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Examining the Impact Information Representation in Eco-Feedback Systems has on Building Occupant Energy Consumption Behavior

Rishee K. Jain[1], John E. Taylor[2], Patricia J. Culligan[1]
[1]Department of Civil Engineering & Engineering Mechanics, Columbia University, USA
[2]Charles E. Via Department of Civil & Environmental Engineering, Virginia Tech, USA

Abstract: The built environment accounts for a substantial portion of global energy consumption. Concerns over rising energy costs and climate change have led a growing number of researchers to examine the impact building occupant behavior has on energy consumption. By combining sustainable infrastructure management philosophies and information technology, researchers have developed eco-feedback systems that provide occupants with real-time information on their energy consumption. While such eco-feedback systems have been observed to drive significant reductions in energy consumption, little is known about the specific system design features that are driving such reductions. One such design feature is the way in which feedback information is represented to users. In this study, we aim to examine the role information representation plays in encouraging reductions in energy consumption. We conducted a one month empirical study with 39 participants in an urban residential building in which occupants were provided email based eco-feedback. Participants were broken into two different study groups; one group was provided with feedback in kWh and a second group was provided with feedback in the equivalent trees required to offset emissions associated with their kWh energy usage. Results revealed that information representation has a statistically significant impact on the energy consumption behavior of users. These results indicate that information representation plays an important role in an eco-feedback system's effectiveness and motivates further research to understand how information representation can be leveraged to maximize energy savings.

1 Introduction

The built environment accounts for over 40% of energy consumption in the United States (U.S. Department of Energy 2011) and in many parts of the world making it a primary target for increasing energy efficiency. Concerns over rising energy costs coupled with the environmental impacts associated with energy consumption have led researchers to examine ways to reduce energy consumption in buildings. Recent research (Kolahdoozan and Leite 2012) has pointed to the potential of reducing energy consumption in existing residential buildings by 29% through energy-efficient retrofits. While such retrofits could boost energy efficiency substantially, concerns exist over the long-term effectiveness of such capital intensive retrofits due the "take back effect" (Haas et al. 1998). The "take back effect" occurs when a building occupant adopts inefficient consumption behavior that could reduce or nullify the efficiency gains associated with a retrofit. For example, if energy efficient compact fluorescent light bulbs are installed in a building but occupants now leave the lights on longer than before, savings associated with the new light bulbs may be significantly diminished. Thus, a comprehensive and effective strategy to decrease energy consumption in buildings must address the behaviors of building occupants. Two independent simulation studies (Azar and Menassa 2011; Yu et al. 2011) found that occupant behavior can have a substantial impact on building energy consumption and further support the need to engage building occupants in building energy management systems.

In order to engage occupants in building energy management, researchers have developed eco-feedback systems. An eco-feedback system provides building occupants with information regarding their historical and current energy consumption through the use of smart metering technology. A meta-analytical study (Fischer 2008) of empirical eco-feedback experiments concluded that eco-feedback systems are an effective tool for reducing energy consumption. Behavior-based efficiency programs, including providing eco-feedback, have also been shown to be among the most cost effective energy efficiency strategies on the market (Allcott 2010). While eco-feedback systems have been observed to drive significant reductions in energy consumption, there is a paucity of research regarding what specific system design features are driving such reductions. One such design feature is the way in which information is represented to occupants. In this study, we aim to examine the impact information representation in eco-feedback systems has on energy consumption behavior.

2 Background

2.1 Eco-Feedback System Design

Numerous eco-feedback systems have been implemented and studied by both academia and industry. Results have been promising with observed energy savings ranging from 2.7%-55% (Allcott 2010; Faruqui et al. 2010; Fischer 2008; Peschiera et al. 2010; Petersen et al. 2007; Ueno et al. 2006; Vassileva et al. 2012). However, this large variance in savings illustrates the need to understand what is driving significant savings in some eco-feedback systems and not others. Thus, researchers have begun to examine the design of eco-feedback systems and its impact on energy savings. Froelich et al. (2010) conducted a comprehensive comparative survey of over 100 eco-feedback systems and concluded that while several guidelines for eco-feedback systems have been established regarding interface design, feedback frequency and information visualization, little work has been done to empirically verify the effectiveness of such guidelines. Karjalainen (2011) examined empirical data from qualitative interviews to understand user preferences regarding eco-feedback interface design but conclusions from this study were not correlated to actual energy savings. A more recent study (Jain et al. 2012) expanded on this work by assessing the effectiveness of specific eco-feedback design components in terms of empirically observed energy savings. This study found that providing occupants with historical comparison visualizations and an incentives feature in an eco-feedback interface correlated with reductions in energy consumption. While these studies have allowed us to gain a high level understanding of eco-feedback design, Pierce et al. (2010) highlights that little is known regarding how specific design details, such as information representation, can impact the effectiveness of an eco-feedback system.

2.2 Information Representation in Eco-Feedback Systems

Research regarding information representation has been limited to secondary analysis within empirical eco-feedback experiments. For the most part, feedback has been presented to building occupants in one of three representative units:

- Direct energy units such as kWh or kW (Jain et al. 2012; Peschiera and Taylor 2012; Peschiera et al. 2010; Petersen et al. 2007)
- Environmental externalities such as associated CO_2 emissions (Grevet et al. 2010; Petkov et al. 2011)
- Monetary units such as US Dollars (Faruqui et al. 2010; Grevet et al. 2010)

A study by Jazizadeh et al. (2012) concluded that users preferred receiving eco-feedback in direct energy units and environmental externalities over generic energy saving tips. Other empirical studies (Bonino et al. 2012; Faruqui et al. 2010; Vassileva et al. 2012) have provided insight into user preferences regarding information representation, but limitations in data capture or survey techniques in these studies did not allow for the impact of information representation on energy consumption to be explicitly tested. While previous work has also pointed to the fact that *"the units of display can have a powerful influence on the consumer as they effectively dictate the comprehension, importance and relevance of energy use to associated environmental problems"* (Wood and Newborough 2007, p.499), the impact of information representation on actual savings has not been substantiated with empirical energy consumption data.

Thus, the primary objective of this study is to ascertain whether information representation in eco-feedback systems can impact energy consumption behavior of building occupants.

3 Methodology

3.1 Experimental Design and Procedure

In order to test the impact that information representation plays in energy consumption behavior, an experiment was designed with two study groups and a control group. Monetary units were not included in the scope of this study because occupants in the instrumented test-bed building do not pay directly for electricity. The study groups were designed as follows:

- *Study Group A* – provided with eco-feedback in direct electricity units (kWh)
- *Study Group B* – provided with eco-feedback in environmental externality units (equivalent number of trees required to offset CO_2 emissions associated with their electricity consumption)
- *Control Group* – not provided with eco-feedback

The study lasted 32 days (March 30, 2012 through April 30, 2012). An eco-feedback email was sent each Friday to participants in Study Group A and Study Group B. A total of 5 emails were sent. A more detailed description of the content contained in eco-feedback emails sent to participants is provided in section 3.4.

Recruitment resulted in a Study Group A of 21 participants and a Study Group B of 18 participants. The Control Group consisted of 39 building residents. Prior to recruiting participants, the research team obtained approval from Columbia University's Institutional Review Board for the human subjects experiment and all recruitment materials. All recruitment materials emphasized participating students would be sent an email once a week detailing their electricity consumption and be entered in a random drawing to win eco-powerstrips or gift certificates to local restaurants. Any potential environmental benefits associated with participating were omitted from recruitment materials and in-person communication to avoid a recruitment bias towards environmentally conscious residents. Recruitment was done both electronically and in-person at the test-bed building. Emails were sent to all residents with a link to a recruitment website that allowed potential participants to view the digital consent form and sign-up for the study. In-person recruitment was done by presenting building residents with a printout of the consent form and having them sign-up by filling out a short paper form. Residents who opted to participate in the study were randomly placed into Study Group A or Study Group B.

3.2 Hypothesis

The primary objective of this study is to establish whether information representation in an eco-feedback systems impacts energy consumption behavior. In order to do so, the following hypothesis was tested:

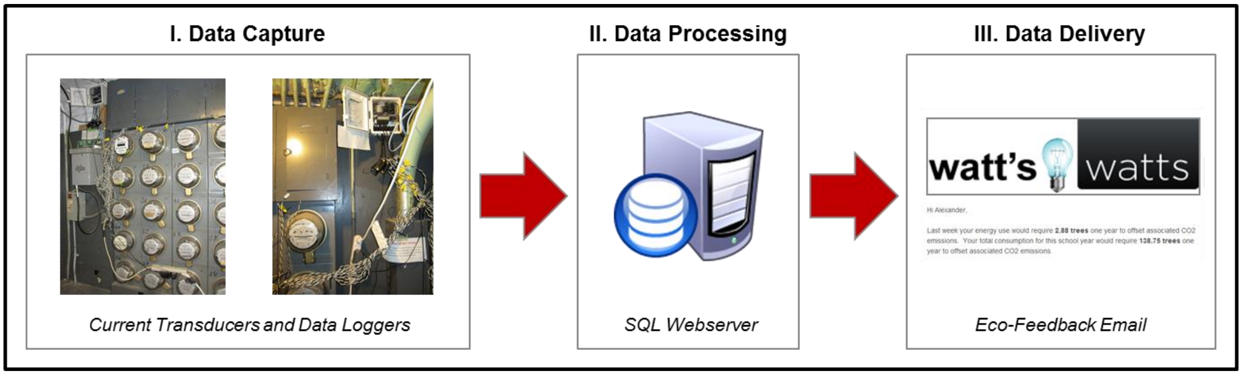
Hypothesis. The units in which eco-feedback information is represented will cause participants in Study Group A (direct electricity units) to consume a statistically distinct amount of energy relative to the Control Group from participants in Study Group B (environmental externality).

3.3 Test-bed Building

The test-bed building is a six story residential building on Columbia University's campus in New York City. Residential units in the test-bed building are either single or double occupancy and have access to natural light via central courtyards or the street. Each unit is comprised of a kitchen, bathroom, living area and bedroom area. The building was built prior to World War II and has high ceiling and thick plaster walls.

3.4 Eco-Feedback System Utilized

For the execution of this study, an email based eco-feedback system was designed, built and utilized. The system consisted of three main components (data capture, data processing and data delivery) as shown in Figure 1.



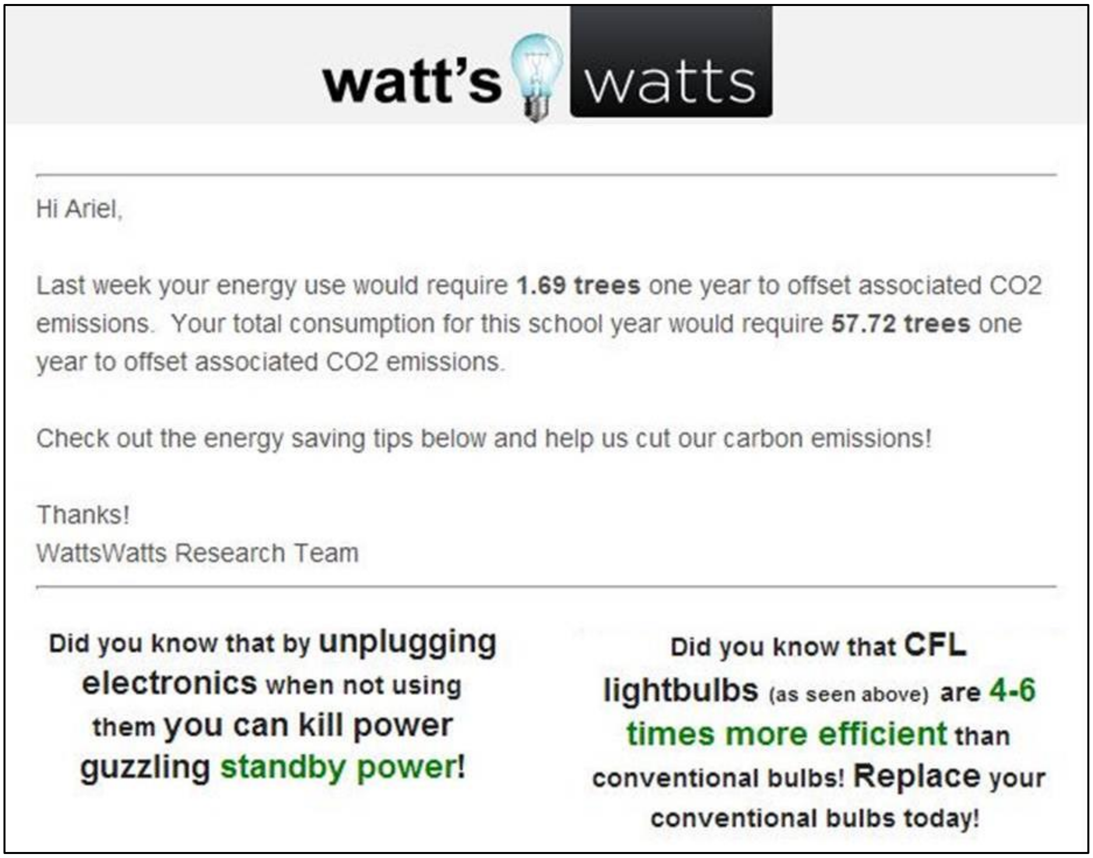
Hi Alexander,

Last week your energy use would require **2.88 trees** one year to offset associated CO2 emissions. Your total consumption for this school year would require **138.75 trees** one year to offset associated CO2 emissions.

Figure 1: Schematic of Eco-Feedback System Utilized in Experiment

Data capture was achieved using Onset Computing HOBO U30 data loggers connected to Continental Control Systems current transducers (range: 0-20 amps). Current transducers captured current data from electricity meters corresponding to each individual unit in 5 minute intervals and transferred this data to one of six data loggers. Data loggers wirelessly pushed amperage data from all electricity meters to a web server every hour. Custom SQL code was written to process and parse amperage values for each unit by first multiplying by 110 volts to calculate apparent power and then taking a Riemann sum of apparent power values over each day to obtain energy consumption values (kWh). Energy consumption values for each unit were then adjusted for occupancy to obtain consumption values for each participant. For participants in Study Group B, values were converted to the “number of trees required to offset emissions associated with their electricity consumption in one year” by multiplying by a factor of .154 for each kWh consumed. This factor was derived from values published by the U.S. Environmental Protection Agency on the average tons of carbon sequestered by an urban tree in one year (.0039 tons of CO_2 per tree each year) and the average emissions of home electricity consumption in the United States (1,301.31 lbs of CO_2 per MWh consumed) (U. S. Environmental Protection Agency 2012). Final electricity consumption values and environmental externality values were exported into a comma-separated value (CSV) file and imported into an email distribution server (Mail Chimp). The email server populated the custom fields in the HTML based eco-feedback emails (e.g. first name, consumption values) and sent personalized eco-feedback emails to all participants on each of the five Fridays in the study period.

Each eco-feedback email contained information on a participant’s energy consumption in the preceding week and cumulatively for the current school year (September thru May). Additionally, each email contained two energy saving tips for reducing energy consumption. Energy saving tips were chosen to reflect efficiency opportunities available to participants during the study period. All participants in study groups A and B received the same energy saving tips each week. A sample eco-feedback email is provided in Figure 2.



Hi Ariel,

Last week your energy use would require **1.69 trees** one year to offset associated CO2 emissions. Your total consumption for this school year would require **57.72 trees** one year to offset associated CO2 emissions.

Check out the energy saving tips below and help us cut our carbon emissions!

Thanks!
WattsWatts Research Team

Did you know that by unplugging electronics when not using them you can kill power guzzling standby power!

Did you know that CFL lightbulbs (as seen above) are 4-6 times more efficient than conventional bulbs! Replace your conventional bulbs today!

Figure 2: Sample Eco-Feedback Email

3.5 Data Analysis

Energy savings was evaluated for each user by determining the change in energy consumption relative to the control group between the study (δ_{study}) and pre-study ($\delta_{\text{pre-study}}$) periods. The pre-study period was taken as the month of February (29 days) to ensure that recruiting efforts that commenced in March did not influence energy consumption of building residents during this period. Energy savings were evaluated relative to the control group to normalize consumption data for external factors, such as weather, daylight and the day of the week on which eco-feedback emails were sent. This analysis approach allowed us to examine energy savings for each user independent of external factors that could affect consumption behavior. The change in consumption ($\Delta_{\text{consumption}}$) for each participant was calculated for each day in the study period using Equation 1.

[1] $$\Delta_{\text{consumption}}\ (\%) = \delta_{\text{study}} - \delta_{\text{pre-study}}$$

where: δ_{study} = consumption for a given day in study period
$\delta_{\text{pre-study}}$ = consumption for the corresponding day of the week
(i.e. Monday in study period evaluated against Monday average in pre-study period)

Consumption (δ_{study}) for each participant was calculated relative to the control group for each day in the study period using Equation 2.

[2] $$\delta_{\text{study}} = \frac{P-C}{C}$$

where: P = a participant's consumption adjusted for occupancy
C = average consumption of the control group

Average consumption for each participant was calculated relative to the control group for each day of the week in the pre-study period using Equation 3.

$$[3] \quad \delta_{\text{pre-study}} = \frac{\sum_{i=1}^{n} \frac{P-C}{C}}{n}$$

where: P = a participant's consumption adjusted for occupancy
C = average consumption of the control group
n = 4 (i.e. first 4 Mondays in pre-study period)

The change in consumption ($\Delta_{\text{consumption}}$) for Study Group A and Study Group B were found to be homoscedastic (having equal variances); hence, a statistical comparison of the two groups was performed using a two-sample Student's t-test. This procedure is based on a method established by Peschiera et al. (2010) and utilized by several empirical studies thereafter. A p-value of below .05 indicated statistical significance in all tests.

4 Results

A plot of the energy savings ($\Delta_{\text{consumption}}$) by day for Study Group A and Study Group B are provided in Figure 3. Results of the statistical analysis are provided in Table 1. Study Group A and Study Group B's average consumption during the study period are shown to be statistically distinct from each other (p-value = .013) allowing us to reject the null hypothesis.

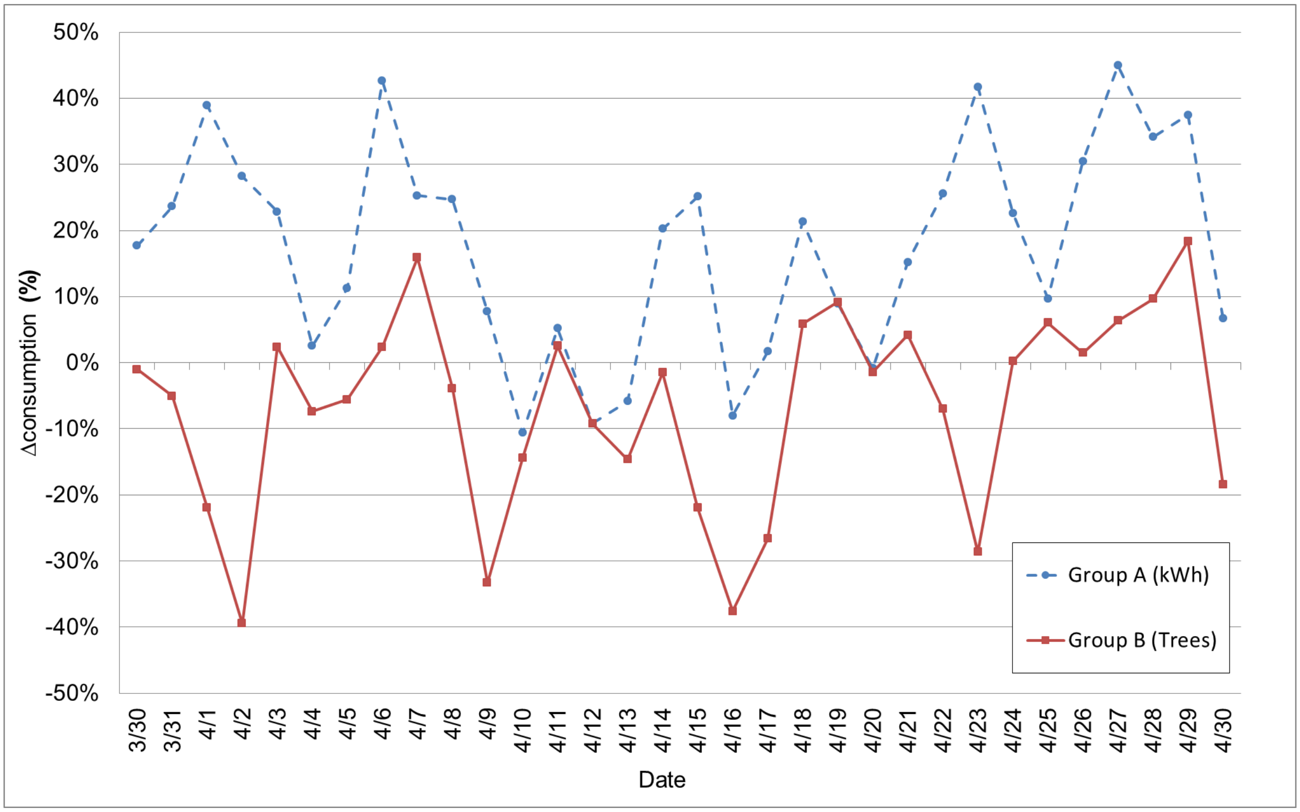


Figure 3: Plot of Energy Savings ($\Delta_{consumption}$) by day for Study Group A and Study Group B

Table 1: Results of the two-sample Student's t-test

	Study Group A	Study Group B	p-value
Average Energy Savings ($\Delta_{consumption}$) over study period	18%	-10%	.013

5 Discussion and Limitations

Disconfirming the null hypothesis indicates that information representation in an eco-feedback system can have a significant impact on energy consumption behavior. The results provide statistically significant empirical evidence to further substantiate literature based arguments made by Wood & Newborough (2007) regarding the impact information representation has on the effectiveness of eco-feedback systems. By linking information representation to actual changes in energy consumption, results from this experiment also extend the findings of previous studies (Bonino et al. 2012; Faruqui et al. 2010; Jazizadeh et al. 2012; Vassileva et al. 2012) beyond the examination of user preferences and into the impact information representation has on observed eco-feedback effectiveness. Moreover, this experiment contributes to the growing body of knowledge regarding eco-feedback design by deepening our understanding of a specific design detail (information representation) as called for by Pierce et al. (2010).

Results also indicate that users who received eco-feedback in terms of an environmentally externality (Study Group B) on average performed better than their counterparts who received eco-feedback in direct energy units (Study Group A). Study Group B on average decreased their consumption by 10% over the study period. Surprisingly, data for Study Group A indicates that over the study period users actually increased their energy consumption on average by 18% despite receiving the same number of eco-feedback emails as Study Group B. In order to further understand this unexpected result, we analyzed the energy consumption data more closely and found response-relapse effects to be presented. Users experienced response-relapse patterns to eco-feedback emails similar to those observed by Peschiera et al. (2010) in both study groups. Eco-feedback emails were sent on the following five dates: 3/30, 4/6, 4/13, 4/20, 4/27. It can be seen that in the subsequent three days after an eco-feedback email was sent energy consumption dramatically drops before rising over the next four days. Specifically, Study Group A can be observed to reduce consumption after receiving an eco-feedback email on 4/6 but unable to sustain this level of conservation beyond 4/10. We postulate that this pattern could be due to users having a limited understanding of the abstract unit of kWh. However, further analysis is required to analyze consumption patterns to understand these observed responses. The presence of response-relapse effects raises pertinent questions regarding the long-term effectiveness of eco-feedback and how information representation can be utilized to deliver sustained energy savings. While preliminary results suggest that providing users with feedback in terms of an environmental externality drives more energy savings, further research is required to reach a more conclusive result and examine energy savings in the context of response-relapse patterns.

As with many empirical experiments our study could have benefited from a larger sample size. However, the sample size utilized was adequate to obtain statistically significant results. Additionally, expanding our study's sample size would have required outfitting a new building with energy monitoring devices that were cost prohibitive. A limitation regarding the email based eco-feedback system was that user engagement among participants was difficult to gauge. While it is possible that one study group could have had a higher user engagement than the other, analysis of the limited engagement data (number of email “opens”) captured by our email distribution server indicated that engagement was comparable across the randomly chosen study groups.

6 Conclusion

The results of this experiment revealed that information representation in eco-feedback systems can have a substantial impact on the energy consumption behavior of building occupants. These results have important implications for how we design eco-feedback systems that are effective in driving energy savings. It is clear that if we are to transition to a more sustainable society and avoid the harshest effects of climate change, we must reduce energy consumption associated with the built environment. If effectively designed, eco-feedback systems combined with sustainable infrastructure management philosophies could be an important tool to achieve sustainable energy reductions in buildings.

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