Optimizing Solar Insolation in Transformable Fabric Architecture: A Parametric Search Design Process

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Abstract. A design studio and a parallel research project focused on transformable fabric architecture. To facilitate a part of this work, computer based shape generation tools were used to optimize the placement of thin-film photovoltaic cells onto a transformable roof structure. In addition, the tension membrane fabric is rigged in a way that is similar to a sailing boat. The fabric is set into position by winches and cables. The winches are hand-operated so as to lower the overall energy cost.

The initial computer models proceeded concurrently with the mockup of small-scale physical prototypes. In addition, the author used an open source programming language to implement a particle spring real time simulation of the fabric shapes. The simulation included a three-dimensional graphical representation of solar insolation and helped to further determine the physical geometry of the project.

One of the primary goals was to evaluate whether larger transformations to the structure as a whole or smaller movements in the fabric would help to optimize the solar insolation benefits. As the examination of potential forms narrowed down to classical saddle shapes, the practical details of rigging the fabric imposed further limitations on its transformable nature. This paper is focused on how modeling with ad hoc tools and real-time computer simulation influenced the direction of the work.

Keywords. Transformable fabric architecture; parametric design; thin-film photovoltaic cells; animation; simulation.

Overview
A design research project developed lightweight lodging structures for a National Park setting. The site, Schoodic Education and Research Center (SERC), is located within Acadia National Park on the northern coast of Maine. The structures are intended to retract when not in use so as to minimize their visual presence and to have a smaller ecological footprint. Tension membrane fabric is the core building technology. Final construction is still in the development and funding stage.

The fabric architecture design work was facilitated in a design studio and also developed in a smaller more technically focused research group. The studio group investigated a wide range of transformation structures applied to the site. The research group worked towards optimizing the orientation of thin-film photovoltaic cells affixed to a few possible fabric structures and more closely examined methods of analysis and simulation. Both groups relied upon discoveries made through the mockup of small-scale physical prototypes. The making of physical prototypes of interoperable building components and tensioning of real fabric material enabled the hands-on exploration of how the structures move, respond to force, and could be sewn together.
One of the challenges facing the future of cities is how to protect the natural environment for relief from the density of urban living. Transformable lodging with a minimal ecological footprint can be an alternative to the extension of cities into unspoiled landscapes. Retractable tension membrane fabric structures can provide temporary seasonal accommodations during the peak summer season where there would otherwise be great pressures for the development of vacation housing.

**Key Challenges**

The benefit of transformable architecture in passive solar systems is well established in theory and practice as described by Arora [2]. For active thin-film photovoltaic systems, several questions were considered. First, does transformable architecture increase the performance of thin-film photovoltaic cells significantly over stationary architecture? Second, what strategy can be used to determine the best shape for a fabric building that would maximize energy performance? Third, how often should a transformable fabric building react dynamically to transient conditions, such as whether to respond to changes in sun position hour by hour, or if it is simply more reasonable to transform less often.

**Precedents and Tools**

Several years of teaching a design studio based on the coast of Maine has also included a study of sail making and boat building methods that have been a longstanding tradition in the region for several centuries. Sail makers adapt fabric towards highly optimized performance. They take into account the bias of material, the pattern of stitching, varied methods of reinforcing it, and how the material is able to move. The range of sails and their methods of construction reflect a legacy of variation in response to specific climate and ocean conditions. Therefore, sail making provides lessons of highly specific functional uses. The studio visited both traditional and contemporary sail makers for a basic sense of how to handle cloth materials with respect to their aesthetics and physical constraints (see figure 1). At the same time, the studio also examined the making and design of fabric architecture and had production facility visits and discussions with fabric design engineers.

**Figure 1**

Sailmaker Nathaniel Wilson with students from the design studio at his loft.

Similar to the craft of sail making, traditional boat builders are highly attuned to methods of molding planks into curved forms according to the properties of varied wood species. There are well-established traditions in boat building where splines are drafted at
full-scale in order to optimize the “fair” surfaces of hulls for minimum drag through water. The studio examined these techniques in a number of boat building yards. At the Apprenticeshop Wooden Boat School in Rockland, Maine, the students also undertook a modest hands-on exercise making wooden oars by traditional methods (see figure 2). The students used handcrafted tools that were custom built at the shop for the construction of the doubly curved oars. That is, using recycled parts, the workshop leader made a distinct plane tool with a blade angled to help facilitate the shape of the oars. Customization of tools for traditional oar making underscored the utility of adapting technology to construction problems at hand and instilled a similar view of how computer visualization tools should be adapted as will be illustrated below (see figure 10).

At the boat yard Rockport Marine, Rockport, Maine, the students were given a demonstration of heavy leaded weights used in the traditional drafting of the spline forms to generate the shape of a hull. This served as a precedent to the use of computer aided design generated spline curves (e.g., bsplines, Bezier curves, etc.) in the student design work. In becoming familiar with the use of such splines in the layout of hulls, the students were better grounded in how such geometry on the computer has a direct connection to real physical materials. Full-scale spline drawings in the boat yard were related to hulls in the same way that detail drawings in the architectural design studio were related to the making of half to full scale building components.

Figure 2
Students take on wood boat oar-making exercise at The Apprenticeshop

In sailboat making, sail rigging is an area of specialization. In the architecture design studio, the rigging of the tension membrane fabric structures for movement took up a good portion of the available time. Methods of rigging were also tested by means of cloth animation tools in Autodesk’s Maya software for a sense of how the fabrics could be retracted and unfurled. In addition, varied kinds of rigging inspired by design engineer Chuck Hoberman’s scissor forms, folded paper, and other techniques such as origami were examined. Workshops were provided in these techniques and the students were then encouraged to develop their own strategies. Chuck Hoberman visited one afternoon and gave a short critique of the student projects at mid-term. The student projects delimited the range of structural movement possible and were assisted by the mockup of interoperable building components.

Both the studio and research groups used a range of computer modeling, energy analysis and animation programs (see acknowledgements) in conjunction with physical modeling, sometimes moving between virtual and physical representations through CNC fabrication and 3D printing technology. This author also wrote a program for dynamic
simulation using an open source language and an available physics library as will be further described below.

**Studio Projects With Varied Retractable Structures**

The studio work produced some retractable roof structures that were designed to transform on an hourly basis. Other studio projects were less dynamic on a daily basis but transformed over seasonal or longer periods of time.

For example, National Park Service policies encouraged reducing the number of buildings over time on the SERC site. A shrinking perimeter to the buildable area was explored in the folding structure of figure 3 based upon a set of rotating elements. The student used hinge joints to attach sleeping, eating and writing surfaces to the primary framing structure so that they could be folded together for quick disassembly and relocation. This project encapsulates pin joints with constraints on movement. It was especially important to the student that the imprint on the landscape be impermanent. This scheme is the foil to all other proposed solutions on this site. It questions the need to build any structure beyond short-term uses. It argues for transportable temporary structures that are more structurally substantial than a tent but not as massive as the wooden cabins more typically found in this setting.

![Figure 3](image)
*Retreating fabric structure, Clare van Montfrans*

The scissor structure in figure 4 is the basis for another student project. The fabric roof would completely retract into a wooden platform when not occupied. Interior sleeping, eating and writing surfaces also retracted into the platform by a similar scissor mechanism. This project incorporated wood and metal joints developed after local wooden boat building traditions. The scissor structure contributes to the general understanding of how an operable shell can fully retract to have a minimal visual profile when not in use.
An alternative proposal shown in figure 5 incorporated an accordion fabric wall system that unfurled linearly along an edge of the structure, expanding the enclosed area when needed for increased occupancy or for greater insulation against cooler temperatures in late spring and early fall. Energy consumption is further minimized in winter when the interior volume is reduced during off-season. The scheme transforms into a compact winterized shell that is protected against colder temperatures.

One of students in the studio derived her work in part from the research team’s analysis and more detailed investigation of a simple saddle shape. Its fabric structure is relatively straightforward in comparison to the more complex transformable structures of figures 3 through 5. The saddle shape in figure 6 has four primary points of support and so its shape is more directly derived from the tension properties of fabric. Easy-roll trolleys move walls into a reduced floor area and enclosed box. An easy-roll trolley was mocked up at full-scale with interlocking column to beam connections. The fabric saddle above the walls can be adjusted to cover an expanded interior wall area during the period of greatest occupancy in the summer, and is removed when the walls of the building are condensed to the smaller box at other times of the year.
Initial Testing Based Upon Parametric Software

Within the non-studio research team the initial testing of solar insolation was first conducted by parametrically exploring fabric surfaces that were scripted through Bentley Systems’ Generative Components. Output through a spreadsheet interface to Autodesk’s Ecotect helped to assess the solar insolation performance of each surface model. Parameters were setup to test variation in roof and wall slope and orientation to sunlight. A more dynamic link between Generative Components and Ecotect was also tested (see acknowledgement to DeBiswas below).

In one case a light fabric vertical wall was pulled outward at equidistant points along its base in the morning and afternoon. The reshaped wall formed a series of vertical bulges. The bulges pick-up solar insolation as depicted in figure 7 when the sun azimuth is relatively east in the early morning or when it is west in the late afternoon. These points were then retracted at mid-day so that the wall as a whole would face more directly south in order to maximize exposure when the sun azimuth was due south. In other tests, the roof as a whole was tilted east and west on a north-south axis to achieve a similar condition of maximizing exposure to the sun at morning, mid-day and evening.

The explorations included a few additional roof and wall types that embedded thin-film photovoltaic cells. The initial studies of the non-studio research team produced some
better understanding of what may be feasible. Yet, most of these solutions were ruled out. Preliminary studies in Ecotect indicated that solar insolation benefits from these structures were minimal when modified on a daily basis. The bulging wall of figure 7 was hard to translate into a practical structure. The bulging wall didn’t necessarily gain that much more solar insolation than a simple southern facing wall. Further still, for any given structure, the very slow transfer of data back and forth between the geometrical model and the software used to measure energy performance hindered the research team’s ability to find its most optimal form. That is, the data transfer methods did work well for discriminating between more distant shape alternatives. Yet, the task to precisely pinpoint the optimal adjustment of a given shape was helped by developing a real-time simulation tool as described at the end of this paper.

Testing of Thin-Film Photovoltaic Cells on Mockup Structures

The testing of thin-film photovoltaic cells was physically initiated on a simple rig with two degrees of freedom as shown in figure 8. That is, the photovoltaic cells were set into a physical surface that could rotate around a north-south y-axis and also around an east-west x-axis. These two rotational movements are also known as “roll” and “pitch”. The two rotations corresponded to variation in sun azimuth and sun azimuth angles. Measurements of photovoltaic cell energy output were taken throughout the day.

A few results were not surprising. During mid-day, generally, the solar cells facing perpendicular to the sun position performed better than those that were less perpendicular. Days of relatively clear skies produced higher energy output. Two cells oriented in the same way had at times uneven performance and so consistency in the quality of the products used had to be factored into any interpretation of the data.

Less intuitively, cells that were 15 degrees off the perpendicular angle to the sun out performed those that were directly perpendicular to it. However, additional measurements indicated that the surface temperature of the photovoltaic cells was also significantly higher for those more perpendicular the sun. It seemed that some cooling or ventilation of the cells might produce better performance. As shown in figure 9, a series of tests on fabric rigged to facilitate air flow below the surface of the cells seemed to achieve the cooling needed and resulted in a higher level of performance.
In addition, the research team found that the photovoltaic cells energy output was less directly increased when they were oriented perpendicular to the sun during the morning or the afternoon than it was when they were oriented perpendicular to the sun during midday. This discrepancy is well established in other studies and theory. During midday, the sun's rays move a shorter distance through the earth's atmosphere and so less solar radiation is scattered or absorbed than during the morning or afternoon [Shining On National Renewal Energy Lab Report [9].

To factor in distance through the earth’s atmosphere, a rule of thumb for calculating solar insolation is (see http://www.theweatherprediction.com/astronomy):

\[ \text{Solar Intensity} = \text{Solar Constant} \times \sin(\text{Sun Angle}) \]

Solar Constant varies according to the specific location on earth and its atmospheric conditions. Sun Angle is the angle of the sun to a horizontal flat surface at that location. This equation was incorporated into the computer simulation described at the end of this paper.

The photovoltaic energy measurements were taken over a period of time that was limited and prone to random equipment error. Therefore, it would be premature to take away broad conclusions from them alone. However, they were largely consistent with more authoritative sources of such data. They also provided a first-hand corroboration that was relevant to the thin-film photovoltaic technology being considered for the design project.

The ease of installing thin-film on tension membrane fabric argues favorably towards its use. Moreover, as reported by Bello [3], thin-film photovoltaic cells have the potential to produce more power over time than more conventional photovoltaic technology because they resist the sun's heat better.

There is also increasing evidence that thin-film photovoltaic cells will begin to become more competitive with conventional, crystalline silicon solar panels. Though typically the efficiencies range from 6 to 11 percent, Bullis [4] claims that the trajectory for commercial development in the near term is 18 percent. In addition, integrating such light weight thin-film photovoltaic technology into a fabric roof material affords the obvious advantage that it can be more flexible in adjusting to movement and imposes less of a load.
After analyzing the energy gains for the varied rigs, the research team concluded that placing photovoltaic cells on the roof of a saddle shaped structure would probably offer the best performance of all the structures under consideration. The saddle shape would allow a greater number of photovoltaic cells to be exposed to solar insolation, was consistent with the angular orientation needed during the key period of occupancy from late spring to early fall, and also seemed well suited to the structural possibilities of fabric architecture. FTL Design Engineering Studio realized a similar application of photovoltaic cells to a saddle shaped roof in 1998 [1].

A saddle roof shape may be obtained by suspending a tension membrane fabric from four primary support points above the ground. Yet, it is not immediately obvious how high to locate these points off the ground so as to optimize the solar orientation of the thin-film photovoltaic cells affixed to the saddle roof. On the whole, it was necessary to account for:

1. The individual heights of the four primary support points above the ground.
2. The shape of the fabric roof resulting from the four points.
3. The optimal rotation of the saddle shape in plan.
4. The fabric’s mass and strength impacting its shape.
5. The best placement of thin-cell photovoltaic cells on the fabric roof.
6. The solar insolation level reaching the photovoltaic cells.
7. Sun azimuth and altitude at the given site longitude and latitude at varied times.
8. The size roof feasible for the given construction method and building site.

The set of conditions was difficult optimize all at once. Therefore, a simulation program was written to color-code and quantify the performance of the saddle roof. Its four control points, orientation and fabric material properties were adjusted in real-time. The conditions depicted in figure 10 are simulated for the morning and noon of March 31st at the building site. The color-coding of the roof, typical of energy analysis and lighting software, used red to blue colors to signify high to low solar insolation values. The value range of each color could be increased to capture smaller increments in solar insolation.

The software application was written in the Processing open source language, relied upon several of its published libraries [7] and was influenced by fabric shape simulation programs developed by several researchers at the University of Stuttgart in Germany (see acknowledgements). The color-coding of the roof could be switched to show either the solar insolation level or the angle of roof fabric to the sun. A sun-tracking algorithm developed by CIEMAT, Madrid, Spain, was incorporated. In addition to the color-coding, solar insolation levels were also reported numerically in real-time.

Seeing the fabric suspended and the insolation color-coded in real-time helped to isolate the optimal conditions. Insolation on the fabric surface increased overall when the four primary supports of the fabric were located at the ends of axes that ran directly north to south and east to west in a diamond shaped plan (see figure 10). In addition, insolation increased by 22 percent at mid-day when the height of the northernmost of the four fabric supports was elevated from 27.5 feet to 47.5 feet during winter solstice. A reduction in height was less beneficial at mid-day during summer solstice; still, solar insolation
increased by roughly 10 percent in the early morning and late afternoon when the northernmost fabric support was lowered back to 27.5 feet at that time of the year.

When the roof shape was fully optimized, the level of solar insolation on March 31 at noon was on average approximately 702 units of watts per square meter (Watts/m²). When least optimized the level of solar insolation was on average approximately 576 units. When fully optimized during winter solstice, the level of solar insolation was on average approximately 523 units on average. When least optimized the level of solar insolation was on average approximately 423 units. Note that these are numbers simply indicate relative performance, but aren’t fully predictive of actual performance which would need to be more carefully calibrated to site specific conditions, fabric movement and other environmental factors. Total kw/h was not estimated for the thin-film photovoltaic cells referenced earlier. Such a calculation is likely to be more meaningful once the complete specification and layout of the cells on the roof is determined. It is assumed that the performance of the photovoltaic cells would likely be proportional to solar insolation though this needs further validation.

Figure 10
Color-coded insolation simulated for morning and noon on March 31st at SERC

Rigging the Fabric
Before further optimization studies could be developed, the research group built a series of physical models to test variations in rigging and material fastening. In synthesizing various schemes, this author designed a solution based upon the use of wooden boat bowsprits. The rig of a bowsprit was adapted to support the roof structure as depicted in figures 11 and 12 in order to facilitate its movement by means of winches and cables. The first walls tested were also made from fabric and suspended from cables.

At the time of writing this paper, the rigging necessary to dynamically adjust the height of the roof is still under development through a series of increasingly detailed physical models. A gooseneck connection anchored the bowsprits to the ground (see figure 11). The northern bowsprit (the tall wooden cylinder in figure 11) was primarily used to raise and lower the roof to adjust for solar insolation angles. However, the rigging and length of the cables needed require further study.
Combining Energy Modeling Techniques

Upon the completion of the particle spring based dynamic energy model described above, the analysis proceeded with a study of ambient indoor temperature and air conditions. The design model was ported into Ecotect for a rough estimate.

The analysis of discomfort degree hours indicated that the lodging structures would be comfortable from May through September, but that occupancy over a longer period would require an additional heating system. Discomfort degree hours (DDH) is the sum of the hourly room air temperatures outside the occupant's comfort zone. The red graph in figure 13 indicates times when the interior space would be considered too hot, and the blue graphic is when the interior space would be too cold. However, there is some uncertainty where comfort zones exist for individual people. Emphasis on ventilation systems may also help to reduce the level of apparent discomfort as noted by Darby [5].
Since there is a potential to occupy the site during the cold days of early spring and late fall, it was determined that the thin film photovoltaic cells were not capable of supplying the full year-round energy needs of the structure. To compensate for this, the next step was to size a radiant heating floor system that could be used during colder time periods.

Taking a Closer Look At Rigging The Structure

It appeared upon closer analysis that re-rigging the structure at the corners was needed to retract it more effectively. Computer animation of the structures hinted at how the rigging would work. Physical mockups were needed to work through complex inter-relationships between cables, winches and pulleys.

In the first of two revisions shown on the left-hand side of figure 14, the winches and pulleys are given greater detail than earlier studies. A single winch with two connected cable spools was tested as a way to synchronize the two functions of 1) movement of the bowsprit off of the ground and 2) retraction and unfurling of the roof fabric. However, the single winch proved impractical due to problems in coordinating the cable length for the two different functions.
In the second of two revisions shown on the right-hand side of figure 14, the single winch was divided into two separate systems. Correspondingly, the movements of the bowsprit pole and the fabric roof were separated and could be more easily adjusted relative to each other. Cable lengths for the two independent winches were also more easily determined. A pulley controls the relationship between the two sets of cables. The resulting rig is more easily controlled for retracting and unfurling the roof structure.

In figure 15 below several images are taken from an unfurling sequence in which the two-winch rig was tested. The cables are of a carefully determined length and the two winches are calibrated to insure that the erection of the bowsprit and the roof are synchronized.

A much larger scale model was completed in Spring 2011 for more detailed evaluation of rigging, fabric construction, and wall surface area and to assist in understanding the overall transformability of the structure as shown in figure 16. It was
quickly realized at this scale that the walls of the structure could be revisited for energy performance with respect to ventilation, easy of operation, insulation, and absorbing humidity, all factors that would contribute to interior comfort.

The larger scale model has led to the present focus on the performance of the wall surfaces and the integration of more pocketed systems for allowing them to control shadow, and humidity and to breathe. A CNC sewing machine is being employed to test a grid of cellular like fabric units. The potential to develop such a system was influenced by a workshop led by Thomson and Karmon at Smart Geometry 2011 in Copenhagen [8], and also the geometry of tessellating metal shading structures being developed by Hoberman Associates, New York in partnership with A. Zahner Company of Kansas City, Missouri.

**Remaining Issues**

In the next stage of development, the project will also evaluate performance studies of thermal mass in conjunction with radiant floor heating. The radiant floor heating system is coupled with photovoltaic energy units housed nearby. A commercial system has been sized for with radiant coils embedded into the floor slab (see figure 17). An active solar system using standard photovoltaic cells is depicted on the left-hand side of figure 17. The intention is to use radiant floor heating only during early spring and late fall when the discomfort degree hours such as depicted in figure 13 would warrant its use.
In addition, more prototypes of the fabric rigging are needed to ensure that it can be raised and lowered as needed to maximize solar insolation. Based upon the solar insolation modeling done in figure 10, it appears that seasonal adjustments to the saddle shape for winter and summer would help to increase the performance of the photovoltaic cells. Manufacturer data also concludes that seasonal rather than daily adjustments are likely to be most effective “compromise between optimizing the energy on your panels and optimizing your time and effort spent in adjusting them.” [Landau, 2011]. As already shown in figure 9, controls that can be used open ventilation channels under the roof would help to cool the photovoltaic cells on hot days and thereby increase their performance.

In an alternative approach, the roof is stationary and thin film photovoltaic cells are affixed to strips of fabric that are suspended just above it. The strips can be rotated to an optimal angle to the sun independently of the roof as a whole. Still, preliminary test models demonstrate that it is difficult to insure that the rotating strips of fabric are protected against debris, ice and snow. The fabric strips are also being tested to help allow for ease of maintenance.

Overall, the simulations and measures that were used provide a sense of relative rather than absolute performance. The final structure will require more precise engineering analysis beyond the limits of the simple particle spring physics system used. MultiFrame Integrated Structural Engineering is a software product that is used by one of the advisors to the studio project for such a purpose. More exact studies will be needed to account for mass, strength, wind load, lift and other properties of the specific fabric material to be chosen. The particle spring model has the advantage of real-time simulation and quick design feedback, and gives an approximate shape of the fabric that needs to be verified by other means. Physical mockups at every stage of this process revealed hidden issues difficult to fully anticipate in the computer based representations.
Building performance analysis through Ecotect was highly approximate and more advanced technology for this is being explored.

Conclusion
In a recent paper that was co-written with Mark Gross and Gabriella Goldschmidt [Mark, 2008], we underscored Martin Woolley’s argument that “in the “post-IT era” tools must be developed ad hoc as needed, where (unlike today) the designer is the tool builder. In this respect, the tool is not selected, but created contingent on the type of design task, the stage it is in, and adapted to circumstances”. In this design project, the architect as toolmaker needed to visualize a continuum of design changes where real-time transformation of the proposed structure was helpful. The project required making a software tool and a number of physical rigging tools.

Similar to the oar maker’s custom-made cutting plane used by the students in the wooden boat-building workshop, a particular computer simulation tool was crafted out of other available algorithms and code fragments. By integrating and adapting available technology for a case specific use, the design issues and relationships could be more clearly visualized and potential design solutions more readily explored.

The simulation used in the project underscores the utility of parametric control over roof shapes used to create the particle-spring physical simulation. More generally, the case study demonstrates a greater potential to shape tools on an ad hoc level when a community of interested designers become interconnected and exchange software modules.

Each investigation into the performance of rigging, fabric and thin-film photovoltaic cells seemed to reveal yet additional issues related to performance and construction. In our process, while software tools have been customized to facilitate our thinking, not all decisions have been arrived at through their representations. The actual realization of the project was also dependent upon the invention of physical rigs such as depicted in figures 8, 9, 12, 14, 15, and 16, that could inform the project. The full-scale construction itself will inevitably introduce some new factors, not untypical of any building project, that will need to be addressed and which could not have been fully predicted by the preceding software or physical prototype analysis. Still, in each step of this project, writing computer software tools and making physical tools have been complimentary to each other. The computer tools identified a wider range of design options than might have been discovered through physical prototypes alone. Physical fabric rigs have been necessary to validate design decisions and to discover hidden issues.

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published 2D fabric simulation developed by Dicky Ferdiansyah and Christoph Waibel at the Institute for Contemporary Design in Stuttgart (see example at Processing.org) served as a helpful starting point for the 3D approach taken in this project. A Processing language tension-active systems fabric module presented at Smart Geometry 2010 by Universität Stuttgart PhD candidate Sean Ahlquist was also instructive. A sun-tracking algorithm published by Centro de Investigaciones Energéticas Medioambientales y Tecnológicas, CIEMAT (http://www.psa.es/sdg/sunpos.htm) was incorporated.

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