Strategy-proof Thermal Comfort Voting in Buildings

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Abstract

Commercial building is a major energy consumer worldwide; and the heating, ventilating and air-conditioning (HVAC) system dominates the total energy consumption. The current practice of the HVAC systems in most commercial buildings is to adopt a fixed temperature setting; and to avoid occupant complaints, building operators usually choose conservative temperatures settings. This leads to massive energy waste; and many times not good in thermal comfort either.

Recently, many works studied the occupant-participatory approach, i.e., occupants can provide their feedback of thermal comforts and a more dynamic temperature adjustment is applied. Though these studies have various optimization objectives, e.g., energy conservation, thermal comfort, or non-intrusiveness, one hidden assumption for all these occupant-participatory approaches is that the occupants are trustworthy, i.e., they do not game the system with false feedback/votes. In this paper, we demonstrate that each occupant can easily have incentives to submit untruthful thermal comfort. We thus propose a strategy-proof framework for thermal comfort voting schemes. We show the conditions for the existence of the strategy-proof voting schemes. In this framework, we classify two types of voting schemes, i.e., individual-based and group-based voting schemes. We propose the strategy-proof voting mechanism for both voting schemes and evaluate their performance via simulation.

Categories and Subject Descriptors

H.1.2 [**Models and Principles**]: User/Machine Systems

General Terms

Theory

Keywords

Thermal comfort, Voting, Strategy-proof

1 Introduction

The ever-increasing energy consumption in buildings has drawn a worldwide concern. It is also commonly agreed that energy conservation must be aligned with the quality of services provided to occupants; otherwise, we can just turn-off all buttons. As a consequence, there are different works to learn the occupants' thermal comfort when they are staying in buildings, which can be broadly classified as predictive-based approaches and user-participatory approaches. Predictive-based approaches mainly rely on the historical data from human activities with the sensors and equipment data [1][2][3]. For example, motion sensors are used to train an occupant's daily working time so that the provision of heating and air-conditioning services are just good enough to suit the occupant's need while conserving energy [1]. Circulo [3] is presented with the same rationale upon the tap water with heater and aimed to save the unused water being wasted before the hot water comes out.

User-participatory approaches collect real-time feedback from occupants, say to handle in the real-time over-cold or over-warm environment, where most of the complaints today come from [4]. With smart phones, users can provide their current perceptions directly through voting on whether they feel cold or hot [4][5][6][7], and the building management system adjusts the setpoint temperature accordingly. Numerous designs are proposed with diverse objectives. In [5], a scheme is proposed with the objective to optimize energy consumption. A scheme is proposed in [4] to enhance the thermal comfort and also seek to minimize the system intrusiveness. Models are built for the occupants and temperature settings can be primarily model-driven so that voting from occupants is minimized.

The results from current studies have shown that a participatory oriented approach is superior in energy conservation, thermal comfort, etc. Thus, it is expected that further advanced schemes may be proposed. Nevertheless, one hidden assumption for all these occupant-participatory approaches is that the occupants are trustworthy, i.e., they do not "game" the system with false feedback/votes. It would become a crucial problem for the occupant-participatory approaches to succeed if this is not true. If we look into the detailed designs of past participatory schemes, however, we can see that occupants can easily have incentives to submit untruthful thermal comfort. For example, for the average scheme proposed in [5], one may vote extreme values to affect the overall result for his own desired temperature. In the computation of linear regression in [4], the scheme will become invalid when collecting false votes. Therefore, one can cast false vote and seek to shape with unreal thermal preference.

We consider that there can be two broad approaches to view this problem. One view is to consider it as a security problem. In this direction, users submitting false votes may be identified as attackers. This may not be appropriate in most scenarios as the false-users are not trying to attack the system, but to manage some individual gains. Another view is to consider it as an incentive problem. In this direction, a voting scheme that guarantees truthful votes is said to be *strategy-proof* and the target of this approach is to design a strategy-proof voting scheme that avoids the user incentives to cast

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false votes. This strategy-proof voting scheme also needs to guarantee the fairness, i.e., no single person should dominate the whole and major preferences should be chosen instead. In this paper, we focus on designing this strategy-proof voting scheme. Although the voting schemes are widely studied by many works [8][9], our work is the first one to design the strategy-proof voting scheme in buildings. The main challenges are: 1) the complex models in buildings, and 2) the imprecise nature of models in buildings.

In this paper, we first abstract a strategy-proof framework for thermal comfort voting rigidly in buildings (Section 2). Under this framework, we classify two specific types of voting schemes in buildings, i.e., *individual-based* and *group-based* voting schemes. The votes from occupants are usually not numerical temperatures, but their thermal sensations from cold to hot instead. Individual-based voting abstracts the scenarios where the numerical thermal comfort models are estimated by occupants' thermal sensations first, and then all numerical models join in the decision-making precess of the adjusted temperature. Group-based voting abstracts the scenarios where the group vote is decided first and then this group vote is used to estimate the adjusted temperature. We next show the conditions for the existence of the strategy-proof voting schemes (Lemma 2), i.e., the occupants' temperature preferences should be single-peaked. Intuitively, the temperature further away from the most desired temperature makes occupants feel worse. We then provide strategy-proof voting mechanisms for both individual-based voting (Section 3.2) and group-based voting (Section 3.3). Finally, we conduct an evaluation through simulation (Section 4).

2 Basic Model

In this section, we consider a set of occupants $\mathcal{N}$ sharing air-conditioning system. We denote the number of them as $N = |\mathcal{N}|$. These occupants can reflect their thermal comfort by voting their thermal sensations from cold to hot. To quantify these thermal comforts, we adopt the seven-point thermal comfort index ,i.e., scaling from -3 to 3, according to the standard of the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE). This index links the thermal comfort from cold to hot[1]. We denote the corresponding index of the vote for occupant $i \in \mathcal{N}$ as $v_i \in \{-3,-2,-1,0,1,2,3\}$. In practice, some occupants may not vote for their thermal comforts. We assume these occupants are staying at thermally neutral.

The thermal comforts are usually estimated by models so as to obtain the optimal or desired room temperature. We use function $P_i(T,\Delta)$ to stand for the estimated thermal comfort of occupant i under the room temperature T, where Δ represents other parameters excluding room temperature T. In this paper, we focus on the dynamic of the room temperature and fix the other parameters Δ. Thus, we just simplify the estimated function as $P_i(T)$. The estimated thermal comfort function $P_i(T)$ is usually increasing under the current models since higher room temperature always means warmer thermal comfort. Note that, the estimated thermal comfort models may be built for all occupants $\mathcal{N}$, instead of each individual occupant. Under this case, each occupant has common estimated function $P_i(T) = P_{\mathcal{N}}(T)$.

Under the occupant-participatory approach, these thermal comfort models are trained by the occupants' actual votes. Denote the vote for occupant i under the room temperature T_0 as $v_i(T_0)$. The adjusted thermal comfort model, denoted as $\widetilde{P}_i(\cdot)$, is assumed to satisfy the following property.

PROPERTY 1. *For any temperature T, the adjusted thermal comfort model satisfies:*

$$\widetilde{P}_i(T)\begin{cases} \geq P_i(T) & \text{if } P_i(T_0) < v_i(T_0), \\ \leq P_i(T) & \text{if } P_i(T_0) > v_i(T_0). \end{cases} \tag{1}$$

The intuition for this property is that if one vote is much larger (smaller) than the predicted thermal comfort, the predicted thermal comfort value for the adjusted model should be also larger (smaller) so as to be closer to the actual vote. This property is usually satisfied by the current works [4][5][10].

The building system reacts to the votes of occupants by changing the room temperature with new temperature settings. The desired room temperature or requirement for each occupant may not be satisfied fully. The target room temperature are determined by the votes from whole occupants in company. We use $F(\mathbf{v})$ to represent this new temperature setting under current temperature T_0 when considering all requirements, where $\mathbf{v} = (v_1, \cdots, v_N)$. Generally, there are two kinds of methods to obtain the best room temperature setting. One method is to estimate the desired room temperature first and then determine the best room temperature according to the desired room temperature from all occupants. We call this method as *individual-based* voting scheme. Under this case, we represent the decision-making mechanism as $M(\mathbf{P})$, where $\mathbf{P} = (P_1, \cdots, P_N)$. Another method is to determine the group vote from all occupants' votes first and then estimate the room temperature according to this group vote. We call this method as *group-based* voting scheme. We use $V(\mathbf{v})$ to represent the decision-making mechanism for the group vote. In either case of methods, each occupant may have incentives to game the system with false vote. We define the truthful voting system as follows.

DEFINITION 1. *A voting system is strategy-proof if $U_i(F(\widetilde{v}_i, \mathbf{v}_{-i})) \geq U_i(F(\mathbf{v}))$ for any $i \in \mathcal{N}$ and any $\mathbf{v}_{-i} \in \{-3,\cdots,3\}^{N-1}$, where $\widetilde{v}_i$ is the truthful vote for occupant i.*

Definition 1 states that a voting system is strategy-proof if voting truthfully always obtains the highest utility for each occupant. When the voting scheme is non-strategy-proof, each occupant may obtain more utility with false vote. This may result in both waste of energy and worse thermal comfort. We use one example to demonstrate the strategy-proof and non-strategy-proof scheme.

An example: Occupant A, B and C's optimal room temperatures are 23°C, 25°C and 26°C, respectively. Larger or smaller temperature than its optimal temperature may result in worse thermal comfort. We first consider the average scheme, i.e., the setpoint temperature is the average of all required temperatures. Then, the setpoint is 24.7°C if each occupant votes truthfully. From occupant A's point of view, if she votes 21°C, then the temperature setting is 24°C given the truthful votes for occupant B and C.[2] Thus, occupant A benefits more if she votes untruthfully. This indicates that occupants has incentives to vote untruthfully and thus average scheme is non-strategy-proof. We then consider the median scheme, i.e., the setpoint temperature is the median of the required temperatures. When each occupant votes truthfully, the setpoint temperature is 25 °C. If occupant A casts false votes, e.g., 21 °C, given the truthful voting for occupant B and C, the median temperature is still 25 °C. Similarly, occupant B and C obtain no more benefit with untruthful votes. This indicates that the median scheme is strategy-proof.

3 Strategy-proof Voting Schemes

In previous section, we point out that the occupants have incentives to cast false votes. This motivates us to design the strategy-proof voting systems. In this section, we first demonstrate the existence of strategy-proof voting schemes. After that, we design

[1] Hot (+3), Warm (+2), Slightly Warm (+1), Neutral (0), Slightly Cool (-1), Cool (-2), and Cold (-3)

[2] Although each occupant votes her thermal comfort, instead of temperature directly, we can still transfer the thermal comfort to the temperature.

the strategy-proof voting schemes under both individual-based and group-based approaches.

3.1 Existence of Strategy-proof Voting Schemes

We first consider the optimal temperature desired by occupant i. When the thermal comfort value is closer to the zero point, the temperature makes occupants more comfortable. We can calculate the desired temperature for occupant i as:

$$T_i = \arg\min_T |P_i(T)|. \quad (2)$$

Since the thermal comfort models are always trained by occupants' votes, the desired temperatures obtained from thermal comfort models are also affected by occupants' votes. We use function $T_i(v_i)$ to represent the desired room temperature setting under the room temperature T_0 for occupant i with vote v_i. Then, this desired room temperature function satisfies the following lemma.

LEMMA 1. *$T_i(v_i)$ is non-increasing with vote v_i*

PROOF. Consider the estimated thermal comfort $v_i = P_i(T_0)$ and one actual vote v'_i. Without loss of generality, we assume that $v_i \leq v'_i$. Denote the new estimated thermal comfort function as $P'_i(T)$. According to property 1, we have $P'_i(T) \geq P_i(T)$. Since $P_i(T)$ and $P'_i(T)$ are increasing functions. Then, we have $\arg\min_T |P'_i(T)| \leq \arg\min_T |P_i(T)|$. That means $T_i(v'_i) \leq T_i(v_i)$. Thus, we finish the proof. □

Lemma 1 indicates that voting warmer releases the information of a low desired room temperature. The intuition is that the trained thermal comfort model by higher vote makes the thermal comfort value under each temperature higher (Property 1). Since the thermal comfort model is an increasing function, the zero point shifts left resulting in lower desired optimal room temperature. This lemma is also true if we consider the desired room temperature of whole occupants, instead of individual occupant, i.e., $T_{\mathcal{N}} = \arg\min_T |P_{\mathcal{N}}(T)|$. That means $T_{\mathcal{N}}(V)$ is also non-increasing with V.

Different room temperatures may result in different utilities for one occupant. We use function $U_i(T)$ to represent the utility for occupant i when the room temperature is changed to T under the current temperature T_0. Denote the optimal room temperature setting under current temperature T_0 as $\widetilde{T}_i$. We assume that the utility for occupant i satisfies the following *single-peaked preference*[3], i.e.,

$$\begin{cases} U_i(\widetilde{T}_i) > U_i(y) \geq U_i(x) & \text{if } x \leq y < \widetilde{T}_i, \\ U_i(\widetilde{T}_i) > U_i(x) \geq U_i(y) & \text{if } y \geq x > \widetilde{T}_i. \end{cases} \quad (3)$$

The intuition of the single-peaked preference is that there exists one desired temperature that maximizes the occupant's utility. Further away from this desired temperature indicates lower utility for this occupant. This assumption is natural since warmer or colder temperature makes the occupant more uncomfortable.

Denote the truthful vote for occupant i under temperature T_0 as $\widetilde{v}_i$. We assume that the model built based on occupants' truthful votes can discover the optimal room temperature under temperature T_0, i.e., $\widetilde{T}_i = T_i(\widetilde{v}_i)$. Since $T_i(v_i)$ is non-increasing with v_i, the utility U_i also satisfies single-peaked preference with respect to occupant's vote, i.e.,

$$\begin{cases} U_i(T_i(\widetilde{v}_i)) > U_i(T_i(y)) \geq U_i(T_i(x)) & \text{if } x \leq y < \widetilde{v}_i, \\ U_i(T_i(\widetilde{v}_i)) > U_i(T_i(x)) \geq U_i(T_i(y)) & \text{if } y \geq x > \widetilde{v}_i. \end{cases} \quad (4)$$

LEMMA 2. *If the occupants' preferences for temperature are single-peaked, there exist at least one strategy-proof voting scheme.*

PROOF. Define one strictly increasing function $Q : [T_{min}, T_{max}] \to [-3, 3]$ with inverse function $Q^{-1}(v)$. This can be a linear function. Consider new utility function $\tilde{U}_i(v) = U_i(Q^{-1}(v))$ and new decision-making function $D(\mathbf{v}) = Q(F(\mathbf{v}))$. Note that $U_i(T)$ is single-peaked function with respect to T. Then, $\tilde{U}_i(v)$ is also singepeaked function with respect to v. Note that $D : [-3,3]^N \to [-3,3]$. The paper [11] states that when the decision-making function D is median function, we have $\tilde{U}_i(D(\tilde{v}_i, \mathbf{v}_{-i})) \geq \tilde{U}_i(D(\mathbf{v}))$ for any $\mathbf{v} \in [-3,3]^N$, where $\tilde{v}_i$ is the truthful vote for occupant i. That means $U_i(F(\tilde{v}_i, \mathbf{v}_{-i})) \geq U_i(F(\mathbf{v}))$ for any $\mathbf{v} \in [-3,3]^N$. Thus, according to definition 1, we get the proof. □

This lemma states that the single-peaked temperature preferences are the guarantee of the existence of the strategy-proof voting scheme. In fact, if the preferences of each occupant are not constraint, the strategy-proof voting scheme does not exist.

3.2 Individual-based Voting Scheme

Under the individual-based voting scheme, the thermal comfort models are trained first, i.e., $\mathbf{P}$, according to the occupants' votes $\mathbf{v}$. After that, a decision-making mechanism $M(P_1, \cdots, P_N)$ decides the optimal room temperature. In this section, we design this decision-making mechanism $M(P_1, \cdots, P_N)$ so as to guarantee the strategy-proof characteristic for the individual-based voting scheme.

We consider median function, denoted as $\pi(a_1, \cdots, a_N)$, and defined by:

$$\pi(a_1, \cdots, a_N) = m, \quad (5)$$

if and only if $\begin{cases} \#\{i | a_i \leq m\} \geq \lfloor N-1 \rfloor /2 + 1, \\ \#\{i | a_i \geq m\} \geq \lfloor N-1 \rfloor /2 + 1, \end{cases}$ where $\#Z$ denotes the cardinality of set Z. Note that $\pi(a_1, \cdots, a_N)$ is one of the a_i. When N is even, there are two medians. Without loss of generality, we assign the median function one of the median values with half probability.

THEOREM 1. *The individual-based voting scheme is strategy-proof if:*

$$M(\boldsymbol{P}) = \pi(\arg\min_T |P_1(T)|, \cdots, \arg\min_T |P_N(T)|). \quad (6)$$

PROOF. Under this decision-making mechanism, $F(\mathbf{v}) = \pi(T_1(v_1), \cdots, T_N(v_N))$. Considering linear increasing function $Q : [T_{min}, T_{max}] \to [-3, 3]$, we have $Q(\pi(T_1(v_1), \cdots, T_N(v_N))) = \pi(Q(T_1(v_1)), \cdots, Q(T_N(v_N)))$. That means $Q(F(\mathbf{v})) = \pi(Q(T_1(v_1)), \cdots, Q(T_N(v_N)))$. Denote $v'_i = Q(T_i(v_i))$ and $\tilde{U}_i(v) = U_i(Q^{-1}(v))$. Then, $\tilde{U}_i(v')$ is single-peaked with respect to v'. Thus, the decision-making function π makes $\tilde{U}_i(\pi(\tilde{v}'_i, \mathbf{v}'_{-i})) \geq \tilde{U}_i(\pi(\mathbf{v}'))$ for any $\mathbf{v}' \in [-3,3]^N$, where $\tilde{v}'_i$ is the truthful new vote for occupant i, i.e., $\tilde{v}'_i = Q(T_i(\tilde{v}_i))$. Then, for any $\mathbf{v} \in [-3,3]^N$, we also have $\tilde{U}_i(\pi(Q(T_i(\tilde{v}_i)), \mathbf{v}'_{-i})) \geq \tilde{U}_i(\pi(\mathbf{v}'))$. Note that $Q(\pi(T_1(v_1), \cdots, T_N(v_N))) = \pi(Q(T_1(v_1)), \cdots, Q(T_N(v_N)))$. Then, we have $\tilde{U}_i(\pi(\mathbf{v}')) = U_i(Q^{-1}(Q(\pi(T_1(v_1), \cdots, T_1(v_N))))) = U_i(F(\mathbf{v}))$. Similarly, $\tilde{U}_i(\pi(Q(T_i(\tilde{v}_i)), \mathbf{v}'_{-i})) = U_i(F(\tilde{v}_i, \mathbf{v}_{-i}))$. Then, we obtain that $U_i(F(\tilde{v}_i, \mathbf{v}_{-i})) \geq U_i(F(\mathbf{v}))$. □

Theorem 1 demonstrates a decision-making mechanism that makes the individual-based voting scheme strategy-proof. This strategy-proof voting scheme first obtains the desired temperature from each occupant. Then, the median temperature of the desired temperatures from all occupants is set to be the optimal room temperature by the decision-making mechanism. This individual-based voting scheme also satisfies the fairness requirement, i.e., the chosen temperature is preferred by majority of occupants. The single-peaked temperature preferences guarantee that the median desired temperature is always preferred by more than half of occupants, compared with any other temperature.

[3]The single-peaked functions are not limited to the ones with single peak. The functions with single continuous set, all points in which are peaks, are also included. Here, we treat the middle point of the set as the single peak.

3.3 Group-based Voting Scheme

Under the group-based voting scheme, a decision-making mechanism $V(\mathbf{v})$ decides the group vote V. After that, the group-based voting scheme obtains the optimal room temperature $T_{\mathcal{N}}(V)$ based on the group vote.

THEOREM 2. *The group-based voting scheme is strategy-proof if:*

$$V(\mathbf{v}) = \pi(v_1, \cdots, v_N). \tag{7}$$

PROOF. Denote the new utility function $\tilde{U}_i(v) = U_i(T_N(v))$. Since $U_i(T)$ is singe-peaked with respect to T, $\tilde{U}_i$ is also singe-peaked with respect to v. Then, according to paper [11], the decision function $V(\mathbf{v}) = \pi(v_1, \cdots, v_N)$ under the new utility function is strategy-proof, i.e., $\tilde{U}_i(\pi(\tilde{v}_i, \mathbf{v}_{-i})) \geq \tilde{U}_i(\pi(\mathbf{v}))$ for any $\mathbf{v} \in [-3,3]^N$, where $\tilde{v}_i$ is the truthful vote for occupant i. That means $U_i(T_N(V(\tilde{v}_i, \mathbf{v}_{-i}))) \geq U_i(T_N(\pi(\mathbf{v})))$ for any $\mathbf{v} \in [-3,3]^N$. Thus, $F(\mathbf{v})$ is strategy-proof. $\square$

Theorem 2 demonstrates that the group-based voting scheme is strategy-proof if the median vote of all occupants' votes is chosen as the group vote by the decision-making mechanism. The optimal temperature can be obtained by the estimated thermal comfort model trained by this group vote. The group-based voting scheme only guarantees the majority preference for the median vote, but not for the optimal room temperature obtained from this vote. This is because the seven-point thermal comfort index may not reflect occupants' accurate preferences of temperatures.

4 Simulation Results

In this section, we evaluate the performance of our proposed voting schemes via simulation. We consider occupants' thermal comfort with linear model, adopted by standard ASHRAE [10]. According to this standard ASHRAE, the temperature range for comfort zone[4], i.e., thermal comfort value within $[-0.5, 0.5]$, is $[22.75°C, 26.25°C]$. Then, we can build the linear model for the general thermal comfort as $P_{\mathcal{N}} = 2/7(T - 24.5)$. The desired temperature for each occupant is assumed to follow Gaussian distribution with mean temperature $24.5°C$. Since the predicted percentage dissatisfied (PPD) value, defined by the percentage of occupants with thermal comfort value outside $[-0.5, 0.5]$, under the predicted mean vote (PMV) model during comfort zone is still 20%, we can estimate the standard variance as 1.37. Usually, errors happen when we estimate each occupant's thermal comfort. We assume they follow Gaussian distribution $G(0, \sigma)$. Based on the thermal comfort value under some room temperature, each occupant votes for their thermal comfort. The index value of thermal comfort vote for each occupant is assumed to be the integer value nearest to its own thermal comfort.

Fig.1 demonstrates the PPD with various numbers of occupants. Generally, both the group-based voting scheme and the individual-based voting scheme with $\sigma = 0.5$ have lower PPD, compared with constant setting. The improvement is reduced as the increase of the number of occupants. The individual-based voting scheme with $\sigma = 0.5$ has lower PPD than group-based voting scheme. This PPD of individual-based scheme increases when the estimated error is large, e.g., $\sigma = 1.5$. The PPD of optimal setting is much smaller than both individual-based and group-based voting schemes. For instance, the PPD of optimal setting is only 0.08, while the individual-based scheme with $\sigma = 0.5$ has 0.18 and the group-based scheme has 0.2. This motivates us to improve the performance of individual-based and group-based schemes in the future work.

5 Conclusion

In this paper, we study the false vote problem by designing strategy-proof schemes. We generalize the framework of strategy-proof thermal comfort voting and classify the schemes into two categories, i.e., individual-based and group-based voting schemes. We demonstrate the conditions for existence of the strategy-proof voting scheme in building. We also design the decision-making mechanisms for both individual-based and group-based voting schemes. We believe our framework of strategy-proof thermal comfort voting schemes provides important insights for researchers to design more efficient strategy-proof voting schemes. One interesting extension of this work is to study the dynamic voting schemes in buildings. We expect to work on these issues as future work.

[4]The comfort zone is decided mainly by six parameters. In this simulation, we take average values for parameters except air temperature.

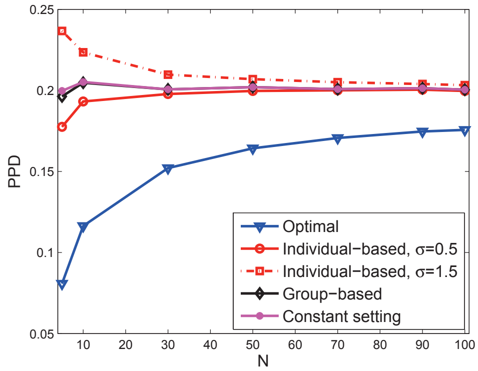

Figure 1: PPD vs. number of occupants

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