Invasive alien species respond to biologically-inspired robotic predators

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ABSTRACT

Invasive alien species threaten natural ecosystems worldwide, prey on native species, and deplete their food sources. Mosquitofish is one of the most invasive freshwater fish worldwide and its negative impacts on the native fauna are alarming. Despite the urgency of contrasting the mosquitofish invasion, we have access to very few methods to combat them. Even when successful, these methods can be excessively labor-intensive or dangerous to native species. Robotic predators may constitute a promising tool in combating mosquitofish. Our group has recently proposed the use of a robotic predator that can perform targeted attacks against mosquitofish. The robotic predator consists of three operational parts: a two-dimensional robotic platform, a magnetically connected replica of a native mosquitofish predator, and an in-house developed live tracking software. The robotic replica was programmed to swim along a predetermined trajectory and randomly target mosquitofish in real time through a dedicated tracking software. Building on available experimental results, we put forward a comprehensive mathematical toolbox based on symbolic dynamics, recurrence quantification, and information theory to detail the behavioral interaction between the robotic predator and mosquitofish.

Keywords: animal-robot interactions, ethorobotics, information theory, invasive species, live-tracking

1. INTRODUCTION

Worldwide, 5.4 billion dollars are lost each year as a consequence of the reduced number of native fish species caused by the introduction of invasive alien fish species into natural ecosystems.[1] One of the invasive species threatening the waterways is the mosquitofish (*Gambusia affinis*) - a fish species purposely introduced in freshwater ecosystems around the world, since thought to be a mosquito control agent.[2] Among all the poeciliids that have been artificially introduced into waterways, mosquitofish has the greatest ecological impact, playing a major role in the elimination and decrease of endangered native species.[3]

To maintain a healthy natural ecosystem, drastic actions against invasive alien species must be taken. Methods to eradicate mosquitofish from water bodies are limited. Toxic chemicals or manual labor are two of the most common ways to combat mosquitofish. However, introducing fish toxicants into water bodies can produce undesired, harmful effects on native fish, possibly damaging them more than mosquitofish.[4] Floating traps targeting mosquitofish are employed with success, but their labor-intensive deployment can only be undertaken in small water bodies and for a short time.[5]

In our recent work, we have proposed[6] a robotics-based approach to combat mosquitofish. Inspired by a native predator of mosquitofish, we designed a robotic predator replica capable of swimming alongside with live fish. The replica swam with different motion patterns, and performed targeted attacks towards a fish, based on its position, acquired by an in-house built live tracking software. A total of six experimental conditions were tested to determine which motion patterns were the most effective in creating anti-predatory response from

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mosquitofish. Experimental results presented therein indicate that real-time interactions at varying swimming speeds can elicit robust antipredator response in mosquitofish.

Here, we seek to further delve into these experimental results through a detailed time-series analysis of mosquitofish behavior. Specifically, we propose to examine the cause-effect relationship between the replica and mosquitofish through an information-theoretic approach grounded in recurrence analysis, symbolic dynamics, and information theory. Recurrence plots (RPs) constitute a valuable tool to identify patterns in the evolution of a dynamical system.[7] Classical RPs discriminate recurrent points from non-recurrent points by looking at the proximity of points in a phase space created from the time-series of a system. In classical RPs, a proximity parameter is used to determine recurrence between two points, thereby creating an arbitrariness in the predictions associated with the selections of a threshold value.

Proposed by Caballero-Pintado *et al.*,[8] symbolic RPs (SRPs) offer a further insight into the behavior of a dynamical system, by capturing recurrences of discrete symbols. These symbols are constructed by mapping the time-series of a system onto a symbolic space. Symbolic representation of time-series overcomes the arbitrariness of thresholding and offer a richer representation beyond the black-and-white visualization of classical RPs. By plotting recurrence of each symbol in different colors, SRPs help researchers identify patterns in systems with ease. For example, Boldini *et al.*[9] analyzed predator-prey interactions through symbolic recurrence quantification analysis (SRQA), demonstrating the connection between mathematical measures, such as determinism, and maximum diagonal length and animal behavior.

Building on SRPs, Porfiri and Ruiz Marín[10] conceived an information-theoretic framework to analyze symbolic recurrent dynamics. They extended the notion of transfer entropy by Schreiber[11] to symbolic recurrences, in an effort to infer causality between dynamical systems from their recurrent behavior. Across a range of numerical and experimental settings, they demonstrated the robustness of the method and its potential advantages with respect to classical transfer entropy analysis.

In this paper, we demonstrate the application of this mathematical framework on experimental results from Polverino *et al.*[6] Gathering insight from all the available experimental conditions, we dissected the effect of the replica's motion patterns on the causal interaction between replica and fish. Our results contribute to an improved understanding of the most effective motion pattern that the replica should perform to elicit a robust anti-predator response in mosquitofish.

2. REVIEW OF EXPERIMENTAL METHODS FROM POLVERINO *ET AL.*[6]

2.1 Ethics

Experiments were performed in accordance with relevant guidelines and regulations and were approved by the University Welfare Committee (UAWC) of New York University under the protocol number 13-1424. Pilot tests on predator fish were performed in Germany under animal care permit (G 0074/15) granted by the Landesamt für Gesundheit und Soziales Berlin (LAGeSo).

2.2 Robotic platform and predator replica

The robotic predator consisted of two parts, a robotic platform and a replica of a native predator. The robotic platform was developed on a commercially available Cartesian manipulator by adding a third stepper motor and an end-effector with embedded magnets. The robotic platform allowed for in-plane motion and rotation around the end-effector's axis, with varying speeds and turn-rates (Fig. 1). The robotic platform was controlled by a microcontroller paired with a motor shield board, running grbl v0.9 software.[12] The accuracy of the platform was 0.2 mm, which allowed for accurate representation of the predator's ethogram.

To implement the closed-loop algorithm, the fish and the replica were tracked using an overhead camera. The algorithm implemented the following steps. We obtained images at 20 frames per second, and converted each of the frames into a grayscale image. These images were turned into binary masks using an intensity threshold value. We used a blob analyzer in Matlab R2019a to find regions of connected pixels within a certain size range, and to detect the centroids of the blobs. Kalman predictors for both the fish and the replica were initiated prior to the trials.[13] Locations of the fish and the replica were predicted with the Kalman predictor under a constant velocity assumption. Then, we created a cost matrix by finding the distance between the predicted locations of the subjects and the centroids from the blob analyzer, to assign centroids to each subject using the Hungarian assignment algorithm.[14]

The robotic replica was designed based on a native predator of mosquitofish. Toward this aim, we obtained pictures of a juvenile largemouth bass (*Micropterus salmoides*), and created a three-dimensional model based on these pictures (Fig. 2). We 3D-printed a spine structure attached to a clear acrylic rod. To replicate the compliant body of a fish, we created a mold based on the model, and casted the replica with skin-safe silicone. The silicone body of the replica was then painted with a pattern matching the coloration in the live predator, and two glass eyes were glued onto it.[15] The 3D-printed spine was inserted into the silicone body, and the acrylic rod was attached to a base containing two magnets, with a diameter of 0.6 cm.

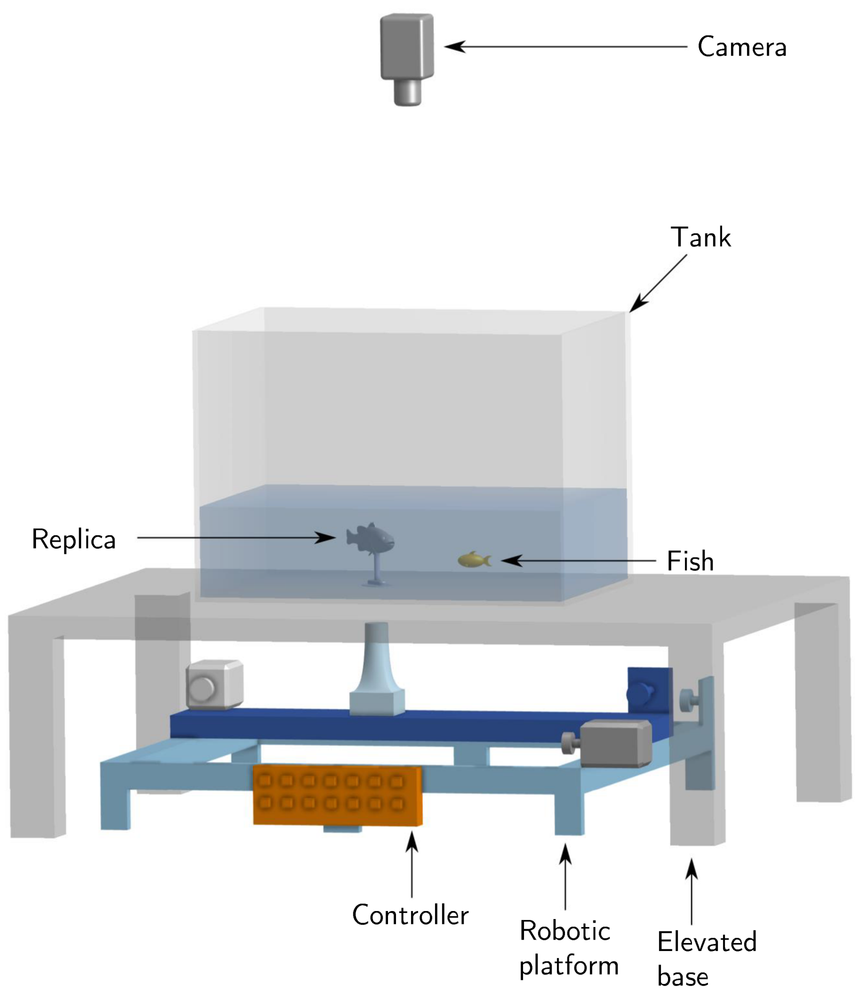


Figure 1: Sketch of the experimental setup illustrating, a mosquitofish, a predator replica, the robotic platform, the platform controller, and the overhead camera.

2.3 Experimental setup and conditions

We positioned the experimental tank ($44 \times 30 \times 30$ cm, length, width, and height) on an elevated base above the robotic platform (Fig. 1). The tank was filled with 10 cm of water. The tank was covered with white opaque contact paper to minimize external disturbance and provide a homogeneous background for tracking. Before each experimental trial, a fish was gently hand-netted into an opaque cylinder, and it was allowed to habituate

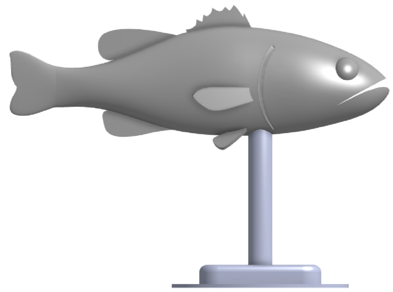


Figure 2: Computer assisted design of the replica of a largemouth bass - a native predator of mosquitofish.

to the water conditions for five minutes. Then, the cylinder was lifted, and camera recording was started. Each experimental trial lasted for ten minutes, and at the end of a trial, the fish was gently hand-netted back to its individual holding compartment.

We tested 74 fish across six conditions: without (no predator, NP) and in the presence of a replica (predator motionless, PM; open-loop 1, OL1; open-loop 2, OL2; closed-loop 1, CL1; and closed-loop 2, CL2). In the NP condition, a fish swam in the tank without the presence of a predator replica. In the PM condition, the replica was stationary at a random position in the tank. In the open-loop conditions, the replica swam with a predetermined trajectory, either with varying speeds from 0 to 20 cm/s (OL1) or with a constant speed of 6 cm/s (OL2). In the closed-loop conditions, the replica exhibited the same behavior as OL1, and it performed targeted attacks every minute, but at a random time within each minute. In the CL1 condition, the replica accelerated at 20 cm/s^2 until stopping 1 cm away from mosquitofish, while in the CL2 condition, the replica reached the targeted position at a constant speed of 6 cm/s.

3. METHODS FOR TIME-SERIES ANALYSIS

3.1 Symbolic recurrence plots

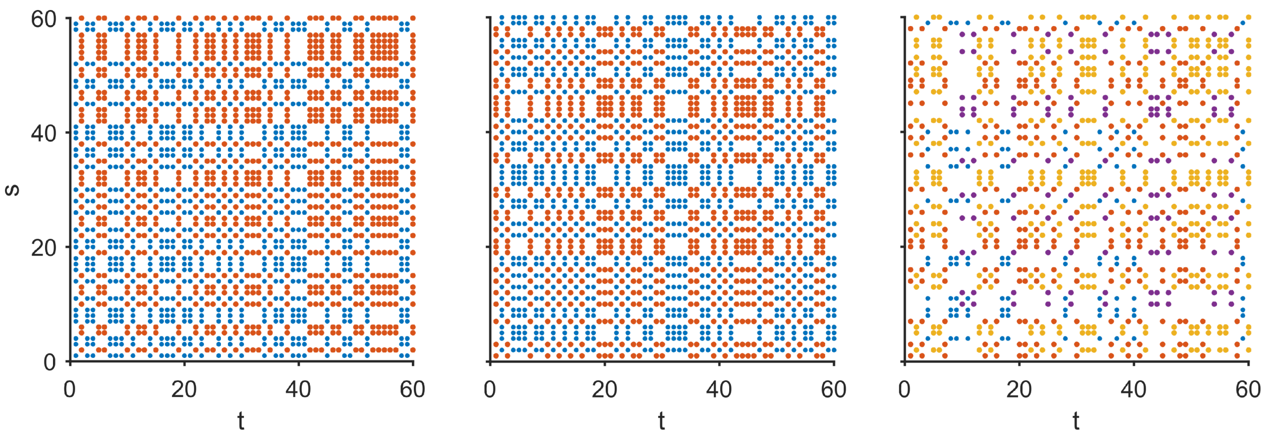
To construct the SRPs, we first downsampled the speeds of the fish and the replica to 1 Hz,[6] and then we mapped them into a symbolic space, using two symbolic partitions. The two symbols encapsulate acceleration or deceleration between two time-steps.[16] The entire analysis focused on calculated change in speed; therefore, we excluded NP, PM and OL2 conditions, since in NP, there was no replica, and in PM and OL2, the replica had a constant speed. Given the time-series of the speed of the fish or the speed of the replica, we defined recurrence at one of the two symbols at time t and s, if that symbol occurred at both t and s. We generated two plots for each of the symbols and overlaid them to create the final SRP (Fig. 3a,b).

Similarly, we created the joint SRP, by mapping the time-series of the speeds of the fish and the replica into a symbolic space with four symbols: increasing speeds for both, increasing fish speed and decreasing replica speed, decreasing fish speed and increasing replica speed, and decreasing speeds for both. We then recorded the recurrence of each symbol at given time-steps t and s. Recurrences were plotted for each of the four symbols, then combined to illustrate the joint SRP (Fig. 3c).

3.2 Symbolic recurrence quantification analysis

Analysis of SRPs can provide valuable insight into the dynamic features of a given dynamical system. We used two measures to quantify the joint interaction between the fish and the replica, namely, determinism and maximum diagonal length. These two measures pertain to different properties of a dynamical system. SRQA was only perfomed over the joint SRPs, converted into a black-and-white representation to focus on the interaction between the time-series across the entire symbol space.

Diagonal lines of length d between (t, s) and $(t + d, s + d)$ are continuous sequence of identical symbols, one starting at time t and the other at time s. Some form of predictability can be determined from these diagonal lines.[9] Specifically, we calculate the maximum diagonal length as a measure of recurrence. From the distribution



(a) (b) (c)

Figure 3: SRPs of the speed of a mosquitofish and the robotic predator in CL1 condition for one minute. (a) SRP for the robotic predator. (b) SRP for the mosquitofish. (c) Joint SRP. In (a) and (b), blue dots represent decreasing symbol and orange dots identify increasing symbol. In (c), blue dots mark decreasing symbol for both, orange dots identify decreasing symbol for predator and increasing symbol for fish, yellow dots refer to increasing symbol for predator and decreasing symbol for fish, and purple dots are associated with increasing symbol for both.

of diagonal lines, determinism can be computed as the probability of a point belonging to a diagonal line, other than the main diagonal. Determinism is related with the predictability of the dynamical system.[9]

We compared these two measures across conditions to investigate the effect of the replica's motion patterns. We used one-way ANOVA to compare the conditions and account for repeated measures of the same individual across conditions. If a significant effect of condition was noted, we used Tukey's honest significant difference criterion to compare the conditions pairwise.

3.3 Transfer entropy on symbolic recurrences

Transfer entropy, originally introduced by Schreiber,[11] measures the reduction of uncertainty in the prediction of the present of a dynamical system from its past, due to additional knowledge of the past of another dynamical system. This quantity is often used to identify causal links between dynamical systems and its value in the diagnostics of interactions between animals and robots has been widely documented.[17]

Porfiri and Ruiz Marín[10] showed that the inference of causal influence between two dynamical systems can be made from their recurrent behavior, by extending the notion of transfer entropy to symbolic recurrences. Following their approach, herein, we computed transfer entropy between the time-series of the speed of the replica and the fish (using again data downsampled to 1 Hz). We examined both directions of interaction in the transfer entropy analysis. The extent of the asymmetry in the interaction between the replica and the fish was used to determine the direction of influence in the pair.

To statistically test influence within the transfer entropy analysis, we performed permutation tests,[18] where we paired 74 fish with 74 random replicas within the same condition and computed mean transfer entropy value between the pairs. We repeated this procedure 20,000 times to create a surrogate empirical probability distribution of mean transfer entropy between random pairs for each condition, and compared the real, experimental mean value at a 5% significance level with one-tail test. To identify if direction or condition had any effect on the interaction, we compared all transfer entropy values within a condition to test for a difference in transfer entropies along the two directions, and between conditions for both directions, using a repeated measures ANOVA model. If a significance was found in ANOVA, conditions or directions were compared using Tukey's honest significant difference criterion.

For conditions where a significant transfer entropy was found, we calculated the net transfer entropy by subtracting the transfer entropy from fish to replica from the transfer entropy from replica to fish. We compared the net transfer entropy values against 0 using a t-test, to understand the direction of influence. Again, we compared the values across conditions using repeated measures ANOVA, to detect a possible effect of the condition on the interaction.

4. RESULTS

We recorded a significant difference across conditions for the determinism ($F_{2,219} = 6.35, p = 0.002$). There was no difference between OL1 and CL2 ($p = 0.998$), however, CL1 was different than other two conditions tested (OL1: $p = 0.005$; CL2: $p = 0.006$). We did not observe any significant difference across conditions for the maximum diagonal length ($F_{2,219} = 0.46, p = 0.632$).

We calculated the transfer entropy from replica to fish, and vice versa. As expected, we did not find a causal link in OL1 (Fish $\rightarrow$ Replica, $p = 0.221$, and Replica $\rightarrow$ Fish, $p = 0.066$). For the CL1 and CL2 conditions, we recorded a significant mutual interaction between the replica and the fish (CL1: Fish $\rightarrow$ Replica, $p < 0.001$, and Replica $\rightarrow$ Fish, $p < 0.001$; CL2: Fish $\rightarrow$ Replica, $p = 0.003$, and Replica $\rightarrow$ Fish, $p < 0.001$). When we compared the effect of condition and direction on transfer entropy with a repeated measures ANOVA, transfer entropy values in the two directions were significantly different ($F_{1,438} = 28.84, p < 0.001$) but, condition had no effect on transfer entropy ($F_{2,438} = 1.49, p = 0.226$). Using Tukey's honest significant difference comparisons, we discovered a difference between directions for OL1 ($p = 0.011$) and CL1 ($p < 0.001$), whereas direction was not significant for CL2 ($p = 0.633$)(Fig. 5a).

Finally, we compared net transfer entropy values for closed-loop conditions only, as transfer entropy values in OL1 were not significant. Both closed-loop conditions were different than zero based on t-test (CL1: $p < 0.001$; CL2: $p = 0.004$). ANOVA comparison between the two conditions suggests that the predator in CL1 caused a significantly larger response in mosquitofish compared to the CL2 condition ($F_{1,146} = 10.56, p = 0.001$) (Fig. 5b).

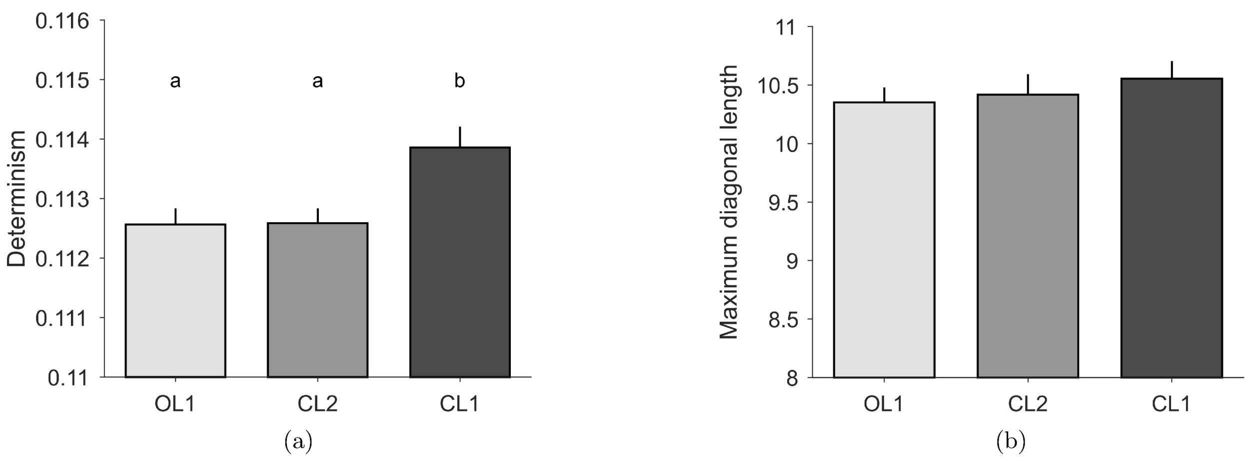
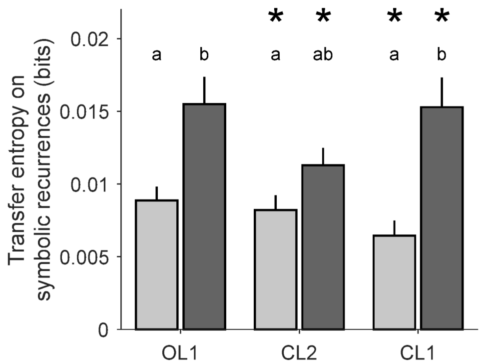


Figure 4: Symbolic recurrence quantification analysis for joint symbolic recurrence plot. (a) Determinism of joint symbolic recurrence plot for conditions OL1, CL2, and CL1. (b) Maximum diagonal length of joint symbolic recurrence plot for conditions OL1, CL2 and CL1. Means not sharing a common script indicate a significant difference.

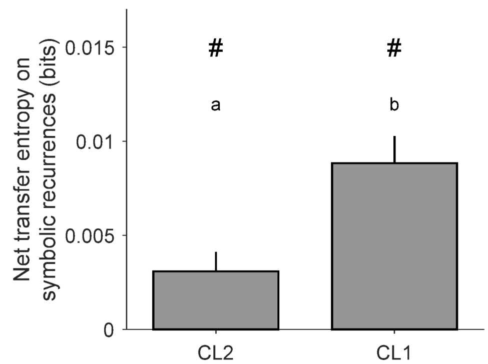
5. CONCLUSIONS

Combating invasive alien species is crucial to protect natural ecosystems. Mosquitofish has shown to be particularly challenging to combat. In our previous work,[6] we have proposed the use of a robotic predator replica that is capable of influencing mosquitofish behavior through repeated attacks. Our experimental results have shown that different behavioral patterns of the predator replica influenced mosquitofish differentially.

Here, we complement these results through additional time-series analyses grounded in symbolic dynamics, recurrence quantification, and information theory. Our new findings on determinism suggest that increasing



(a)



(b)

Figure 5: Transfer entropy analysis on symbolic recurrences. (a) Transfer entropy from the fish to the replica (light gray) and from the replica to the fish (dark gray) for three different swimming patterns of the robotic predator. (b) Net transfer entropy from the replica to the fish in closed-loop conditions. Means not sharing a common script indicate a significant difference, asterisk (*) indicates a significant difference from surrogate data at 5% significance level, and pound (#) indicates a significant difference from zero.

the level of biomimicry of the robotic predator translates into an increased predictability of its interaction with the live animal. Likewise, we determined that the most aggressive movement patterns employed in closed-loop conditions favor a robust behavioral response in mosquitofish. Further studies should seek to clarify the long-term consequences of the exposure to the robotic predator, toward an improved understanding of the practical feasibility of a robotics-approach to control of invasive species.

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