

Thermal Comfort in a Sustainable House by Frank Lloyd Wright

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ABSTRACT Frank Lloyd Wright was an innovator in Architecture, building the Solar Hemicycle buildings, the Textile Block buildings and many other buildings designed to respond to the environment. They each have aspects of sustainable design. But how sustainable are the buildings and perhaps more importantly, do they provide sufficient shelter and human comfort? Any house can be a passive and low energy house if there is no concern for human comfort.

The Freeman House was one of FLW's textile block houses, built with blocks made on site from local materials. A data network, BEEMS, has been monitoring the house since April, 2005. Subsequently, *Onset* Hobo and *Stowaway* and *Maxim* iButton dataloggers have been installed in parallel locations. Data from three different systems are compared for accuracy and normalization, in order to provide consistent data over the entire house.

The thermal comfort of the house is analyzed using human comfort charts. To what extent does the house save energy at the expense of the occupants' comfort? What parts of the house are comfortable and what parts are not? Why? Was Frank Lloyd Wright an early example of "greenwashing" (making unsupportable claims for a new building type?) How does the building compare to normal construction around it? In addition, the benefits and difficulties associated with the more complex monitoring systems and the more simple systems are also discussed.

Keywords: energy, comfort, Frank Lloyd Wright, historic preservation, sustainability

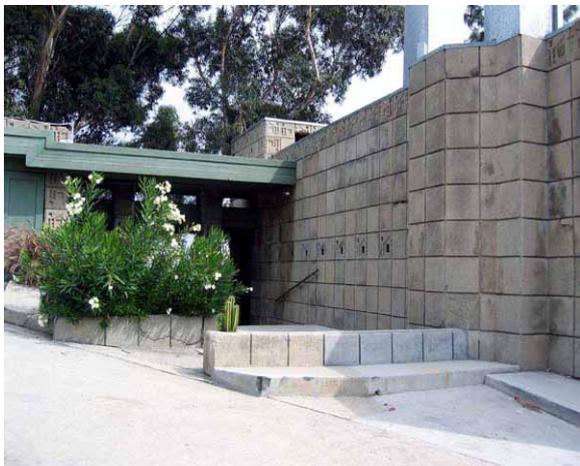


Figure 1: Entrance at Upper Level

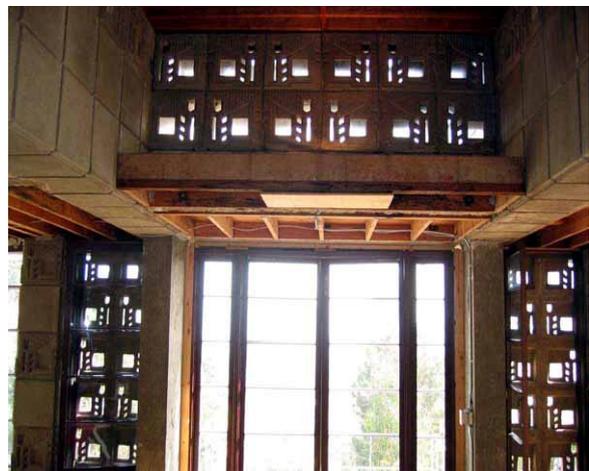


Figure 2: Textile Block w/ Glass, Upper Floor

1. INTRODUCTION

Frank Lloyd Wright (FLW) set out to develop a form of climate responsive affordable housing for the American Southwest in the 1920's. He rejected the habit of borrowing heavily from the Midwestern and Spanish Mission styles and concentrated, instead on the more indigenous Mayan and pueblo building forms. At the same time, he combined locally available sand with a cement binder to create a house which grew from the ground that it was built on and could be manufactured locally by semi-skilled labour. Of the many designs he drew, three houses were

constructed. The Storer House was completed in 1923, the Ennis House in 1924 and the Freeman House, also in 1924.

The blocks are 16 inch x 16 inch (40 cm x 40 cm) square and relatively thin, with concave edges designed to receive grout or steel reinforcing bars. The steel bars were to be woven together, with the blocks filling in the "warp and weft" of the bars.



Figure 3: Two Blocks

were built in parallel layers and tied with reinforcing, leaving a hollow space between the two, for drainage and (scant) insulation.

The horizontal surfaces, including floors and roofs, were wood framing, often cantilevered at the corners to allow for corner glazing. See Figure 4.



Figure 4: Southwest Corner

The Freeman House sits on a steep hillside in Hollywood, with a tremendous view on the south side of the site. It is approximately 250 m² of interior space designed by Wright with a wonderful terrace on the south side accessed by stairs from the lower floor. There were later additions by Rudolph Schindler, which are somewhat separate from the building and are not monitored nor reported in this paper. See Figures 5 and 6.

Although the house was supposed to be FLW's prototype for the Southwest, by the time the house was under construction, FLW had returned to the Midwest and the house was built under the supervision of his son, Lloyd Wright, who had a separate architectural practice in the area. The house rapidly became more and more expensive, as site work and a high failure rate of the hand made blocks required more and more labor. The original budget was \$3.60 / sq. ft. and the final cost was \$9.20 / sq. ft. This made the Freemans unhappy, as they had to do without furniture for the first few years. It represents his lack of success at creating affordable housing, despite the excellent intentions.

There is disagreement as to the original heating system. Chusid maintains that there were 13 electric resistance wall heaters, plus the two fireplaces. Schindler is known to have added several unvented gas heaters, which have been disconnected. Dimster maintains that there is a radiant floor system, also

non-functional at the current time. The only heat in the building during the monitored period was a freestanding electric space heater, used by the current occupant, Professor Romanach, in her room (to keep from freezing.)

2. THE SENSORS

Three different types of sensors were used in this study. The BEEMS wireless sensor network was already in place, installed mostly at ceiling height. Additional HOBO and iButton dataloggers were placed adjacent to the BEEMS sensors to evaluate the wireless sensor network.[2] Additional sensors were placed at separate locations.

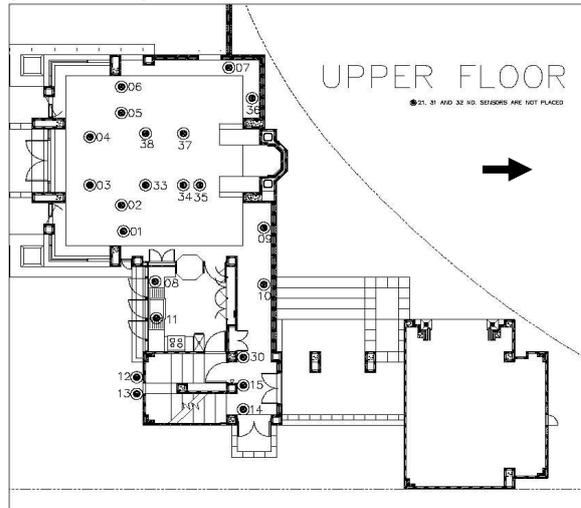


Figure 5: Upper Floor w/ Sensors

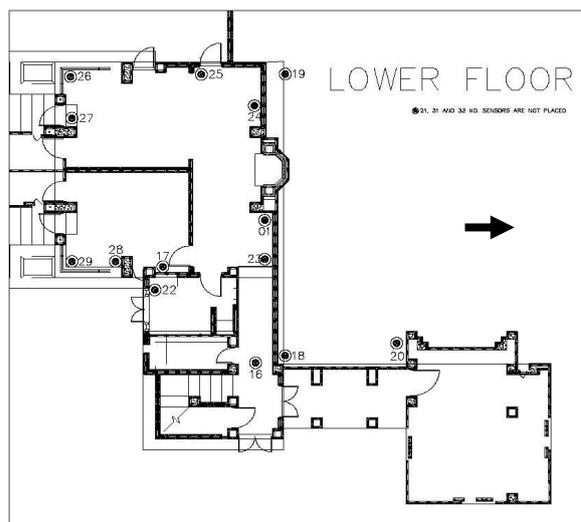


Figure 6: Lower Floor w/ Sensors

2.1 iButton Temperature Data Loggers

A total of 11 Maxim iButtons were used for the study. [3] The dataloggers are 16mm in diameter and completely sealed, with lithium batteries. The surface

is the download contact, so there is no possible leakage point. The measured temperature range is from -40 °C to + 125 °C with an accuracy of ± 1 °C. They were programmed to record at hourly intervals.

2.2 HOBO Temperature and Relative Humidity Data Loggers

Six Onset HOBOS were placed to measure temperature and relative humidity. [4] One was of the sealed outdoor type. HOBOS record from -20 °C to + 80 °C (-4 °F to 158 °F) with the accuracy of ± 0.7 °C at 21 °C (±1.27 °F at 70 °F). Relative humidity is recorded from 25% to 95% with an accuracy of ±5%.

2.3 BEEMS Wireless Sensor Network and Weather Station

The Building Envelope Environment Monitoring Services (BEEMS) system is a wireless sensor network plus a Weather station. It was set to record at 15 minute intervals.

The network consists of 38 wireless sensors (10mm x 30mm in size), 7 routers and one gateway computer running iMON software. Most of the sensors are installed just below ceiling level, while a few are embedded in the wall. The gateway monitors all seven routers and each router monitors three to five endpoints. The location of BEEMS sensors is shown in Figures 5 and 6 (see again.)

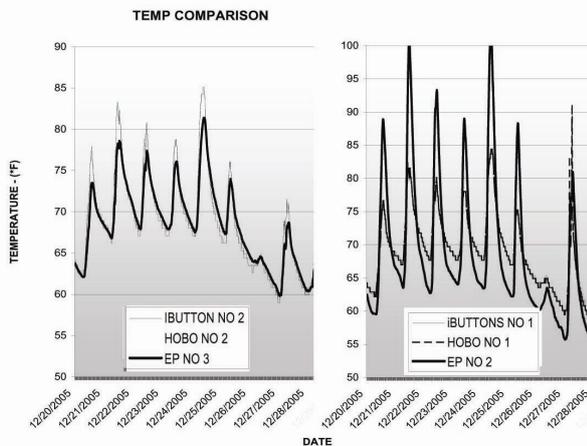


Figure 7: BEEMS vs. iButton vs. HOBO, good correlation and anomalous data

2.4 Sensor Preparation and Comparison

The iButton and HOBO dataloggers were tested and normalized prior to placement. One iButton was discarded because of anomalous readings. With that exception, the readings remained within .75 C (1.5 F) of one another.

Several dataloggers were placed adjacent to BEEMS sensors to verify BEEMS data. Five locations resulted in nearly identical readings ± .75 °C (± 1.5 °F). A sixth location showed agreement among the dataloggers and extreme gyrations by the BEEMS sensor. The BEEMS sensor data was discarded for that sensor. See Figure 7.

2.5 Data Representation

Data was captured and viewed for prototypical periods in time series plots and in Olgay human comfort chart formats.

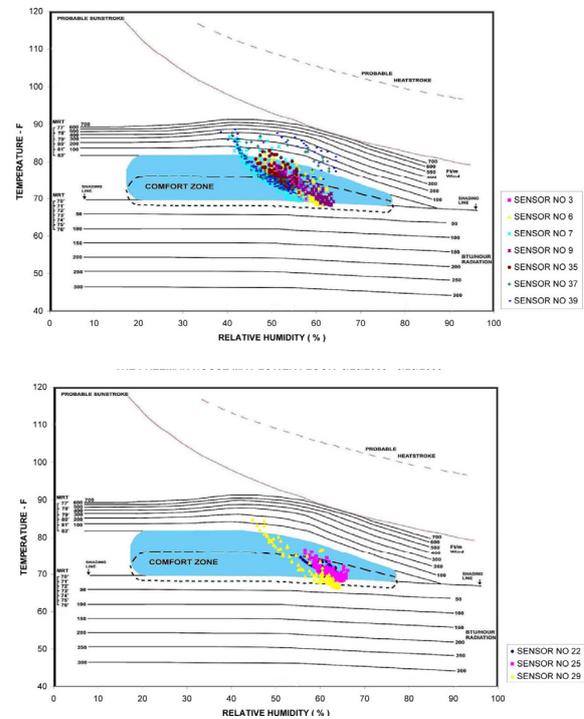


Figure 8: May Upper and Lower Floors

3. COMFORT ANALYSIS

3.1 May

Both upper and lower floors appeared to be comfortable in May. The upper floor varied due to solar gain and skin losses. The greatest variation on the upper floor came from sensor 38, which is near the ceiling on the West side of the upper floor and heats up in the sun, then cools down drastically because of window losses. The lower floor benefits greatly from the earth sheltering effect, remaining within the comfort zone nearly all the time. The Relative Humidity is slightly high, but this comes primarily from the fact that the infiltration air is being cooled passively, without being dehumidified. See figure 8.

3.2 August

About half of the hours fall above the comfort zone, with the lower floor benefiting less from the earth sheltering as the mass has now warmed up from the summer months. See Figure 9. Compare to Figure 8.

The upper floor shows a variation primarily because sensor no 7 is near west window and sensor no 37 is near west wall, while sensor no 38 and 9 are east side back of the space. The lower floor shows a significant time of day effect because sensors 22 and

25 are next to the west side wall while sensor no 29 is east side next to the window. See Figure 10.

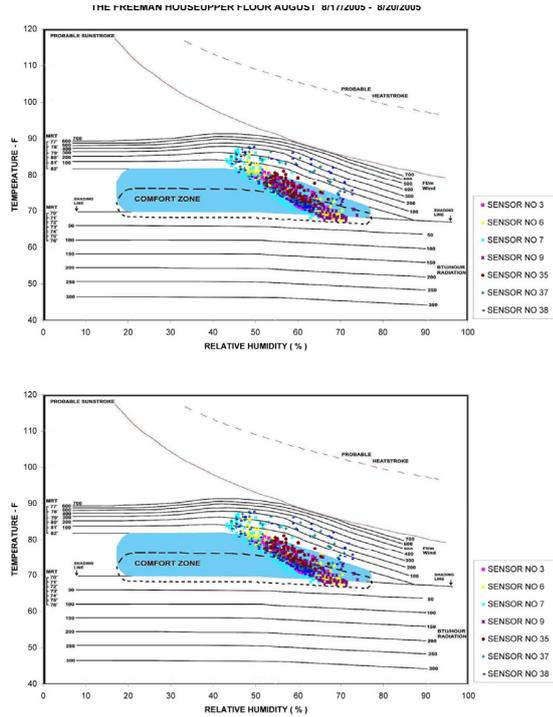


Figure 9: August Upper and Lower Floors

other losses and the high mass walls only serve to keep the space uncomfortable even during sunny afternoons. The lower floor is too cold, but benefits again from the earth sheltering effect and some solar gain on the SE corner. See Figure 11.

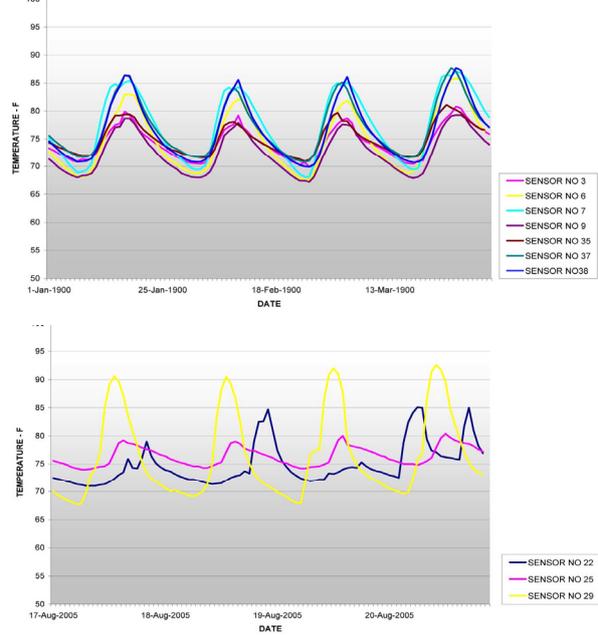


Figure 11: Time Series, Upper, Lower Sensors

3.3 January

The upper floor is simply too cold almost all of the time. The solar gain does not begin to offset the

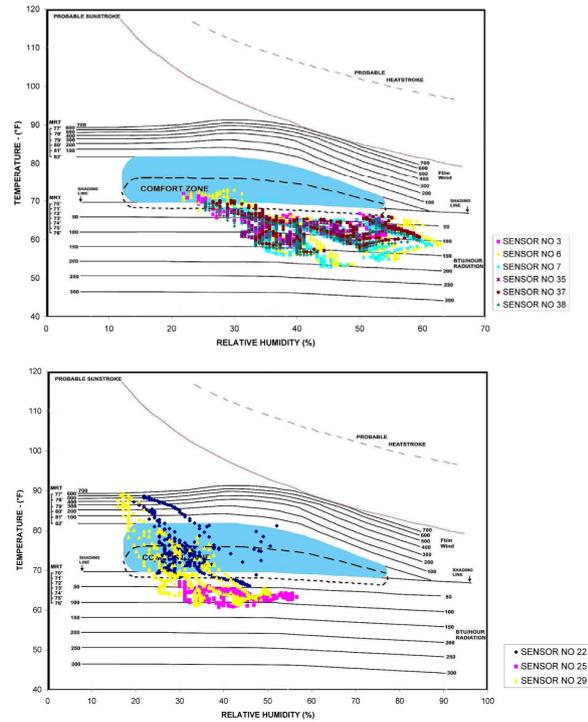


Figure 10: January Upper and Lower Levels

3.4 March

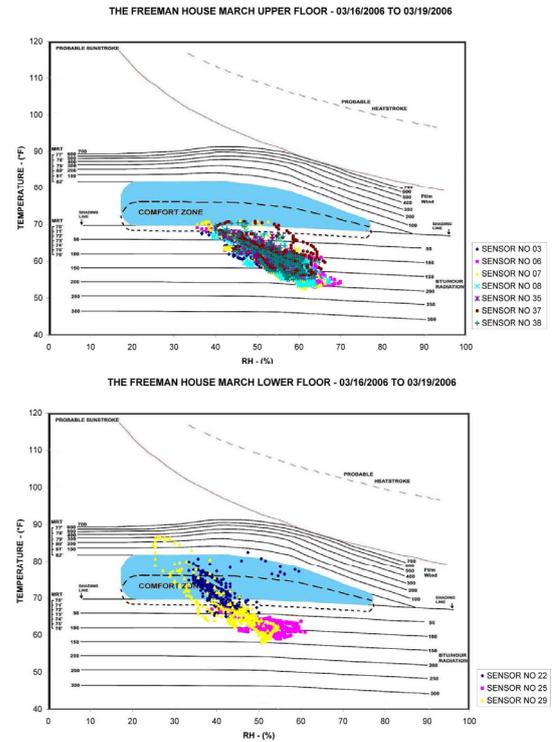


Figure 12: March Upper and Lower Levels

Finally, in March, see Figure 12, the time lag and thermal storage effects of the high mass walls and earth sheltering have been completely damped out by the temperature history and a series of rainy days. Both upper and lower floors are too cold, all of the time. Note that even with a space heater, Professor Romanach (the current occupant) can barely hold the temperature comfortable in her space.

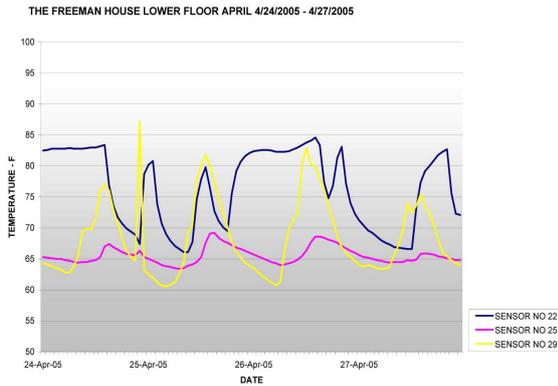


Figure 13: Light switch proxy behaviour

3.5 Anomalies

There were other anomalies observed in the data, which did not reflect the actual behavior of the house, but rather the learning curve associated with monitoring buildings.

One triplet of sensors which were placed close together did not track in parallel. See figure 13.

Upon returning to the site, it was found that one of the sensors was immediately adjacent to a light fixture and the temperature rose whenever the fixture was turned on. It was possible to know when the light was on, but not what the temperature of the space was. This is similar to Heisenberg's Uncertainty Principle!

4. COMPUTER SIMULATIONS

The Freeman House was also simulated in two computer programs, to see what sort of improvements might occur with the addition or substitution of modern building materials.

4.1 HEED

The Home Energy Efficient Design (HEED) program was developed by Murray Milne's Energy Design Tools Group at UCLA expressly to deal with residential and small commercial construction. It is extremely user friendly and surprisingly sophisticated for small buildings. However, as is typical of most U. S. origin programs, it is designed primarily to evaluate energy usage rather than calculate a temperature float and the resulting human comfort in unconditioned buildings. So comparisons must be made by assuming a system which will maintain a

comfort range and checking the loads which result. See Fig. 14.

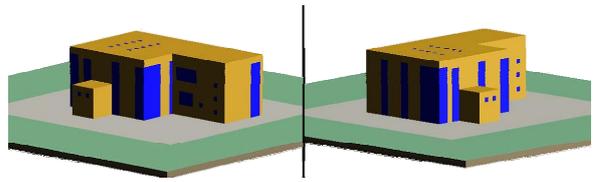


Figure 14: SE and SW views of the HEED simulation model

For the simulation, a default HVAC system was added to the house. It did not pass code (Title 24). Then two alternatives were simulated. In the first, there was added insulation of $R = 11 \text{ hr F ft}^2 / \text{Btu}$ ($1.94 \text{ m}^2 \text{ K} / \text{W}$) on all exterior walls. There was a significant reduction (from \$1,803.05 to \$1,424.86) in the energy costs and the building also passed Title 24 (the California energy code.) The second alternative substituted clear double pane low-e of $U=0.67 \text{ Btu} / \text{hr F ft}^2$ ($3.8 \text{ W/m}^2\text{K}$) glazing for the clear single pane of $U=1.27 \text{ Btu} / \text{hr F ft}^2$ ($7.21 \text{ W/m}^2\text{K}$). In that case, the energy cost results were reduced by nearly half (from \$1,803.05 to \$940.54).

4.1 DOE2.2 / eQuest

The utility supported Quick Energy Simulation Tool (e-QUEST) is based on DOE2.2. DOE is capable of much more detailed and complex simulations, but still does not calculate a true temperature float and human comfort. It is necessary to set a comfort range and test the resultant loads. It was possible to build up a more articulated model of the Freeman House. See Figure 15.

This time, three window treatments were tested: single pane, double pane low-E and triple pane low-E glass types. The energy utility bills decreased gradually with the change of glass up to \$100 per month (Fig.15).

The house was also simulated with increasing insulation in the exterior walls, while retaining the primarily masonry approach to the building. The gap between the two wythes was filled with $R=4$ and then $R=8$ insulation. This time again there was significant (up to \$60 per month) decrease in monthly utility bills.

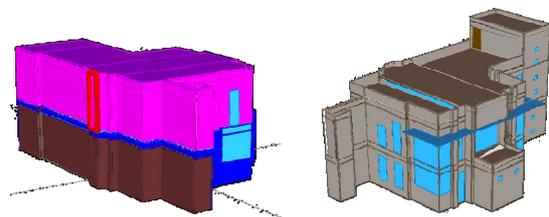


Figure 15: NW & SW views of the eQuest/DOE model

5. SUMMARY

It is unfortunately clear that, although the Freeman House is a beautiful building on a fantastic site, it is not an energy efficient or environmentally sustainable building, as designed and executed by Frank Lloyd Wright.

Wright's contention that the building would work as low cost housing is clearly not true. It cost three times the budget. Wright wrote of using the sun as a thermal source and later demonstrated the concept in the "solar hemicycle" houses. The Freeman House is open to the South, made of high thermal mass materials and embedded into the hillside. But the high mass walls do not make up for the complete lack of insulation (the air gap is simply not sufficient) and the single pane windows lose more heat than they gain. The computer simulations imply that the buildings could be kept comfortable with less than half the energy if there were insulation in the air gap and double pane low-e windows.

The use of dataloggers to verify comfort levels and building performance is a powerful tool for understanding how buildings work. The iButtons are ~\$15 each, the HOBOs are ~\$75. They are reliable and accurate, often more so than very complex and expensive systems, although they are limited to placement where they can be easily retrieved and they require on site visits instead of remote data access.

6. CONCLUSION

Greenwashing has occurred throughout most of architectural history, in one fashion or another. Indeed, the word fashion is appropriate. It may become fashionable for an architect to claim that a building is "green" and revolutionary. But only by testing the performance of buildings is it possible to know whether that is the case. The European approach of requiring certain building performance subsequent to construction seems to be a step in the right direction. It would be quite useful if there were a similar system in the U. S. and if both systems were to actually measure and understand how buildings work, based on real measurements and basic design principles.

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