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Subtle interactions and electron transfer between U(III), Np(III) or Pu(III) and uranyl mediated by the oxo group

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Abstract: A dramatic difference in the ability of the reducing An(III) center in $AnCp_3$ (An = U, Np, Pu; Cp = C_5H_5) to oxo-bind and reduce the uranyl(VI) dication in the complex $[(UO_2)(THF)(H_2L)]$ (L = 'Pacman' Schiff-base polypyrrolic macrocycle), is found and explained. These are the first selective functionalizations of the uranyl oxo by another actinide cation. At-first contradictory electronic structural data are explained by combining theory and experiment. Complete one-electron transfer from Cp_3U forms the U(IV)-uranyl(V) compound that behaves as a U^V-localized single molecule magnet below 4 K. The extent of reduction by the Cp_3Np group upon oxo-coordination is much less, with a Np(III)-uranyl(VI) dative bond assigned. Solution NMR and nIR spectroscopies suggest $Np^{IV}U^V$ but single crystal X-ray diffraction and SQUID magnetometry suggest a Np^{III}-U^{VI} assignment. DFT calculated Hirshfeld charge and spin density analyses suggest half an electron has transferred, and explain the strongly shifted NMR spectra by spin density contributions at the hydrogen nuclei. The Pu(III) - U(VI) interaction is too weak to be observed in THF solvent, in agreement with calculated predictions.

The uranyl(VI) dication UO_2^{2+} is the most common form of uranium in the environment, and is reduced by minerals and microbes to the less stable uranyl(V) monocation UO_2^+.[1] One of the notable features of the $5f^1$- uranyl(V) ion is its tendency to coordinate to other metal cations through the oxo group, behaviour more reminiscent of the heavier f^1 and f^2 neptunyl and plutonyl cations which form a variety of oxo-bridged cation-cation interactions (CCIs) that interfere with nuclear waste manipulations.[2] Reduction of U^{VI} uranyl to the more Lewis basic U^V uranyl ion dramatically increases CCI interactions, providing good models for the behaviour of the Np and Pu ions, which are significantly more radioactive than the uranyl ion. In addition to the actinyl ions, civil nuclear waste also contains a large number of 5f metal cations from fuel additives and cladding bombardment.[3] Thus, understanding the interaction of uranyl, which represents *ca* 98 % of spent fuel, with other 5f metal ions is important.

Simple U^{III} complexes can reduce and activate inert small molecules,[4] but no such reactivity has been reported for transuranic An^{III} complexes in which the An^{IV} formal oxidation state is less thermodynamically favoured compared to U^{IV}. However, the reduction of U^{VI} to U^V in the uranyl ion is thermodynamically accessible,[5] and recent work by us and others has shown that reduction can be accompanied by oxo-group functionalization with either main group[6] or magnetically more interesting 3d- and 4f- metal cations.[7] The strong anisotropy of the f-block ions has enabled recent breakthroughs in the design of molecular magnets with slow relaxation times that could have applications in spintronic devices, for example.[8] Actinides have been favored over lanthanides in this area due to the relatively greater proportion of covalency (and therefore potential for magnetic communication) in their bonding interactions. Furthermore, the axial symmetry of the uranyl ion offers a design element to control the orientation of the magnetic vector of the single 5f electron in U^V uranyl complexes and has been used to construct mixed, oxo-bridged uranyl-transition metal single molecule magnets (SMMs).[7d]

The difference in preferred coordination geometries of actinyl and actinide cations has been used successfully to make coordination network materials that combine uranium as U^{VI} uranyl and the transuranic neptunium(IV) cation in a phosphate structure,[9] but to the best of our knowledge no reaction to form a heterobimetallic actinide complex through an inner-sphere redox reaction has been reported. We envisaged that the binding and redox-reaction of the uranyl oxo group with potentially reducing f-block metal cations could provide fundamental information on the behaviour of actinyl cations in solution, and a versatile and powerful design principle for the synthesis of electronically coupled, redox-active, 5f elements.[7c] Here, we report synthetic routes to the first actinide-functionalized uranyl(V) complexes and a study of their 5f-5f magnetic coupling.

The reaction between THF solutions of $[(UO_2)(THF)(H_2L)]$ A and Cp_3An (An = U, Np, Pu, Cp = C_5H_5**)** results in a color change of the greenish solution of **A** to brown or red-brown for U and Np, but no observable reaction for the Pu analogue; presumably the Pu cation is insufficiently Lewis acidic and the THF donor solvent thus becomes competitive with Pu-oxo coordination (Scheme 1). For U and Np crystals of $[Cp_3AnOUO(THF)(H_2L)]$ (An = U, **1a** dark orange; **1b** golden-brown; An = Np, **2a** dark red, **2b** dark red-brown), are isolated in yields of around 30 %. All the complexes are highly air-sensitive, but in general, the octamethyl ligand derivatives (b) are much easier to isolate as they crystallize as

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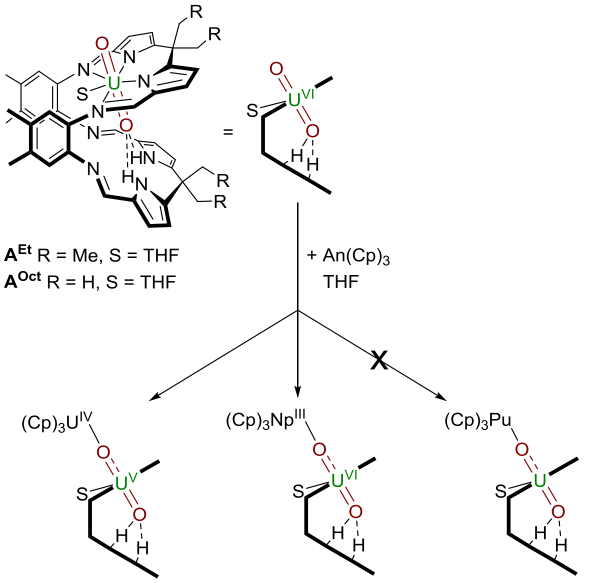
Supporting information for this article is given via a link at the end of the document large blocks that are readily separable from powdery impurities. Complexes **2** are the first molecular heterobimetallic uranium-neptunium complexes.



Cp_3U-$OUO(H_2L^{Et})$ **1a** Cp_3Np-$OUO(H_2L^{Et})$ **2a** Cp_3Pu-$OUO(H_2L^{Et})$ **3a**
Cp_3U-$OUO(H_2L^{Oct})$ **1b** Cp_3Np-$OUO(H_2L^{Oct})$ **2b**

Scheme 1. Reductive oxo-metalation of uranyl complexes by $AnCp_3$ (An = U, Np, Pu).

The new An-OUO complexes are exclusively *exo*-oxo metalated, as characterised by ^1H NMR, NIR and IR spectroscopy, and single crystal X-ray diffraction, and are readily oxidised by trace impurities to form the known An^{IV} complexes $[\mathbf{Cp_3}An]_2(\mu\text{-}O)_2$[[10]] and the U^{VI} uranyl starting material **A**. The solution stability of **2b** is greater than that of **2a**, enabling a full NMR spectroscopic assignment (see SI).

In the ^1H NMR spectrum of **1a** the two ligand pyrrole NH protons in the *endo*-cavity resonate at 51.4 ppm (51.1 ppm in **1b**, 55.5 in **2a,** 54.8 ppm in **2b**). These highly paramagnetically shifted resonances, along with other macrocyclic ligand resonances strongly suggest that both $\mathbf{Cp_3}An^{III}$ fragments have reduced the uranyl to U^V uranyl forming An^{IV}-U^V uranyl complexes with strong NH-O_{endo} hydrogen bonding interactions.[5a, 11] The resonances for the Cp-ring protons are not similarly diagnostic, however, appearing at 3.17 ppm in **1a** and 3.30 ppm in **1b**. For the *pseudo*-tetrahedral [Cp_3U]-containing complexes reported, the corresponding value for the Cp H is −15.41 ppm in $\mathbf{Cp_3}U^{III}$(THF), with U^{IV} values ranging from −3.48 ppm in $\mathbf{Cp_3}U^{IV}Cl$ to −8.8 ppm for $Cp_3U^{IV}(OPh)$ and −18.4 for $Cp_3U^{IV}(OEt)$.[12]

The chemical shift of the Cp protons of −12.1 ppm in **2a** and −11.8 in **2b** are very similar to the Cp ring resonances in the THF-solvated Cp_3Np^{III}(THF) (δ_H = −9.65 ppm) and around 10 ppm higher in frequency than the value of −21.49 ppm in the Np^{IV} complex Cp_3NpCl.[13] Although there is only scant data for comparison, it suggests the Np center is closer in character to Np^{III}, with the uranyl oxo behaving as a donor atom to Np.

The absorption for the uranyl asymmetric stretch is best assigned to uranyl(V) in all four Cp_3U and Cp_3Np complexes in the FTIR spectra with absorptions at 893 cm^{-1} (**1a**), 897 cm^{-1} (**1b**), 892 cm^{-1} (**2a**), and 891 cm^{-1} (**2b**). In each case the value is shifted from that in the parent U^{VI} complex (907 cm^{-1}) in accordance with a weakening of the UO_2 multiple bonding in uranyl(V). Additionally, UV-Vis-nIR spectroscopic characterization of **2** shows several bands characteristic of the C_{3v}-symmetric Cp_3Np^{IV} group (in particular around 1066 and 987 nm)[14] and no evidence of the strong absorption at 1260 nm of Cp_3Np(THF).

Comparison of the solid state structures of **1a** and **2a** (Figure 1), and of **1b** and **2b** (SI) confirm their isostructurality and all of the metrics argue for formal U^{IV} and U^V uranyl assignment as a result of complete single electron transfer, but are less conclusive for the choice of Np^{III} or Np^{IV} in **2**.

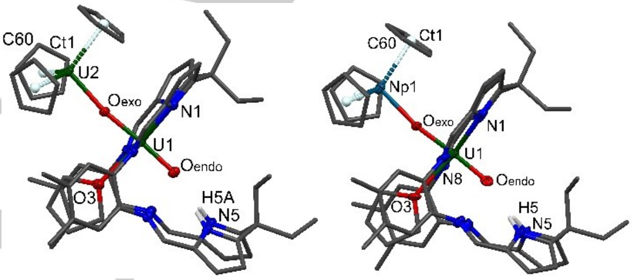


Figure 1. Solid-state structures of **1a** and **2a**. For clarity, all hydrogen atoms except the pyrrole NHs and all solvent molecules are omitted (displacement ellipsoids are drawn at 50% probability for non-C/H atoms). Selected bond distances (Å) and angles (°) for **1a**: U1-O_{endo} 1.844(3), U1-O_{exo} 1.986(3), U2-O_{exo} 2.245(3), U2-cent1 2.456, U1-O3 2.503(3), U1-N1 2.464(3), U1-N2 2.673(3), O_{endo}-N5 3.070, U2-C60 2.776(5), O_{exo}-U2-O_{endo} 176.93(12), U1-O_{exo}-U2 171.27(14); for **2a**: U1-O_{endo} 1.826(7), U1-O_{exo} 1.975(7), Np1-O_{exo} 2.249(7), Np1-cent1 2.413, U1-O3 2.496(7), U1-N1 2.450(10), U1-N2 2.459(10), O_{endo}-N5 3.147, Np1-C60 2.724 (9), O_{exo}-U1-O_{endo} 176.9(3), U1-O_{exo}-Np1 170.5(4).

In each case, the uranyl remains linear (O_{exo}-U1-O_{endo} = 178.05(12)° in **1a**, 176.9(3)° in **2a**), and the bimetallic bridge is also close to linear (An-O_{exo}-U1 = 170.70(15)° in **1a**, 170.5(4)° in **2a**). The uranyl ions are equatorially bound by the four macrocyclic N donors, with a coordinated THF molecule in the fifth site. The elongated U=O_{yl} bond lengths in all four imply singly reduced U^V uranyl, with a significant lengthening in particular to the metalated *exo*-oxo (in **1a** U-O_{exo} is 1.976(3) but U-O_{endo} is only 1.840(3) Å). The geometry around the An cation which is coordinated to the *exo*-oxo is unremarkable with approximate C_{3v} symmetry rather than tetrahedral An geometry due to centroid-An-O angles that are smaller than the tetrahedral angle. The average An-C(Cp) distance is 2.733 Å in **1a** and 2.709 Å in **2a**. These data are consistent with a formal oxidation state of U^{IV} as the average U-C distance in $Cp_3U^{IV}(OPh)$ is 2.74 Å,[15] and in Cp_3U^{III}(THF) is 2.79 Å.[12] The average Np-C distance in $Cp_3Np^{IV}(OPh)$ (2.73(3) Å) is somewhat greater than found in **2a** but there are no structurally characterised Np^{III} cyclopentadienyl complexes for comparison. The Cp_3An-O distance in **1a** is

2.245(3) Å and in **2a** is 2.497(7) Å. In **1a** this is consistent with a covalent single bond to U^{IV} although there is a wide range, for example 2.119(7) Å in $Cp_3U^{IV}(OPh)$,[15] and 2.551(10) Å in $Cp_3U^{III}(THF)$.[12] However, in **2a**, this is more consistent with a long single bond or dative bond; the covalent single Np-O bond is 2.136(7) Å in $Cp_3Np^{IV}(OPh)$,[16] whereas the dative Np-O bond in $CpNp^{IV}Cl_3(OP(Me)Ph_2)_2$ is in the range 2.265(12) - 2.283(12) Å.[17]

In the anticipation that this synthetic approach could generate actinyl-actinide complexes with magnetic coupling through the bridging oxo group, we have studied the variable temperature magnetic behaviour of **1b** and **2b** by SQUID magnetometry. The dc susceptibility (χ) curves (Fig. 2) show that both complexes have an effective magnetic moment around 2.4 μ_B at low temperature, but upon increasing the temperature their behaviour differs. While the χT product for **1b** rapidly increases well above the upper theoretical limit expected for a U^{III}-U^{VI} pair, and at room temperature approaches the expected value for a U^{IV}-U^{V} pair, the effective moment for **2b** slowly reaches the value corresponding to a Np^{III}-U^{VI} pair and tends to saturate without increasing further. This indicates that the electron transfer in the Np-U **2b** adduct is extremely poor, whereas reduction of the uranyl group has taken place in the U-U analogue **1b**.

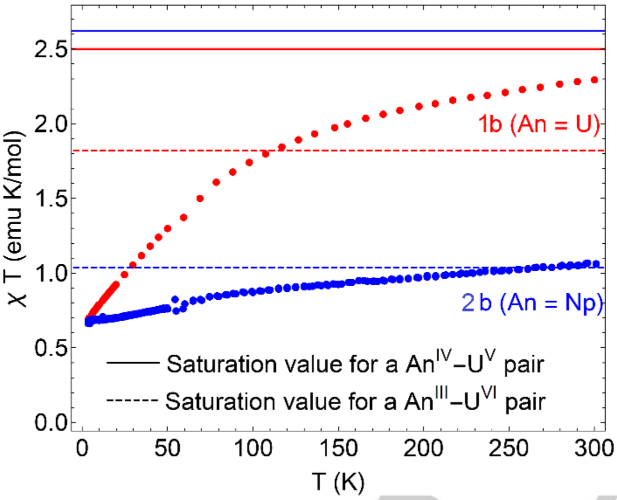


Figure 2. dc magnetic susceptibility (χ) curves measured as a function of temperature (T) for complexes **1b** (red dots) and **2b** (blue dots), plotted as $\chi_{dc}T$ vs T. Data were collected with an applied field of 1 Tesla. The saturation values expected at high temperature for An^{IV}-U^{V} and An^{III}-U^{VI} pairs are also plotted (in blue for An = Np and in red for An = U) as continuous and dashed lines, respectively.

Because of this, we have investigated the dynamic magnetic properties of **1b** by ac magnetic susceptibility measurements (Fig. 3). Clear peaks in the out-of-phase component of the ac susceptibility indicate that slow magnetic relaxation takes place and that **1b** behaves as a single-molecule magnet below 4 K. The temperature dependence of the relaxation time τ can be fitted equally well to a Raman or an Orbach relaxation pathway, in addition to a direct process; however, we note that both the characteristic time τ_0 = 3.26×10^{-8} s and the thermal activation barrier Δ = 26.9 K are very similar to previously reported U^{V} based single-ion magnets.[18] This, together with the consideration that U^{IV} is often non-magnetic in low-symmetry geometries, and with the absence of any clear sign of magnetic interaction between the two uranium sites in the susceptibility curves, allows us to attribute the slow magnetic relaxation to the uranyl(V) group. We note that a more symmetrical heterodimetallic uranyl(V)-Mn(II) complex has the highest reported relaxation barrier for a mono-U(V) system, of 81±0.5 K, presumably due to the high Ising anisotropy.[7a]

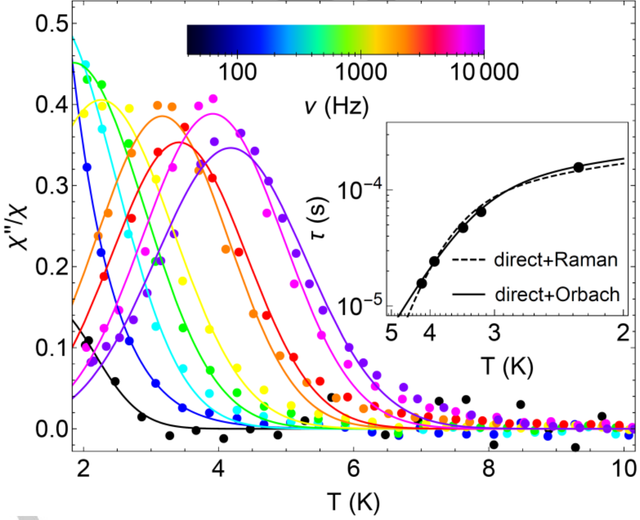


Figure 3. Out-of-phase component of the ac magnetic susceptibility (χ") for **1b** measured as a function of temperature, for various values of the frequency ν of the 5 G driving field. The plot shows χ''/χ_{dc}-vs-T curves, since the relaxation time τ becomes equal to $(2\pi\nu)^{-1}$ exactly at the temperature which corresponds to the peak in χ"/χ.[19] The values of τ derived with this procedure are shown in the inset as a function of temperature in a log-reciprocal plot, together with curve fits obtained considering respectively a Raman (dashed line) and an Orbach (full line) relaxation path in addition to a direct process (see SI for details).

It is therefore clear that not all of the experimental characterisation data agree on the extent of electron transfer from the organometallic actinide to the uranyl group:

- NMR: the paramagnetic shifting of the resonances in the macrocyclic ligand in both **1** and **2** is suggestive of singly reduced uranyl(V) in both. The paramagnetic chemical shifts of the Cp ring protons are less diagnostic; in the U-U complexes **1** the chemical shift of the Cp protons is similar to most U^{IV} complexes whereas those in the Np-U complexes **2** are comparable with those of Np^{III} cyclopentadienyl complexes.

- NIR-UV-Vis-IR: The vibrational data support a U^{IV}-U^{V} oxidation states for **1** and Np^{IV}-U^{V} oxidation states for **2**.

- XRD: The crystal structures of both the Cp_3An-(OUO) systems are fully isostructural, and present convincing evidence for single electron transfer in **1** but less so in **2**. The data show characteristic elongation of the U-(*μ*-O)-An distances and to smaller extent also U-O(endo), suggestive of the uranyl(V) ion in both but the $An-O_{exo}$ uranyl distances are more in line with U^{IV} and Np^{III} formal oxidation state assignments.

- SQUID magnetometry: For **1b** the data are consistent with full electron transfer to form a U^{IV}-U^{V} complex. However, for **2b** the magnetic ground state saturation values closely match those of the isolated Np^{III} ion, suggesting a donor-acceptor oxo bridged Np^{III}-U^{VI} product.

DFT calculations on models of **1b** to **3b** help with the bond type assignments and support the proposed decreasing level of electron transfer from Cp_3U through Cp_3Pu. The Gibbs Free Energies for each reaction in Scheme 1 were calculated (Table S3) and the positive gas phase value (2.81 kcal/mol) for Cp_3Pu suggests the reaction to form **3b** is unfavorable. The calculated uncorrected, gas-phase Cp_3An^{IV}/Cp_3An^{III} reduction potentials *vs* ferrocene (Table S4) are −1.21 eV for U, −0.81 eV for Np, and −0.41 eV for Pu and follow the same trend as the experimental data, i.e. the reduction of Cp_3AnCl is -1.80 V for U^{IV} and -1.29 V for Np^{IV} in THF *vs* ferrocene.[20] We previously measured the relatively facile reduction of the uranyl complex $\mathbf{A^{oct}}$ as −1.18 V *vs.* ferrocene in THF solution[21] and so comparison of these reduction potentials predicts that it will be more difficult to transfer an electron from Cp_3Np^{III} than Cp_3U^{III}. The calculated charges and spin densities on the An and uranium centers (Tables S5 and S6) agree with the oxidation states assigned by SQUID magnetometry, with the spin density on the U(V) centers decreasing in the order **1**>**2**>**3** because all the unpaired electrons in these systems are very localized (Figures S12-S14). Thus, the extent of electron transfer can be deduced by comparing the separated fragments Cp_3An^{III} and $U^{VI}O_2(H_2L^{oct})$ to the final products **1b**/**2b**/**3b** (Table S6). The spin density analyses indicate that the U-U system (**1**) has complete one-electron transfer but in contrast Np-U(**2**) and Pu-U(**3**) have just half. An orbital composition analysis (Table S7) shows that the three SOMOs in the U-U complex **1b** have *f* ; with minor *d* contributions. The Np-U system (**2b**) is similar, but has non-negligible *s* character in a singly occupied orbital which may contribute to the observed paramagnetically shifted ^1H NMR spectrum. More importantly in this respect, the spin density on the Cp hydrogen atoms (Table S8) is on average twice that of the U system.[22]

To conclude, we report here the first reduction of the uranyl dication by another actinide complex, and the first use of a redox reaction to generate a heterobimetallic transuranic complex. For the more reducing An^{III} ions the oxo group provides a capable bridge between the two actinide cations. Although there is some disagreement between techniques as to the formal oxidation states, in combination they show that the extent of electron transfer to the uranyl is U>Np>Pu. There is no apparent magnetic communication between the actinide centers in these $Cp_3An(UO_2)$ systems, the U^{IV}-U^{V} complex **1b** is a single ion magnet (singly reduced uranyl, d^0f^1), with a relaxation barrier of 19 cm^{-1} and relaxation time of 2.5 x 10^{-8} s at infinite temperature. A strong donor-acceptor interaction, or perhaps even non-integral formal oxidation states for Np and U are probably most appropriate for 2. Somewhat surprisingly, any interaction between the Pu(III) and U(VI) is too weak to be observed in the presence of coordinating THF solvent and calculated free energies suggest that the reaction is unlikely to happen. Characterizing paramagnetic actinide complexes with complicated electronic structures is very challenging even with modern techniques, and at first glance the classical interpretations of the data give contradictory pictures. However, we have shown how a satisfying electronic structure definition can be arrived at by a combined experimental and computational analysis of each. This new synthetic route should provide opportunities for new uranyl functionalization with other f-block metal cations to form other unusual and potentially interesting f-electron behaviours.

Acknowledgements

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Keywords: uranyl • neptunium • plutonium • macrocycle • redox

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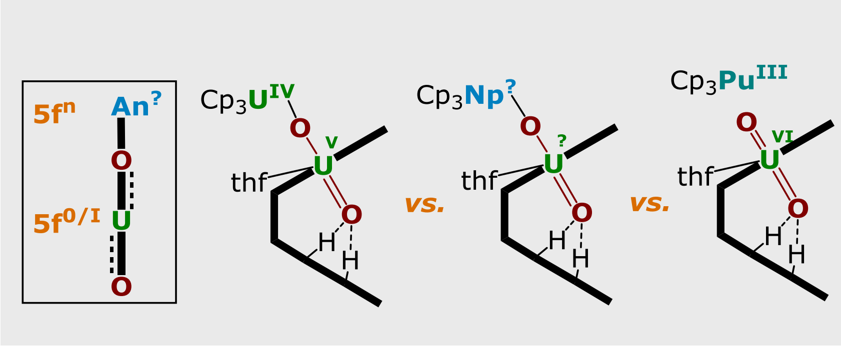
COMMUNICATION



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