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Giant soap curtains for public presentations

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Abstract
Hydrodynamicists have produced giant soap curtains for laboratory research and adapted them to public presentations. For the World Year of Physics 2005, we have automated their method. We have made thousands of 10, 15 and 18 m high soap curtains, with width up to 4 m, surface up to 34 m^2 and lasting up to 20 min. We explain here the methods we use, from the simplest one, a 2 m high curtain you can prepare in 30 min in your kitchen, to the most elaborate. We review some pedagogical projects which have been stimulated by soap curtains and suggest how to have a lot of fun. The present paper is thus a complement, oriented towards public presentations, of Rutgers *et al*'s more specialized article (Rutgers M A, Wu X L, Daniel W B 2001 *Rev. Sci. Instrum.* **72** 3025).

(Some figures in this article are in colour only in the electronic version)

1. Introduction

1.1. The object itself

1.1.1. Brief presentation. This object is impressive and fascinating, but difficult to describe (figure 1). It is a tall lozenge, typically several metres high and 1 m wide. It is colourful, everchanging, thin, fluctuating and fragile.

Take two vertical fishing wires, hanging from the ceiling. Let water (with some dishwashing liquid) flow along the wires. When they are wet, pull them apart. The curtain appears between them (figure 2). It consists of a thin layer of water, stabilized by the soap, freely falling unto the floor.

1.1.2. Vocabulary. We suggest calling it a 'soap curtain'. The word 'soap' is slightly misleading, since it consists mainly of water and only a small amount of dishwashing liquid. We observe that words other than curtain, such as 'blade' or 'screen', are even more confusing.

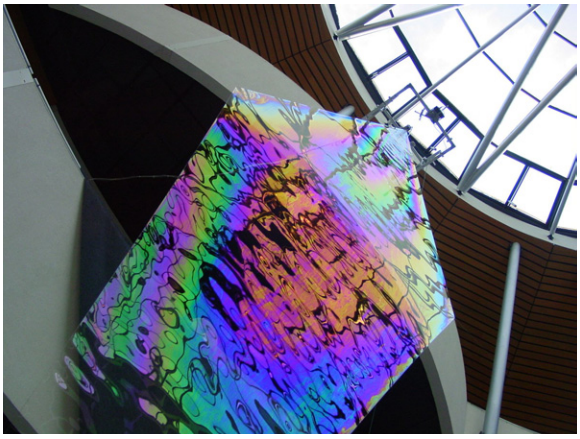


Figure 1. A 10 m high soap curtain in the modern architecture of Villeneuve Secondary School, Grenoble. Photo F Mondot.

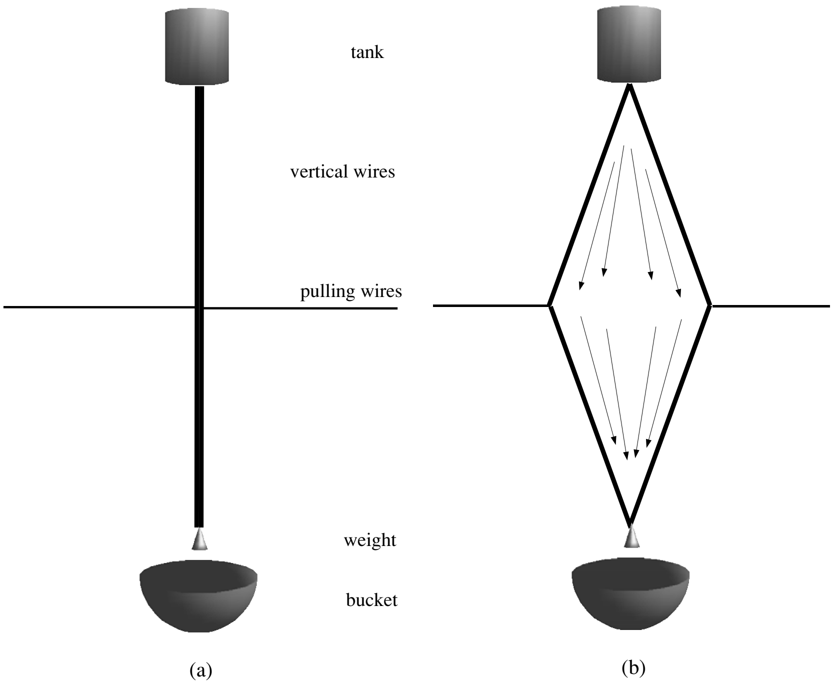


Figure 2. Schema of the set-up. (a) Initially, the vertical wires are closed and the water contained in the tank drips onto them. (b) Pulling the vertical wires open forms between them a curtain with the shape of a lozenge.

When we say ‘soap wall’, lots of people imagine boxes of soap piled up. The words ‘soap film’, more used in the scientific community [1, 2], are often not understood by non-specialists. Conversely, the public often calls it a ‘soap bubble’: this is wrong, since a curtain is flat (see section 4.4).

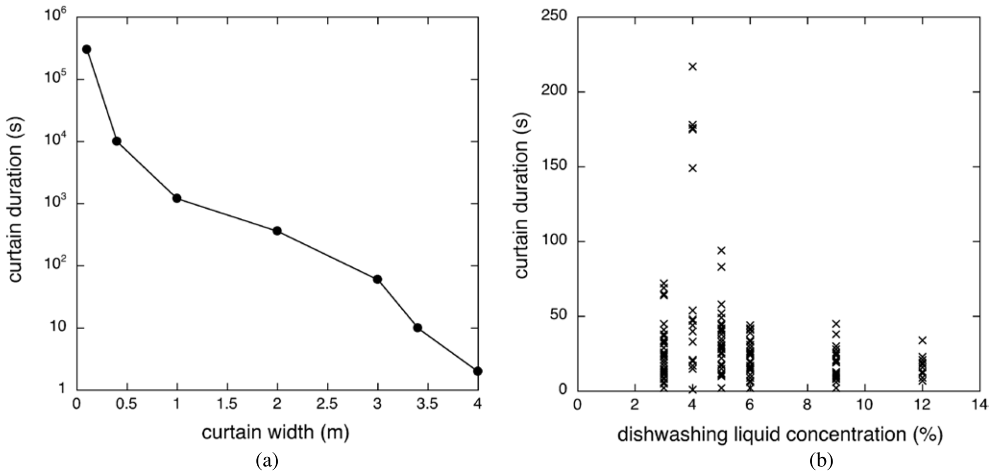


Figure 3. Time before the curtain breaks. These results are only indicative (see section 2.4.3). (a) A few record durations collected from different experimental set-ups, conditions and curtain widths (see section 1.1.3); note the semi-log scale. (b) Statistics for a 5 m high, 1 m wide curtain prepared with different concentrations of Dreft in tap water.

1.1.3. Records. In a laboratory environment, hydrodynamicists routinely produce and maintain curtains, typically 2 m high and 10 cm wide, during several days (figure 3(a)), while they could in principle last for longer. To our knowledge, the maximum height, approximately 20 m (and 1 m wide), has been reached by Rutgers, Koehler and Huber at the James Franck Institute at the University of Chicago [3].

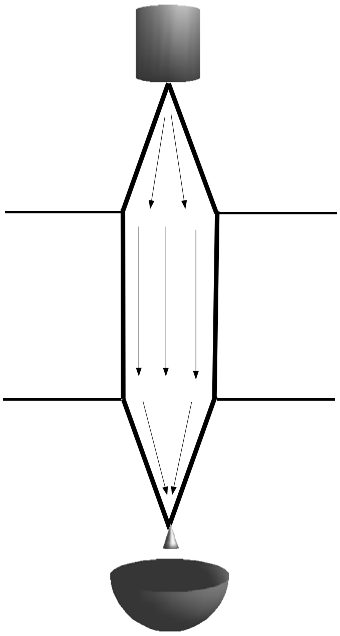
In a public presentation, the tallest curtain is our 18 m high one in Paris [4]. The widest one is by Rutgers, who reports 4 m or more with a 13 m high curtain [5], lasting for a few seconds [6] (figure 3(a)). The largest surface is 34 m^2, for our 15 m high, 3.4 m wide hexagonal curtain in Grenoble [7] (figure 4(b)). Our 3 m wide curtains typically last from seconds to minutes (figure 5). In Paris one 2 m wide curtain lasted 6 min [4] and in Grenoble a 1 m wide one lasted 20 min [7] (figure 3(a)). Davoudian produces apparently everlasting 40 cm wide, 3 m high curtains that he stops after a few hours [8].

1.2. Frequently asked questions

We now address two common questions regarding the origins of these curtains. Other frequently asked questions are discussed in the following sections:

- How does it work? sections 1.1.1, 2.3.
- Where do these colours come from? section 2.2.2.
- Why does it break? section 2.4.
- What is the recipe? section 2.1.2.
- Can we blow on it? section 4.4.
- Can we touch it? section 4.4.

1.2.1. Who had this idea? Let us summarize briefly the history of these soap curtains. Couder, Gharib and coworkers [9, 10] were probably the first to use soap curtains to perform 2D hydrodynamics studies, mostly oriented towards 2D turbulence. Several labs have used and improved this technique, including Kellay, Wu, Goldburg, Rutgers and coworkers. Kellay *et al*



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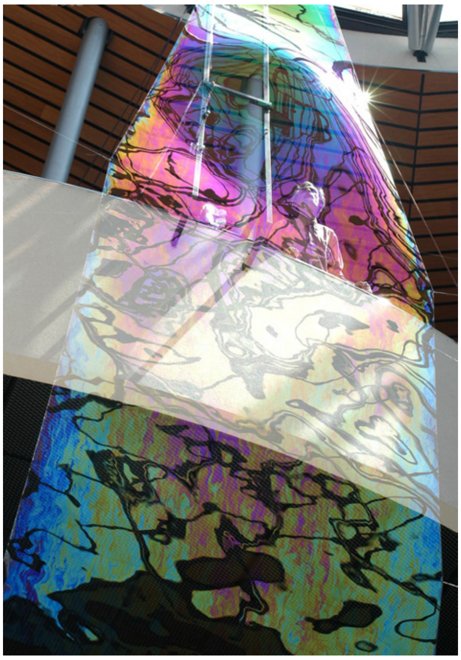


(*b*)

Figure 4. Hexagonal curtain. (a) Set-up, with four pulling wires instead of two. (b) A 15 m high hexagon in Villeneuve Secondary School, Grenoble. Photo F Mondot.

[11] improved several details to make the curtains last long enough and gain good turbulence statistics, in particular by placing them vertically and alimenting them permanently. Reference [3] is a detailed paper, very useful, but mostly optimized for laboratory use. The present paper is thus a complement, oriented towards public presentations, of this original one.

Rutgers was one of the first to use curtains for public presentations [5]. For ten years, he has presented them in various places such as the Carnegie Science Center in Pittsburg, the San Francisco Museum of Modern Art, science festivals or the 1999 Centennial Meeting of the American Physical Society. Largely due to Rutgers' influence, curtains spread from hydrodynamics into three other communities: artists, science museums and foam physicists.

We belong to the latter and, in 2002 like other colleagues, began to show them in science festivals [12]. For the World Year of Physics 2005, we installed a 10 m high curtain for two weeks in the very middle of a secondary school, to perform tests (figure 1). Then we came back six months later with a 15 m high automated version, with an hexagonal shape (figure 4(b)), for two more weeks during which the secondary school opened its doors to the public [7]. The Palais de la Découverte, a science museum in Paris, then asked us to build a 18 m high version for the 2005 Science week (figure 6) [4].

1.2.2. Why do you do that? It is really useful, since it is beautiful [13]. The main goal is pedagogical. This is suitable for science festivals; it attracts the attention of both children and adults, as well as local newspapers and television (but not radio, of course). However, to go beyond the simple visual effect, we try and embed this work in a pedagogical environment, which we present below. In fact, a curtain suscitates a lot of questions in different domains, presented in section 4.2.

Figure 5. The curtain is robust enough to pass across it a finger, a hand or an arm (wet with water and dishwashing liquid). This particular curtain was 18 m high and the handshake lasted for more than 30 s [4]. Photo O Gatine.

Figure 6. A 18 m high soap curtain in Paris Science Museum, a 19th century historical monument [4]. Photo Palais de la Découverte.

Increasing the size is not a goal by itself. In many cases, the best height is between 5 m and 10 m. It is this size which is the most appreciated by somebody standing near the bottom of the curtain. Moreover, this size is still manageable by one person, so that it is possible to offer a self-service version for manipulation by the audience.

However, there are a few reasons for creating larger curtains. First, of course, the fun of the challenge, since up to now we are not aware of any theoretical maximal size limit. Second, the impression we feel is determined by the width, but to increase the width requires increasing the height (section 2.4.1). Third, higher curtains can be seen from a larger distance, thus by more persons at a time. Fourth, some phenomena which are too quick on small curtains can visibly be seen on a high one: flow of water, wave propagation and especially propagation of the crack when the curtain breaks. At roughly 2 ms^{-1}, it takes a few seconds for a high curtain to break from bottom to top.

We are also often asked: *are you paid to do that?* Not really. We are paid to do research, and this is not research. As opposed to hydrodynamicists, we do not intend to discover any scientific result. But science festivals and similar initiatives are supported by our public employers: the University of Grenoble, the French National Centre for Scientific Research and the Ministry.

2. Manual set-up

With some practice, we can prepare a 2 m high curtain in 30 min starting from scratch, using standard material found in a kitchen or a school: cotton thread and a plastic bottle with a small hole drilled in the plug. Section 2.1 lists these minimal requirements. However, several persons including us have compiled a list of optional improvements to make higher, larger or longer lasting curtains, or to make manipulation easier (section 2.2). Some of them can be explained by understanding the physics of the curtain's stability (section 2.3) and breakage (section 2.4), but some are not understood yet (section 2.4.3).

2.1. Basic set-up

2.1.1. Materials. You need the following items:

- A room with a high ceiling, where you can attach the tank.
- A tank full of water and a few per cents dishwashing liquid, with a hole in the bottom, if possible with a tap.
- Two long wires, attached together at both ends, of exactly the same length (which is easier if you rather take a single wire and fold it in two). The top of the wire(s) passes through the hole and is attached inside the tank.
- A bucket to receive the water falling down.
- A weight of a few hundred grams (up to a kg). It is attached to the bottom of the vertical wires.
- Two short pulling wires, one attached to each of the vertical wires.
- A lot of . . . patience (see section 2.4.3).

2.1.2. Recipe. The recipe is simple: tap water, plus a few per cents of dishwashing liquid. No other ingredient is added (section 2.4.1), except for special effects (section 4.4).

What is crucial is the choice of the dishwashing liquid. Commercial dishwashing liquids have very advanced formulations, and it is difficult to match their quality using home-made formulations. However, their composition is confidential and subject to change. We, and many colleagues, have made systematical tests with various brands. From our discussions, what emerges is the following, which we cannot guarantee.

Apparently, Procter and Gamble uses one molecule (probably an aminoxide) which strongly increases the surface elasticity of the water–air interface (section 2.3.1). They include it in the product which they market under the brand Dreft in northern Europe, Fairy in British islands, Dawn in USA and Australia. For marketing reasons, they do not include it in the brand they market in France (although we can occasionally find a Fairy–Dreft in professional circuits).

Check in your own country. Since the same brand is sold under different concentrations, you should discover yourself how much product you want to add to the water. Tests performed by colleagues, students and ourselves usually find an optimum concentration in the range 1%–10% (figure 3(b)).

2.2. Practical details

2.2.1. Wires and set-up. Start to practice with 2 m high curtains and then progressively increase the height. By finding higher and higher rooms, we did the following progression: 2, 3.5, 5, 10, 15 and 18 m.

We prefer to use smooth inelastic wires. Diameters of 0.2 mm and above seem fine. For curtains of 10 m or higher, the strength becomes important. We use 0.6 mm diameter (tuna fishing) nylon wire for the vertical wires; and usually for the pulling wires too, although we sometimes use a trout fishing wire which is thinner and lighter but has the same resistance.

According to your own preferences, attach each pulling wire strongly (any knot is fine, as long as it does not have loose strings which can pierce the curtain) or let it freely slip vertically (make a loop or tie it to rings which passe around the vertical wires). The other end should preferably be attached somewhere on the walls or to a hook to avoid unwanted knots.

To produce the curtain, two persons can each pull a wire. Or you can pull both wires yourself. If you let them pass into hooks on the wall and then come back towards you, you can even pull both with a single hand.

You can install four pulling wires, so that the curtain is a hexagon (figures 4) rather than a diamond. Passing four pulling wires in a fishing reel enables one person to operate a hexagon [6], which otherwise requires two to four persons. Many people pulling at various angles yield weird shapes: for instance many sided, asymmetric or non-planar.

Balconies or staircases enable visitors or you to blow on the middle of the curtain. According to the number of visitors you expect, try to plan in advance where they will be, how they can see, whether you will allow them to blow on the curtain or even manipulate it themselves.

Begin with a small weight: you can begin by using a pair of scissors or pliers; then increase it until you feel it is heavy enough. Its first role is to force vertical wires to touch when they are at rest; in fact, they never exactly touch, but it suffices that they are 1 mm apart: when the water arrives and wets them they get glued together by capillary forces.

The second role is to keep the wires straight rather than curved so that the curtain has a nice diamond shape. We expected the minimal required weight to scale like the height of the curtain, and were surprised to observe that it rather scales like the height squared. To prevent the weight from turning, attach it to the bucket or to the floor by two loose wires.

2.2.2. Colors and flow rate. The colours are entirely natural: we do not add any dye to the water. They arise when the curtain is so thin that it is able to 'decompose' the white light. It creates light interferences, like oil spills on a wet road or on a lake surface[1]. Each colour corresponds to a curtain thickness. If you look perpendicularly to the curtain, an intense red or blue indicates a thickness of 0.6–1 μm, while a dim pink or green indicates 1.4–1.6 μm [14].

However, the exact correspondence between colours and thickness depends on the angle at which you look at the curtain (with the nice consequence that its aspect changes when you

[1] This is *not* geometrical dispersion like in a rainbow or in a prism; this is not diffraction like on the surface of a CD.

move around it). We usually look at it at grazing angle, where the reflection and thus the colours are more intense. Empirically, the longest lasting curtains correspond to uniformly dim pink and green surfaces [6, 15]. Small currents of intense blue and red are much more beautiful but are thinner and usually last a shorter time. Transparent curtains are either too thick or too thin and break quickly (section 2.4).

The flow rate can thus be adjusted by looking at the colours. There is an optimal thickness, of the order of a micrometre, and a limit free fall velocity for the water, of the order of m s^{-1} (section 2.3.2). Thus for a 1 m wide curtain, the flow rate should be around 1 m $\times$ 10^{-6} m^3 $\times$ 1 m s^{-1} $\approx$ 10^{-6} m^3 s^{-1} or 3–4 l h^{-1}. The optimal flow rate (independent of the curtain height) increases proportionally to the curtain width, and we use 4–8 l h^{-1} in 2 m width, around 10 l h^{-1} in 3 m width. The recipient and the bucket should be chosen accordingly.

The hole in the recipient should be small (especially if there is no tap to regulate the flow rate), but if it is too small drops appear and splash on and around the curtain. Such a rain has two unwanted effects: breaking the curtain and spilling water on the floor. According to the floor's material, it can be preferable to surround the bucket by a plastic sheet against splashes. Sawdust might help too.

2.3. Why is it stable?

2.3.1. Soap. Soap is made of molecules with a polar head, which like to be dissolved in water ('hydrophilic'), and a long hydrocarbon tail which does not ('hydrophobic'). Thus, the whole molecule both likes and dislikes water ('amphiphilic'). Its preferred position is thus adsorbed at the air–water interface, with its head in water and its tail in the air: it forms a one-molecule thick layer ('monolayer'). It can also adsorb at a water–oil interface. That is how soap washes: since oil does not mix with water, one cannot wash fat with water alone; conversely, fat droplets covered with soap can be carried away by water[2]. Thus, washing properties arise from the amphiphilicity.

Foaming properties is a side effect, often undesirable, for instance in washing machines (where antifoaming agents must be added to the washing powder). It is related to a molecule's ability to stabilize a thin water layer. In fact, for pure water, van der Waals forces tend to decrease the distance between both water–air interfaces: a thin layer of pure water is always unstable [16]. Some amphiphilic molecules are charged: for instance, the sodium dodecyl sulfate (SDS) contained in the dishwashing liquid carries a negative electrostatic charge ('anion'). In that case, both surfaces of the water layer are covered by charged monolayers. They repel each other, thus stabilizing the water layer at a thickness such that the electrostatic repulsion balances the van der Waals forces favouring the thinning [16].

A monomolecular layer is only ∼1.5 nm thick. A small volume of dishwashing liquid, for instance a teaspoon, is enough to cover a huge surface, like a football ground (or the surface of a lake, as in Franklin's legendary experiment). Both monolayers amount to 3 nm thickness, that is around 0.3% of the curtain volume.

The concentration of dishwashing liquid we need is of this order of magnitude, but larger (figure 3(b)). This probably means that this electrostatic mechanism is not the main reason for the curtain stability. In fact, it plays a role when the curtain is very thin, that is, at the time of its formation (since without dishwashing liquid, the curtain does not form) or in the case of large fluctuations, due to air currents or dust, which greatly decrease the thickness; or if most of its water has drained.

[2] Soap lowers the surface tension of the air–water interface, but this has almost no effect on the soap curtain stability and is not discussed here.

But the curtain is much thicker, typically a micrometre, and its stability has another origin. Briefly, it is related to the amphiphilic molecules' ability to heal a defect in the curtain. If the curtain thickness fluctuates or if the density of molecules in the monolayer fluctuates, molecules have a tendency to bring it back to its stable state. It is characterized by the monolayer's 'surface elasticity' and is called the 'Gibbs–Marangoni' effect. Adding more and more molecules fills the monolayer and increases this surface elasticity, until a critical concentration, beyond which excess molecules begin to fill the bulk solution. Surface elasticity passes through a sharp maximum at this critical concentration, 2.3 g l^{-1} for SDS.

This is experimentally observed in a static bubble wall in an usual foam, for instance in a sink. Here, we observe such a sharp maximum, but its position depends on the experimental conditions and is an order of magnitude larger than 2.3 g l^{-} (figure 3(b)). Why?

2.3.2. Fluid dynamics. The water moves relatively to the room air: there must be a spatial (transverse) variation of velocity either within the water or at the air–water interface or within the air. Since air is much less viscous than water, fluid dynamics teaches us that most of this velocity variation arises from a velocity gradient within the air, localized just near the curtain ('boundary layer'). The velocity discontinuity at the air–water interface, as well as the transverse velocity gradient within the water itself, is much smaller and their effect is negligible.

The waterfall is not as free as it would be in vacuum. In a steady flow (reached after a transient regime which corresponds to several tens of centimetres below the tap), the weight of the water is balanced by the viscous friction in the air, due to the velocity gradient. Thus, the boundary layer fixes the water velocity: typically a m s^{-1} for a micrometre thick curtain. The boundary layer is itself around a micrometre thick. The resulting velocity gradient in the boundary layer is of the order of a m s^{-1} divided by a micrometre, that is a shear rate around 10^6 s^{-1} [6]. This means that each monolayer of amphiphilic molecules is solicited over a very short time scale, of the order of microseconds. It can respond quickly if and only if there are many excess molecules in the bulk solution, close to the air–water surface and ready to fill any hole in the monolayer. This might explain why our curtain requires more amphiphilic molecules than a static bubble wall.

2.4. Why does it break ?

2.4.1. Feeding the corners. The curtain is made of water, which constantly falls. All parts of the curtain must be constantly refilled. Check the colours: if you observe a region which is not well fed, it usually thins and breaks within 20 s. Viscosity should thus be kept low[3], except for special effects (section 4.4).

The water spreads over the whole curtain if the angle at the top is not too wide. Rutgers and Davoudian find that the maximum angle is around 30° [6, 8], while we reach slightly more than 35° (figure 2(b)): 1.7 m width for a 5 m high lozenge, 3.4 m for a 10 m high one.

Beyond this angle, the corners are not well fed. Increasing the angle would be possible in principle if we could add nozzles at the corners, but in practice it is difficult because they would have to be very light and mobile.

The hexagonal shape is narrower than the lozenge of same height and same angle at the curtain top (figure 4(a)). However, the flow at the corners is smoother, so that corners are better fed.

[3] A giant bubble is very different from the curtain discussed here. Once formed, it is not alimented, and thus breaks if its water escapes: so that sugar is used to prevent evaporation or viscosifiers such as glycerine to prevent drainage.

2.4.2. Shock waves. If the curtain is too thick, that is at high flow rate, there is a curious phenomenon. In fact, the sound velocity in a flat membrane is $c = \sqrt{\gamma/\rho_s}$. Here, $\gamma \sim 0.06$ N m^{-1} is the curtain's surface tension, equal to twice the surface tension between the soap solution and air. The surface mass density is $\rho_s = \rho h$, where $\rho = 10^3$ kg m^{-3} is the water density and h is the curtain thickness. Hence $c \sim 8h^{-1/2}$, where h is in μm and c in m s^{-1}. When h increases up to a few μm, c decreases to a m s^{-1}. Thus, the water velocity in the curtain becomes comparable to c and the flow becomes supersonical. Small waves develop first near the top and the bottom of the curtain, where the curtain has less width, hence a higher h, hence a lower c. If the flow rate increases, these waves increase and become shock waves which break the curtain [6].

Adjusting the flow rate and the angle fixes the length of the region affected by these shock waves: if the angle is wide enough, this region is small and the shock waves do not have time to develop.

2.4.3. Irreproducibility. The curtain is not reproducible and it is frustrating. With the same set-up, there can be one day where only 30% of our attempts do form curtains, and they last for 20 s, while the next day almost all attempts succeed and curtains last for minutes. Once we even had, during a whole morning, a very surprising regular alternance of one successful formation followed by one failed attempt. Of course, the curtain obeys Murphy's law: it usually fails in the presence of a journalist.

That is why the times we indicate in figure 3(b) cannot be generalized. That is also why patience is important. You must be ready to adapt the flow rate, dishwashing concentration or curtain width to changing conditions. We now list some possible causes of this variability.

Cleanliness of the solution and the wires. For instance, in the morning, the stability improves during the first hour, probably because the solution rinses the wires which got slightly polluted during the night. Rutgers insists on the choice of wires, knots and materials which touch the water: he chooses hard plastic bottles and high quality silicone tubing; to recycle the water from the bucket, the weight has to be clean too [3]. However, we do not see a clear correlation between cleanliness and stability; we sometimes work very cleanly and see our curtains fail, while on other days we have contaminations (especially corrosion of steel by the dishwashing liquid) but the curtains are very stable. The tap water we use is a potential source of variability, since its composition can vary from day to day. However, we sometimes use deionized water: it apparently makes no improvement.

Humidity. According to Rutgers [6], the air boundary layer limits the exchanges between the water and the room air. Not only does it prevent dust from approaching the curtain, but it also drastically reduces the evaporation. He thus observes that the room humidity is not important. On the contrary we note that we obtain our records on rainy days; while the sun shines directly on the curtain it seldom lasts more than 1 min. The test would be to humidify the whole room but this is not always easy.

Air currents. Strong air currents can break the curtain, but gentle ones do not affect it. It is thus surprising to observe that the stability decreases in the presence of visitors, even if they are quiet and do not smoke.

Size. We understand why the curtain durations depend on the angle (section 2.4.1). However, if the angle is less than the maximum one, what is important is the curtain width (figure 3(a)). We do not understand why width matters more than area. It is difficult to compare statistics made with different heights (that is, different set-ups), but we have the intuition that 5 m $\times$ 1 m, 10 m $\times$ 1 m or 15 m $\times$ 1 m curtains have equivalent stability.

Others. Ultimately, when we think we have removed all causes of breakage, it still breaks unpredictibly. Cosmic rays [6]?

3. Automation

3.1. Motivations

Rutgers or Kellay like to present manual curtains: they are easy to install, they enable visitors to create the curtain themselves and play with it, and they prove that one can do funny and beautiful science with cheap simple material.

Conversely, automating the set-up requires work and money. We thus suggest you first practice with a manual set-up and ask yourself seriously why you should automate at all.

Our main reason to undertake this task was that we wanted to be able to present the curtain continuously for one to two weeks. For the World Year of Physics 2005, we totalled five weeks of presentation, which amounted to around 10 000 curtains (up to 500 in a single day). Automation meant we could at least leave the curtain, have a drink and come back after 1 h.

There are other advantages.

- Having automated the tap too (figure 7(b)) this means we do not need to climb to the ceiling each time we change the flow rate. We can easily let the water flow out or shut the tap or optimize the flow rate or even, as discussed in section 3.2.2, vary the flow rate in real time, while pulling the wires to create the curtain.
- When there are many visitors, and you want to discuss with them, it is much easier if the set-up runs by itself; conversely, if there are less visitors, you can revert back to manual mode so that they can manipulate the curtain.
- The automation usually impresses the visitors and stimulates questions.
- The computer automatically records the duration of each curtain and the number of failed attempts; so that we can gather statistics, helpful to optimize the different parameters: geometry, pulling speed, flow rate, composition of the solution (figure 3(b)).
- Last but not least, we found that for 15 m and above it becomes tiring to repeatedly pull a wire under a few kgs of tension over a width of a few metres.

There is one drawback: during the time lag where the wires are closed and the water slowly wets them, nothing attracts the visitors' attention. In Paris we had to place a large sign saying 'Come closer, wait for one minute and look up'.

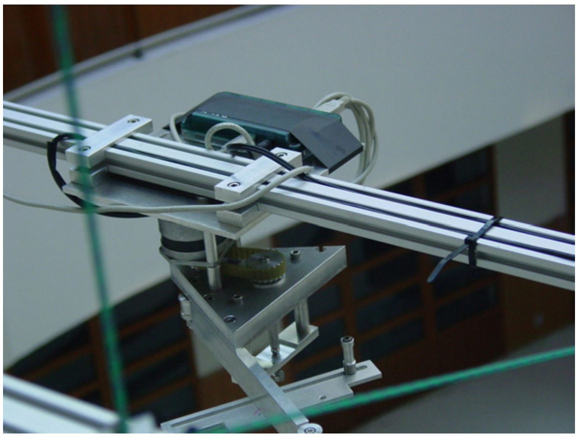
To decrease the total waiting time to 10–15 s, Rutgers [6] uses a manual or semi-automated set-up to switch quickly between three flow rates: low to start the curtain, medium to sustain it, very high to regenerate it. This lets a burst of fluid run down the wires for a few seconds (creating a lot of rain).

3.2. Method for the automation

3.2.1. Set-up. The material consists in one motor for each of the two (or four) pulling wires and one to control the tap, a camera, a light and a computer.

We have developed home-made software to control a cycle, as follows. First, a timer waits for a given time, required for the water to flow along the vertical wires and wet them completely; the water velocity along the wire depends on the flow rate, and is typically of the order of 1 m s^{-1}, smaller than for the free fall. Thus, including a safety margin, for a 18 m high curtain, we usually set the timer to 25–30 s. The motors then begin to pull, at the

(a)



(b)

Figure 7. Pieces of the set-up. (a) 20 l tank. (b) Motor for the tap. Photos F Mondot.

required speed, to open the vertical wires, until the required position. The camera images the reflection of the light in the curtain. As soon as the curtain breaks, the light reflection of course vanishes and image analysis detects that the grey levels decrease. The computer then records the duration of the curtain and lets the motors in the reverse direction so that the wires close back to the rest position.

If air flows or visitors blow on the curtain, its shape deforms. When the camera loses the reflection, the computer believes the curtain is broken and closes the vertical wires. It is thus better to place the light and the camera near the top of the curtain, which moves less. Alternatively, with several lights rather than one, the camera always detects at least one when the curtain is present.

3.2.2. Flow control. When the set-up runs, it is advisable to come and look regularly. We use a sensitive tap (with an acute home-made cone to block progressively the hole) and adjust the flow rate several times a day, according to the weather, air flows, number of visitors and other perturbations. In our 18 m high curtain, we have had concerns for the resistance of the wires after one week of continuous operation and we limited the width to 3.40 m (although during trials we easily reached around 3.80 m).

Automation means that a presentation can last for hours. Moreover, large width implies high flow rates. We thus have to consider the question of autonomy in water. To reach 2 h autonomy, we use 20 l tanks (cut from water dispensers) when a balcony gives access to the curtain's top (figure 7(a)). However, in most cases, it becomes necessary to have a pump to elevate the water from the tank to the curtain's top. The water should arrive at the tap with a very small overpressure.

For that purpose, we drill a hole in a commercial pressure cooker, to let pressurized nitrogen enter, and another hole with a pipe to let water flow out. In one case where nitrogen was desperately lacking, we used helium: this is expensive, but works (unlike carbon dioxide, which makes bubbles). Since a commercial pressure cooker usually works at 0.5 atm, this is a nice way to elevate the water by up to 5 m (or, in practice, rather 4 m, due to pressure drops in the pipes and in the tap). Some recent models allow for 0.9 atm, hence 8 m: check their notice. Removing the safety valve (which you should do at your own risk), these figures increase to 0.9 and 1.5 atm, respectively, allowing for 8 m and 13 m. This last value was enough in Paris where the balcony was 9 m high. Higher pressures could require home-made tanks, or, better, commercial pumps [3].

If you think not in hours, but in months, it makes sense to recycle the water and directly pump it back to the top of the curtain, as is routinely done in a laboratory environment. In public, Rutgers [6] once used a regulation mechanism like a toilet tank: when the water level would get too low, a magnet would slide in a glass tube and activate a REED switch which would activate a pump.

A private science museum in Sweden [17] thus has a recirculation of water, working the whole year long (the water is changed once or twice a year, and 10–15 bottles of 'Yes' detergent are used each year [18]). The vertical wires are constantly wet and touching each other, so that a visitor only has to pull them apart to see the 6.5 m $\times$ 2 m curtain. The Palais de la Découverte is currently examining with us the possibility of building a permanent version of our set-up, combining the automation and the water recirculation.

The probability to create a curtain seems better if the flow rate increases with the opening of the wires. That is, we begin with a small flow rate and, during the few seconds required to open the wires, we progressively increase the flow rate, until we reach the full width and the corresponding optimal flow rate.

4. Applications

4.1. Pedagogy

4.2. Physics

Once a curtain is prepared, it can help attract the attention of children and students. We like to first make them guess or feel the orders of magnitudes. A curtain is 100 times thinner than a hair, 1000 times thinner than a millimetre. Despite its large surface area (up to 34 m^2, like a two-room apartment), it weights less than a 100 g yoghurt. It is so thin that its height is 10–100 millions times larger than its thickness (imagine a 100 km long blanket).

Starting from observations, we can thus answer or stimulate a lot of questions. They start for instance with keywords such as

- thickness;
- colours, irisations, interferences;
- flow, turbulence;
- surface tension;
- minimal surfaces;
- bubbles and foams;
- wave propagation in the curtain, shock waves;
- fractures and their propagation;
- molecules which favour water or oil;
- cleaning with soap;
- automation, detection, computer control.

4.3. Projects

During the World Year of Physics, around 20 projects were driven by teachers around our curtain. One of their most important features was their simplicity, that is, what we can observe using daily material.

In primary schools, they were photo and video projects, creation of a small exhibition, realization of two 2 m high curtains (in self-service, during recreations), construction of artistic minimal surfaces and 1 h 30 min discussions around foam in classes.

In the Villeneuve Secondary School where the curtain was installed, most classes came for a 1 h presentation. An art teacher made some classes draw around the theme of bubbles and soap. Since we came twice, separated by six months, the science teachers used this interval to supervise a group of volunteers. They synthesized their own soap, searched for the history of soap fabrication and hygiene. They built a small exhibition, with posters, that they presented in a science competition in Grenoble, then later in Paris' Palais de la Découverte. It was illustrated by 2 m long soap bubbles, by a 1 m wide bars-and-bowls model of a soap molecule and by many small tabletop demonstrations on minimal surfaces. They realized their own 3.5 m high curtain, that their friends could manipulate, especially to pass the hand across the curtain; they made a set-up with three, then four vertical wires, to observe the minimal surfaces and their rearrangements.

High school students participated in a project to optimize the composition of the soap solution. One of them came to our laboratory for three days to collect the data presented in figure 3(b). In a technical high school, a group of 12 undertook the construction of a scaffold helping us to safely reach the 15 m high ceiling.

Physics and engineering students, as well as colleagues, participated in the animation, presenting the curtain to the public in Paris or in Grenoble. They answered a lot of questions, entered persons in 2 m high cylindrical bubbles, designed posters, prepared tabletop experiments to demonstrate the strength of surface tension or the drainage of coloured and transparent soap films.

4.4. Demonstrations

Wet your finger with the same solution (water with dishwashing liquid) used to make the curtain. Then gently touch the curtain: you can cross it without breaking it. If you have no hair (which usually applies to children and women), you can even wet your hand or your whole arm and insert it into the curtain (figure 5). Your arm can thus stay in the curtain for

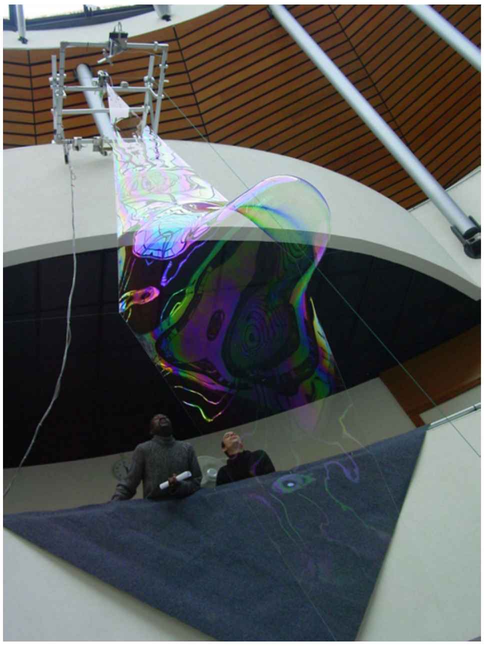


Figure 8. Blowing bubbles can require several persons. Photo F Mondot.

30 s or 1 min! Note that, to our surprise, we even sometimes succeeded in inserting a dry finger without breaking the curtain, but that is extremely rare.

Inserting a (wet) object or finger in the curtain, we can see the flow around it and its wake. Rutgers made nice demonstrations of von Karman pairs of eddies behind a round obstacle.

To evidence the surface tension (that is, show that all parts of the curtain are constantly pulling), Rutgers inserts a loop of cotton thread in the curtain, and holds it by two knives crossing the curtain, one at the top of the loop and one at the bottom. With a chopstick he holds in his mouth, he then breaks the small piece of curtain which is enclosed within the loop. The loop is pulled open by the curtain and becomes circular [6].

When the curtain is wide open, switching for a very short period to a low value creates nice travelling bands of colour as a thin piece of curtain travels down [6]. In 'la Cité des Sciences', Paris' other science museum, the rectangular curtain built by Davoudian is not fed at all so that the drainage is visible: the curtain thins, its colours disappear and it breaks [8].

Looking at the curtain breaking is fascinating. We can observe the fracture propagation, but also play with it. For instance, when the curtain's bottom breaks, increasing the flow rate sometimes prevents the crack from going up and invading the whole curtain, so that it stays at intermediate height for some time, the curtain's top part remaining intact. Kellay mixes (thoroughly, because it does not dissolve well) 25–50 mg l^{-1} of a polymer (PEO) with the water solution [15]: it stabilizes the curtain, which lasts much longer, and even when it breaks the crack barely propagates. With practice and patience, this gives spectacular results [7].

Blowing on the curtain from a close distance easily makes 0.1–1 m diameter bubbles, which detach. Blowing from a larger distance creates 3–5 m diameter bulges, but this often requires several persons (figure 8). It is difficult to detach this bulge to form a bubble; a solution, which requires practice, is to quickly close the vertical wires. An electric fan may help, but it should be adjusted so as not to break the curtain. Similarly, it can be funny to make a

2 m high curtain outdoors; it will change according to the wind: a gentle breeze would keep it bulging, but a stronger wind will completely prevent the curtain formation.

4.5. Visualization

To take pictures or movies, it should be kept in mind that the curtain is a mirror, but a very bad one. Looking at it perpendicularly (normal incidence), it reflects only around 4% of the light, which means that you mostly see across it. A possible solution is to have a black background behind the curtain and behind you a diffuse source of light [3]. In a lab, measurements of curtain thickness use a monochromatic light, like a laser or a low pressure sodium lamp, which produces sharp interference patterns; but in public it turns out that the effect is not impressive and it is not safe (laser beams can be dangerous for the eye and sodium lamps raise electric safety concerns). Bubbles and bulges, especially seen from the side, are always more visible than a flat curtain.

If we have a small number of visitors, we prefer to tell them to look from the side (grazing incidence), in which case the curtain reflects more the light and has brighter colours. For a larger number of visitors, the sunlight (or very powerful artificial lights, useful only if the room is very dark) reflected on the curtain illuminates walls with ever-changing reflections, reminiscent of a swimming pool, but much more colourful. For pictures and movies, we obtain the best results when the diffuse light of a window reflects on the curtain at grazing incidence: especially if an object is visible through the window and thus appears on the picture.

Finally, in a performance room, it is a challenge to make the curtain visible (and even visually attractive) to an audience sitting a few tens of metres away. After a lot of attempts, we find that it is best to have one powerful light, not visible by the audience, which lights the curtain from the side. Its effect varies according to the direction of the curtain. If the curtain reflects the light towards the back of the stage, it produces colourful reflections on the wall visible by the whole audience. Or if the curtain is seen from its side, it becomes visible if and only if it is blown, which makes it look mysterious. Or if it redirects the light towards the audience, a few persons will receive direct light in their eyes, while others will not see anything; thus it is necessary to constantly move the curtain and create waves, and the audience sees ascending and descending coloured spots mimicking a firework.

Davoudian [8] dissolves a paint in the water: he found it to work with Plakkaatverf Tallens extrafine (this is soluble, but can settle at the bottom of the tank and block the tap, so it is advisable to mix it every few hours). Thus, instead of reflecting like a mirror, the curtain diffuses light like a screen and appears coloured. If the paint is white, one can project slides on it: Davoudian projected a face, we tried it with astronomy pictures. With practice, the result can look very nice.

Rutgers [6] uses a smoke machine to blow smoke against the top of the curtain. It gets trapped in the small layer of air carried along the water flow and it quickly travels down. Some performers also blow smoke in bubbles to make them visible. We have only tried with cigarette smoke and found it disappointing; we should probably practice more.

Amongst the ideas that we are currently testing are collaborations with artists, as Rutgers did with a dancer [5]. We are trying to set a performance with dancers and musicians and note that their technical constraints require specific adaptations. We are also considering a computerized image analysis to create ever-changing sounds correlated to the changes in colours. The feedback of sound on the curtain, through a powerful loudspeaker, would be possible in principle but would require a control of the curtain position which is much easier with smaller curtains [19].

Finally, it seems that these fascinating curtains offer possibilities limited only by our imagination.

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