THE DRY DROPS ON FOLIEN 1

INTRODUCTION

We submitted information on the "dry drops", as well as the part of Mr Zeelenberg's testimony that deals with the dry drops, to Professor Robert Deegan from the University of Michigan for his expert opinion.

Professor Deegan is a renowned expert in Fluid Dynamics and has, amongst others, conducted research and published research papers on ring deposit formation from evaporating drops. For more information on Professor Deegan please see: http://www-personal.umich.edu/~rddeegan/.

Prof Deegan's opinion (2012b) was that it is impossible to determine whether the drop marks formed on a vertical or horizontal surface. He stated that the problem with using general principles to differentiate between these cases is that there are too many unknowns (for example: state of the surface, velocity of impact, substance (water versus saliva versus sweat)) that could qualitatively change the outcome.

We appreciate and agree with Prof Deegan's finding that without acute knowledge of the substrate as well as the properties of the fluid at the specific time the drops were deposited and dried on whichever substrate, no one can make conclusive findings in this regard. And this certainly include Mr Zeelenberg and Mr Wertheim who are no experts in fluid dynamics.

Whatever the substrate, a drinking glass or a DVD cover, we will not know how dirty or clean it was at the specific time of deposition. Remember the glass from which Folien 1 was supposedly lifted was never produced and the DVD cover was dusted and then returned to the video store. We will also not know for certain what type of fluid it was and what went on in that fluid. There is a fundamental difference in the chemical composition and properties of fluids like for example water, sweat and saliva. It can affect the way they act and dry on a surface. We can under no circumstances know for certain what the fluid was that dried on Folien 1 and how and when it was deposited. A black and white lift of a foline unfortunately provides us only with a fairly basic capturing of traces.

Thus, acknowledging that it is not possible to claim conclusively that the drops were deposited on a flat horizontal or round vertical substrate, we will proceed to investigate and analyze the available evidence with the objective of determining the most likely result in the most likely scenario. And we will also test it against the defence's theories which would suggest a fairly normal glass (which was never found or produced we must remind ourselves) and water spatter. Using numerous well respected scientific papers and research on the subject as foundation we will thus look at what the result most probably would have been if the substrate was an average clean conical smooth drinking glass, spattered with drinking water – and with average impact velocity at a play (think about flicking water with your fingers). Thus we will look at a fairly everyday situation and we will not venture to extreme sides. We will also do a practical test where we will see how the same spatter from the same source reacts on the two surfaces (vertical and horizontal) at the same time. We compare them there and then on the spot (please see the "SPATTER EXPERIMENT" report).

We look at the facts and science at hand and we support our theories with practical tests, but we will not make loose assumptions as to how and why the drops arrived on the substrate. Nobody will ever know how those drops came onto whichever object, even if they were water drops. The fact that water drops are at stake certainly does not imply a drinking glass by default. A DVD cover can take spatter just about any place where a drinking glass can take it. Whatever fluid is the source. So we will leave the where, why and how aside. We will look at what facts and science tells us about the behaviour of drops in a specified and most likely scenario.

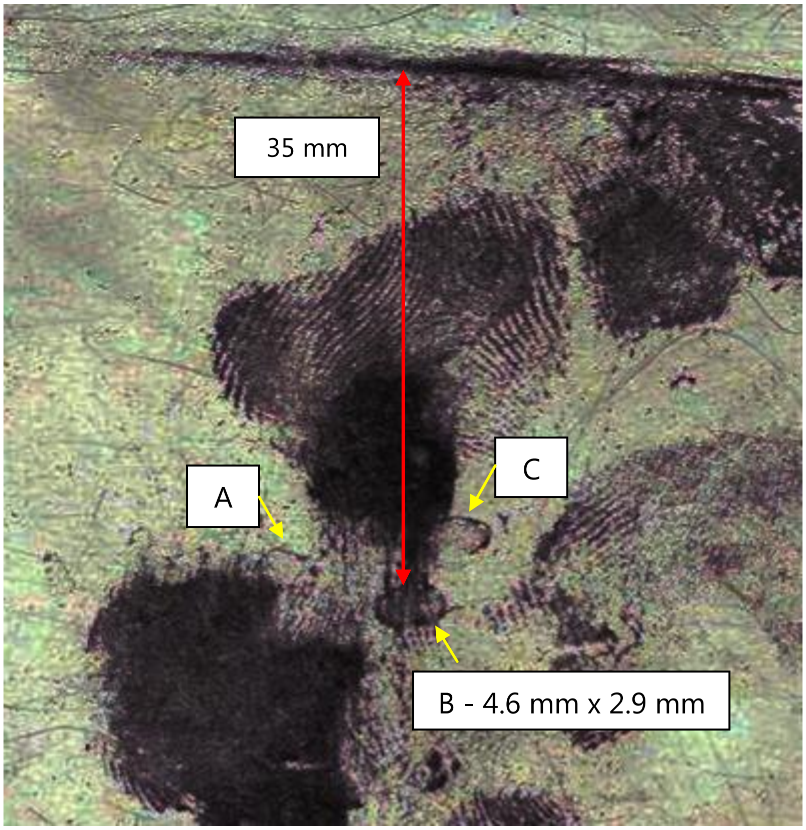
The premise of this report thus being:

If we for the sake of the investigation assume that normal tap water was the source of the dried drops, did the drops impact, remained stationary and then dried on an inclined vertical and curved surface? Or is it more likely that they impacted and then dried on a flat horizontal surface? We will in the process investigate the claim by Mr Zeelenberg that spatter would not produce similar shaped and sized drops on a flat horizontal surface. This is simply not accurate. We will hence look closely at this claim of his.

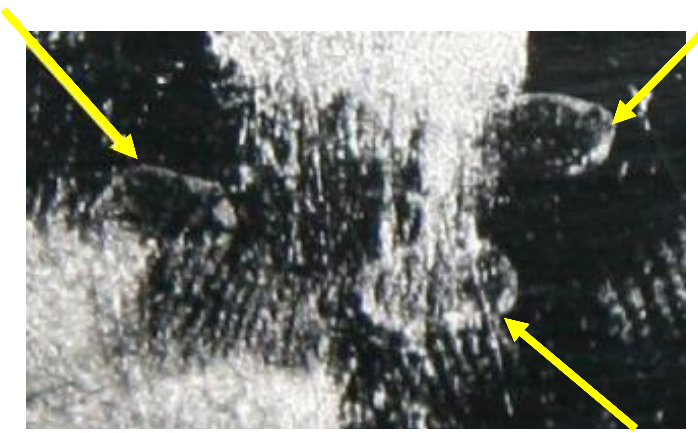
The experts, Mr Wertheim and Mr Zeelenberg, stated conclusively that the drops are consistent with a vertical round glass surface and inconsistent with a flat DVD surface. By their credentials it does not appear as if Mr Wertheim and Mr Zeelenberg are suitably qualified experts in Fluid Dynamics. Although they can certainly offer or have theories, they simply were not qualified enough to make <u>conclusive findings</u> in this regard. Fluid Dynamics is a highly specialised and scientific field. By testifying on a field of science that they are not experts in they have lead the court to arrive at potentially incorrect/false conclusions regarding the drops (and hence the validity of Folien 1).

THE INVESTIGATION

Folien 1 contains marks of several dried drops (which we for now assume is water). The drops are ellipsoidal and range between 4.5 mm to 4.6 mm in length and 2.7 mm to 2.9 mm in height. There is consensus that the drops were deposited and then dried on the surface prior to the fingerprints. However, the source of the drops has been under dispute.



What is more likely? Did these 3 drops arrive and dry on an <u>inclined curved vertical</u> surface or on a <u>flat horizontal</u> surface?



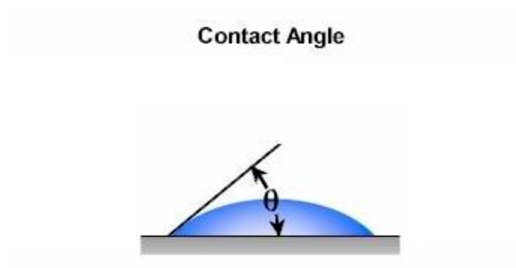
THE BEHAVIOUR OF WATER DROPS ON AN INCLINED GLASS SURFACE

The movement and shape of liquid drops moving on inclined surfaces have been studied by numerous researchers. For example, Le Grand et al (2005) studied the shape and motion of drops sliding down an inclined plane. At a certain threshold angle the drop starts moving at a constant velocity. As the angle continues to increase, the velocity increase and the drop becomes longer and thinner (i.e. the aspect ratio change). However, the thickness of the drop remains unchanged. As the aspect ratio changes a threshold is reached where the drop develops a sharp corner at the back. At even higher velocities the sharp tail breaks into smaller drops – called pearling.

Hang Ding et al (2009) describes the development of droplets i.e. when drops break free from the surface. They state that droplet formation and sliding compete with each other. As droplet ligaments start forming it leads to conditions that increase sliding velocity. Increased velocities in turn hinder droplet formation. It can thus be inferred that even if drops drip from an inclined glass there should still be evidence of slipping.

The drops on Folien 1, by their relatively intact and even contact lines and horizontal alignment show no evidence of slipping or droplet formation. According to Mr Zeelenberg's expert testimony Drop A has a slight "tear effect" – thereby implying that the dropped slipped on a vertical surface. It will be shown that the irregular contact line (edge) of Drop A does not necessarily mean that the drop slipped and that it could also have occurred on a horizontal surface.

Roura et al (2001) states that when a water drop starts sliding down a hydrophilic surface, such as glass, it leaves behind a thin water sheet. A hydrophilic surface is a surface where the static ***contact angle*** (θ) between water and the surface is less than 90 degrees. This contact angle determines the shape of a drop resting horizontally on a flat surface.



Source: http://www.ramehart.com/glossary.htm

There are no standard values for the static contact angle between glass and water. The contact angle is extremely sensitive to surface properties, fluid composition and additives. In addition surfactants, originating from household cleaning products e.g. dishwashing liquid, also have an impact on contact angles. It is not unrealistic to assume that a normal drinking glass has been contact with and may be impacted by the presence of surfactants.

However, the general consensus is that the contact angle for water on glass is low, often even zero or close to zero. Lunkad et al (2007) reports a static contact angle of between 6 and 10 degrees for water on glass.

Using laws of physics and fluid dynamics it is possible to determine at what angle a water drop with known volume (size), ***surface tension*** and contact angle will start sliding on an ideal glass surface.

Surface tension is the cohesive force that acts along the surface of water. It is the force that allows water drops to form, for drops to adhere to horizontal, inclined and vertical surfaces, and for drops to retract after spreading across a surface due high speed impact.

The surface tension of water depends on its temperature. Vargaftik et al (1983) provides the following values for the surface tension of water at different temperatures.

Water Temperature	**Surface Tension N/m^2**
0^oC	$74.95 * 10^{-3}$
10^oC	$74.23 * 10^{-3}$
$15\,^oC$	$73.50 * 10^{-3}$
$20\,^oC$	$72.75 * 10^{-3}$
$25\,^oC$	$71.99 * 10^{-3}$

To be conservative and to be consistent with water drops possibly originating from a fridge, surface tension (γ_{LV}) of $73.50 * 10^{-3}$ will be assumed in further analysis.

Determining the critical inclination angle

Roura et al (2001) describes the procedure to determine the critical inclination angle at which a drop will start slipping.

The force of gravity acting on a water drop – acting parallel to the glass surface is given by:

$$F = V \rho g \sin(\alpha) \ [1]$$

V = Volume of the drop (m^3)
ρ = Density of drop (1000 kg/m^3)
g = Gravitational constant (9.81 $m/^{s2}$)
α = Inclination angle

The volume of an ellipsoidal drop is given by (Wikipedia – Ellipsoid):

$$V = 4/3\ \pi\ h\ x\ y\ [2]$$

x – Length of ellipse /2
y – Width of ellipse /2
h – Height of drop

The height of a drop on a surface with contact angle θ and surface tension γ_{LV} is given by: (Wikipedia-Surface Tension)

$$h = \sqrt{\frac{2\gamma_{LV}(1-\cos\theta)}{g\rho}}\ [3]$$

Please note that the height does not depend on the shape of the drop.

According to the laws of Newton the energy performed to move a drop by a distance δx is given by:

$$\delta Ug = F\ \delta x\ [4]$$

Derived from the well-established laws of Laplace and Young the following equation describes the energy required to form a film and for a drop to slip down an incline by a distance δx. (8)

$$\delta U\gamma = L\ \delta x\ \gamma_{LV}\ (1-\cos\theta)\ [5]$$

L = Drop width (measured perpendicular to slope of inclined plane) (m)
γ_{LV} = Surface tension of water (N/m)
θ = Contact angle (degrees)

At the point of equilibrium **δUg = δUγ.** If we equate Eqn's 4 and 5 and simplify, we get:

$$\sin\alpha_c = \frac{\gamma_{LV}(1-\cos\theta)L}{\rho g V}\ [6]$$

α_c = Critical angle at which drop becomes unstable due to film formation

Results

Assuming a range of possible contact angles between 5 and 90 degrees, Eqn. 6 was used to calculate the critical inclination angle for a 4.6 mm by 2.9 mm ellipsoidal drop (Drop B) on a glass surface.

Contact Angle (degrees)	h (m)	V (m^3)	sin(a)	Critical Angle (Degrees)
5	0.000238791	3.33582E-09	0.03931535	4
10	0.000477128	6.6653E-09	0.07855585	7
15	0.000714557	9.98209E-09	0.11764683	11
20	0.000950625	1.32799E-08	0.15651385	14
25	0.001184884	1.65524E-08	0.19508294	18
30	0.001416888	1.97934E-08	0.23328068	21
35	0.001646194	2.29967E-08	0.27103436	25
40	0.001872366	2.61562E-08	0.30827211	28
45	0.002094975	2.9266E-08	0.34492304	32
50	0.002313595	3.232E-08	0.3809174	35
55	0.002527812	3.53126E-08	0.41618665	39
60	0.002737217	3.82379E-08	0.45066368	42
65	0.002941411	4.10904E-08	0.48428283	45
70	0.003140006	4.38647E-08	0.51698013	49
75	0.003332624	4.65555E-08	0.54869333	52
80	0.003518898	4.91576E-08	0.57936205	56
85	0.003698473	5.16663E-08	0.60892793	59
90	0.003871009	5.40765E-08	0.63733468	62

The results show that a normal and natural drop of water with the dimensions of Drop B on Folien 1 would likely start slipping on an ideal (smooth and clean) glass surface if inclined between 4 and 62 degrees, depending on its contact angle.

However, one often observe large drops of water defying gravity and sticking to vertical or near vertical surfaces – where according to theory the drops should not remain stationary. The reason why this happen is due to a phenomenon called ***contact line pinning.***

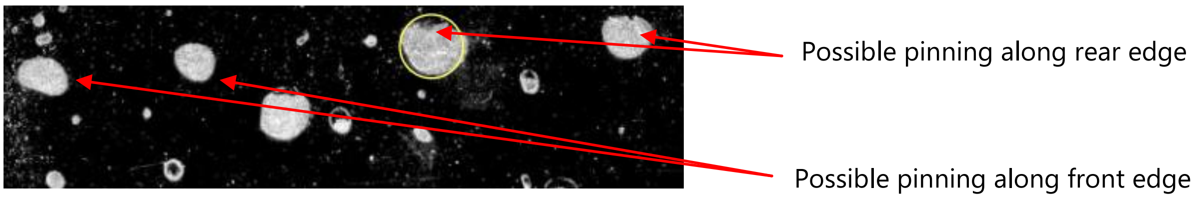
Contact Line Pinning

Applying Equation 6 to calculate the critical inclination angle, one must assume that the drops are on an **ideal** surface. In reality however surfaces are not always ideal. They can be rough or have chemical or topographical defects. Even microscopic defects can have a strong influence on drop dynamics. When a moving contact line encounters a defect the contact line could get pinned and the drop could remain stationary (Beltrame, 2008).

There are three pinning scenarios (Beltrame, 2008): 1) The drop gets pinned at the front and the rear end, 2) the drop gets pinned at the rear end by a hydrophilic defect, and 3) the drop gets pinned in the front end by a hydrophobic defect. Each scenario will result in a different drop shape. Scenario 2 (pinning at the rear end) will result in a drop with an elongated shape (stretching). Scenario 3 (pinning at the rear end) will cause the drop to contract, bunch up and perhaps spread out above the front end contact line.

<u>Conclusion:</u> Depending on the pinning scenario, large drops pinned to a vertical or near vertical surface can take a variety of shapes that are not necessarily perfectly elliptical.

As an example look at the picture below that was obtained from Mr Zeelenberg's expert witness testimony. He wetted a glass surface in a vertical position.



The photos above show water drops sticking to windows sometime after a rain storm.

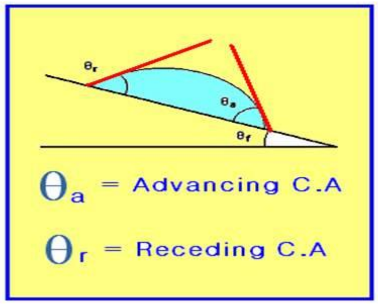
Please note:

- The wide variety of irregular shapes
- The absence of near perfect ellipsoidal horizontal drops
- The high number of drops that show vertical deformation
- The bunching and spreading op drops above a hydrophobic defect
- Small drops that remain spherical.

The pinning of contact lines, irrespective of the pinning scenario, gives rise to ***contact angle hysteresis***.

Contact angle hysteresis

On an inclined or vertical surface contact angle hysteresis occurs when gravitational forces or other external forces deform the drop such that it has a larger contact angle at the front end (advancing contact angle – θa) than at the rear end of the drop (receding contact angle – θr) (Luo et al., 2012 & Snoeijer et al, 2007).



Source: http://www.s-eo.co.kr/zboard/zboard.php?id=contact_angle_app

For each drop of water on a surface there are unique critical advancing and receding angles, such that if the front angle exceeds the critical angle and the rear end angle is less than the critical receding angle the drop will de-pin – i.e. slip free from the pinning condition and slide down (Luo et al, 2012).

This explains why if we have two identical size drops on an inclined surface the one may slide and the other remains stationary.

The magnitude of the critical advancing and receding angles, and the difference between them depends, amongst others, on the condition and characteristics of the surface and can vary across the surface of the object. These values can only be determined through experimental testing.

The equilibrium between gravitational forces and surface tension forces is described by the ***Bond number*** (Antoine, 2010). When the Bond number is equal to 1 or less surface tension forces dominates and a drop under the influence of gravity will remain spherical. When the Bond number is higher than 1, gravitational forces dominate and a drop will deform under the influence of gravity.

The Bond number tangential to the plane for a drop on an inclined surface is given by (Annapragada, 2001):

$$B_t = \frac{D^2 \sin\alpha}{L_c^{\ 2}}$$

D – Diameter of free surface curvature when drop is horizontal
L_c = Capillary length = 2.7 mm

The wetted diameter D_w is determined as follows (Quere et al, 1998):

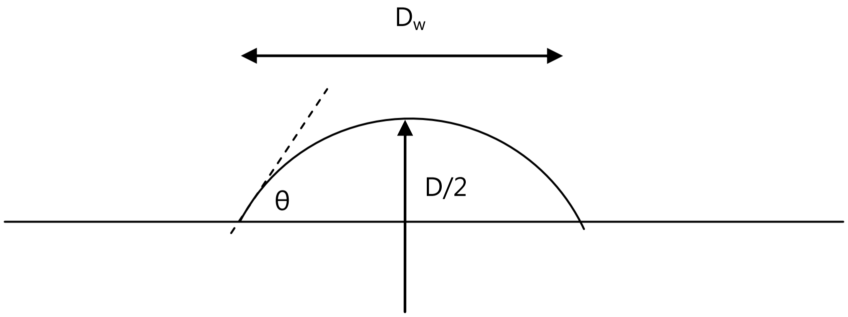
$$D_w = D.\sin\theta_s$$

θ_s = Static contact angle (< 90 degrees)

If we assume a static contact angle of 30 degrees and the smallest dimension of Drop B of 2.9 mm = D_w we get D = 2.9/sin(30°) = 5.8 mm

Calculating B_t we get 5.8^2 * sin (90)/2.7^2 = 4.6

For a contact angle of 60 degrees we get B_t = 1.54



<u>Conclusion</u>: Even with conservative assumptions, with respect to the wetted diameter and contact angles, the Bond numbers for Drop B on a vertical surface exceed 1, and we can therefore expect that gravity would have influenced the shape of the drop if it were on a vertical surface – resulting in contact angle hysteresis.

After a drop is deposited on a surface it immediately starts to evaporate. The evaporation process gives rise to the development of ***contact line deposits.*** The drops of F1 all show signs of contact line deposits – what Mr Zeelenberg called the "white rim".

Contact Line Deposits

These solid rings are formed when solids (minerals, salts, etc.) dispersed in a drying drop, migrate to the edge of the drop. This migration is caused by an outward flow within the drop that is driven by evaporation and a fixed contact line boundary (Deegan et al, 1997, 2000).

Some of the characteristics of the process are (Deegan et al, 2000):

1. Non-circular drops have uneven deposition rates. For example, the more convex the region the stronger is the evaporating flux and denser the deposits.

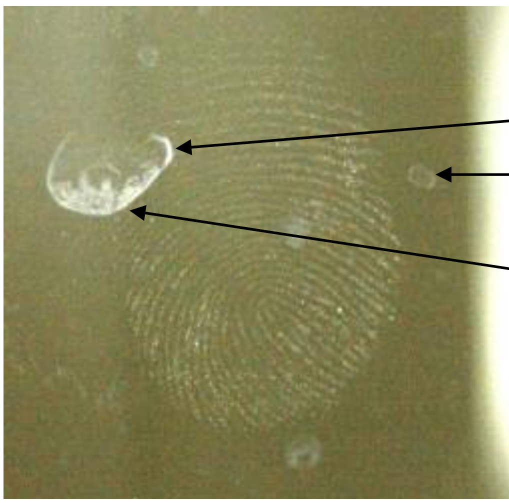
2. Ring formation is not sensitive to temperature, humidity and pressure.

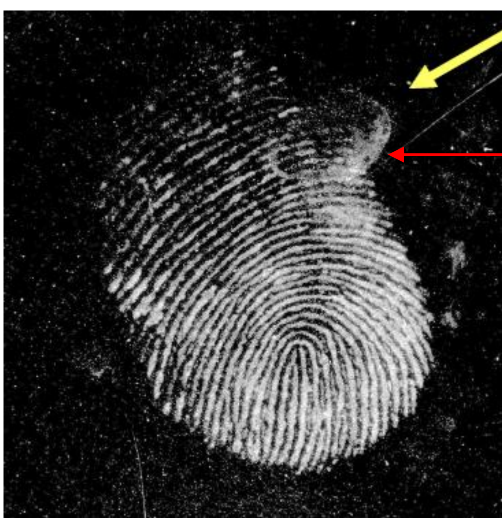
3. Evaporation rate is strongest where there is the lowest density of neighboring evaporation sites. When two drops are placed next to each other the vapor fields overlap and there is less evaporation and less deposition.

It is evident from the research that on a horizontal surface the contact line deposits should be consistent and symmetrical.

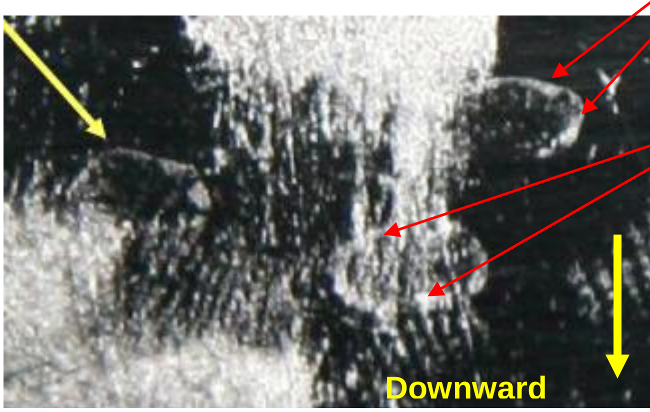
According to Deegan (2012a) he expects that when a drop is bigger than the capillary length, that the contact line deposit should be to be thicker along the bottom.

This is clearly illustrated in the following images used by Mr Zeelenberg in his expert witness testimony.





The photo below shows the three drops on Folien 1.



CONCLUSIONS

1. It has been shown that on an ideal glass surface water drops, similar in size to those on Folien1 would likely have slipped before a maximum inclination of 62 degrees and can we therefore assume that the drops would have slipped on the sloped sides of a drinking glass, irrespective if the glass were upright or upside down.

2. Therefore the drops, if they were from the side of a drinking glass, must have been pinned, likely because of surface irregularities.

3. Since all the drops are expected to have Bond numbers > 1, along the vertical plane, the drops must have been deformed by gravity i.e. experienced contact angle hysteresis.

4. Therefore the contact line deposits should have been unequal, as confirmed by Mr Zeelenberg’s own experiments.

5. The drops on Folien 1 together do not display a degree of unequal contact line deposits that is consistent with drops that dried on the side of a drinking glass.

Could the drops have been from a horizontal surface such as a DVD cover?

Mr Zeelenberg is of the opinion that the drops must be from a glass because they are ellipsoidal and have similar sizes.

Mr Zeelenberg however failed to consider several feasible scenarios that would result in similar sized ellipsoidal drops on a horizontal surface.

Firstly – ellipsoidal drops on a horizontal surface occur when a spherical droplet strikes a surface at an angle. The impact angle determines the shape of the ellipsoidal drop. The smaller the impact angle the longer and thinner is the drop, and the larger the impact angle the more rounder the drop until it is a perfect circle when the drop falls directly from the top.

Secondly – In everyday life there are many examples of events that would result is similar sized drops striking a horizontal surface. Water drops dripping from a wet object such as a glass, or a bottle will have similar sizes. The maximum size of these drops would depend on the contact angle, surface tension and characteristics of the substrate. A water jet or a large drop travelling at high speed will break up into smaller similar sized drops before hitting a surface. The size would depend on the surface tension, speed and thickness of the jet. Flicking wet fingers is one way to impart a high velocity to a volume of water that would cause it the break up in smaller drops.

The following formula is used by forensic scientists to determine the angle of impact from the length and width of an ellipsoidal drop (Nordby, 2006).

$$\alpha = \arcsin\left(\frac{Width}{Lenght}\right) \quad (7)$$

What happens when a droplet strikes a surface is dependent on several factors which include – drop size, impact velocity, fluid and surface properties.

Van Der Wal (2006) describes the dynamics of when a drop impacts a solid surface. When a water drop hits a solid surface, inertial effects cause it to spread radially outwards. Surface tension forces then start slowing the spreading until it reaches a maximum diameter. After kinetic energy has dissipated, surface tension will cause the drop to retract into a shape that gives it static equilibrium. Because of ***contact angle hysteresis*** there are many states of equilibrium. If the retraction speed is slow the drop will reach equilibrium at the receding angle. For higher retraction speeds the drop will reach a contact angle between the critical receding and the advancing contact angles.

When a drop hits a surface at an angle, because of a tangential velocity component, the drop deforms ellipsoidal and then retracts under the influence of surface tension and contact angle hysteresis to maintain approximate ellipsoidal shape.

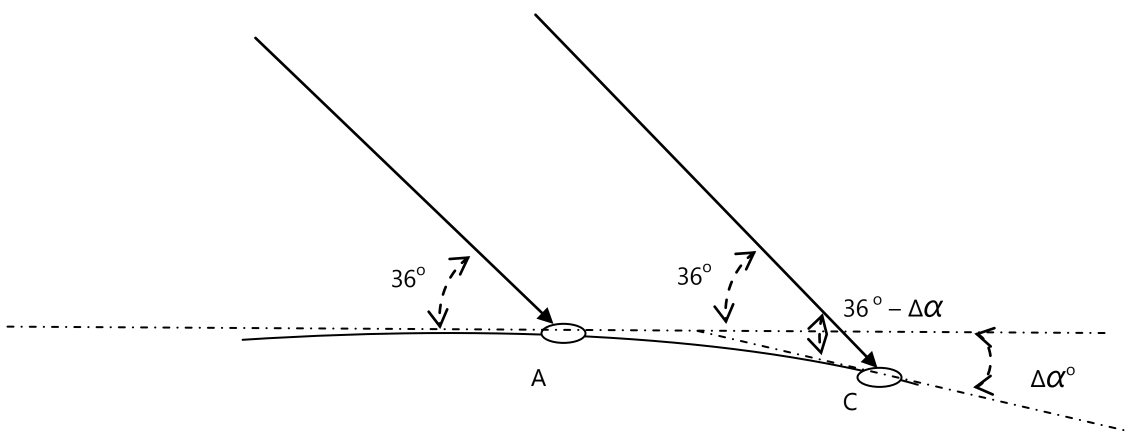
However during the retraction process the inward moving contact line (edge of drop) may get pinned by defects resulting in somewhat irregular shapes and contact lines (Van Der Wal, 2006). Drop A shows such an irregular contact line along the top side that could be due to pinning during the retraction stage.

If we apply the dimensions of Drop B (length = 4.6 mm and height = 2.9 mm) to Eqn 7 we get a contact angle of **36 degrees**.

It is difficult to measure the dimensions of Drops A and C with the same accuracy as Drop B. The aspect rations (width/length), however, appear to be very similar to that of Drop B and can one assume that their impact angles are in the vicinity of 36 degrees, give and take about 2-3 degrees either way.

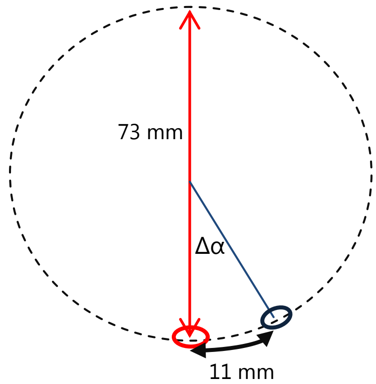
What would happen if the same drops hit a curved surface?

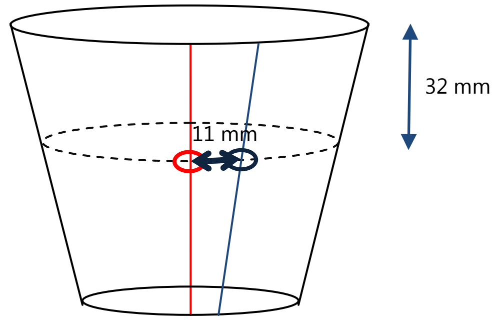
Assume two drops are approaching a curved surface at an angle of 36 degrees. The one drop is to hit at the location of Drop A and the other at the location of Drop C.



At A the drop will hit at 36 degrees, but at C the drop will hit at a smaller angle of *36 - Δα*.

Δα depends on the distance between the drops and the radius of the horizontal plane the drops are situated on. On Folien 1 Drops A and C are located about 11 mm apart. For the sake of simplicity we will assume that the centers of Drops A and C are situated at 32 mm from the top rim of this glass (the actual distances are 31 mm and 33 mm respectively). At this distance down the glass the diameter of the glass is about 73 mm (assuming Wertheim's Glass #2 – with a top diameter of 79 mm, height of 82 mm and bottom diameter of 64 mm).





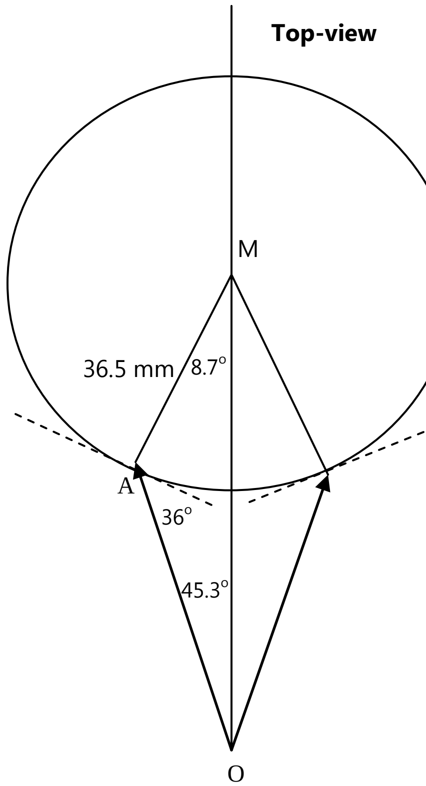
We can calculate Δα as follows:

*Δα = 360 * 11/(π.73) = 17.3 degrees*

Therefore the impact angle at C would be about 36 – 17.3 = 18.7 degrees. If we apply this angle to Eqn 7 and work backwards, we get a width/length ratio of about **0.32**. The width of the drop should therefore be about a third of its length. Neither Drop C nor Drop A on Folien 1 has such an elongated shape. The aspect ratios of Drop A and C is between 0.57 and 0.60.

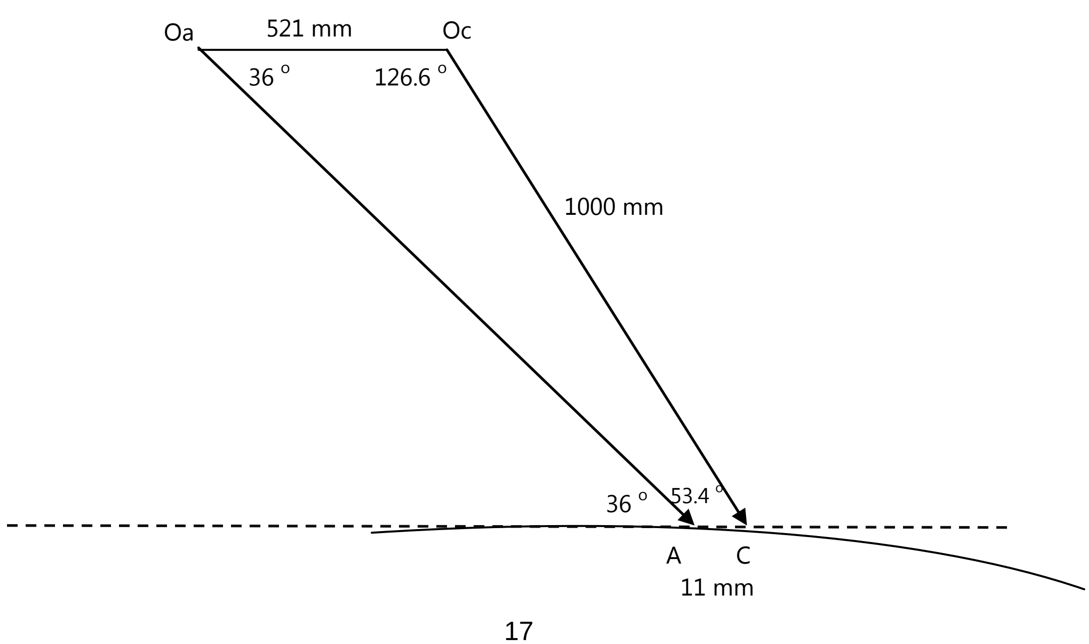
There are two possible scenarios for three drops of such similar sizes to have been deposited on a curved surface.

Scenario 1: The two drops originated and diverged from the same source and both struck the surface at 36 degrees, but on opposite sides of the centreline M-O. See the Figure below.



Using trigonometry we can calculate the distance M-O. It is **41.5 mm**. This means that the drops impacting the glass surface at 36 degrees originated about **5 mm** (41.5 – 36.5) away from the glass surface. This is obviously not a very realistic scenario.

Scenario 2: The drops hit the surface at their respective locations at about 36 degrees. The figure and analysis below show that this scenario will require the drops to originate from sources a significant distance apart and likely at different times.



For example – at a distance of 1 metre away from the surface Drop A and C originated from sources about 52 cm from each other. At a distance of 50 cm the separation would be 26 cm.

To accept this Scenario one must consider the extremely small probability that not two, but three drops from different sources in space and time would hit the glass at almost identical impact angles.

<u>Conclusion</u>: Due to the curvature of a drinking glass and the differences in impact angles that result from it, it is extremely unlikely to find three drops like Drops A, B and C that are so similar in their aspect ratios. The scenarios that would give rise to such similarities are extremely unlikely to occur in reality.

What would happen if the same drops hit a near vertical surface?

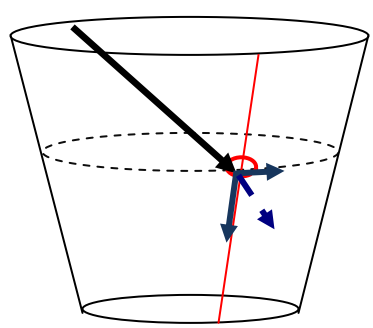
A drop flying through the air has kinetic energy. Newton's well known equation for kinetic energy is:

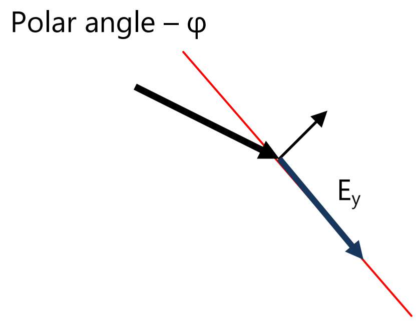
$$E = 0.5mv^2$$

Therefore, the bigger and faster a drop moves the more is its kinetic energy. When a drop with kinetic energy collides with a solid surface such as glass, this kinetic energy has to be dissipated.

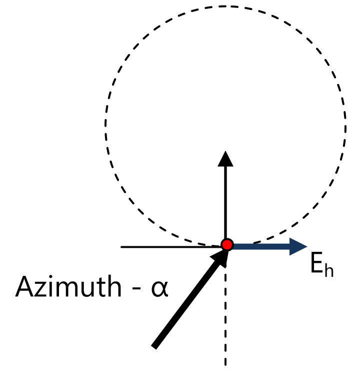
The kinetic energy of a drop that collides with a near vertical surface has three components:

- A component perpendicular to the glass surface
- A vertical component along the glass surface (see Side-view)
- A horizontal component tangential with the glass surface (see Top-view)





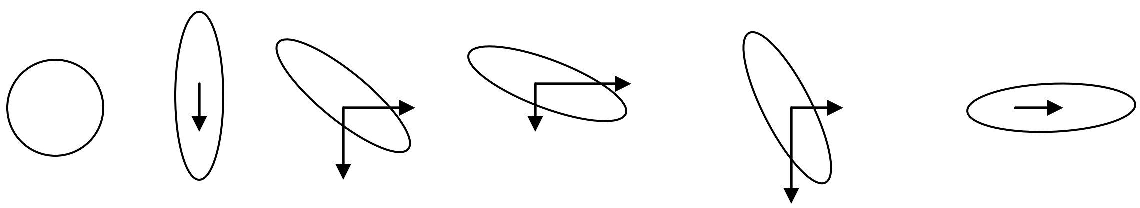
Side-view



Top-view

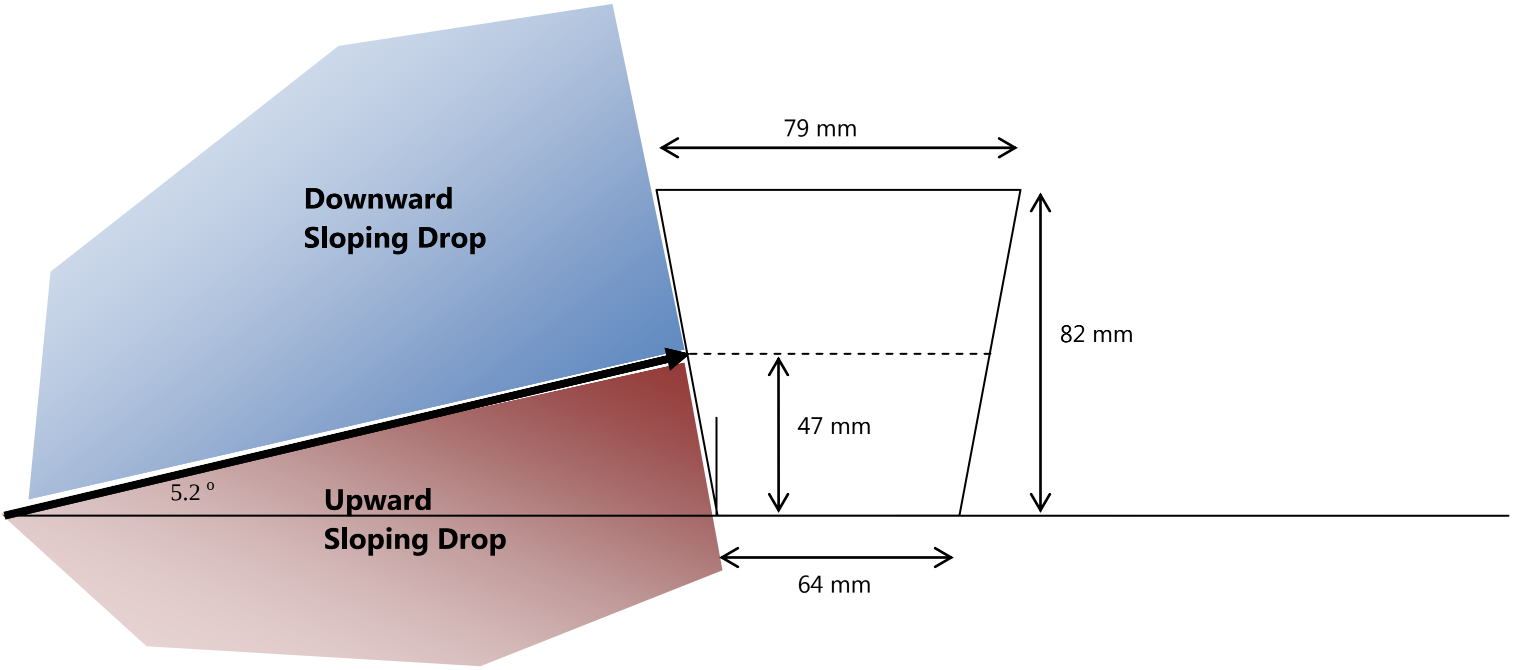
As long as the impact angle relative to the glass surface (the polar angle) is less than 90 degrees there will be a kinetic energy component downwards along the glass (E_v). And as long as the azimuth is bigger than 0 degrees there will be a horizontal kinetic energy component (E_h) tangential to the glass.

The relative magnitudes of E_v an E_h will determine how the drop behaves on impact.



$E_v = 0$	$E_v > 0$	$E_v > 0$	$E_v > 0$	$E_v > 0$	$E_v = 0$
$E_h = 0$	$E_h = 0$	$E_h > 0$	$E_h > 0$	$E_h > 0$	$E_h > 0$
	$\alpha = 0^o$	$E_v = E_h$	$E_v < E_h$	$E_v > E_h$	$\varphi = 90^o$

The drops on Folien 1 all lie with the long axis of the ellipse horizontal. This only occurs in the very unique situation where the polar angle is exactly 90 degrees. For glass standing normally this means the drop approaching from the bottom at an angle of 5.2 degrees.



In the Figure above any drop that approached the glass through the blue area – as one would expect in normal and everyday situations, there would have been a vertical kinetic energy component which would have distorted the drop in the vertical direction.

Please see conclusion on next page

***Conclusion**: If the drops were deposited by radial splatter, one would expect by the balance of probabilities the drops to have approached the glass surface at a polar angle of less than 90 degrees. This would have resulted in a vertical kinetic energy component that would have caused the drop to slant downwards to some extent. On Folien 1 no downward (or upward) slant is evident in the alignment of the drops – which means that all three drops hit the surface at right angles (polar angle = 90 degrees).*

We have already determined that the only practical way the drops could have been deposited on a glass is from different sources in space and time. So now we have to consider the probability that all three drops, originating from different sources, hit the glass at exactly the same polar AND azimuth angles in such close proximity to each other.

The holistic conclusion of this report is that in a most likely scenario the "dried drops" on Folien 1 would more likely have been deposited on a flat horizontal surface than on a curved vertical surface.

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Please see references on next pages

PLEASE SEE "SPATTER EXPERIMENT"

BIBLIOGRAPHY & REFERENCES

1. Annapragada, S.R, J.Y Murthy, and S.V Garimella. "Drop Retention on an Incline". *CTRC Research Publications. Paper 160*. <http://docs.lib.purdue.edu/coolingpubs/160>.
2. Antoine, Diana, Martin Castillo, et al. "Sessile drop wettability in normal and reduced gravity". *Microgravity Science and Technology*. 22.2 (2010).
3. Beltrame, PH, P Hanggi, and U Thiele. "Depinning of three-dimensional drops from wettability defects". physics.fly-dyn. Nov 2008.
4. Beltrame, Philippe, and Uwe Thiele. "Time Integration and Stead-State Continuation for 2d Lubrication Equations". *Journal of Applied Dynamical Systems*. 9.2 (2010): 484-518.
5. Bird, James C, Scott S H Tsai, and Howard A Stone. "Inclined to splash: triggering and inhibiting a splash with tangential velocity". *New Journal of Physics*. 11.063017 (2009): 1-10.
6. Bussmann, M., J. Mostaghimi, and S. Chandra. "On a three-dimensional volume tracking model of droplet impact". <http://www.mie.utoronto.ca/labs/cact/Pub/CACT-Pub_files/pof.bussmann.pdf>.
7. Chen, Jeng-Horng. "Characteristics of Drop Impact on Elastic and Compliant Surfaces". *Journal of marince Sciences and Technology*. 13.2 (2005): 156-161.
8. Clanet, Christophe, Cedric Beguin, et al. "Maximal deformation of an impacting drop." *Journal of Fluid Mechanics*. 517. (2004): 199-208.
9. Deegan, Robert D. "Question re. Ring Deposits on Vertical or Inclined Surfaces". Message to John McAlpine . 20 Jul 2012. E-mail.
10. Deegan, Robert D. "Re: Drops - Report excerpt - Practical experiment". Message to Henry McAlpine. 30 September 2012. E-mail.
11. Deegan, Robert D, and Olgica Bakajin et al. "Capillary flow as the cause of ring stains from dried liquid drops". *Nature*. 389. (1997): 827-829.
12. Deegan, Robert D., Olgica Bakajin, et al. "Contact line deposits in an evaporating drop". *American Physical Society. Physical Review*. 62.1 756-765.
13. Ding, Hang, Mohammad N.H. Gilani, and Peter D. M. Spelt. "Sliding, pinch-off and detachment of a droplet on a wall in shear flow". *Journal of Fluid Mechanics*. 644. (2010).
14. Eggers, Jens. "A brief history of Drop Formation." *University of Bristol*. <www.maths.bris.ac.uk/~majge/moreau.pdf>.
15. ElSherbini, A.I, and A.M Jacobi. "Liquid drops on vertical and inclined surfaces. II. A method for approximating drop shapes". *Journal of Colloid and Interface Science*. 273. (2004): 566-575.
16. Kim, Ho-Young, Heon Ju Lee, and Byung Ha Kang. "Sliding of Liquid Drops Down an Inclined Surface". *Journal of Colloid and Interface Science*. 247. (2002): 372-380.
17. Lautrup, Benny. *Physics of Continuous Matter*. 1st. Taylor and Francis. 2004. 70-94.

18. Le Grand, Nolwenn, Adrian Daerr, and Laurent Limat. "Shape and Motion of drops sliding down and inclined plane". *Journal of Fluid Mechanics*. 541. (2005): 293-315.
19. Lunkad, Siddharta F., Vivek V. Buwa, and K.D.P Nigam. "Numerical simulations of drop impact and spreading on horizontal and inclined surfaces". *Chemical and Engineering Science*. 62 (2007): 7214-7224.
20. Luo, Mingxiang, Rohni Gupta, and Joelle Frechette. "Modulating Contact Angle Hysteresis to Direct Fluid Droplets along a Homogenous Surface". *Applied Materials & Interfaces*. 2012.4 890-896. Web. 14 Sep. 2012. <www.acsami.org>.
21. Nordby, Jon J. "Basic Bloodstain Pattern Analysis". *Final Analysis Forensics*. (2006).
22. Quere, David, Marie-Jose Azzopardi, and Laurent Delattre. "Drops at Rest of a Tilted Plane". *Langmuir*. 14. (1998): 2213-2216.
23. Rios, P.F, H. Dodiuk, et al. "The effect of polymer surface on the wetting and adhesion of liquid systems". *Journal of Adhesion Science Technology*. 32.3-4 (2007): 227-241.
24. Roura, Pere, and Joaquim Fort. "Equilibrium of drops on inclined hydrophilic surfaces". *American Physical Society. Physical Review*. 64.011601 1-5.
25. Snoeijer, J.H., L Limat, et al. "Cornered drops and rivulets". *Physics of Fluids*. 19.042104 (2007): 1-10.
26. Still, Tim, Peter J. Yunker, and Arjun G. Yodh. "Surfactant-Induced Marangori Eddies Alter the Coffee-rings of Evaporating Colloidal Drops". *American Chemical Society*. 28. (2012): 4984-4988.
27. Thiele, Uwe, Kai Neuffer, et al. "Sliding drops on an inclined plane". *Colloids and Surfaces: Physiochemical and Engineering Aspects*. 206. (2002): 87-104.
28. Van der Wal, B.P. "Chapter 7: Behaviour of Water Drops on Impact". (2006): <dissertations.ub.rug.nl/FILES/faculties/science/2006/b.p.van.der.wal/c7.pdf>.
29. Vargaftik, N.B., B.N. Volkov, and L.D. Voljak. "International tables of the Surface Tension of Water". *Journal of Physical Chemistry*. 12.3 (1983): 817-820.
30. Wang, Huamin, Peter J. Mucha, and G Turk. "Water Drops on Surfaces". *ACM Transactions on Graphics (TOG) - Proceedings of ACM SIGGRAPH 2005* . 24.3 (2005): 921-929.