, the glass is observed to recover almost immediately its freedom of movement, signalling that the friction between the glass and the surface suddenly drops. In this phase, the glass is sealed by a liquid meniscus at its perimeter, see Fig. 3, and experiences a lift-off. Accordingly the contact between the glass crystallizer and

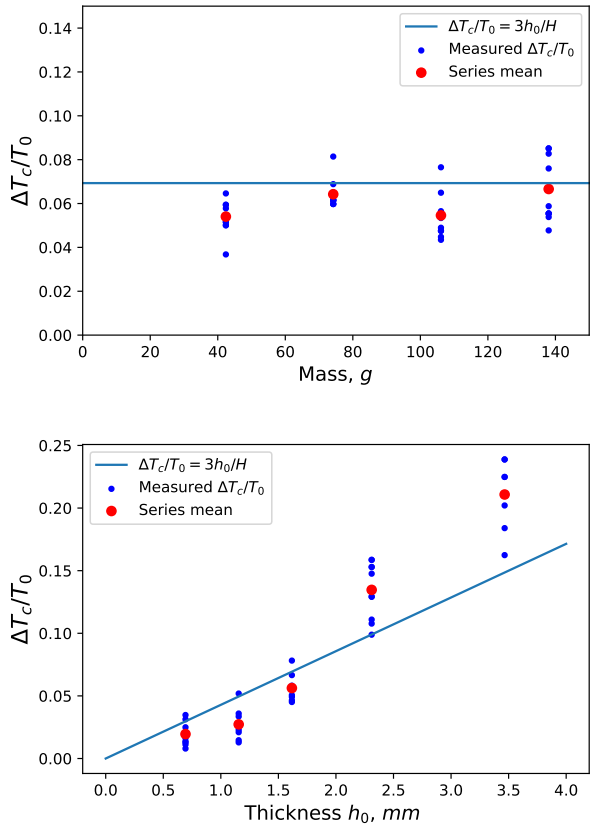

FIG. 4. Evolution of the critical temperature as a function of the glass mass and height of the water layer. The blue solid line corresponds to the prediction $\Delta T_c/T_0 = 3h_0/H$ Each experiment was repeated five times and the larger circle corresponds to the mean value of the five measurements.

the surface becomes lubricated and the glass can moves freely under minute forcings (Note that in our setup, and contrary to real life observation, the motion of the glass motion is constrained by the wires connecting the electrical elements: loss of friction is accordingly heralded by a sudden jerk of the glass).

We call T_c the temperature at which the glass starts moving and we measured it as a function of the thickness of the water film h_0, as well as the mass of the funnel. The results of these measurements are displayed in Fig. 4). We observe almost no dependence of the critical temperature on the mass of the glass, while T_c increases roughly linearly with the height h_0 of the liquid film.

When the temperature is increased even further we reach a second threshold T_b where bubbles start to appear at the bottom of the funnel, showing that the capillary bridge is no longer strong enough to sustain the pressure building-up inside the glass. Contrary to T_c, T_b displays a strong dependence on the mass of the glass that we illustrate in Fig. 5.

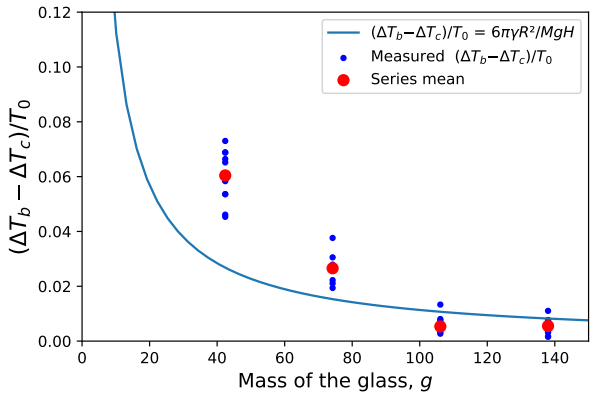

FIG. 5. Evolution of the critical temperature vs glass mass and height of the water layer. The solid line corresponds to the capillary bridge stability condition 15

III. MODEL AND INTERPRETATION

Let's now turn to the interpretation of the observations discussed in the previous section. As long as the interior of the funnel is sealed by the capillary bridge, the number of molecules enclosed in the funnel is constant. Describing the air as an ideal gas, the pressure P, the volume V and the temperature T satisfy the equation PV/T =constant. When we heat up the air, pressure starts to build up and to push both on the glass and the liquid film. Because of gravity, the glass does not immediately lift off. Indeed, as long as it is in contact with the surface of the crystallizer, one can write the force balance condition $mg = N + \Delta P \pi R^2$, where N is the support reaction force and ΔP is the inner excess pressure. Gravity will press the glass on the crystallizer as long as N is positive, ie as long as $\Delta P \leq mg/\pi R^2$. In this first phase, the glass experiences a direct solid-on-solid contact with the surface and the friction is high: the glass does not move.

However, because of the pressure drop, water starts flowing through the interstices and cracks between the funnel's edge and the crystallizer. Assuming a laminar and quasi-stationary regime, we can model the flow of water by the phenomenological law

$$\Phi = G\,(P_{\rm in} - P_{\rm out})\,, \qquad (1)$$

where G is the hydraulic conductance of the cracks between the funnel and the crystallizer and $P_{\rm in}$ (resp. $P_{\rm out}$) is the inner (resp. outer) pressure at the surface of the crystallizer. Assuming a Poiseuille-like law, we can estimate the hydraulic conductance as $G \simeq \frac{R\varepsilon^3}{e\eta}$, where ε is the height of a typical interstice or crack, e the thickness of the glass wall, η the water viscosity and we assume that such interstices occupy a significant portion of the perimeter of the glass/crystalizer contact line. Taking

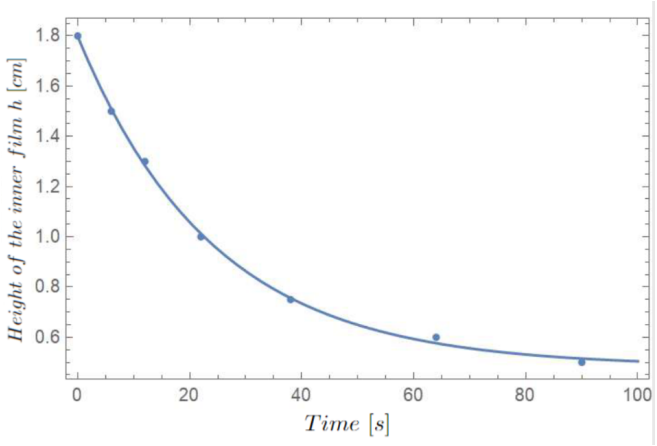

FIG. 6. Evolution of the height of the inner film under its own weight. The solid line corresponds to an exponential fit from which we deduce the value of the hydraulic conductance of the leakage at the bottom of the funnel.

typical values $\varepsilon \simeq 0.1$ mm and $e \simeq 1$ mm, one estimates $G \sim 10^{-7}$ m^2/s/Pa. We performed a direct measurement of the hydraulic conductance G in order to assess this estimate. To achieve this, we filled the funnel with a liquid film of height h_0 on a dry crystallizer. We left the top of the funnel open to let the film drain out under its own weight. The evolution equation of the film height remaining in the funnel is

$$\pi R^2 \dot{h} = -G\rho g\,(h - h')\,, \tag{2}$$

where ρ is the water mass-density and $h' = (h_0 - h)R^2/(R_c^2 - R^2)$ is the height of the water film outside the funnel (accounting for the fixed total volume of liquid in our experimental setup). The solution of this equation is

$$h(t) = h_\infty + (h_0 - h_\infty)e^{-\pi R^2 t/\rho G g}, \tag{3}$$

where $h_\infty = h_0 R^2/R_c^2 \simeq 0.18 h_0$. The evolution of the height of the inner film is shown in Fig. 6. Experimental data is fitted using an exponential trial function from which we deduce an experimental value of the conductance $G \simeq 1.6 \times 10^{-8}$ m^3/s/Pa. This value for G is accordingly a in semi-quantitative agreement with the previously discussed order of magnitude.

Let us now consider the phantom-glass setup, now in the situation where the top of the funnel is sealed, and the inner air pressure cannot equilibrate with the outside. The hydraulic dynamical equations write accordingly

$$\pi R^2 \Delta\dot{h} = G\left[\Delta P + \rho g\,(h - h')\right] \tag{4}$$

with $h = h_0 - \Delta h$ and ΔP is the excess pressure inside the funnel. Volume conservation imposes that $h' = h_0 + \Delta h/(R_c^2/R^2 - 1)$. Second, using the equation of state of the ideal gas, the excess pressure ΔP is the result of both the heating (that increases ΔP) and the variation of the gas volume due to the recess of the inner meniscus (that reduces ΔP). More precisely, we have

$$\frac{\Delta P}{P_0} + \frac{\Delta V}{V_0} = \frac{\Delta T}{T_0}, \tag{5}$$

with $\Delta V \simeq \pi R^2 \Delta h$ is the volume variation due to the receding meniscus and $V_0 = \pi R^2 H/3$ in the inner volume of the funnel. Combining Eq (4) and (5), we have

$$\frac{\pi R^2 H}{G P_0}\frac{\Delta\dot{h}}{H} = \frac{\Delta T(t)}{T_0} - 3\frac{\Delta h}{H}\left[1 + \frac{\rho g H}{3P_0}(1 + R^2/R_c^2)\right]. \tag{6}$$

In our typical conditions, the ratio $\rho g H/P_0$ is about 10^{-2} and can therefore be safely neglected in our analysis. Moreover, we see that the equation involves a relaxation time $\pi R^2 H/G P_0 \simeq 10$ ms. This time is very short compared to the typical heating time (few seconds). We can therefore assume that the system is in a quasi-equilibrium regime and one can neglect the time derivative in Eq. 6. We finally obtain

$$3\frac{\Delta H}{H} = \frac{\Delta T}{T_0}. \tag{7}$$

The inner film vanishes when $\Delta h = h_0$, which corresponds to a threshold temperature

$$\frac{\Delta T_1}{T_0} = 3\frac{h_0}{H}. \tag{8}$$

We note that the quasistatic approximation implies that the excess pressure can be written as

$$\Delta P = \rho g \Delta h\left(1 + R^2/R_c^2\right). \tag{9}$$

Since $\Delta h \leq h_0$, the excess pressure is bounded by $\rho g h_0(1 + R^2/R_c^2)$. As discussed earlier, the glass lifts off when the force exerted by the inner pressure overcomes the weight of the glass. Since $\pi\rho h_0 R^2/M \lesssim 10^{-1}$, we conclude that the glass stays in contact with the crystallizer during this first heating phase.

From this analysis, we conclude first that the threshold does not depend (or depends weakly) on the glass mass, in agreement with the observations reported in section II. Moreover, We have plotted in Fig. 4 the prediction $\Delta T/T = 3h_0/H$ that agrees quite well with experimental observations.

When the inner film is expelled, pressure starts to build up inside the funnel. ΔP now follows the evolution equation

$$\frac{\Delta P}{P_0} = \frac{\Delta T}{T_0} - 3\frac{h_0}{H} = \frac{\Delta T}{T_0} - \frac{\Delta T_1}{T_0}. \tag{10}$$

The glass lift-off occurs at a temperature ΔT_2 given by

$$\frac{\Delta T_2}{T_0} = \frac{\Delta T_1}{T_0} + \frac{Mg}{\pi R^2 P_0}. \tag{11}$$

For typical experimental values, we have $\Delta T_1/T_0 = 3h_0/H \simeq 10^{-1}$, while in contrast, $Mg/\pi R^2 P_0 \simeq 10^{-4}$.

This means that once the inner film is fully drained, a minute temperature increase suffices to lift the glass.

Despite the increased inner pressure, the glass does not rise indefinitely. Indeed, as long as the integrity of the capillary bridge between the glass and the crystallizer is maintained, the number of air molecules contained in the funnel is constant and the ideal gas condition PV/T=constant remains valid. When the glass rises at constant molecule number, the trapped volume increases and the inner pressure decreases until it balances the glass weight. Note that the capillary force $F_c \simeq 2\pi R\gamma$ exerted by the liquid on the glass plays a very small role here since it remains negligible compared to the weight of the funnel (we have typically $F_c/Mg \simeq 10^{-2}$).

The equilibrium height ξ is reached when the following force balance is achieved:

$$\frac{Mg}{\pi R^2 P_0} + 3\frac{h_0+\xi}{H} = \frac{\Delta T}{T_0}, \tag{12}$$

or, in other words,

$$\xi = \frac{H}{3T_0}\left(\Delta T - \Delta T_c\right). \tag{13}$$

At a more microscopic level, the capillary bridge holding the glass can be approximated by a cylinder of radius r satisfying Laplace's law (see Fig. 3, lower panel)

$$\begin{aligned}\frac{\gamma}{r} &= \Delta P - \frac{\rho g h_0}{1-R^2/R_c^2} \\ &= \frac{Mg}{\pi R^2} - \frac{\rho g h_0}{1-R^2/R_c^2} \\ &\simeq \frac{Mg}{\pi R^2},\end{aligned} \tag{14}$$

where we have used the fact that the excess pressure balances the weight of the glass and that the mass M of the glass is much larger than that of the film initially in the funnel. The capillary bridge is stable as long as $\xi \lesssim 2r$. Beyond that threshold, equilbrium can only be obtained by breaking the capillary bridge in order to allow air bubbles to escape the glass and reduce the internal pressure. Combining Eq. (13) and (14), we see that bubbles appear when the temperature reaches a threshold ΔT_b given by

$$\frac{\Delta T_b - \Delta T_c}{T_0} = \frac{6\pi\gamma R^2}{MgH}. \tag{15}$$

This equation predicts a dependence of the bridge stability domain on both the mass of the glass and the surface tension of the liquid. Both variations are tested experimentally and the results are reported in Fig. 5 and 7.

We see that both trends are correctly predicted, but that our model slightly underestimate the measured temperature range. A better agreement can probably be met by improving our control over the temperature of the air trapped in the glass. Indeed, we have always assumed in our model that the temperature and the pressure were uniform while it is obviously not the case in our setup due to the local nature of our heating scheme.

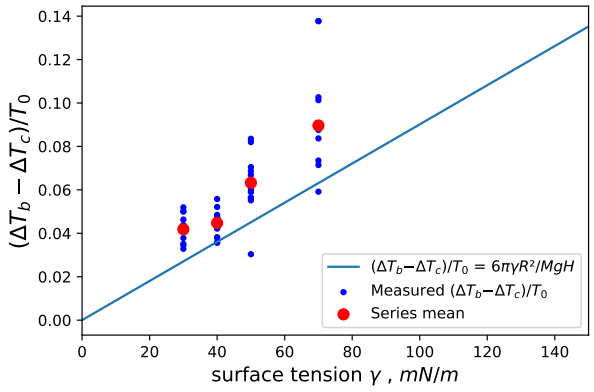

FIG. 7. Dependence of the temperature width of the levitation regime with surface tension. The blue line represents Eq. (15).

The maximum height at which the funnel can levitate is $\xi_{\max} \simeq 0.2$ mm. To test this value, we rested the funnel on three cm-wide, 0.1 mm-thick plastic pads. When a single layer of pad is added, the glass can still levitate. However, when two layers of pads are added, bubbles form at the bottom of the funnel as soon as heating is turned on, proving that the system cannot support the capillary bridge necessary for the glass to levitate.

IV. CONCLUSION

In this article we have presented an experimental and theoretical study of the phantom-glass effect in a controlled setting. We have found that our observations could be interpreted within a three-step mechanism that leads to quantitative agreement for the temperature at which the glass experiences a lift-off and starts moving: at this threshold, a transition between a direct (solid-on-solid) and a lubricated contact occurs between the glass an the surface, allowing for the glass to move (nearly) freely. We also explain in a semi-quantitative way the apparition of bubbles at high temperature that we explain by the rupture of the capillary bridge over which the glass floats. Note that the initial liquid layer is not a prerequisite for the observation of the phenomenon as the capillary bridge can form from the gravitational draining of the water wetting the surface of the glass itself.

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