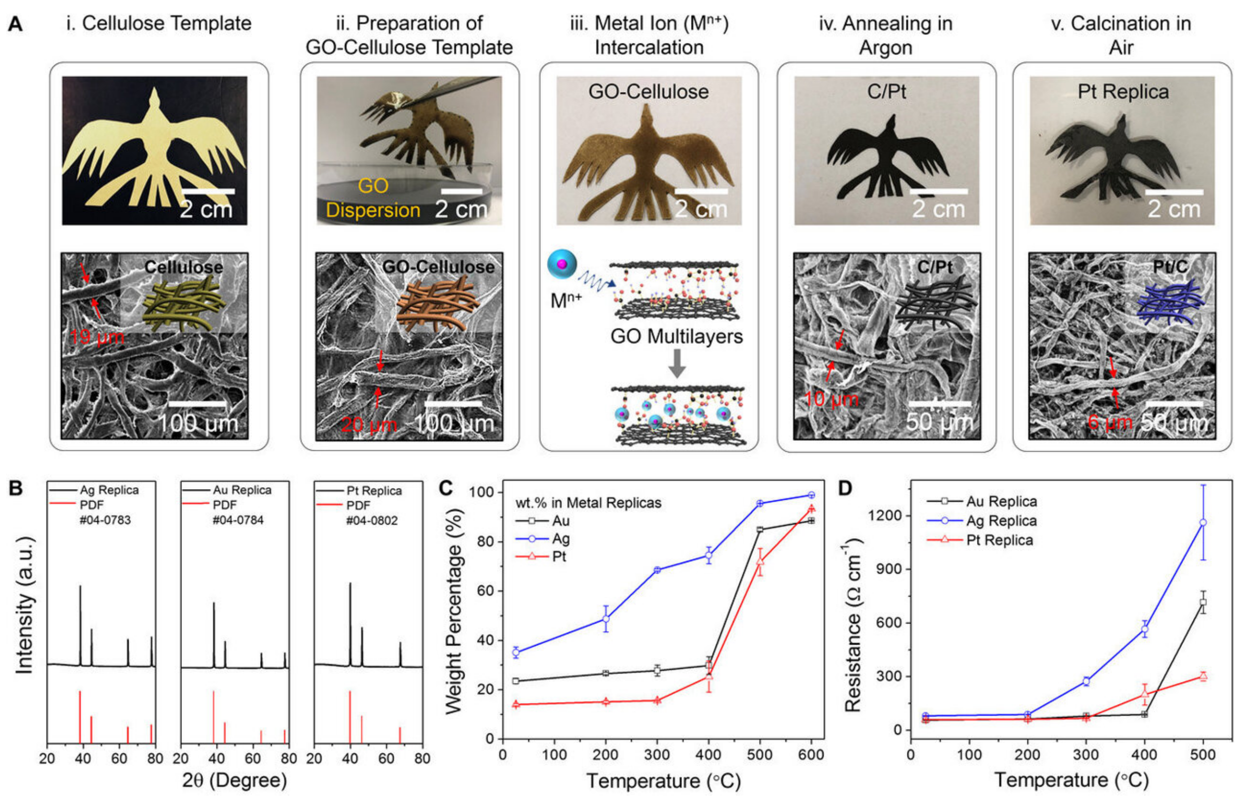
TechXplore

Multifunctional metallic backbones for origami robotics

September 5 2019, by Thamarasee Jeewandara

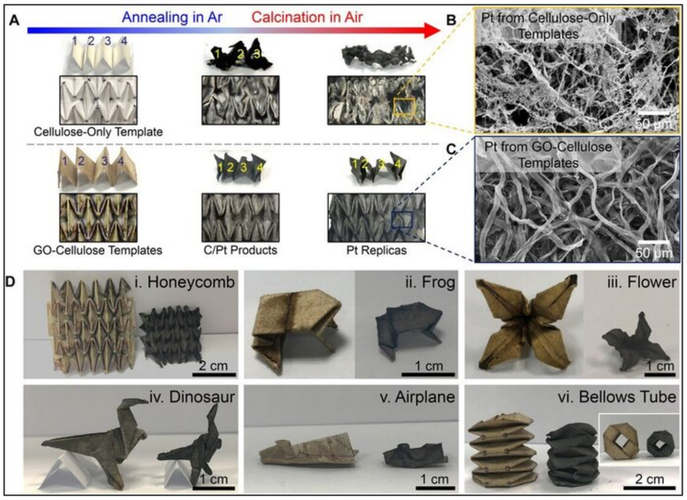


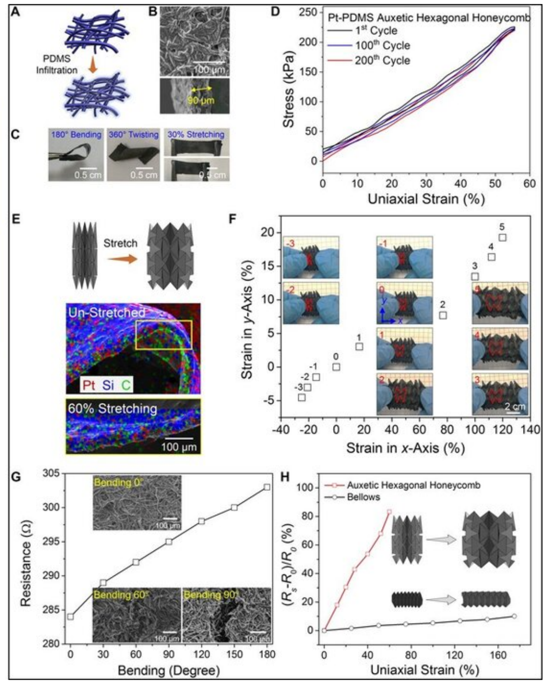
GO-enabled templating synthesis of noble metal replicas.(A) The GO-enabled templating synthesis to transform cellulose paper to noble metal replicas. The synthesis of a phoenix-shaped Pt replica is demonstrated. The SEM images showed that the network morphologies of cellulose paper and GO-cellulose template were very similar. The diameter of microfibers decreased from ~20 to ~6 µm after two-stage annealing/calcination. (B) XRD (x-ray diffraction) spectra of as-synthesized metal replicas after two-stage annealing/calcination. The spectra were consistent with their corresponding "powder diffraction files (PDF)" from "joint committee on powder diffraction standards." (C) Weight percentages of metallic contents in the templated replicas after the calcination in air at different temperatures. The weight percentages are determined by EDS (energy dispersive x-ray spectroscopy) analysis. (D) Resistance of templated metal replicas (across 1 cm) after the calcination in air at different temperatures. The error bars indicate the differences in measurements from four samples. Credit: Science Advances, doi: 10.1126/scirobotics.aax7020.

Origami robots can be formed by tightly integrating multiple functions of actuation, sensing and communication. But the task is challenging as conventional materials including plastics and paper used for such robotic designs impose constraints to limit add-on functionalities. To install multifunctionalities to the system scientists must typically include external electronics that increase the weight of the robot. In a recent study now published on *Science Robotics*, Haitao Yang and colleagues at the interdisciplinary departments of Chemical and Biomolecular Engineering, Biomedical Engineering and Electrical and Computer Engineering in the U.S. and Singapore developed a graphene oxide (GO)-enabled templating synthesis process to produce reconfigurable, compliant and multifunctional metallic backbones. The backbones formed the basis for origami robots coupled with built-in strain sensing and wireless communication capabilities. Using the GO method, the researchers formed complex noble metal origamis as structural replications of paper templates.

The research team could reproduce platinum origami structures made stable with thin elastomers to form multifunctional backbones to create the new origami robots. The new robots were more deformable, fire-retardant and power-efficient than those built using other materials. Yang et al. observed added capabilities for the new platinum robots (Pt robots) including on-demand resistive heating, strain sensing and built-in antennas without external electronics. For additional capabilities, they included monitoring or recording robotic movement in real time, wireless communication between robots, heat regulation and magnetic control. The new work enriched the robotics material library to engineer versatile soft robots.

Researchers in robotics had previously explored the ancient Japanese art of origami to engineer artificial muscles, self-folding machines, spring origami systems and robotic metamorphosis. Conventionally, they used cellulose paper, polyester, polyether ether ketone and polytetrafluoroethylene to fabricate backbones for such inventions. Despite the mechanical support on offer, paper or plastic backbones lacked functionalities of stimuli responsiveness, sensing and wireless communication. Instead of installing external equipment to deliver such functionalities, research teams now aim to develop multifunctional soft robotic backbones for tight integration. Research efforts have not yet demonstrated such prototypical soft robots with conductive origami backbones with sensing and communication potential. As a result, scientists are keen to develop a new fabrication scheme to produce mechanically stable, soft and conductive robotic backbones.

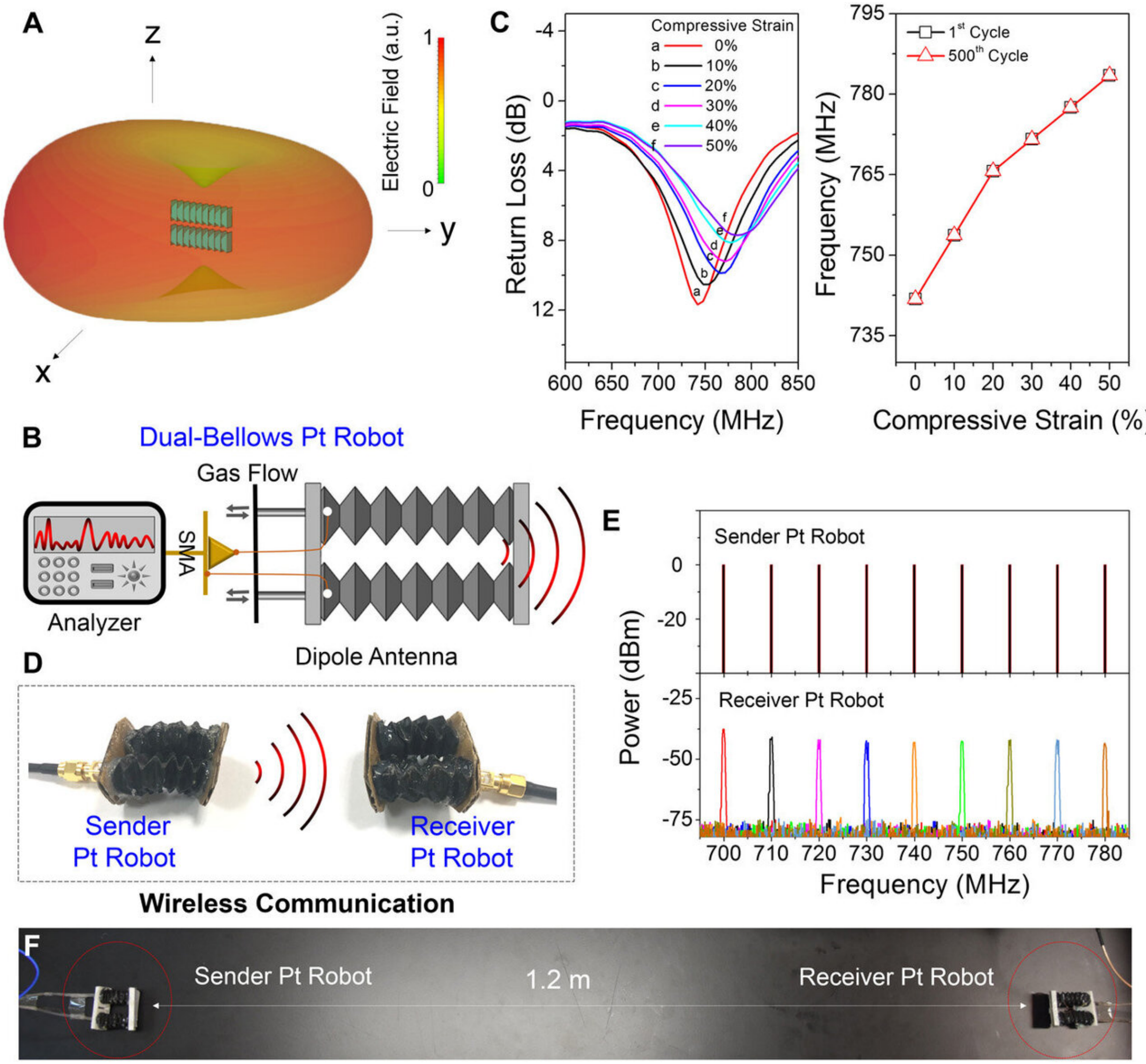




LEFT: Fabrication of metal origami structures. (A) Photos of the fourfold and auxetic hexagonal metal origami products synthesized from cellulose-only (top row) and GO-cellulose templates (bottom row). Pt-based products at different annealing/calcination stages are shown. SEM images of Pt products synthesized from (B) cellulose-only and (C) GO-cellulose templates. (D) Photos of GO-cellulose origami and as-templated downsized Pt origami replicas, including (i) honeycomb, (ii) frog, (iii) flower, (iv) dinosaur, (v) airplane, and (vi) bellows tube. RIGHT: Turning Pt origami replicas into deformable Pt-elastomer metamaterials. (A) Infiltration of dilute elastomer liquid into templated Pt replicas enables the fabrication of Pt-elastomer metamaterials. (B) Top-down and cross-sectional SEM images of Pt-elastomer composite. The thickness of Pt-elastomer composite is about 90 μm. (C) Large deformability of a planar Pt-elastomer thin film (180° bending, 360° twisting, and 30% stretching). (D) Stress-strain curves of a Pt-elastomer auxetic hexagonal origami during the stability test for 200 cycles. (E) In situ SEM images with EDS mapping of a Pt-elastomer crease under 90% uniaxial stretching. (F) The patterns of Pt-elastomer auxetic hexagonal origami is strain dependent during the uniaxial compressing (marked with −1 to −3) and stretching processes (marked with 1 to 5). The figure marked with 0 represented the initial state. (G) Resistance changes of a flat Pt-elastomer film under bending from 0° to 180°. (H) Relative resistance changes of auxetic hexagonal and bellows Pt-elastomer origamis under various uniaxial strains. Rs is the resistance of Pt-elastomer origami under uniaxial strains; R0 is the resistance of unstrained Pt-elastomer origami. Credit: Science Advances, doi: 10.1126/scirobotics.aax7020.

During the process of manufacture, Yang et al. used graphene oxide (GO) multilayers to intercalate a variety of metal ion precursors, followed by high temperature annealing and calcination to produce the high dimensional GO structures. The metal oxide replicas included microtextures, free-standing strands and complex origami structures with excellent chemical control and structural replication. The proposed GO-derived method will provide a new platform to produce complex metallic architectures as multifunctional backbones for soft robots.

Yang et al. converted the cellulose paper films or origami shapes into a variety of metal replicas using the GO-enabled templating process. They followed four main steps during the process of manufacture starting with a phoenix shaped template to form noble metal salt (Mn^{+})-intercalated GO-cellulose complexes (M-GO-cellulose). The resulting metal replicas underwent further annealing and calcination processes during manufacture and the research team controlled them by tuning their calcination temperature. The scientists created complex metallic origami structures such as hexagonal honeycombs, frogs, flowers, dinosaurs, airplanes and bellows by converting various 3-D origami structures from cellulose paper form into platinum metal.



Origami Pt robot with built-in wireless communication capabilities. (A) Simulated 3D radiation patterns for two Pt-elastomer bellows tubes at 741.8 MHz under 0% strain. (B) Schematic demonstration of a dual-bellows Pt robot, which also served as a reconfigurable dipole antenna. (C) Left: Return loss of the reconfigurable dipole antenna under different compressive strains from 0 to 50%. Right: The resonant frequencies are a function of compressive strains before and after 500-cycle robotic actuations. (D) Photograph of a sender Pt robot (sending signals) (left) and a receiver Pt robot (receiving signals) (right). (E) The pulse signals (the sender Pt robot sent) were well received by the receiver Pt robot. The frequency of sent signals was identical to the received signals. (F) Two Pt robots were able to communicate remotely across 1.2-m distance. Credit: Science Advances, doi: 10.1126/scirobotics.aax7020.

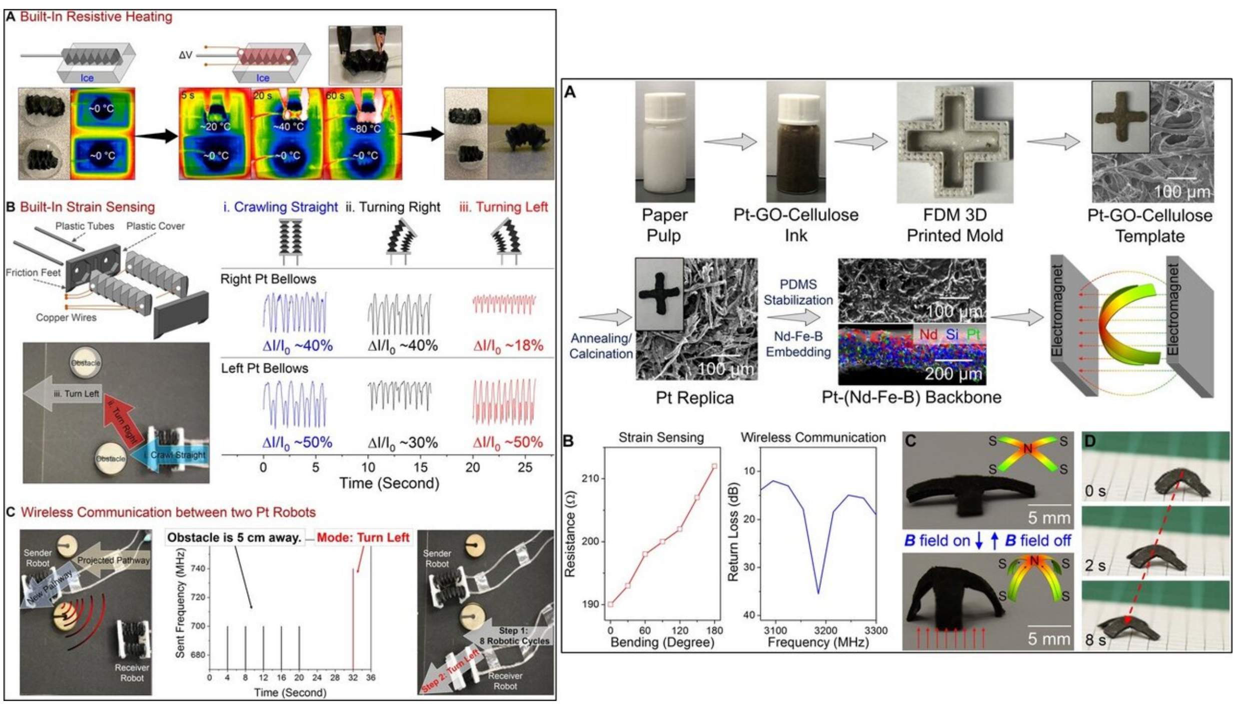
To improve mechanical stability, they included thin elastomers to the metal origami structures for large deformability and reversible reconfiguration. Yang et al. chose platinum metal due to its efficient structural preservation, high mechanical flexibility and high electrical conductivity compared with gold (Au) or silver (Ag). The team optimized the Pt-elastomer backbone for high-electrical conductivity and mechanical flexibility, for the resulting planar Pt-elastomer composite to sustain large and repeated deformations—ideal for soft robotic backbones. The reconfigurable metallic backbones introduced multiple and distinct functionalities to form metamaterial origami robots including intrinsic potential for fire resistance. The research team tested this feature by allowing Pt robots to sustain direct contact with a flame for prolonged exposure (800^0C for 30 seconds), in comparison a paper robot ignited in seconds (less than 5 seconds).

The Pt-elastomer backbone was thinner and lighter than the cellulose paper robots but remained mechanically stable during reversible robotic actuation. The paper-based robot required large pressure changes to elongate or contract; whereas the Pt robot only required lower pressure changes. Yang et al. then developed the conductive Pt origami robot to send and receive electromagnetic (EM) waves and serve as a reconfigurable antenna for wireless communication. Prior to manufacture, the research team simulated 3-D radiation patterns to explore the use of Pt robots as radiating antennas and fabricated them thereafter. The scientists also showed wireless communication between two Pt robots that served as a sender and receiver. When a sender robot sent pulse signals at different frequencies, the receiver robot stationed 1.2 m away received them without frequency deviation between the sent and received signals.

Comparison of the gas pressure between paper and Pt robots. Credit: Science Advances, doi: 10.1126/scirobotics.aax7020.

The team compared five categories of robotic features in the work to demonstrate technical advantages of using the GO-enabled Pt metallic backbones relative to (1) backbone density, (2) mechanical stiffness, (3) energy efficiency, (4) strain sensing capabilities and (5) wireless communication capabilities. The research team further optimized the two Pt robots for wireless communication, where a sender robot wirelessly delivered navigational instructions to a receiver robot to successfully bypass an engineered obstacle by following a guided pathway.

The team then expanded applications of the system using additive 3-D manufacture, where they combined Pt-Go-cellulose ink with fused deposition modeling (FDM) to 3-D print metallic robotic backbone molded shapes. Subsequently, they engineered Pt robots for remote control with magnetic fields. For this, Yang et al. synthesized a Pt replica with Pt-Go-cellulose ink and infiltrated the polymer solution with magnetic particles to create a magnetic Pt backbone. The new structures contained the usual built-in strain sensing and wireless communication capabilities, with added magnetic motion. The magnetic Pt robots could undergo reversible shape and body transformation under magnetic actuation to move forward in alignment to rotating magnetic fields.



LEFT: Demonstrations of multifunctional Pt robots. (A) Single-bellows Pt robot with built-in resistive heating capability. Two Pt robots were frozen in ice cubes. Under an applied voltage of 20 V, the upper Pt robot was quickly heated to ca. 80°C in 60 s, escaped from the ice, and continued to crawl forward. (B) Dual-bellows Pt robot with built-in strain sensing capability. The Pt robotic backbones were connected with copper wires, and the connection was fixed using silver paste. The proposed pathway for the dual-bellows Pt robot involved (i) crawling straight, (ii) turning right, and (iii) turning left. The robotic actuations along the whole pathway were monitored by reading the current profiles of left and right Pt bellows tubes. (C) Wireless communication between two dual-bellows Pt robots. The sender robot was blocked by an obstacle on the projected pathway and turned left to bypass the obstacle. The sender robot sent a series of signals to the receiver robot. The signals were then interpreted into the moving guideline for the receiver robot, enabling the robot to take the proposed pathway without encountering the obstacle. RIGHT: Fabrication of magnetically actuated Pt robot via Pt-GO-cellulose ink. (A) Alternative fabrication of Pt robots was demonstrated by developing Pt-GO-cellulose ink and incorporating with FDM 3D printing. After two-stage annealing/calcination, PDMS stabilization, and embedding with Nd–Fe–B particles, a magnetically actuated Pt–(Nd–Fe–B) tetrapod robot was fabricated. (B) Built-in strain sensing and wireless communication capabilities of Pt–(Nd–Fe–B) tetrapod robot. (C) Pt–(Nd–Fe–B) tetrapod robot arched up and down under magnetic actuations. (D) Pt–(Nd–Fe–B) tetrapod robot moved forward by following the trajectories of rotating magnetic fields. Credit: Science Advances, doi: 10.1126/scirobotics.aax7020.

In this way, Haitao Yang and colleagues developed a Go-enabled templating synthesis protocol to produce reconfigurable, compliant and multifunctional metallic backbones to build metallic origami robots. The robots contained built-in strain sensing and wireless communication capabilities. The synthetic metallic backbones made with complex noble metals including silver, gold and platinum were high structural replications of their paper counterparts. Compared to traditional papers and plastics, the reconfigurable Pt-elastomer backbones offered light weight, deformability and power efficiency. Yang et al. envision practical applications for metallic origami robots ranging from activities in high-risk environments, for use in artificial muscles and robotic arms, and as remote controlled untethered robots. They aim to optimize metallic backbones with electrochemically active materials to form energy storage devices next. Such developments will enrich the robotic materials library to fabricate diverse soft robots with high-functional integration.

More information: Haitao Yang et al. Multifunctional metallic backbones for origami robotics with strain sensing and wireless communication capabilities, *Science Robotics* (2019). DOI: 10.1126/scirobotics.aax7020

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