Supporting Information

Fusion of Poly(vinyl acetate-*b*-vinyl alcohol) Spherical Micelles in Water Induced by Poly(ethylene oxide)

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Materials

All reagents were purchased from Sigma-Aldrich Chemical Company (Milwaukee, WI, USA) and used as received unless otherwise noted. 2,2'-Azobis(isobutyronitrile) (AIBN) and V-40 (Wako Chemicals, USA) were both recrystallized from CH_3OH prior to use. Vinyl acetate (VAc) was fractionally distilled at ambient pressure prior to use from $NaBH_4$. Vinyl chloroacetate (VClAc) (TCI America, Inc.) was stirred over $NaBH_4$ and distilled under reduced pressure. The RAFT chain transfer agent *O*-ethylxanthyl ethyl propionate was synthesized according to a previous literature procedure.[1]

All ^1H NMR spectra were acquired in $CDCl_3$ or DMSO-d_6 on a Bruker AC+ 300 spectrometer operating at 300 MHz. The spectra were referenced to tetramethylsilane ($(CH_3)_4Si$) internal standard on $CDCl_3$ or residual protiated solvent peak in DMSO-d_6 in the sample.

Size exclusion chromatography (SEC) analyses were performed on a Viscotek GPCMax system equipped with two Polymer Labs Resipore Columns (250 mm x 4.6 mm), a differential refractometer, dual angle light scattering modules (7º and 90º), and a four-capillary differential viscometer with tetrahydrofuran as the mobile phase. All analyses were conducted at 40 ˚C and a flow rate of 1.0 mL/min. A Mark-Houwink corrected poly(vinyl acetate) (PVAc) calibration curve was constructed using 10 narrow molecular weight distributions polystyrene standards with $M_n = 580 – 377400$ g/mol (Polymer Labs, Amherst, MA) from which the molecular weight for the homopolymers were calculated. The molecular weight distributions ($Đ = M_w/M_n$) were calculated using polystyrene standard calibration curve. Absolute molecular weight determination of poly(ethylene oxide) (PEO) was performed according to previous reports.[2]

Representative synthesis of a PVAc$_{132}$-*b*-PVA$_{129}$ diblock copolymer. The synthesis of poly(vinyl acetate)-*block*-poly(vinyl alcohol) (PVAc-*b*-PVA) relies on the sequential block copolymerization of VAc and VClAc, followed by selective hydrolytic deprotection of the chloroacetate ester as recently reported by our group, as described briefly below.[3]

O-ethylxanthyl ethyl propionate (0.267 g, 1.20 mmol) and the thermal initiator AIBN (0.0198 g, 0.121 mmol) were dissolved in freshly distilled VAc (46.8 g, 544 mmol). This solution was degassed by three freeze-pump-thaw cycles, left under vacuum, and placed in an oil bath at 60 ˚C for 1.4 h. The resulting xanthate-terminated homopolymer was isolated by precipitation into hexanes and freeze-dried from C_6H_6. Purified PVAc$_{132}$-macro RAFT agent ($M_n = 11.4$ kg/mol,

$Đ = M_w/M_n$ = 1.18, 11.93 g, 1.05 mmol) and V-40 (0.0252 g, 0.103 mmol) were dissolved in freshly distilled VClAc (44.72 g, 371.0 mmol) and dichloroethane (37.5 mL). An aliquot (25 mL) of this solution was degassed by three freeze-pump-thaw cycles, left under vacuum, and placed in an oil bath at 75 ˚C for 5.75 h. The resulting diblock $PVAc_{132}$-b-$PVClAc_{151}$ diblock copolymer was purified by precipitation into hexanes and freeze-drying from C_6H_6.

$PVAc_{132}$-*b*-$PVClAc_{151}$ (M_n = 29.6 kg/mol, N_{PVClAc} = 151.0, 2.033 g, 10.37 mmol of ClAc ester units) was dispersed in CH_3OH (30 mL). K_2CO_3 (0.073 g, 0.53 mmol) was added to the dispersion and allowed to react for 7.2 h to selectively hydrolyze the chloroacetate esters in the block copolymer, after which the CH_3OH was removed by rotary evaporation. The resulting $PVAc_{132}$-*b*-PVA_{129} diblock copolymer was triturated and washed with double distilled water (10 mL x 3), followed by centrifugation to isolate the product. The product was then dried *in vacuo*. The diblock copolymer composition was measured by quantitative ^1H NMR spectroscopy in DMSO-d_6, and the overall molecular weight was calculated based on the composition and the molecular weight of the $PVAc_{132}$ macro-RAFT agent. Selective hydrolysis of the $PVAc_{132}$-*b*-PVA_{129} diblock copolymers was confirmed by treatment with trifluoroacetic anhydride, as described previously.[3]

Table S1: Molecular characterization of the polymers used in this report.

Sample	$M_{n,\ total}$ (kg/mol)[a]	$Đ$ [b]	mol% PVA
$PVAc_{132}$-*b*-PVA_{95}	15.6	1.36	43.6
$PVAc_{132}$-*b*-PVA_{129}	17.1	1.41	51.1

[a] Molecular weight after hydrolysis.
[b] $Đ$ was measured against PS standards previous to hydrolysis.

Preparation of micellar aggregates. Aqueous dispersions of $PVAc_{132}$-*b*-PVA_{95} were produced by dropwise addition of ultrapure water to a vigorously stirred solution of diblock copolymer in dimethyl sulfoxide (DMSO) to yield a final polymer solution concentration of 6.9 wt%. The aqueous dispersions were dialyzed against ultrapure water for 5 days to remove all the DMSO, using a dialysis membrane with a MWCO = 1000 g/mol. In general, 11 kg/mol PEO aqueous solutions were mixed with dialyzed $PVAc_{132}$-*b*-PVA_{95} spherical micelles using two separate syringes attached to the arm of a Y-shaped connector to yield a final PEO concentration of 3.1 wt%. A similar approach was used for studies with 30.7 wt% PEO. Both solutions (PEO and spherical micelles) were filtered through 1 mm syringe filter prior to mixing. The final spherical micelle concentration was 2.0 wt%.

Dynamic Light Scattering (DLS). Dynamic light scattering studies employed a Brookhaven Instruments multi-angle light scattering instrument fitted with a 532 nm, 100 mW laser (Compass 315M-100, Coherent, Santa Clara, CA). Samples were mounted in a temperature-regulated glass cell at 25 °C filled with decahydronapthalene (Fisher Scientific, Pittsburg, PA) as a refractive index matched fluid. Scattered light intensity from the aqueous block copolymer dispersions was measured at angles of 30º, 60º, 90º, 120º, and 150º relative to the incident beam. The autocorrelation functions were obtained using a Brookhaven BI-9000AT digital autocorrelator (Brookhaven Instruments, Holtsville, NY).

DLS data fitting. To describe the two diffusive modes observed in our system (free micelles and hydrogen-bonded micelles), the intensity autocorrelation functions $g^{(2)}(\tau)$ were analyzed using the double-exponential expression (Figure S2 A and C)

$$g^{(2)}(\tau)-1=\left[A_1\exp(-\Gamma_1\tau)+A_2\exp(-\Gamma_2\tau)\right]^2 \quad (1),$$

in which A_1 and A_2 represent the relative contributions to the scattered field of the decay rates, Γ_1 and Γ_2.[4] Using the previous equation, Γ was determined for different wavevector values, $q = 4\pi n\lambda^{-1} \sin(\theta/2)$, where n is the solvent refractive index (water) and θ is the scattering angle. The mean diffusion coefficient D_t for the free micelles and hydrogen-bonded complexes were determined via a forced fit of Γ *v.* q^2 through the origin (Figure S2 B and D). Assuming that the aggregates are spherical, the mean hydrodynamic radius (R_h) was calculated from the Stokes-Einstein equation $D_t=\dfrac{kT}{6\pi\eta R_h}$, with a 95% confidence interval. Note that these uncertainties represent the standard error associated with the fitted value of D_t.

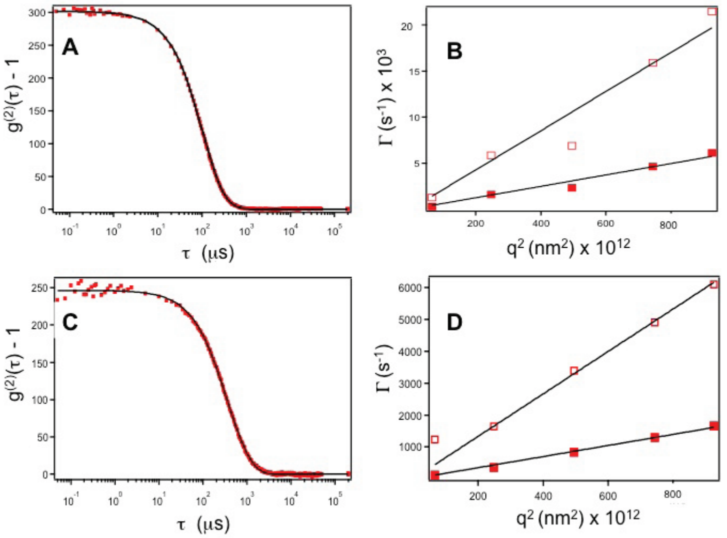

Figure S1: Representative analysis of (A) DLS autocorrelation functions for PVAc_{132}-b-PVA_{129} spherical micelles in H_2O at 25 °C obtained at a 90° scattering angle fit with a double-exponential function. (B) Linearly fitting the two decay rates (Γ) versus the square of the scattering wavevector (q^2) for the multi-angle light scattering data yields the diffusion constant, from which we calculate the hydrodynamic radius using the Stoke-Einstein relation (assuming hard spheres) to obtain radii: Fast mode = 11.5 ± 0.8 nm; Slow mode = 39.6 ± 2.1 nm. Similar analyses of the DLS autocorrelation functions (C) for mixtures of PVAc_{132}-b-PVA_{129} and 11 kg/mol PEO 3.8 wt% in H_2O yield (D) radii: Fast mode = 37.9 ± 1.8 nm; Slow mode = 143.5 ± 3.4 nm. In plots (B) and (D), the slow diffusion mode is indicated by the filled squares and the open squares denote the fast mode.

Cryogenic Transmission Electron Microscopy (cryoTEM). Vitreous cryoTEM samples of aqueous block copolymer dispersions were prepared for real-space TEM imaging following two protocols.

1. **Free Micelles:** A 5 μL droplet of the aqueous micellar solution of the polymer amphiphile (3.2 wt% polymer in H_2O) was placed on a lacy carbon-coated copper grid (Ted Pella, Inc.) in a humidity controlled environment vitrification system (Vitrobot, FEI, Inc.). The sample was blotted to wick away excess solvent to create a thin film of the dispersion on the grid surface using a -4 mm blotting force, a 0.5 s blot time, and a 10 s drain time to equilibrate any stresses in the sample caused by blotting. The resulting sample grid was vitrified by plunge freezing into liquid ethane (-183 ˚C).
2. **Micelles mixed with 11 kg/mol PEO**: A 10 μL droplet of the mixed block

copolymer aqueous dispersion with PEO (2.0 wt% spherical micelles, 3.1 wt% PEO) was placed on a lacy carbon-coated copper grid (Ted Pella, Inc.) in a humidity controlled environment vitrification system (Vitrobot, FEI, Inc.). The sample was blotted to wick away excess solvent to create a thin film of the dispersion on the grid surface using a -4 mm blotting force, a 1 s blot time, and a 10 s drain time to equilibrate stresses in the sample after blotting, and (3) samples were plunged into liquid ethane (-183 ˚C) to vitrify the samples.

Vitreous samples were subsequently transferred under liquid Nitrogen to either a Fischione cryo transfer specimen holder or a Gatan cryo transfer specimen holder and imaged at -178 ˚C. We used both an energy-filtered LEO-EM912 TEM operating at 120 kV and a Tecnai T-12 TEM operating at 120 kV to produce the images reported on this publication.

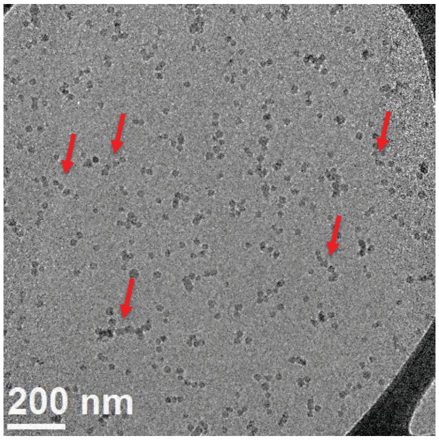

Figure S2: CryoTEM image showing the formation of short strands ascribed to the hydrogen-bonding of the PVA corona blocks of $PVAc_{132}$-*b*-PVA_{95} aqueous dispersions.

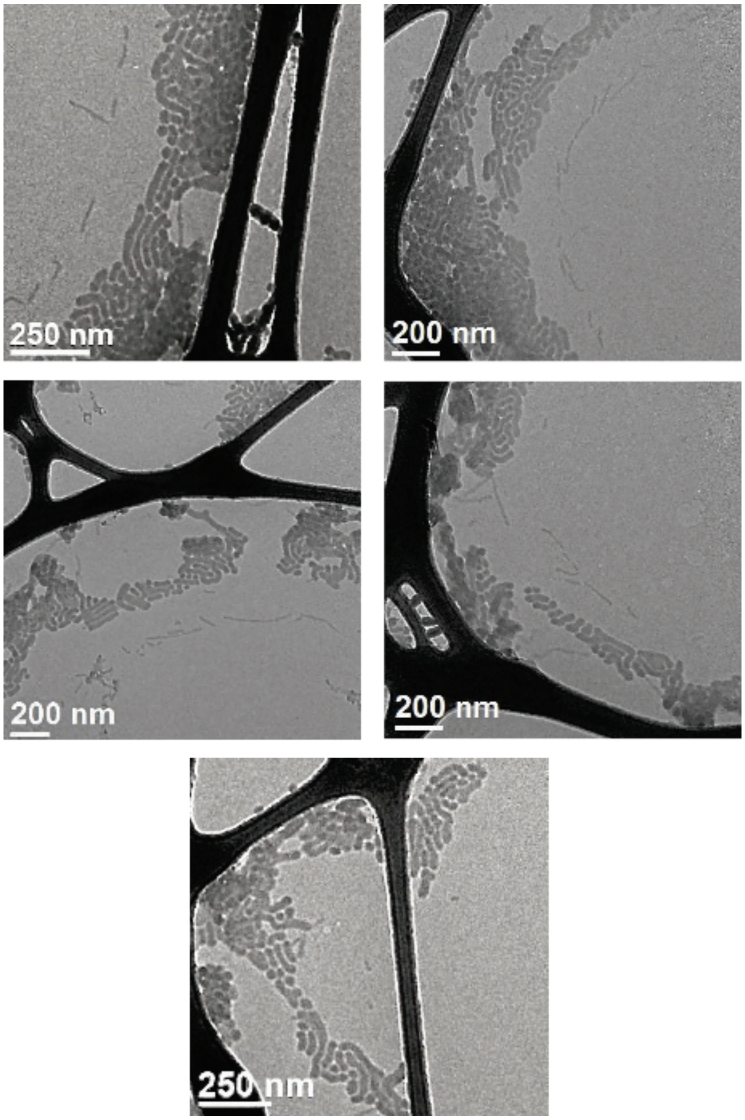

Figure S3: Collection of cryoTEM images showing the worm-like nature of $PVAc_{132}$-*b*-PVA_{95} after the addition of 11 kg/mol PEO 3.1 wt%.

Synchrotron Small Angle X-ray Scattering (SAXS). Synchrotron SAXS analyses were conducted at the DuPont-Northwestern-Dow Collaborative Access Team (DND-CAT) 5-ID- D beamline of the Advanced Photon Source at Argonne National Laboratory (Argonne, IL). 3.2 wt% aqueous solutions of polymeric micelles were loaded into 2 mm quartz capillaries and exposed for 1 s to X-rays with an incident beam energy of 16 keV ($\lambda = 0.7293$ Å) and a 3.068 m sample-to-detector distance (calibrated using silver behenate). Two-dimensional SAXS patterns were recorded on a MAR-CCD detector (133 mm diameter active circular area). 2D SAXS patterns were azimuthally integrated to obtain one-dimensional intensity *I(q) versus* scattering wave vector (*q*) plots. These SAXS intensity profiles were background corrected using an H_2O blank and the excess scattering from an aqueous PEO homopolymer solution (4.04 wt% 11 kg/mol PEO). The SAXS patterns were fit to various form factor scattering models using Jan Ilavsky's IRENA software.[5] X-ray contrast was calculated for the core (poly(vinyl acetate), the shell (poly(vinyl alcohol)), and the solvent (water) based on the electron densities using IRENA.

For reference, Figure S4A shows synchrotron SAXS data for a spherical micelle dispersion of PVAc_{132}-*b*-PVA_{95} in the absence of any added homopolymer. Fitting this data with a spheroid model (aspect ratio 1) with a radius r = 13.4 nm (std. dev. = 0.26) provides a modest fit, wherein we attribute the higher observed scattering intensity at low *q* to the presence of micelles aggregated by hydrogen bonding (as determined by DLS; *vide infra*).

Figure S4B shows synchrotron SAXS intensity profile obtained from a mixture of PVAc_{132}-*b*-PVA_{95} with 11 kg/mol PEO and [EO]:[VA] = 5. The form factor scattering for this sample is reasonably well fit by a cylinder model with a cylinder radius r = 17.4 nm (std. dev. = 0.22) and a cylinder length fit to 250 nm at moderate and high values of *q*. The observed scattering derivates from that predicted by the model at low q values, by virtue of the length polydispersity of the worm-like micelles. If we instead try to fit the worm-like micelles SAXS intensity profiles with a spheroid model (aspect ratio = 1) with a radius r = 15.7 nm (std. dev. = 0.28) as shown in Figure S4C, the model predicts substantially lower low q intensities than observed.

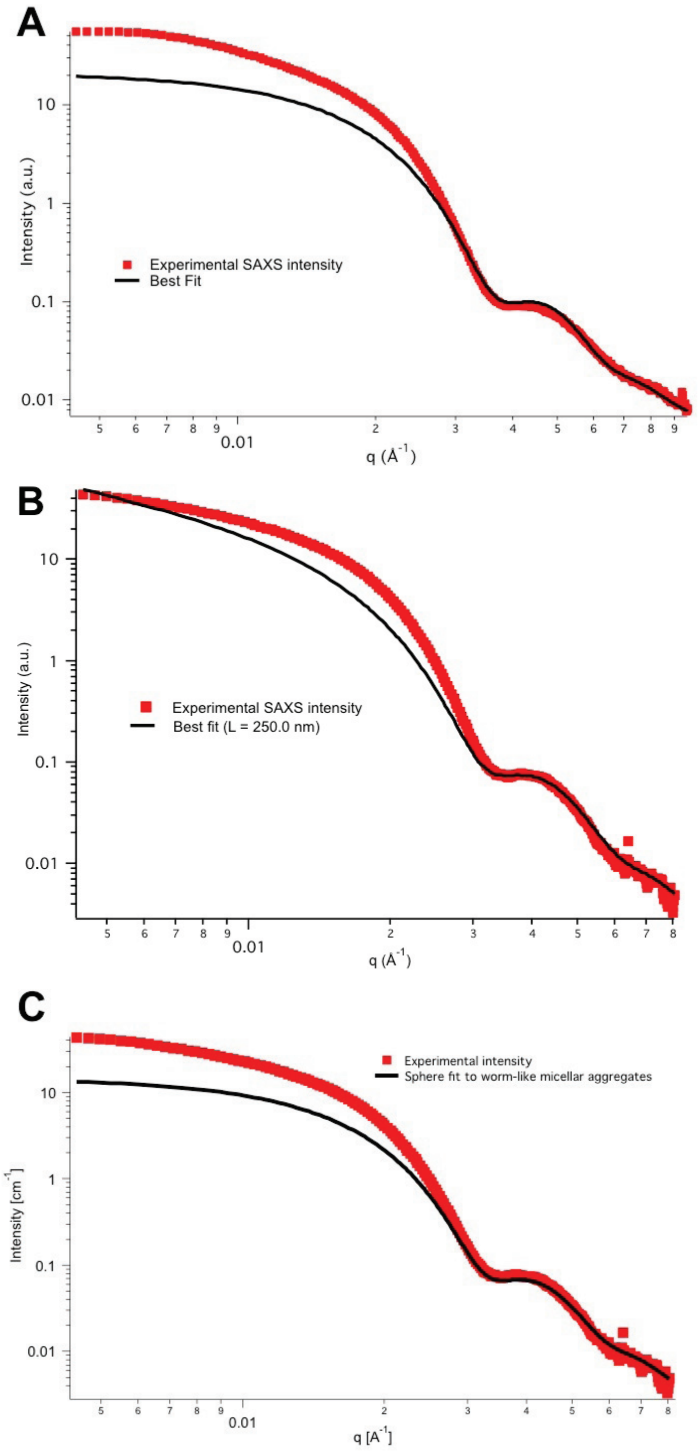

Figure S4: Synchrotron small-angle X-ray scattering intensity profiles (*red*) and form factor model fits (*black)* for: (A) spherical micelles of PVAc$_{132}$-*b*-PVA$_{95}$ with a radius r = 13.4 nm (std. dev. = 0.26), consistent with DLS and cryoTEM measurements, (B) worm-like micelles derived from addition of 3.1 wt% 11 K PEO to PVAc$_{132}$-*b*-PVA$_{95}$ spherical micelles with radius r = 17.4 nm (std. dev. = 0.22) and a mean cylinder length of 250 nm, and (C) form factor fit of the same data show in (B) using a spherical micelle model with radius r = 15.7

nm (std. dev. = 0.28), demonstrating a poor fit. These data indicate that the bulk solution morphology associated with the data in Panel (B) is worm-like micelles.

Determination of c* for 11 kg/mol PEO. To determine the overlap concentration (c^*), we measured the intrinsic viscosity ($[\eta]$) of aqueous PEO solutions using an Ubbelohde viscometer thermostated at (25.0 ± 0.1) ˚C. Starting with an initial PEO stock solution with a concentration of 0.0502 g/mL, we measured the flow time (± 0.01 s accuracy) of the solution through the capillary (1.26 mm diameter) of the viscometer referenced against that of pure water. The relative viscosity (η_r) can then be calculated, $\eta_r = \frac{\rho_{PEO} t_{PEO}}{\rho_{H_2O} t_{H_2O}}$, where ρ_{PEO} is the density of the PEO solution, t_{PEO} is the run time in seconds, ρ_{H2O} is the density of water at 25.0 ˚C, and t_{H2O} is the run time for water. The same procedure was used for three additional solutions prepared by serial dilution and all measurements were performed in triplicate. Following these measurements, the ratio of specific viscosity ($\eta_{sp} = \eta_r - 1$) to that of PEO solution concentration (c) yields the reduced viscosity (η_n), which is plotted in Figure S5.[6] The intrinsic viscosity ($[\eta]$) was then determined by the extrapolation of the η_n to the limit of zero concentration. The overlap concentration, c^*, is approximated by $c^* \sim \frac{1}{[\eta]}$,[7] and we find that $c^* = 0.0407$ g/mL.

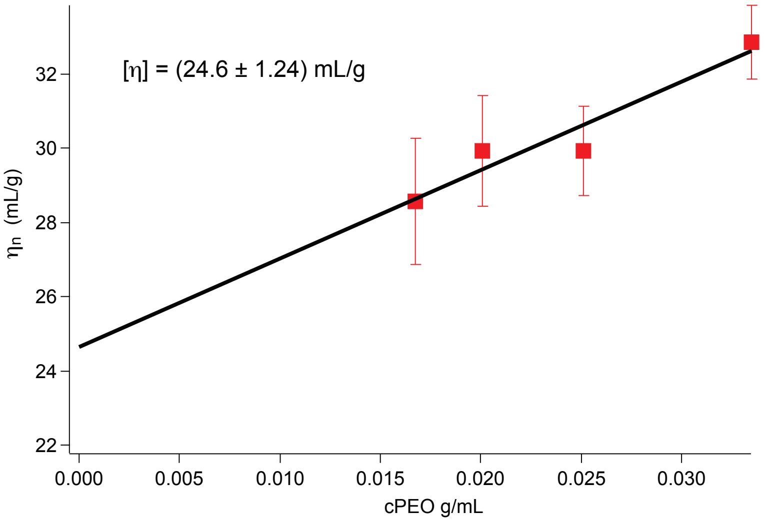

Figure S5: Dependence of the reduced viscosity on the concentration of an 11 kg/mol PEO solution. The extrapolation to the y-intercept yields an intrinsic viscosity of (24.6 ± 1.24) mL/g from which the c^* was determined ($c^* = 0.0407$ g/mL).

References:

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