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Tribute to an exemplary man: Yves Couder

Teaching, arts / *Teaching, arts*

Terra Bulla, the influence of Yves Couder on the emerging domain of arts and physics sciences

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Abstract. At the beginning of the eighties Yves Couder started to work in pattern formation field trying to observe and understand structures in complex flows. His approach was different using humble experiments to materialise simple but powerful and elegant ideas. He was establishing with Pierre Gilles De Gennes and Étienne Guyon in particular a novel way of making scientific proof by using demystified "experiences de coin de table" where the simplicity of the setting made the demonstration even more powerful. Science was becoming performative and scientists were in public talks as well as in the lab engaged physically in a tactile way with their experiments. One of Yves first contributions was to use soap films to perform hydrodynamics experiments in two dimensions. The experiments with soap films brought a sense of fragility, emotion and poetry into science; they started and entirely new field of research on bidimensional turbulence using films. This research and novel approach to science opened a pathway for some current domains like table-top sciences, frugal sciences, new types of popularisation like "la main à la pate", but also the rapidly developing field of arts & sciences. In the present article I will draw on the affiliation of Yves' works with the arts and sciences using several examples from my own work which is greatly inspired by his approach but also from the work of the fantastic artist duo Evelina Domnitch and Dmitry Gelfand.

Keywords. Soap film, Arts & sciences, Bubbles, Drops, Twodimensional hydrodynamics, Geophysics, Poetry.

Terra Bulla

Terra Bulla, the Earth as a Bubble, refers to the Latin maxim *Homo Bulla* evoking the fragility of human life, its evanescence and the mystery of the soul that was symbolised by the Roman proverb, and resurfaced in the culture of the Renaissance through the Emblems (Erasmus of Rotterdam [1]) and later in the XVIIe century painting Vanities (Bergström [2]), but which dates back to ancient Greece (Prosperetti [3]).

But a soap bubble illuminated in monochromatic sodium light, iridescent with black and orange streaks that mark the variations of a quarter wavelength in the thickness of an aqueous film that composes it, reveals the scientifically analogous inner storms of our own atmosphere. For physics, when environments appear continuous, only the forces present count, and the shapes

are born from the rupture and return to equilibrium. There is then no more scale, no more meaning to the measurements in metres and seconds that come from our anthropocentric relationship to the world – but instead from similarities of scale, from chaotic and fractal dynamics. Thus, from the point of view of balance shifts, the soap bubble becomes the exact equivalent of the Earth's atmosphere.

Yves Couder [4] was the first in the early eighties to bring to life the inner world of a soap bubble, to have the intuition that the internal movements of the film could be represented by those of a two-dimensional fluid otherwise inaccessible in the space of the laboratory, a miniature analogue of planetary atmospheres.

With Henri Thomé, Marc Rabaud and then me, he explored various experimental installations where a soap film stretched over a brass frame revealed the dynamics of a flat or curved two-dimensional universe, free turbulence or the ascent of a missing space delimited by a knotted hair that the surface tension of water transforms into an empty circle, therefore lighter than the outer membrane (Figure 1). The vacuous 2D balloon then rises up into the soapy atmosphere, shedding vortices that roll up in a larger structure and entrain thicker and thus heavier film parricides (Couder *et al.* [5]).

A second installation that Yves proposed to Marc and me to study, consists of a device where a circular membrane is stretched over a metal plane consisting of a central disc and a peripheral ring that can rotate at different speeds in different directions. Such a flow is found at the poles of several planets, the central disc constituting the polar vortex (Chomaz *et al.* [6]). When the rotation is different between the pole and the periphery, a shear appears which destabilizes, giving rise to a regular polygon made up of eddies in the same direction (Figure 2). Such a regular flow is observed on the planet Saturn, and takes the form of a white hexagon on the north pole, appearing stable over the course of thirty years of observation by exploratory missions (Figure 2).

The same type of flow is observed in a spherical geometry where the membrane must be inflated before a complex rack system is used to raise a metal sphere, the upper part of which rotates at a different speed from the equatorial part. Thereby shear is created at mid-latitudes. In the pictures taken by Henrri Thomé and Yves Couder (Figure 3), there is a disturbing visual similarity with the images of Earth from outer space, emotionally validating the physical correspondence between the atmosphere and the thin layer of soapy water in a bubble.

Yves, Marc and I have documented these transitions and theoretically described these dynamics by going beyond similarity by including the physical chemistry of soap solutions to explain the link between the thickness of the film and the flow that animates it. These studies, initiated by Yves, have launched a fascinating new experimental field by the forms that the dynamics produce, and by a physical relationship to these ephemeral and memorable universes of bubbles, reminiscent of childhood and playfulness.

In 2012, the artist group HeHe with whom I had already collaborated to realize the installation "Fleur de Lys", and myself were invited to take part in the art–science exhibition Carbon12 at the Espace Electra of the EDF Foundation. With the only roadmap being "art and climate change", I decided first to return to these studies from the eighties, under the title Terra Bulla, to reveal the relationship to fragility and ephemerality that is implied by working with soap membranes. The frugal side of the means and the link to the universe of childhood make these experiments vanities, where scientific knowledge becomes situated, essential and derisory. Then I invited Yves to exhibit with us, and we presented Figures 2 and 3 in large format in the exhibition space. At the same time, with the help of Antoine Garcia, Pascal Hemon and Caroline Frot, I resumed experiments with soap and produced a video (Figure 4) where a bubble 7 centimetres in diameter responds to the solicitations of breath through a performer's straw. Here, the bubble is still illuminated in sodium light, yet no longer by reflection but rather transmission, producing images where both sides of the bubble are visible.

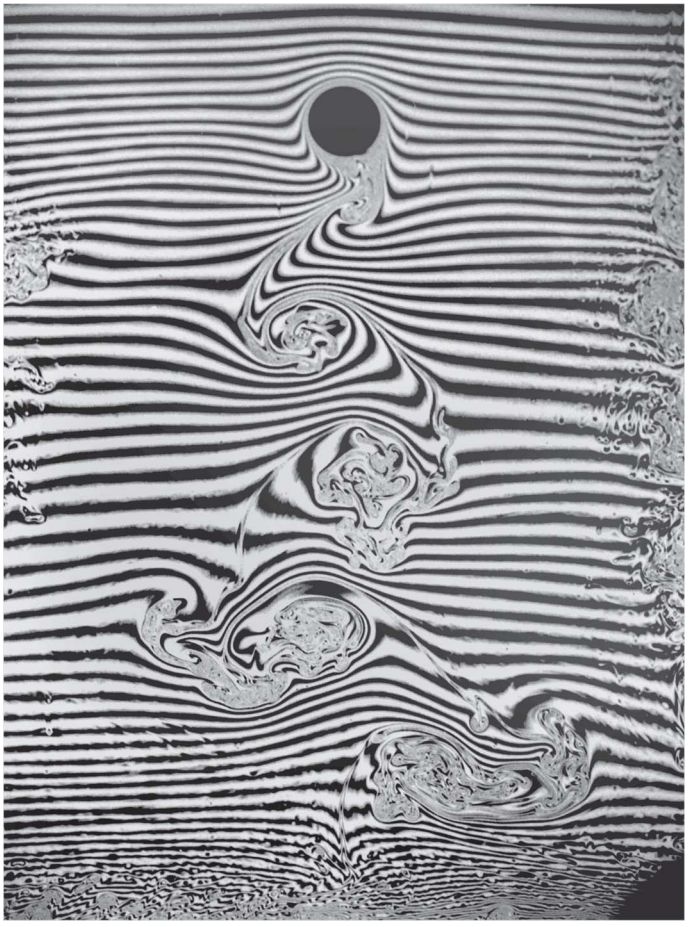

Figure 1. The ascent of a void in a vertically stretched membrane that has been stratified by drainage. The flow is unstable and the void rises in a zigzag pattern, releasing vortices which in turn coil up smaller structures. The visualization is by means of interference with fringes of equal thickness. The scene is illuminated by a low pressure sodium lamp. Photo Yves Couder.

The Terra Bulla video thus shows us an ephemeral analogy of our planet, which is at the same time a physical model, a representation, an icon and a symbol of the dynamics of the Earth's atmosphere.

In the exhibition space the two photographs of Yves (Figures 2 and 3) took on the status of a work of art, of derisory and sublime vanity, still persisting like the vibration when Yves triggered the shutter.

The fragmentation of the ocean

The fragmentation of the ocean would be a wonderful title for an art installation, a poem or a catastrophe but this is the title of a article *Focus in Fluid*, Yves wrote in the Journal of Fluid mechanics commenting on the article by Lhuissier and Villermaux [7]. Amazingly, this study takes the dynamics presented in Figures 3 and 4 up to the critical point where the bubble breaks as presented on Figure 5. This is the ultimate evolution of *Terra Bulla*, its implosion

Figure 2. Dynamics of a circular shear visualized by a soapy water membrane. Photo Yves Couder.

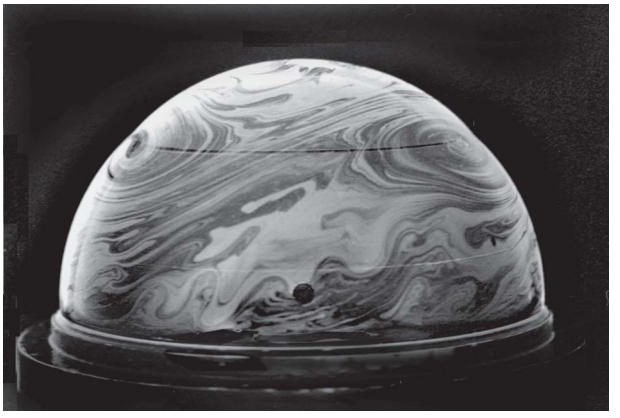

Figure 3. Dynamics of circular shear at mid latitude in a spherical shell visualized by a hemispherical soapy water membrane. Photo Henri Thomé and Yves Couder.

when fluctuations generate a hole, the edge of which is then pulled extremely fast by the, now, unbalanced surface tension. This is a situation impossible in gas or three-dimensional liquid where the pressure that replaces the tension is positive, but one that can occur in a gel or a solid where the pressure can be negative. The rupture leads to a cascade of events, the formation of a rim, its destabilization by the centrifugal acceleration (Rayleigh–Taylor instability). The rim then forms a series of parallel ligaments. These liquid threads break into droplets due to the Plateau–Rayleigh instability. By taking into account the succession of these phenomena, the authors obtain an estimate of the mean droplet size and the number of drops produced per bubble. The resulting experimental distribution of droplet size is in excellent agreement with the field measurements of Preobrazhenskii [8] and Wu *et al.* [9].

Figure 4. Dynamics inside a hemispherical soap buble, excerpt from the video "Terra Bulla", hemispherical soapy water membrane. Monochromatic light from a low pressure sodium lamp revealing the movement through interference fringes of equal thickness. Photo Antoine Garcia, Pascal Hemon, Caroline Frot and Jean-Marc Chomaz.

The Focus really appreciated the work of Lhuissier and Villermaux, as it proceeded from the approach of simplicity and elegance that Yves has always promoted with the emotion of a visual to make not only a proof but a statement. A complex behavior observed in nature, results in most situations, from a single process that determines its essence, form and statistics by repeating itself iteratively. This work, like Yves', is a demonstration that a single simple mechanism, in the present case the bursting of a bubble, can produce a probability distribution at several scales and that a complete physical process and the precise analysis of a simple model can provide an accurate interpretation of complex measurements in the field.

It is surprizing to think that here the busting of a bubble, a breaking wave created on the ocean surface, seeds the air with a fractal dust of drops smaller than one micron. These drops are so small that they evaporate, and are carried away by the turbulence, becoming dry fragments of ocean, trapping grains of salt, bacteria or plankton. They form solid nuclei on which water vapour will condense to form fog, mist and cloud.

Thus the bubbles that were planets in Yves' experiments turn the sky into ocean and the rain into bitter tears twinkling down our cheeks the day Yves passed away.

10000 Peacock Feathers in Foaming Acid

In 2007 the artist duo Evelina Domnitch and Dmitry Gelfand created the art installation *10000 Peacock Feathers in Foaming Acid* using soap film and bubbles to transport a large audience into outer space (Figure 6). Evelina and Dmitry have both an artistic and scientific background and they develop their art installations as if they were scientific studies exploring the scientific literature, working on the theory to propose works extremely close to a scientific set-up, yet not to make a proof, but to instead connect with a larger poetic universe. By doing so they became aware of Yves's contributions both to science and to a form of emotion, of the sublime that illuminates

his work. Since that first imagined encounter, Yves became one of their heros and amazingly their works present a mysterious interconnection with Yves.

The piece *10000 Peacock Feathers in Foaming Acid* uses a "white" laser light made of three collimated diodes blue, green and red, reflecting on a soap bubble created on a small disk, which the performer can rotate to change the part of the membrane struck by the laser. The laser is nearly tangent to the surface of the disk so as to make the reflected light reach and embrace the entire sky (Figure 4). The laser's focused beam generates an extremely complex interference pattern, the reflection of which reveals the inner structures and motions of the soap film, creating a fascinating light journey across the entire room. The performer achieves the bubble pattern by blowing through a straw and may then drive the laser to reflect on a single curved external interface or the flat film between two bubbles or to traverse multiple surfaces of the bubble aggregate, thereby superposing several images. Highly unusual figures appear when approaching the singular triple line between the three surfaces of adjacent bubbles. The music is created live using some of the optical signals and vibrations of the soap film, which the feather performers try to connect during their journey into complexity. Visually, the voyage is some how reminiscent of the slit scan kaleidoscopic sequence of Stanley Kubrick's *2001 space odyssey* – the time travel episode near the end of the movie. Here, it is generated live, with the artists preforming the sound and bubble multiverse. Depending on the viewer's connection to space, bubble behaviours viewed in such proximity may evoke a range of scales, from the dynamics of living cells to those of cosmic origin.

In 2017 at the {un}{split} festival in Munich, Evelina and Dmitry invited me to perform with them in the double dome of the *Sphaerae*, and I realized how complex and exiting it is to invent a narrative, a soap symphony. I tried to make the journey through a singularity going down into the dimension of the triple point between three bubbles, the intersection of two singular contact lines. The smaller the dimensionality of the object the larger the universe unfolded by the laser beam. During that performance as well as each presentation of *10000 Peacock Feathers in Foaming Acid*, Yves's imaginative space is evoked as well as explained to the public, and his contributions are referenced.

Mucilaginous Omniverse

Evelina Domnitch and Dmitry Gelfand share another fluid Universe with Yves: since 2009 they have been presenting the performative installation *Mucilaginous Omniverse* (Figure 7), where droplets bouncing on a liquid surface generate capillary waves that control their interaction on a longer range than the size of the droplet. The droplets may then assemble into crystalline geometries that a performer may construct and dissolve by varying the low frequency sound arising from underneath a bath of silicone oil. Capillary forces and air cushions keep the falling oil droplets from coalescing with the bath. Repeated impacts of the droplet on the oscillating surface excite waves that in turn generate an alternatively attractive and repulsive potential with the wavelength of the capillary wave at the sound frequency. This interaction potential results in the orbital motion of droplet pairs and self-organising lattice formation when more droplets are introduced into the system.

Amazingly, a few years before in 2005 Yves (Couder *et al.* [10], Couder *et al.* [11], Protiere *et al.* [12], Protière *et al.* [13], Eddi *et al.* [14]) discovered and described the same phenomena going beyond the artistic installation: Yves' experiment with bouncing droplets offers macroscopic analogues of quantum behaviour, such as quantized orbital motion, quantum tunnelling, and wave-particle duality. Evelina and Dmitry made an art installation incredibly similar to the experiment, while not being aware of Yves's publication. They were astonished when they later discovered Yves' work and the quantum interpretation that they missed in their first intuition. For

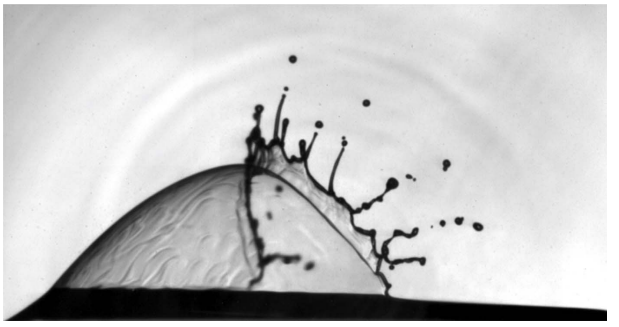

Figure 5. The breaking of an emerging bubble (courtesy of H. Lhuissier and E. Villermaux).

Figure 6. Public presentation of *10000 Peacock Feathers in Foaming Acid* by artist duo Evelina Domnitch and Dmitry Gelfand. Photo Miran Kramar.

these quantum evocations to arise, the acoustic amplitude has to be quite close to the threshold of the Faraday instability. As described by Yves Couder, "the droplet moves due to its interaction with the distorted interface, this means that it is guided by a pilot wave that contains a path memory. Through this wave-mediated memory, the past as well as the environment determines the [droplet's] present motion" [14]. In Figure 5 from Domnitch and Gelfand's performance of *Mucilaginous Omniverse*, the wave is visible just at the droplet location, whereas close to the Faraday threshold, the correlation length diverges and the wave evanescence length also diverges allowing for the memory time to interact with the dynamics leading to quantisation.

Luminiferous drift

We met with Evelina and Dmitry at the festival Exit, MAC Creteil in April 2013 where they were presenting their piece *Hydrogeny* and the artist collective HeHe and I, the installation Fleur de Lys the result of our first collaboration to be suppressed. We realised then our connection through Yves' work, and when they came to work with me the next year I organized a visit to Yves' lab. Their encounter was extremely intense, sharing so much even before meeting. Since that time they have regularly revisited Yves' research, not only for the sake of propelling new art projects, but also to plunge again into his imagination, which leads even to a certain form of spirituality emanating from scientific explorations.

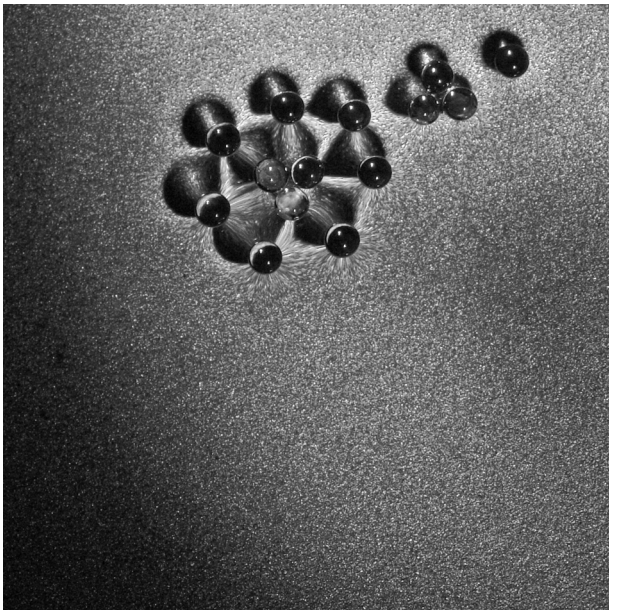

Figure 7. Image from a performance of MUCILAGINOUS OMNIVERSE with bouncing droplets – created by artist duo Evelina Domnitch and Dmitry Gelfand. Photo courtesy of the artists.

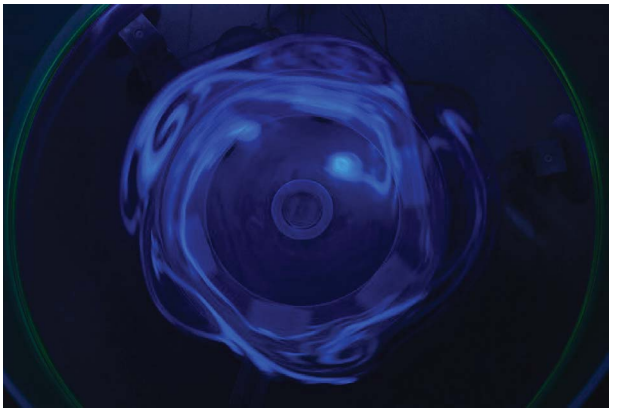

Figure 8. *Luminiferous Drift* by Evelina Domnitch and Dmitry Gelfand in association with Jean-Marc Chomaz and Erik Werner; sound by Richard Chartier. *Wetware* exhibition, Beall Center, UCI, 2016. Photography from, the first test in LadHyX with Gaétan Larisson and Camille Duprat.

The first work we did together with Evelina and Dmitry ended up being connected to Yves' work on circular shear flow (Figures 2 and 3). In the installation Luminiferous Drift (Figure 8) the public observes as if from outer space, the light storms of a hypothetical planet. One motivation of the work is to shift the question of climate change to that of Saturn where space missions have revealed the existence of a hexagonal cloud existing only at the North Pole. This phenomenon is probably due to the instability of the polar vortex, which is reproduced in the exhibition space by using a turntable, as in the laboratory. A specific transportable installation has been

Figure 9. ER = EPR (2017) installation Evelina Domnitch and Dmitry Gelfand in collaboration with William Basinski, Jean-Marc Chomaz and LIGO. Photo courtesy of the artists.

created at LadHyX, with the participation of Antoine Garcia and Gaétan Lerisson, allowing a differential rotation of the core of the vortex with respect to the periphery, akin to the circular shear experiment we did with Yves in the 80s. To reproduce the modality of Saturn's hexagonal cloud in a rotating tank, an inner disk rotates at a slightly different angular velocity compared to the table itself. The fluid is water and the mean rotation is large compared to the shear at the periphery of the inner disk, so as to be in the quasi-geostrophic approximation where the dynamics is two dimensional. The inner disk has a conical edge in order to include the so-called beta effect that mimics the sphericity of the planet – since the scale of the observed hexagon is large. Despite this difference in geometry, the dynamics is similar to the one described in Chomaz, Rabaud and Couder (1987) where soap films with shearing at the border of the polar vortex destabilise into a regular figure with an integer number of peripheral vortices decreasing when increasing the intensity of the polar vortex: variation of rotation. The visualization is actuated by an injection of luminescent protocells – developed in collaboration with the Huck Group, Radboud University – which are generated in situ by a microfluidic chip created by Erik Werner at the Hui Lab, University of California, Irvine.

The installation also connects with the question of the origins of life. Since these double-emulsions, where several aqueous solutions are mixed and injected into an oily membrane, may be considered as protocells that create prebiotic cellular conditions characterized by an enzyme-activated metabolism releasing energy in the form of light.

ER = EPR

In 2017 I created a second installation with Domnitch and Gelfand called ER = EPR (Figure 9), where two vortices, connected to by a thin vortical bridge, hover across a long aquarium. Under the aquarium an expanded white laser field propagates through the surface of water and transforms the vortex pair into a dynamic lens, projecting two entangled black holes surrounded by shimmering halos. As soon as the "vortex" link between the black holes tears, the vortices dissipates, like the collapse of a wave function of a pair of entangled particles. In association with the CalTech division of LIGO (Laser Interferometer Gravitational-Wave Observatory) and in discussion with Juan Maldacena, cosmologist, the proposal imagines a pair of holes considered as entangled quantum holes. The conjecture by Juan Maldacena and Leonard Susskind that wormholes are an example of quantum entanglement on a cosmic scale, goes back to two publications from 1935. The EPR (written by Einstein, Podolsky and Rosen) paper introduced the concept of

quantum entanglement. The second paper by Einstein and Rosen (ER) developed the theory of bridges, later known as wormholes. The theory that equates Einstein–Rosen bridges with EPR ultimately implies that the "reliable structure of space-time is due to the ghostly characteristics of entanglement". (Maldacena)

Yves imprint in arts & sciences

This symbiotic research between art and science is, to me and to many artists who have known Yves's work, a creativity of demystified, but immensely imaginative and emotional science. How to understand the climate of a planet by blowing a soap bubble, how to question quantum mechanics by bouncing droplets on an oscillating liquid surface, how to embrace quantum entanglement by the breaking of a vortex dipole on the calm surface of water? The style of Yves' research, the simplicity and sometimes seemingly naïve setting in relation to the big question it was supposed to address, have transformed the very nature of science somewhere between essence and derision, vanity and the sublime, but above all human. To me, Yves' work and the contemporary form of art named artscience (or arts & sciences) raise epistemological questions aimed at redefining the science-society link, regaining possession of the notion of progress, and restoring the freedom to invent the future. The installations presented here, linked or inspired by Yves' contributions, test our ability to perceive natural phenomena and to adapt to new sensory conditions. They provoke emotional situations capable of sensing current issues in a different way in order to contribute constructive new narratives of a world involving hybridization, the duality between art and science. A science citizen, human, simple and beautiful, an art with a form of humour and self-derision, the teasing smile and double-meaning remarks are Yves living in the heart of all of us.

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