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Research

Minimal Surfaces and Architecture: New Forms

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Abstract. Michele Emmer discusses the relations between soap films, arts, mathematics, visual arts, architecture with very recent examples.

> *It's because I don't do anything, I chatter a lot, you see, it's already a month that I've got into the habit of talking a lot, sitting for days on end in a corner with my brain chasing after fancies. It is perhaps something serious? No, it's nothing serious. They are soap bubbles, pure chimeras that attract my imagination.*
>
> Fedor Dostoevsky, *Crime and Punishment*

Introduction

The connections between architecture and mathematics have always been very deep and rich. Minimal surfaces, including those expressed by soap film and their use as models for geometry and architecture, constitute a specific aspect of the relations between architecture and mathematics, one that started to be developed in the twentieth century and has continued into the twenty-first. It started only in the twentieth because the geometry of soap films was developed only in the second half of the previous century by the Belgian physicist Joseph Plateau. In reality the theory of minimal surfaces actually began in the seventeenth century and some properties like the isoperimetric one were even known to the Greek mathematicians thousands of years ago. However, only with Plateau's experimental works did the theory of the minimal surfaces develop, allowing the application of its results in different areas of knowledge, not only in mathematics, but also in architecture.

This article presents a few examples of the connections between mathematics and architecture through minimal surfaces, starting from the architecture of recent years, furnishing for every example the mathematical details that partially motivated their applications in architecture. For a complete history of the relationships between minimal surfaces, architecture, geometry, mathematics, art and design see the volume *Bolle di sapone tra arte e matematica* [Emmer 2009].

A first example: Walliser 2009

In a recent paper the architect Tobias Walliser described his interest in mathematics for architecture, including the use of new digital technologies:

> In my article "Other geometries in architecture: bubbles, knots and minimal surfaces" [Walliser 2011], I described the fascination of using mathematical models as source of inspiration for architectural design. Key is not so much the complete understanding of the underlying mathematical formulae but the *imagination* to transfer these concepts into architectural models... Through the advance of digital design methods in architecture, not only new tools become

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available but also a new understanding of the design process is under way. This in turn will led to new definitions and a new understanding of form and matter. The current transformation process has the potential to unite the use of computational techniques in architecture which are applied for discrete parts of the design and construction process at present [Walliser 2009].

Walliser was describing one of his latest projects, a *Water Hotel* based on Costa-Hoffman-Meeks surface.

> We were approached by a client to develop a master plan for a huge leisure theme park to become a new tourist destination on the Pacific ocean in Mexico. While the main parts of the master plan were meant to be located on a volcanic hill, the most striking element was a hotel entirely located in the ocean...
> Digital experiments were done in a *less scientific but highly intuitive* way which allowed us to use the idea of dropping a volume into water as a design tool... maximizing daylight and views for the lower and upper levels. The interpretation of the Costa-Hoffman-Meeks minimal surface as insertion of multiple directional holes connecting the top to the water and the water at the bottom to the sky provided a single gesture combining all aspects.
> The external shape defined additionally as the minimal surface does not provide any building volume or enclosed volume. Our first proposal was to locate the minimal surface within a spherical volume as the object with optimized ratio of contained volume and surface. For visual reasons the volume was stretched to obtain a shape more in line with the water drop idea...
> Experimental testing of different configurations for the outer articulation and the space programme allocation lead to the definition of a minimal surface branching into three tubes which became a tripod stability system for the twenty-floor high hotel tower. A parametrical model was used to design the continuation of the different volumes. Changing parameters allowed for the existing of different articulations, silhouettes and relationships. A protocol of connections in the background functions as a programmed design tool which is used to produce a wide variety of variations [Walliser 2009].

So the key idea for the project was the use of a mathematical surface, the Costa-Hoffman- Meeks surface discovered by the three mathematicians in 1982. And why use mathematical ideas for an architectural project? Here is Tobias Walliser's answer:

> The constantly evolving new computational design possibilities come along with the difficulty that software possibilities take over the design decisions and are applied without critical reflection. Therefore a strong conceptual framework for the design is needed to develop coherent architectural designs. A great potential lies in the *combination of intuitive ideas and vague formal explorations in combination with mathematically defined relationships and rule-based interdependencies*. Mathematics can play a role in both parts, as overall conceptual inspiration for the generation of ideas and as tool for the geometrical relationships of elements. The Costa-Hoffman-Meeks surface proved to be a great inspiration for the design a highly functional and very emotional new icon for the Mexican coast (fig. 1).

Fig. 1. © LAVA & Tobias Walliser

> *Elegant, simple, bold and rich in experience*, this building will be a tribute to the meaningful adoption of mathematical models in architecture which is only possible using advanced computational methods in an *intuitive* way. And this is what architecture is all about: defining a process to incorporate exact data and rules to create spatial experiences [Walliser 2011 (italics mine)].

It is interesting to note that in the last 20 years important results have been obtained for minimal surfaces using computer graphics. In fact, I wrote in a paper in 1993:

> Thanks to this new tool it was possible not only to obtain a visualization of the minimal surfaces already known, but also to generate images of minimal surfaces that cannot be obtained with soapy water, and even more interesting, to see new surfaces whose shapes were previously unknown. It was thus possible to solve open problems in the theory of minimal surfaces. And one of the main exemplars is just the Costa-Hoffmann and Meeks surface [Emmer 1993].

The Costa-Hoffmann-Meeks surface 1982

Until 1982, only three complete, embedded minimal surfaces of finite topology were known (complete meaning more or less no boundaries and embedded meaning that the surfaces do not fold back and intersect themselves). The three known surfaces were the plane, the catenoid and the helicoid, all of them very often used in architecture in different periods.

All these three minimal surfaces are of genus zero by the point of view of topology. They are all equivalent to a sphere. Now if we insert a handle on a sphere, we obtain a surface of genus one. For example a torus (doughnut) is a surface of this type. So the only known complete embedded minimal surfaces with finite topology were all of genus zero. The conjecture of many mathematicians was that these were the only possible examples, no surfaces could have genus more than one.

In 1982 the Brazilian mathematician Celso Costa published an example of a surface that was minimal, suggesting that this surface was an example of genus one. David A. Hoffman and William H. Meeks III, by considering the equations obtained by Costa, using James T. Hoffman's graphic programming were able to see the surface on their video terminal and convince themselves that the surface was free of self intersections and therefore embedded. Then Hoffman and Meeks were able to obtain a formal mathematical proof of the topological property of the surface.

So the mathematical problem was solved. It was the first important example of the solution of a non-trivial open problem in mathematics in which the use of computer graphics was essential.

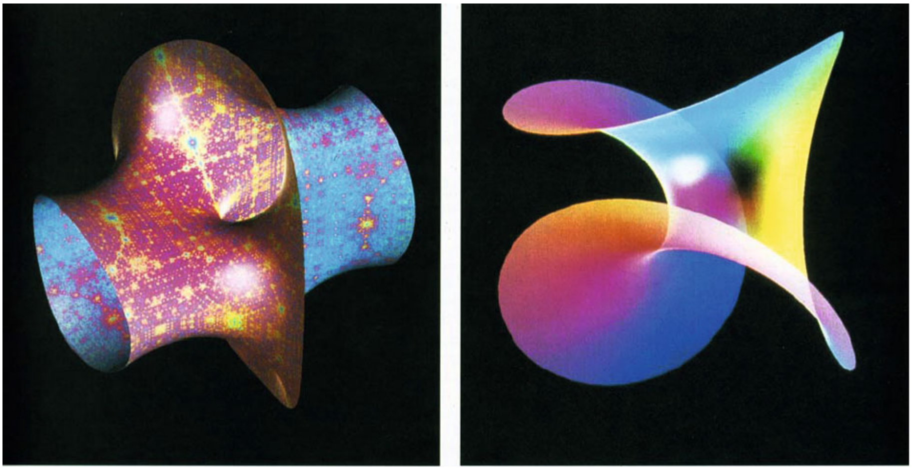

Fig. 2. The Costa-Hoffman-Meeks Surface

Apart from their obvious interest for mathematics, the computer generated images obtained by Costa, Meeks and Hoffman were so beautiful that an exhibition based on them was organized in 1986 by the National Academy of Sciences with the title "Getting to the surface". The exhibition also moved to Europe and included the new series of discovered surfaces (Hoffman and Meeks discovered a family of minimal surfaces with all possible genus greater than one).

So the images of these surfaces became popular. As Walliser pointed out, the problem for the architect is not the complete understanding of the underlying mathematical formulae but the imagination to transfer these concepts into architectural models. And the models were beautiful and stimulating!

A second example: the Watercube 2004

A few years before this project, Walliser had involved in another project together with his colleague Chris Bosse, also based on the geometry of soap films and soap bubbles. For both Bosse and Walliser "Learning from nature" was important, and they were thinking in particular of the work of the famous German architect Frei Otto.

In his paper "Bubble-ism. Architecture of foam" Bosse wrote:

> If the architect has an understanding of the disciplines of Engineering, and if the engineer has an understanding of design, they have a perfect base for collaboration. Frei Otto, who is an architect, but always worked at the interface with engineering, found inspiration in *self-organisation and naturally evolving systems* in nature.

> Looking at his work the *question of architecture or engineering* doesn't even arise. It is both. The buildings have beautiful structures, inspired by nature, and are beautiful in their own right, they create beautiful spaces and atmospheres [2008].

In the section "Learning from Nature", he adds:

> In the series of pavilions that we have now built around the world (THE MOET marquee just won the IDEA awards in Melbourne), we use the principle of Minimal surfaces in Nature. With a minimum of material we fill an enormous space, making use of the self organizational properties of membrane structures. Frei Otto used these principles, dipping wires into soap-films to create the shape for the Munich 1972 Olympic roof, a floating cloud hovering above the landscape. We can now create minimal surfaces that wouldn't have been possible without computation that are *extremely efficient and look incredibly sexy*. Light animates these structures and fills them with life.

At the beginning of 2002 Bosse was part of a high-rise competition:

> We had the idea to break up the concept of an extruded tower with an applied façade by creating a tower that was façade and structure at the same time. We looked at skeletons, spider webs, corals and foam. With a bunch of imagery we went into a workshop with Charles Walker of the *Advanced Geometry Group* at Arup in London. We came up with the idea of packing of Spheres in space.
> A box filled with spheres would assume the state of densest packing when you shake it.
> This would be a somehow stable system. If you slice through that, you get a slice of structure, that looks organic and random, but it is highly efficient and structural.
> We remembered that Frei Otto, (who was my mentor at the Institute of Lightweight Structures at Stuttgart University) had done experiments with soap bubbles and foam. (In the sixties the German architect Frei Otto started to experiment with soap films. He had in mind to use the models of minimal surfaces to produce a complete new structure to be used in architecture. He created the so called Tensile Structures all based on soap film models. His most famous project is the tent for the Olympic Stadium in Munich for the Olympic Games of 1964).
> The Highrise Project unfortunately terminated, but we received a copy of Frei Otto's book [Otto 1969] from Charles Walker, which showed circles transforming into 3-dimensional foam.
> So when 1 year later I moved on to Sydney, and we started the competition, we could come back onto this thought, and it was a perfect match with the idea of water in a building form.
> However it took another 3 months before we got our heads around to actually do it, and finally Tristram Carfrae and his team at ARUP found the 3-dimensional geometry of foam through research, on the website of the Irish Institute of Foam Physics at Dublin's Trinity University.

It was the project for the *Watercube* for the Olympic Gems in Beijing 2008. This is how it was described by the Jury of the *Mostra Internazionale di Architettura, Biennale di Venezia 2004*:

The special award for the most accomplished work in the section Atmosphere is awarded to the Australian architecture firm PTW Architects, CSCEC + Design and Arup for the project National Swimming Centre, Beijing Olympic Green, China. The project demonstrates in a stunning way, how the deliberate morphing of molecular science, architecture and phenomenology can create an airy and misty atmosphere for a personal experience of water leisure.
The entire structure of the Watercube is based on a unique lightweight-construction, developed by PTW with ARUP, and derived from the structure of water in the state of aggregation of foam.

Fig. 3. *Water Cube,* design by C. Bosse, J. Bilmon & M. Butler, © PTW ARUP CSCEC

Behind the totally randomized appearance hides a strict geometry as can be found in natural systems like crystals, cells and molecular structures – the most efficient subdivision of 3-dimensional space with equally sized cells.)
By applying this novel material and technology the transparency and the appearing randomness is transposed into the inner and outer skins of ETFE cushions. EFTE, ethylene tetrafluoroethylene, is a transparent plastic which absorbs solar radiation and reduces thermal loss. This is the first time EFTE has been used in China and it is the world's largest and most complex EFTE building ever constructed.
Unlike traditional stadium structures with gigantic columns and beams, cables and backspans, to which a facade system is applied, in the Watercube design, the architectural space, structure and facade are one and the same element.
The structure of the National Swimming Centre is based on the most efficient subdivision of three-dimensional space. This pattern is extremely common in nature being the fundamental arrangement of organic cells, the crystalline structure found in minerals, and the natural formation for soap bubbles.

In the poster displayed at the Biennale in Venice 2004 there were pictures of foams, of soap films, of radiolaria, and quotations from the famous book by D'Arcy Thompson, *On Growth and Form* [1942]. A full chapter in the book of Thompson is dedicated to the geometry of soap bubbles and soap films, showing the connections of this geometry to the shapes of some skeletons of the radiolaria, microscopic animals that are part of marine plankton.

"The peculiar beauty of soap bubbles, the resulting forms, are so pure and so simple that we come to look on them as a mathematical abstraction", wrote Thompson.

Since the publication of the book by Thompson some of the images of radiolaria have been always linked to the geometry of soap films. These images have influenced many designers, artists and architects, in particular for projects of submarine architecture in the late 1980s (for more details and the connections with art, see [Emmer 2009]).

It is interesting to note that o December 9, 1992, the French physicist Pierre-Gilles de Gennes, professor at Collège de France in Paris, after being awarded the Nobel Prize for physics concluded his conference in Stockholm with a poem on soap bubbles, adding that no conclusion seemed more appropriate. The poem appears as a closure to an engraving of 1758 by Daullé from François Boucher's lost painting *La souffleuse de savon*. De Gennes did not want to allude to the allegorical meanings that soap bubbles have had for many centuries: symbol of vanity, fragility of human ambition and of human life itself. Soap bubbles and soap films were one of the subjects of his talk, which was entirely devoted to the Soft Matter. Bubbles that "are the delight of our children," he wrote. A reproduction of the engraving was included in the article [de Gennes 1992].

Fig. 4 . *La Souffleuse de savon*, etching by F. Boucher (1758); see [Emmer 2009]

The Lord Kelvin conjecture and the geometry of soap films

In the late nineteenth century, Lord Kelvin posed a problem: "If we try and subdivide three-dimensional space into multiple compartments, each of equal volume, what shape would they be when the subdividing surfaces are of minimum area?" This is an interesting problem, not only as a theoretical exercise, but also because such shapes are prevalent in nature [Thomson 1887].

The study of soap bubbles is probably a good place to start when considering Lord Kelvin's challenge. Antoine Ferdinand Plateau (1801-1883) began his scientific career in the field of astronomy. In 1829 during an experiment he exposed his eyes too long to sunlight, causing irreversible damage to his sight. From 1843 he was completely blind. He took an interest in the nature of forces in molecular fluids, to discover the forms that generate soap films contained in metal wires immersed into soapy water. In 1873 he published the result of fifteen years of research in a two-volume work: *Statique expérimentale et théorique des liquides soumis aux seules forces moléculaires* [Plateau 1873].

Plateau himself introduced the general principle that is the basis of his work. The idea is to draw a closed contour with the only condition that it contains a limited portion of the surface and that it is compatible with the surface itself; if then a wire identical to the previous contour is constructed, plunged entirely in the soapy liquid and then pulled out, a set of soapy films is generated representing the portion of area under consideration. Plateau could not help noting that these surfaces are obtained 'almost by magic'.

And here is the great discovery of Plateau, incredible at first sight: however high the number of soap films that come into contact with each other, there can be only two types of configurations. To be precise, the three experimental rules that Plateau discovered about soap films are:

1. a system of bubbles or a system of soap films attached to a supporting metallic wire consists of surfaces flat or curved that intersect with each other along lines with very regular curvature;
2. surfaces can meet only in two ways: either three surfaces meet along a line or six surfaces that give rise to four curves that meet in a vertex;
3. the angles of intersection of three surfaces along a line or of the curves generated by six surfaces in a vertex are always equal in the first case to 120°, in the second to 109° 28′.

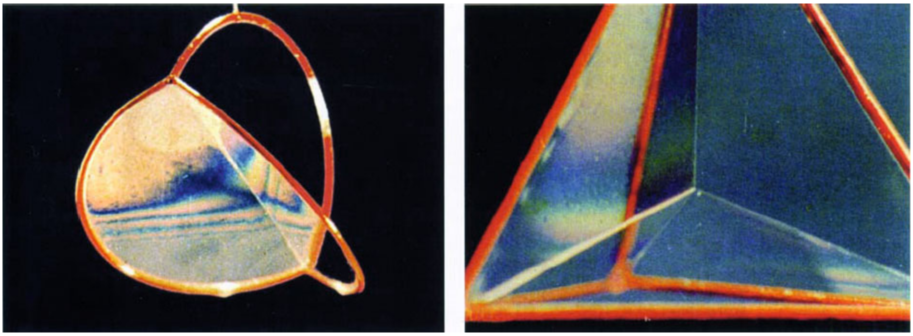

Fig. 5. Soap Films by Michele Emmer. The two rules of Plateau. © M. Emmer

Another question remained still open: were the laws discovered experimentally by Plateau for the geometry of soap films correct or not?

> In this work we provide a complete classification of the local structure of singularities in the three-dimensional space, and the results are that the singular set of the minimal set consists of fairly regular curves along which meet three films of the surface with angles equal of 120° and isolated points where meet four of these curves giving rise to six films also with equal angles.
> The results apply to many real surfaces that are generated by surface tension, as to any aggregate of soap films, and so provide a proof of experimental results obtained from Plateau over a hundred years ago.

Thus begins one of the best known work of mathematics of the last century. Written by Jean E. Taylor, entitled "The Structure of Singularities in Soap Bubble-and-Like Soap-Film-Like Minimal Surfaces" [Taylor 1976]. So Plateau was right. Fred Almgren and Jean Taylor wrote another well-known article that was published in *Scientific American* [1976].

In 1979 I realized the film *Soap Bubbles*, in the series Art and Mathematics, starring Fred Almgren and Jean Taylor [Emmer 1979]. The film was made at Princeton University, using real models with soapy water, while in the film on minimal surfaces produced by A. Arnez, K. Polthier, M. Steffens and C. Teitzel at University of Bonn and at Technical University of Berlin in 1995 all models are made with computerized animation [Arnez et al. 1999].

A few years before the experimental results of Plateau, the German mathematicians Schwarz found the solution to what would later be called "The Plateau problem" for a non-planar quadrilateral. One century later, the architect Frei Otto used this solution for his architectural projects of tents.

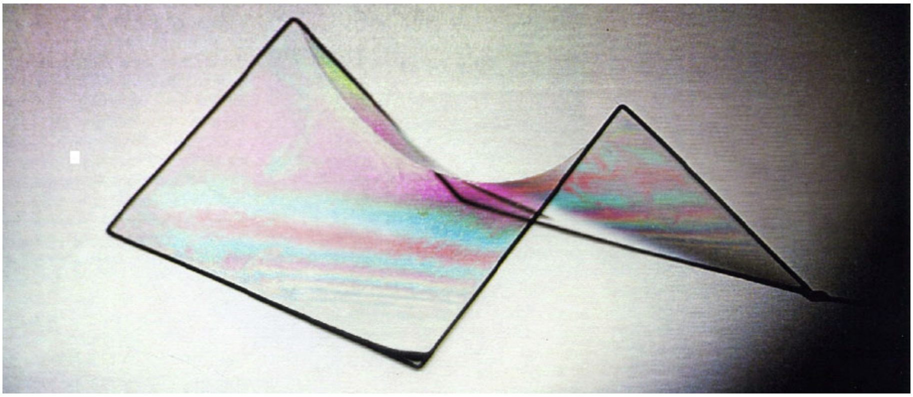

Fig. 6. Schwarz solution; see [Emmer 2009]

In 1887, Lord Kelvin proposed a solution to his own problem based on a fourteen-sided figure made of eight regular hexagons and six squares. This figure can be constructed by cutting off the corners of a regular octahedron.

However, the corner angle of a square is 90° and a hexagon, 120°. Both of which are some distance away from Plateau's observed ideal of 109.47°. A regular pentagon has a corner angle of 108°, but dodecahedra (twelve-sided figures made from regular pentagons) cannot be joined together to tile space – they leave gaps between them.

It was supposed for some time that figures comprising some combination of pentagons and hexagons would be more efficient than Kelvin's Foam. But it was not until 1993 that two Irish professors, Denis Weaire and Robert Phelan, constructed foam of two different cells, one of fourteen sides (two hexagons and twelve pentagons) and one of twelve sides (all pentagons) that used less surface area than Kelvin's foam.

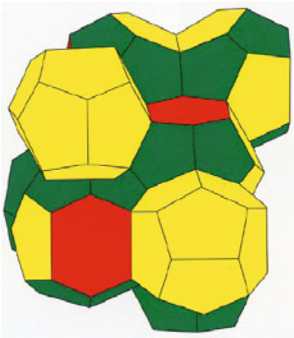

Fig. 7. Solution of Weaire and Phelan

The Weaire-Phelan foam remains today the optimal subdivision of three-dimensional space and was used as the basis of the structure for the Beijing National Swimming Centre.

It was recently proved by the mathematician Frank Morgan [2008] that there is a absolute minimum to this problem that is the best solution. But it is not known if the best solution is the one of Weaire and Phelan. The mathematician John Sullivan has produced very interesting models using computer graphics of both the Lord Kelvin and Weaire and Phelan solution.

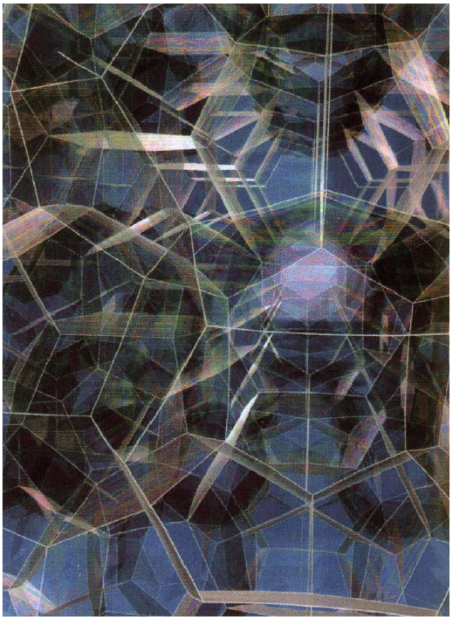

Fig. 8. The solution of Weaire and Phelan, by John Sullivan © J. Sullivan

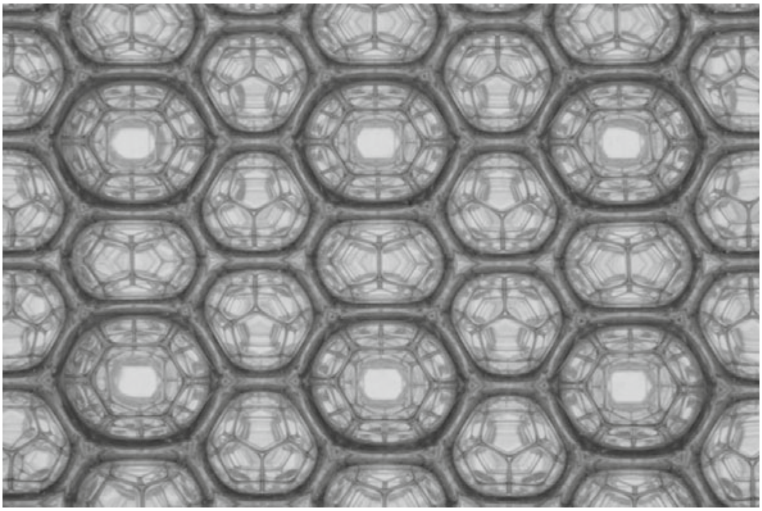

Fig. 9. Photograph of the experimentally produced Weaire-Phelan foam. The sample contains approximately 1,500 bubbles, arranged into 6 layers. Many fine details are observed confirming the absence of defects

The solutions proposed by Lord Kelvin and by Weaire and Phelan were not produced physically. They were abstract models, drawings or computer generated images, like the one of John Sullivan.

In November 2011 the abstract geometrical model became a real physical model made of soap films. Ruggero Gabbrielli, an Italian scientist from the University of Trento, went to Trinity College to cooperate with the team of Weaire and Phelan. He had in mind a physical solution of the Lord Kelvin problem. The team coordinated by Gabbrielli was able to produce the experiment. With the help of Kenneth Brakke, the creator in the 1970s of the free software Surface Evolver, an interactive program for the modeling of liquid surfaces shaped by various forces and constraints [Brakke 2009] the team realized a complex structure that represented physically the abstract solution of Weaire and Phelan. It was possible to produce a picture of the structure obtained of soap films. “Wonderful!” said Weiare, today Emeritus professor, “We will call it an Italian Job”. The paper with the picture was published in the same magazine in which Lord Kelvin had proposed the problem, more than a century before, the *Philosophical Magazine* [Gabbrielli et al. 2012].

The first scientist to investigate soap bubbles and soap films was Isaac Newton in *Opticks* [2007], the first edition of which was published in 1704, to describe in detail the phenomena that are observed on the surface of the soap films. In volume II, Newton describes his observations on soap bubbles. In particular he observes that if a soap bubble is formed with some water made more viscous using soap, it is very easy to observe that after a while a great variety of colors will appear on its surface. Newton noted that in this way colors were disposed according to a very regular order, like many concentric rings beginning from the highest part of the soap bubble. He also observed that as the soap film became thinner due to the continuous diminution of the contained water, such rings slowly dilated and finally covered the whole film, moving down to the low part of the bubble and then disappeared.

Soap bubbles attracted many artists starting in the sixteenth century. It is very likely that playing with soap bubbles was a very popular children's game at that time. And it is also natural that scientists became interested in the phenomena surrounding the formation of soap bubbles and the colors on their surfaces.

A short conclusion

In 1890 Boys completed his book *Soap Bubbles* [1959], in which he summarized his own experience in explaining to a large public the geometry of soap bubbles and soap films:

> I do not suppose that there is anyone who has not occasionally blown a common soap bubble, and while admiring the perfection of its form, and the marvelous brilliancy of its colour, wondered how such a magnificent object can be easily produced.
> I hope that none of you are yet tired of playing with bubbles, because as I hope we shall see, there is more in a common bubble that those who have only played with them generally imagine.

As foreseen by Lord Kelvin, artists, architects, mathematicians, physicists and biologists among others continued to study color and shape in soap films throughout the centuries. The story of soap bubbles in mathematics, science, architecture and art is a never-ending story.

Fig. 10. Anonymous, Netherlands, seventeenth century, private collection

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Michele Emmer is full professor of mathematics at the University of Rome "La Sapienza". His areas of interest: PDE and minimal surfaces, computer graphics, mathematics and arts, architecture, cinema, culture. Member of the board of the journal *Leonardo: art, science and technology*, MIT Press. Filmmaker, author of the series "Art and Math" broadcast by the State Italian television and other television; distributed in many countries. Homage in several Film Festivals: Bellaria, Bergamo, Rome Animation, Torino Museo del cinema, La Villette, Paris. He organizes the annual conference on "Mathematics and Culture" at the University of Venice; editor of the series "Mathematics and Culture" by Springer-Verlag; the series "The Visual Mind" by MIT Press; video series "Video math" by Springer-Verlag. Most recent books: *Bolle di sapone* (Bollati Boringhieri, 2009), Viareggio award best Italian essay 2010; *Matematica e Cultura 2011* (Springer-Italia, 2011); *Il mio Harry's bar* (Archinto, 2012);*Flatland* with DVD (Bollati Boringhieri, 2008); *Visibili armonie arte cinema teatro matematica* (Bollati Boringhieri, 2006); *The Visual Mind 2* (MIT Press, 2006); *Mathematics and Culture V* (Springer-Italia, 2006); a chapter in *Venise* (Flammarion, 2006). He has been member of the Commission for the popularization of math of the European Math Society.