Designing and Experimenting Nudge Signals to Act on the Energy Signature of Households and Optimizing Building Network Interaction

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RESUME. La transition énergétique en Europe conduit à la production décentralisée par des sources renouvelables intermittentes. Lorsque ce paysage énergétique changeant exerce certaines contraintes sur le réseau énergétique, il exige intensément une flexibilité dans la consommation d'énergie. La flexibilité directe (généralement sous forme de demande réponse) est déjà en place, tandis que l'impact de la flexibilité indirecte n'est pas très clair. Selon RTE, le secteur résidentiel est le plus gros consommateur d'énergie en France, il est donc important pour l'application de la flexibilité indirecte. Dans ce travail de recherche, nous avons testé notre hypothèse de flexibilité indirecte par des signaux « Nudge » pour un groupe de ménages. L'impact des signaux est mesuré en comparant le groupe traité avec le groupe contrôle et en comparant la courbe de charge de consommation avec une courbe de charge de référence pour chaque ménage de groupe traité. Dans une perspective future, cette étude aidera les gestionnaires de réseau à minimiser la congestion grâce à flexibilité indirecte pour le secteur résidentiel.

MOTS-CLÉS : Les Sources d'Energie Renouvelables, Flexibilité Indirecte, « Nudge », Secteur Résidentiel

ABSTRACT. The energy transition in Europe leads towards the decentralized procurement by intermittent renewable sources. Where this changing energy landscape exerts certain constraints on energy grid, it also intensely demands flexibility in energy consumption. The direct flexibility (generally in the form of demand response) has been already in place; however, the impact of indirect flexibility is not very clear. According to the French national grid operator (RTE), residential sector is the biggest energy consumer in France: therefore, it seems to be significant for the application of indirect flexibility. In this research work, we tested our hypothesis of indirect energy flexibility through designed nudge signals for a group of households. The impact of signals is measured by comparing the treated group with control group and by comparing the consumption load curve with a reference load curve for each household of treated group. In the anticipated future prospect, this study will help the energy grid operators to minimize issues related to intermittent generation by applying indirect flexibility for residential sector.

KEYWORDS: Renewable Energy Sources, Indirect Flexibility, Nudge, Residential Sector

1. INTRODUCTION

The decentralization of renewable energy tends the consumers to produce and consume energy locally (also known as auto-consumption). The energy surplus can either be sold to the energy grid through net metering or through P2P (peer-to-peer) transaction in real time. Energy flexibility is inevitable to maintain equilibrium in the network, as this intermittent energy poses constraints of energy scarcity or network congestion. According to the French national grid operator (RTE), the residential sector consumed 36% of the total annual energy consumption in 2019 (RTE France 2020); therefore, it is a key sector to implement energy flexibility at consumer side.

The DSO/aggregator can implement energy flexibility in two ways. Direct flexibility allows the DSO to curtail remote loads through a switch installed in the grid. It is expensive because it requires installation of protection switches at consumer end. The estimated time of execution is from 10 seconds to 30 seconds (IRENA 2018). The remote switching causes loss of comfort, therefore, it is not pleasant for residential consumers. Alternatively, the indirect flexibility prompts the occupant to manage energy consumption through behavior change. In this case, the occupant needs occasional notification from the DSO for either upward flexibility (load shifting towards the interval of auto-consumption) or downward flexibility (curtailing partial load during peak hours). The estimated time of execution of indirect flexibility is 1 hour to several days and can be used for load curtailment, load shifting and valley filling.

Certain DSOs and research centers have carried out interdisciplinary research to quantify consumer behavior towards energy consumption. Usually, a monetary gain or competition incentivizes the subjects to achieve energy flexibility. These experiments remained effective for the intended duration; however, they do not have a lasting impact. Nudge is a tool of behavioral economics, "which is an aspect of the choice architecture that alters people's behavior in a predictable way without forbidding any options or economic incentives." (Thaler and Sunstein 2008). "The choice architecture refers to the practice of influencing choice by organizing the context in which people make decisions" (Shafir 2013).

This article deals with an experiment regarding energy consumption behavior of households. The objective is to test a hypothesis that the knowledge of energy intermittency would influence energy consumption behavior of households and use of nudge would bring a positive reinforcement in the energy consumption behavior. The following section presents a literature review of earlier research experiments and the current mechanisms for energy flexibility in France. Section 3 presents the design of experiment and section 4 presents the comparison of control group and treated group. The formulation of reference load curve is significant to measure the impact of nudge signal; therefore, section 5 demonstrates different techniques considered for the formulation of reference load curve. Section 6 and section 7 presents the results and conclusion respectively.

2. LITERATURE REVIEW OF INDIRECT FLEXIBILITY

The energy crisis in 1970s forced North America to experiment energy flexibility. In this context, (Ehrhardt-Martinez and Donnelly 2010) classified the energy flexibility experiments into two eras namely; energy crisis era (between 1974 and 1994) and climate change era (from 1995 onwards). These experiments obliged the experimenters either to provide feedback to their subjects in real time (direct flexibility) or to send feedback after consumption (indirect flexibility). These subjects are collectively called treated group. Figure 1 classifies these early experiments according to the type of feedback.

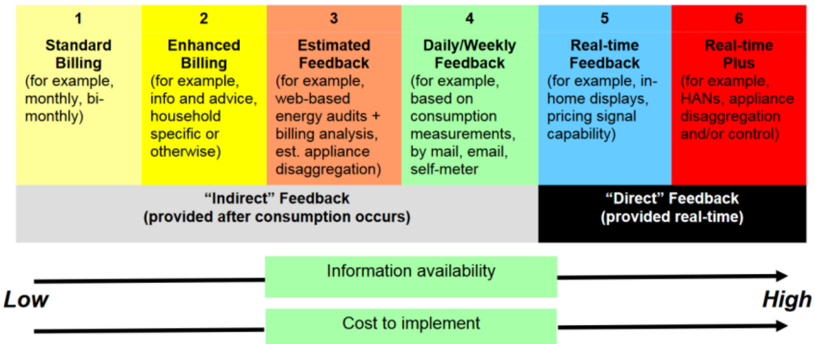


Figure 1: Feedback delivery mechanism spectrum (Neenan 2009)

In a number of experiments, a control group is created with similar characteristics of treated group. "The control group is not subjected to any treatment and it is needed to acquire an average load curve similar to the treated group" (Lesgards and Frachet 2012). However, it is not realistic to make two groups with same characteristics; therefore, a reference load curve for each subject was needed. The reference load curve was compared with measured load curve in order to evaluate energy flexibility. It was either formulated on normal distribution or leptokurtic distribution (Lesgards and Frachet 2012). In terms of energy saving, a method called "Difference of differences" is used to measure the impact of energy flexibility. With an assumption that the consumption of both groups is identical over the same period, the differences ΔT and ΔC eliminate the temporal effects linked to the evolution of both groups while the second difference ΔT - ΔC eliminates the selection bias between the groups (Hatton and Charpentier 2014). Figure 2 illustrates the difference of differences method.

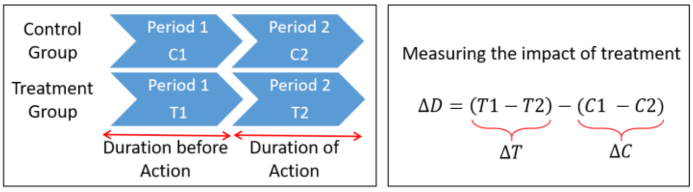


Figure 2: Difference of differences method

Energy flexibility is in practice for many decades in France. TEMPO is a mechanism of critical peak pricing introduced by EDF (Electricité de France), in which the tariff for color-coded day D varies according to the color assigned on day D-1. The tariff on day D is cheaper than TOU price for blue color, slightly expensive than TOU price for white color and very expensive for red color (Albadi and El-Saadany 2007). EJP (peak day curtailment) is another instrument of critical peak pricing, in which the peak consumption day is color-coded in red and the subscribers pay a low tariff all year round, except for the 21 red days with higher tariff (Bivas 2011). EDF notifies subscribers on day D-1 about the color of TEMPO for day D. PP1/PP2 (peak period 1/peak period 2) are the days of high electricity consumption as determined by RTE. PP1 corresponds to extreme weather forecast (maximum 15 days/year) while PP2 corresponds to the network congestion (maximum 25 days/year).

3. Design Of Experiment

For this experiment, GAEL lab recruited 175 households (equipped with LINKY smart meter) around a medium French city. LINKY transmits the daily measured load curve at a sampling period of 30 minutes to ENEDIS server (Duplex, Gosswiller, and Fagnoni 2013). G2ELab fetches the daily load curve of each subject from ENEDIS server and anonymizes the data as per GDPR consent signed with each subject. The participants of treated group also signed a commitment form, stating the appliances that they will use or not use during green or orange period respectively. The commitment form consists of a list of all the appliances that consumes energy in each subject's household and the timeslots during which these appliances are used.

Two types of alerts are defined i.e. green alert (for load shifting) and orange alert (for load curtailment). The green alert is based on forecast of zero nebulosity in Grenoble and the forecasted consumption of each subject for next day. The orange alert is based on the declaration of PP1/PP2, EJP or TEMPO for next day. Subsequently, the green period refers to the duration between noon and 3:00 PM on green alert day while orange period refers to the duration between 6:00 PM and 8:00 PM on orange alert day. For the sake of comprehension, Figure 3 illustrates the timeline of orange alert.

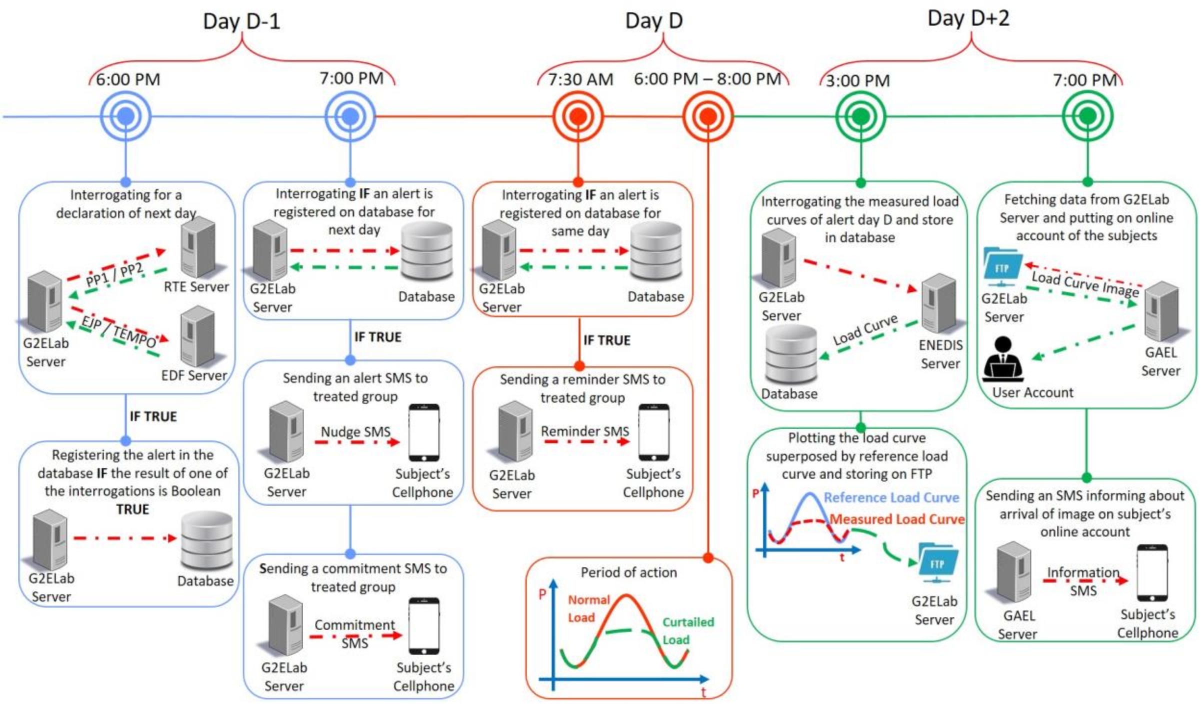


Figure 3: Timeline of orange alert

The subjects are categorized into control group and treated group. The control group represents as a reference for electrical consumption of households in treated group. It ensures that the energy consumption of treated group is only influenced by the nudge during alert day. The treated group receives a set of SMS as nudge signal for each alert day. Alerts are not triggered for weekend and school vacations. The nudge has three elements, which are given as follows.

- Information related to energy production and its environmental impact i.e. elevated production of thermal power plants for orange period and maximum use of renewables for green period.

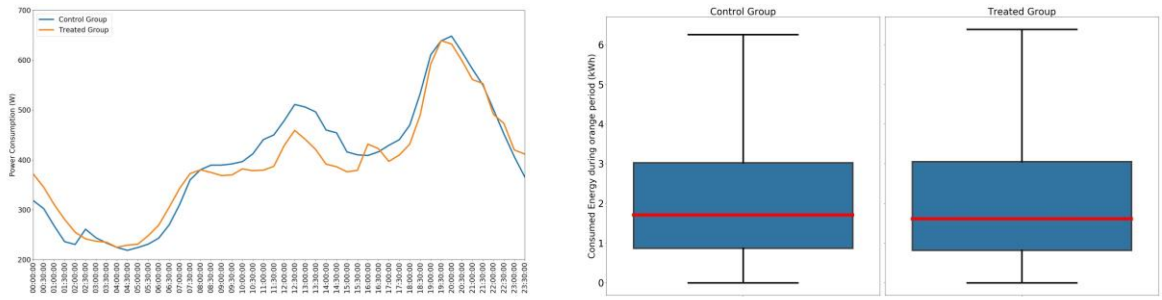
- A customized set of advice for each subject about how to optimize energy consumption with commitments. The subjects must commit themselves to the actions they think they will take during orange or green period. For this purpose, a URL is added in the message that permits the subjects to modify their default commitment by accessing their personal account.

- Regular feedback to the subjects in the form of an image of the measured and reference load curve.

4. Comparison Of Control Group And Treated group

Before formulating the reference load curve, it is essential to evaluate the habitual energy consumption behavior of both groups. For this purpose, an average of daily load curves of control group (comprising of 79 subjects) and treated group (comprising of 96 subjects) is taken between 1st September 2019 and 28th February 2020 with a sampling rate of 30 minutes. Figure 4(a) demonstrates that the average daily load curve of both groups is similar in the evening. The two box plots in figure 4(b) represents the distribution of energy consumption for both groups between 6:00 PM and 8:00 PM. The two box plots have surprisingly similar distribution and very close median values, which validates our assumption that the two groups are identical in terms of energy consumption in the evening.

$$Average\ Daily\ Load\ Curve\ of\ Group|_{00:00}^{23:30} = \frac{\sum_{i=1}^{n} Daily\ Load\ Curve\ of\ Subject\ i\ |_{00:00}^{23:30}}{Number\ of\ participants\ in\ the\ group} \quad (1)$$



(a) (b)

Figure 4: (a) The average daily consumption load curve of control group and treated group, (b) The distribution of energy consumption for both groups between 6:00 PM and 8:00 PM

5. Formulation Of Reference Load Curve

A reference load curve has an important role in this study. It helps in scientific evaluation of the efficiency of nudge signal. Besides, the reference load curve is itself a nudge. On day D+2, each subject views his/her measured load curve against reference load curve and measures the impact of his/her effort. Three techniques that are compared to formulate the reference load curve are given below.

- **Using Kernel Density Estimation:** For each half-hourly timestamp of (green or orange) period, the peak value of the kernel density estimation of historical data is taken as reference data point for reference load curve.
- **Using newly devised BM technique:** For each (green or orange) period on day D, the load curve of day D-1 for the same half-hourly timestamp is taken. In addition to that, the load curve with maximum energy consumption between days D-2 to D-5 is taken. The average of the two load curve yields the reference load curve.
- **Using the maximum values occurred in last 5 days:** For each half-hourly timestamp of the (green or orange) period, the maximum value of last 5 days is taken as reference data point for reference load curve.

To select one of the method as reference load curve, the performance of energy difference indicator for each method is observed. The following steps are taken to evaluate the performance of indicator for each method given above. Note that this analysis is only performed for orange period.

- The historical consumption data of treated group between 1st September 2019 and 28th February 2020 is taken with a sampling rate of 30 minutes. The data of weekend and school vacations is removed from the taken sample. After this step, we are left with historical data of 126 days.
- A reference load curve is generated for each method using the historical consumption data.
- By taking the difference of reference load curve and measured load curve, a difference load curve is generated. The energy difference indicator for orange period is calculated by taking the sum of difference load curve of each day between 6:00 PM and 8:00 PM.
    - The energy difference is ***positive***, if the measured energy consumption during the period is less than the reference energy consumption.
    - The energy difference is ***negative***, if the measured energy consumption during the period is greater than the reference energy consumption.

Figure 5 illustrates a distribution of energy difference indicator using each method. The boxplot for Kernel density estimation method demonstrates that energy difference for most days and the median value is negative. If we select this method, the measured load curve will be often greater than the reference load curve, and therefore the action of the treated group for each nudge signal will be underestimated. Hence, this method is not suitable for nudging the subjects as it underestimates their efforts. The boxplots for 2nd and 3rd method depicts that the energy difference is predominantly positive (with most of the data lying above zero and positive median value). Both methods over-estimates the action of treated group towards nudge signal and therefore the suitable method should be selected.

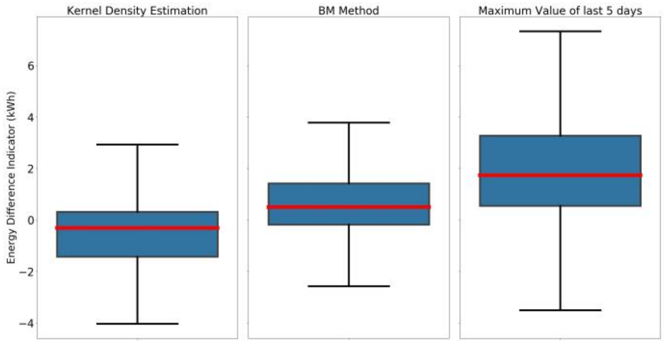


Figure 5: The distribution of energy difference indicator for treated group w.r.t three methods

The data of 3rd method is widely dispersed as it takes maximum values during the previous 5 days. The maximum value of energy consumption may occur at D-4 or D-5, hence this method may not take evolving energy consumption as function of temperature and time. The boxplot of 2nd method shows that the energy difference indicator of treated group is not widely dispersed. It helps in better prediction through reference load curve since the historical data points are more closer to median value than 3rd method. It takes into account the evolution of energy consumption with respect to time as it includes the energy consumption of day D-1. Besides, it does not nullify the effect of maximum energy consumption occurred at any day D-n (where $2 \leq n \leq 5$). Therefore, 2nd method (also named as BM technique) is selected as reference load curve for better estimation of the effort of each subject.

6. RESULTS AND DISCUSSION

It is necessary to evaluate the impact of nudge to validate the endogenous and exogenous of the results. The endogenous verification makes it possible to establish that a cause and effect relationship within the experiment has attracted attention of subjects. The exogenous factor verifies the extent to which the results obtained during the experiment is applicable to a bigger population than sample size. Therefore, two key performance indicators are used to evaluate the result of 6 alert days for which the nudge signals were sent. These nudge signals were sent between 1st September 2019 and 28th February 2020 on the days when one of the three declarations of PP1/PP2, EJP or TEMPO was TRUE.

6.1. COMPARISON BETWEEN ENERGY CONSUMPTION OF BOTH GROUPS ON ALERT DAYS

This indicator compares the energy consumption of control group and treated group during orange period against the nudge signal. This comparison is significant to extrapolate the exogenous impact of the experiment. Figure 6 illustrates that energy consumption of treated group remained less than energy consumption of control group on alert days. The difference of median values of box plot yields that the treated group saved 0.62 kWh of energy per orange period. The individual effort generated different values however, extrapolating cumulative energy saving of 0.31 kWh per hour (0.62 kWh per orange period) for 29 million French households (INSEE France 2019) gives an energy saving of 8.7 GWh per hour (between 6 PM and 8 PM), which is significant in terms of indirect energy flexibility at peak hours.

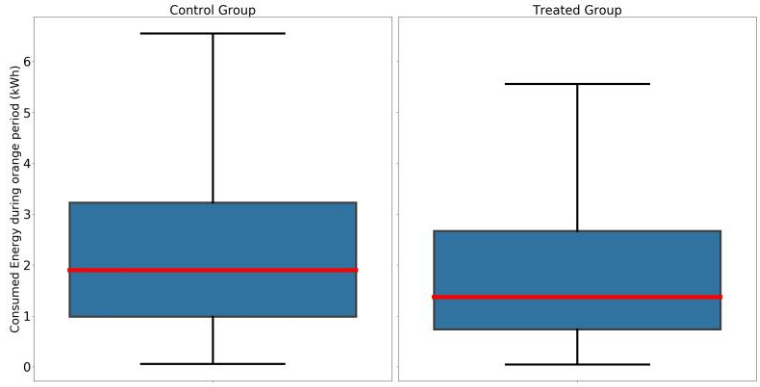


Figure 6: The comparison of energy consumption of control group and treated group for alert days

6.2. Comparison Of Energy Difference Indicator

The energy difference indicator is calculated for 6 alert days and 120 non-alert days by taking the difference of reference load curve and measured load curve. This endogenous indicator measures the impact of nudge signals on the subjects for decreasing their energy consumption during the orange period. Figure 7 illustrates the actions of some subjects who responded positively and those did not responded positively. Note that the box plot representing the energy consumption during alert days is lower than the box plot representing energy consumption on non-alert days for positively responded subjects. This means that the subjects who responded positively have consumed less energy than their reference energy consumption. The case is inverse for subjects who consumed more energy on alert days than on non alert days.

$$E_{diff\_orange,subject}\Big|_{18:00}^{20:00} = \sum_{18:00}^{20:00} Reference\ Load\ Curve - \sum_{18:00}^{20:00} Measured\ Load\ Curve \quad (2)$$

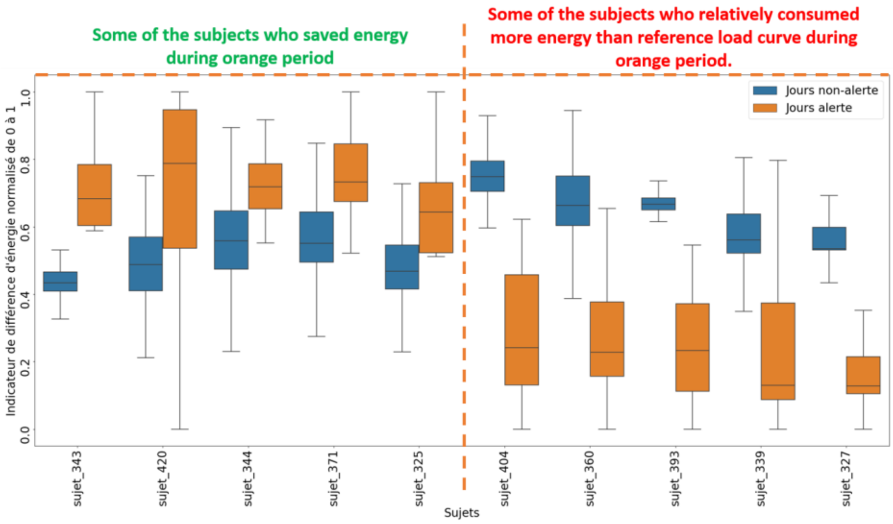


Figure 7: The comparison of energy difference indicator between alert days and non-alert days of top five positively responded subjects, stable subjects and negatively responded subjects

Overall, the difference of medians between alert days and non-alert days reveals that 60% subjects (58 out of 96 subjects) responded positively to the nudge signal by decreasing their energy consumption during orange period and the rest of the subjects consumed more than the reference on alert days.

7. CONCLUSION

Indirect flexibility can be implemented to residential sector for upward flexibility (load shifting) or downward flexibility (load curtailment). In this experiment, we tested a hypothesis that the forecasted information of intermittent energy generation and network congestion could nudge the residential consumers to implement indirect flexibility. The performance of treated group is compared with control group to evaluate the exogenous impact of the signals. An extrapolation of result reveals that a significant amount of energy can be saved through nudge signals during the peak consumption days (i.e. the days when peak power plants are running).

An image containing a reference load curve superposed on measured load curve is presented to each subject of the treated group, so that each subject can view the impact of his/her effort against the nudge signal. This may positively reinforce him/her to act better next time. The reference load curve also helps to calculate an energy difference indicator to measure the extent of energy saving. The analysis of energy difference indicator yields that a good number of subjects responded positively by implementing downward flexibility, whereas the impact of upward flexibility is yet to be seen. In nutshell, the nudges might be impactful to implement indirect flexibility for energy equilibrium in the grid.

8. ACKNOWLEDGEMENT:

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