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Pub Physics –

The Science of Beer

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> I'm drinking beer.
>
> *Richard Feynman*

Richard Feynman was once at a party in Princeton, when a newly arrived European physicist came and sat next to him. He asked Feynman "What are you doing?", in the hope of learning what research he was currently involved in. "I'm drinking beer.", responded Feynman. Realising he had misinterpreted the question, they went on to talk about Dirac's use of the Lagrangian in quantum mechanics (Brown, 2003). If they had instead discussed the beer itself, they would have found no lack of interesting physics. This article will follow the journey of a beer, starting from the pour and ending with its loss of height over time, and the physics going on at each step. Many processes that we are entirely accustomed to turn about to be difficult to explain without involving some nuanced physical theories. Phenomena including the glugging that occurs during pouring, the apparently unphysical behaviour of the bubbles within the glass and the explosion of beer caused by a knocked bottle will all be demystified.

The Pour

After a long day of physics, you grab yourself a can of beer from the fridge. Instead of the satisfying, continuous pour you'd hoped for, the beer exits its container in sections of high and low flow, as if hindered by a mysterious force preventing it from leaving all at once.
Why does a beer 'glug' as its poured?
When a drink is poured from a hole in an otherwise sealed container, a small vacuum is created in the empty space once occupied by the liquid. Atmospheric pressure responds by pushing air back in to fill the vacuum. This obstructs the flow of water until the vacuum is replaced by air, and there is no longer a pressure gradient. The liquid can once again flow. This new flow blocks the aperture of the container, and as more liquid leaves, a vacuum is again created. Air then flows back in the container and so the process continues. This results in the observed 'glugging'. Reducing this effect is trivial; widen the aperture, or even better introduce a secondary entry point for air (Hsu and Luo, 2013). The *Churchkey Pilsner* brand had a slim can with two equally sized holes, and a more recent attempt by *Miller Coors* involved a small punchable hole, as in Figure 1.

Figure 1: *Two approaches used by beer companies to reduce the 'glugging' effect common with other cans. Top (The World's Best Ever Blog, 2012), bottom (Look What's Down Blog, 2014).*

The Bubbles & The Head

Sat down with the beer, you notice that the bubbles aren't flowing equally in all parts of the glass. There seem to be areas of the glass where no bubbles ever rise, and columns full of bubbles; they seem to have some preference as to where they appear. By the time they've almost reached the head (the foamy bit sitting at the top of the beer) they appear much larger, faster and more spread out than they were at the bottom. Also, the head itself is white even though the beer is not.

Why do bubbles in a glass stick to specific channels and increase so dramatically in size, speed and separation before reaching the head? Why is this head, despite being made of the same stuff as the rest of the beer, an entirely different colour?

Despite being carbonated and thus saturated with CO_2, bubbles will not form spontaneously in a beer glass as a liquid will not spontaneously transform into a gas; a nucleation site is required where pockets of gas form bubbles. These sites are often modelled as conical pits for geometrical convenience, as illustrated in Figure 2.

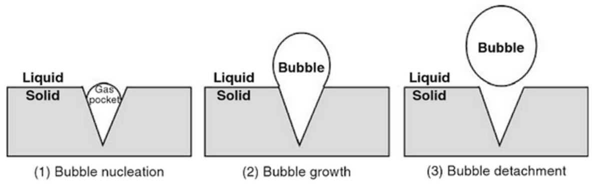

Figure 2: *A diagram depicting bubble formation in a conical pit model. (Bamforth, 2011)*

Air within these pits escapes as bubbles when the buoyant force of the bubble exceeds cohesive forces between the bubble and the glass (Lynch and Bamforth, 2002). A perfectly clean, unscratched glass will therefore be free of bubbles. This is demonstrated by putting a porous bead into such a glass. As nucleation only occurs on the bead, all bubbles formed will remain in a channel above the bead, as in Figure 3. Brands often take advantage of this effect by etching their logos into the bottom of pint glasses, so bubbles flow pleasingly from the base of the beer.

With a large nucleation site it can be hard to distinguish between, and analyse the behaviour of, individual bubbles. Figure 4 shows a long thin glass with a small nucleation site, resulting in a linear stream of singular bubbles. This can be explained by considering partial pressures. The partial pressure of the CO_2 dissolved within the beer is much greater than that of the CO_2 in the beer. The CO_2 therefore travels from the liquid into the bubble, increasing the number of CO_2 molecules within the bubble. Assuming this pressure difference remains approximately constant, the rate of bubble growth will be proportional to its surface area, giving

$$\frac{dN}{dt} = \gamma \left(4\pi r^2\right) \tag{1}$$

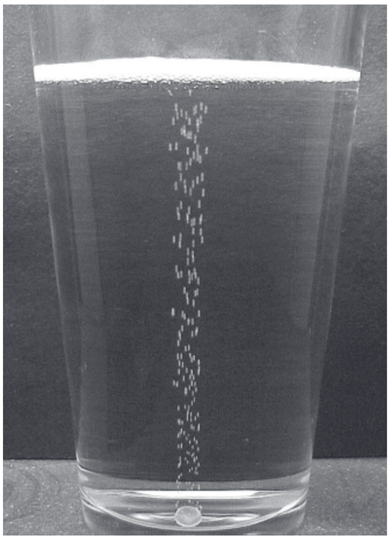

Figure 3: *A porous bead placed in the bottom of a smooth pint glass, with all bubbles isolated to a channel above the bead. (Lynch and Bamforth, 2002)*

Figure 4: *A tall pint glass with a small nucleation site, showing bubbles increasing in size and separation with altitude. (Shafer and Zare, 1991)*

where N is the number of CO_2 molecules in the bubble, γ is a constant of proportionality and r is the radius of the bubble. We can describe this simply by assuming the temperature T of the bubble is maintained by the beer, and pressure P is maintained by the atmosphere, with pressure due to the liquid beer being negligible in comparison.
Modelling the CO_2 within the bubble of volume V as an ideal gas so that $PV = Nk_BT$, we can express Equation 1 as

$$\frac{dN}{dt} = \left(\frac{P}{k_BT}\right)\frac{dV}{dt} = \left(\frac{P}{k_BT}\right)4\pi r^2\frac{dr}{dt} \tag{2}$$

with all terms as previously defined.
Equating the two and solving the resultant first order differential equation gives

$$r = r_0 + \mu_r t \tag{3}$$

where r_0 is the initial radius of the bubble, and $\mu_r = \frac{\gamma k_B T}{P}$. From Figure 2 it is clear that $r_0 \neq 0$, as for a bubble to escape it must have some radius. This gives us an expression for a bubble's radius over time, explaining the increasing size of bubbles towards the top of the glass.
But why do they get so much faster? We know from Archimedes' principle that the buoyant force on the bubble F_B is equal to the weight of fluid displaced by the bubble,

$$F_B = V\left(\rho_{beer} - \rho_{bubble}\right)g \approx V\rho_{beer}g = \frac{4\pi r^3}{3}\rho_{beer}g \tag{4}$$

where $\rho_{beer}, \rho_{bubble}$ are the densities of the beer and bubble, V and r are the volume and radius of the bubble as before, and g is the acceleration of free-fall. We approximate $\rho_{beer} - \rho_{bubble} \approx \rho_{beer}$ as the density of one of the bubbles is negligible in comparison to that of the beer. In most physical systems with a buoyant force, we expect a travelling object to reach some terminal velocity. However here, we have the buoyant force term dependent on the radius of the bubble, and the radius increasing linearly with time. The drag force increases with radius, but less rapidly than the r^3 term. This explains why the bubbles get faster and more spread out with increasing altitude within the glass; each bubble is travelling faster than the one below it. The entire derivation above was adapted from (and experimentally verified in) Shafer and Zare, 1991.

When these bubbles finish their journey at the top of the glass, they join many other bubbles in the frothy white head. But why is it white, when the beer is normally a shade of golden brown? We know that light refracts when incident on a boundary between two media. Assuming the glass itself has little/no effect on the observed colour of the beer, there are only two boundaries to consider: the entry air-beer boundary and the exit beer-air boundary. Within the head, there are two such boundaries each time the light passes through a bubble's wall. As there a numerous bubbles within the head, the light is refracted many times in random directions, scattering it. Light incident from the surroundings is composed of a random combination of all colours, within the beer itself more wavelengths corresponding to blue light are absorbed and those corresponding to red and green are reflected, so the beer appears brown. In the head, the effects of absorbing are far less important than scattering. The incident blend of colours is mixed by the scattering processes which, when observed, is perceived as white light, thus the head of the beer appears to be white (Nees, 2014).

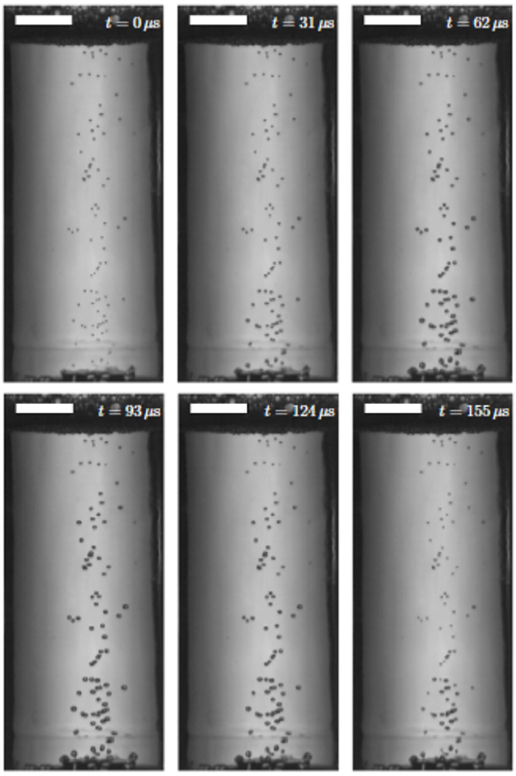

Figure 5: *This figure depicts the instant after the impact on the bottle, demonstrating the first expansion-compression cycle. A metal disk was placed at the bottom to provide a nucleation site, ensuring a constant flow of bubbles. (Rodríguez-Rodríguez and Fuster, 2014)*

The Tapping

Thinking about all the physics of drinking your beer from a glass has given you a headache, so you decide to drink directly from the bottle. You sit down and a mate knocks the top of your bottle with the bottom of theirs. The foam that you thought you'd avoided by choosing a bottle is now pouring out all over the table. This is the messy past-time known as 'Beer Tapping'.

Why does knocking a bottle of beer cause a dramatic eruption of froth?

This phenomenon can be explained by the trans-

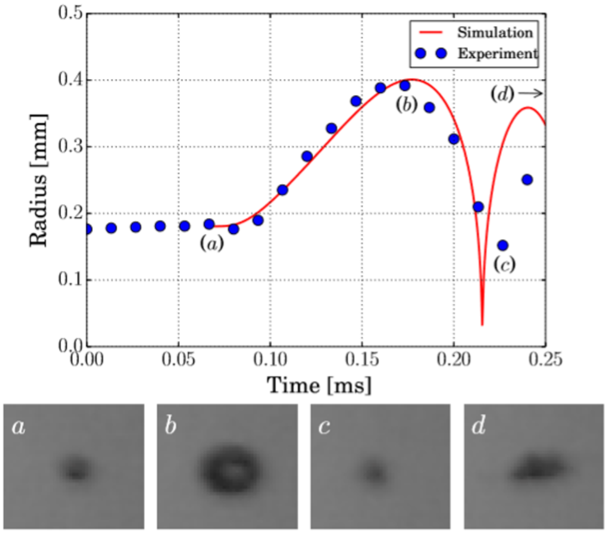

Figure 6: *Analysis of the radius of an individual bubble over time compared to the simulated results using the Rayleigh-Plesset law. From $a \to b$ the bubble increases in radius, but a greater rate that in an undisturbed beer due to expansion wave. From $b \to c$ the individual bubble collapses and a bubble cloud forms. (Rodríguez-Rodríguez and Fuster, 2014)*

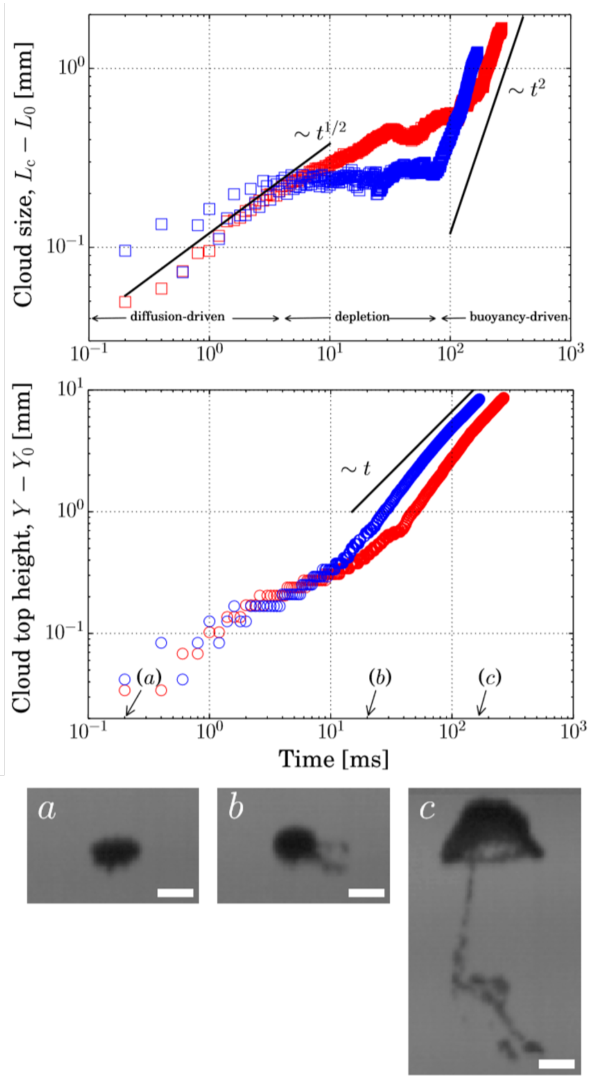

Figure 7: *This figure shows the behaviour of bubble clouds over time, where $L_c - L_0$ is the vertical length of a bubble cloud and $Y - Y_0$ is the vertical distance of the cloud from the bottom of the bottle. The blue lines represent the behaviour of already formed bubbles after the bottle is struck and the red lines represent the same for laser-induced bubbles. The laser-induced bubbles were used to reduce noise associated with acoustic waves. The shape of the cloud during the different stages evolves from a roughly spherical bubble, to looking more like a jellyfish as the cloud rises. (Rodríguez-Rodríguez and Fuster, 2014)*

port of pressure waves within the bottle and the breakdown of large bubbles into bubble clouds (Rodríguez-Rodríguez and Fuster, 2014). When the top of the bottle is struck, a compression wave is generated that travels through the glass walls to the base of the glass. When the wave reaches the bottom, it is partially transmitted to the liquid as an expansion wave that travels to the surface of the beer. At the surface, this wave bounces back as a compression wave. An expansion wave is one that decreases the density of a fluid it passes through, and a compression wave is one that increases the density. These waves bounce back and forth in the beer until they gradually die out due to damping effects.

We'd expect, from the previous section, that the bubbles would be larger towards the top of the glass. This is clearly not the case in Figure 5; in fact at time $t = 155\mu s$ it appears that bubbles near the top are smaller. This illustrates the action of the waves propagating within the beer; a compression wave at the top will shrink the bubbles that would otherwise be the largest. The Rayleigh-Plesset equation can be used to describe the motion of a spherical gas bubble under pulsation within an infinite body of liquid, applicable in our situation due to the small volume of a bubble compared to the volume of the bottle (Leighton, 2007).
We can tell from Figure 6, although the images are not of high resolution due to the small size of an individual bubble, that the bubble is definitely not growing in size. The deformation in shape shown in the images and the deviation from the behaviour expected for an individual bubble in the simulation suggest that by c and d there is no longer a single bubble, but a bubble cloud.

This break up of a single bubble into many is likely due to Rayleigh-Taylor instability. This instability occurs at the interface of two fluids of different densities, where the less dense fluid is pushing against the denser fluid (Sharp, 1983). This is the case within the beer, as the gas bubbles expand within the denser liquid beer.
The collapse of the bubble causes a sudden increase in the area of the gas-liquid interface, as many small bubbles have a greater surface area/volume ratio than a single bubble of the same volume. As predicted by Equation 1, this results in a greater rate of expansion

of bubble volume. Buoyant forces have a substantial influence on the behaviour of these relatively large clouds. The radius of the bubble clouds scales very differently to the linear growth described by Equation 3, shown in Figure 7. Before the breakdown into bubble clouds, individual bubbles under the influence of the waves grow according to $t^{\frac{1}{2}}$, from the 'diffusion-driven' stage into the 'depletion' stage. This stage is when they break down and become clouds of rapidly increasing radius. The clouds then enter the 'buoyancy-driven' stage, where the radius grows as t^2, greater than individual bubbles would in an undisturbed vessel. This is due to a loop where as a cloud grows and rises it is exposed to more CO_2 dissolved in the beer, causing it to grow more and thus rise faster. By the time a cloud reaches the top of the bottle, it is significantly larger than any individual bubble. Therefore rather than forming a neat head, we observe a rapid expulsion of gas bubbles as the clouds expand to beyond what can fit within a bottle. The foamy mess goes everywhere and your hand is in a sticky state, just like the guy in Figure 8.

Figure 8: *The carnage that ensues from 'Beer Tapping'. (Scientific American, 2014)*

The Decay

After having your bottled beer 'tapped', you resort back to having your beer in a reliable pint glass. You've had a few too many and as you take a sip of your pint, you can't for the life of you recall what beer it is you have in your glass. You do, however, feel up for taking some scientific measurements.

How can I tell which beer I ordered?

From the simple assumption that the volume of head disappearing in a given time interval is proportional to the volume of the head present at that time we can model this process as an exponential decay. This is heuristically valid as bubble popping seems to be a largely random process, and can be validated by empirical data. In a cylindrical pint glass, common to many pubs in the UK, the volume of the head is proportional to the height of the head. From this we get the exponential decay equation

$$h(t) = h(0)e^{-\frac{t}{\tau}} \tag{5}$$

where $h(t)$ is the height of the head at time t, $h(0)$ is the initial height of the head and τ is a constant of the decay for a given beer. This analysis of the exponential decay of beer heads (Leike, 2001) won the 2002 *Ig Nobel Prize* in physics (awarded for 'research that makes people laugh and then think').

The decay constant τ is different for each beer and as such can be used to identify what you have in your glass, exemplified in Figure 9. By determining the

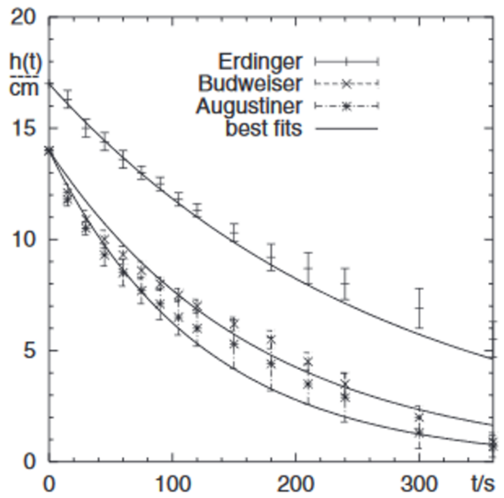

Figure 9: *The height of a beer head against time for three different beers, each showing an exponential curve. (Leike, 2001)*

decay constant of the head in your glass, and comparison with the reference book of decay constants for all known beers that you spent hours compiling, you can work out exactly what it is that you're drinking.

Last Orders

You've tried out different beer cans to perfect the pour, you unravelled the secrets of the bubbles in your glass, you made a sticky mess on the table after your bottle was tapped, went back to a pint glass, forgot what you ordered and worked it out, and learnt some physics along the way. This is far from a closed topic, and if simply drinking a beer isn't sufficiently entertaining for you, there are many questions to still be explored. How does the smoothness of the pour change the formation of the head of a beer? Would different beers and bottle shapes affect the explosiveness of a tapped beer? What specific processes cause the bubbles in the head to pop? There is interesting physics to be found in all areas of life, and the pub is no exception. So grab a beer and get thinking. Cheers!

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