



Colorimetric and fluorometric chemosensors for selective signaling toward Ca^{2+} and Mg^{2+} by aza-crown ether acridinedione-functionalized gold nanoparticles

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ABSTRACT

The aza-crown ether acridinedione-functionalized gold nanoparticles (ACEADD-GNPs) **6** have been synthesized and investigated as a fluorescent chemosensor for metal ions. A blue shift along with an intensity enhancement of emission and color change are observed in the presence of both Ca^{2+} and Mg^{2+} ions. The enhanced fluorescence intensity is attributed to the photoinduced electron transfer (PET) suppression through space and color change of the suspension from red to blue due to shifted surface plasmon resonance (SPR) with aggregation of nanoparticles by the sandwich complexation.

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Design of functional nanomaterials is of current interest because of a variety of potential applications ranging from chemistry to biological sciences. Metal and semiconductor nanoparticles exhibit interesting size- and shape-dependent properties.¹ The nanosized metal particles are emerging as important type of colorimetric reporters because their extinction coefficients are several orders of magnitude larger than those of organic dyes² and the transition of the nanoparticles from dispersion to aggregation leads to a distinct change in color.^{3–7} The phenomenon is termed surface plasmon absorption, and the color change upon aggregation is due to the coupling of the plasmon absorbances as a result of their proximity to each other.^{8,9}

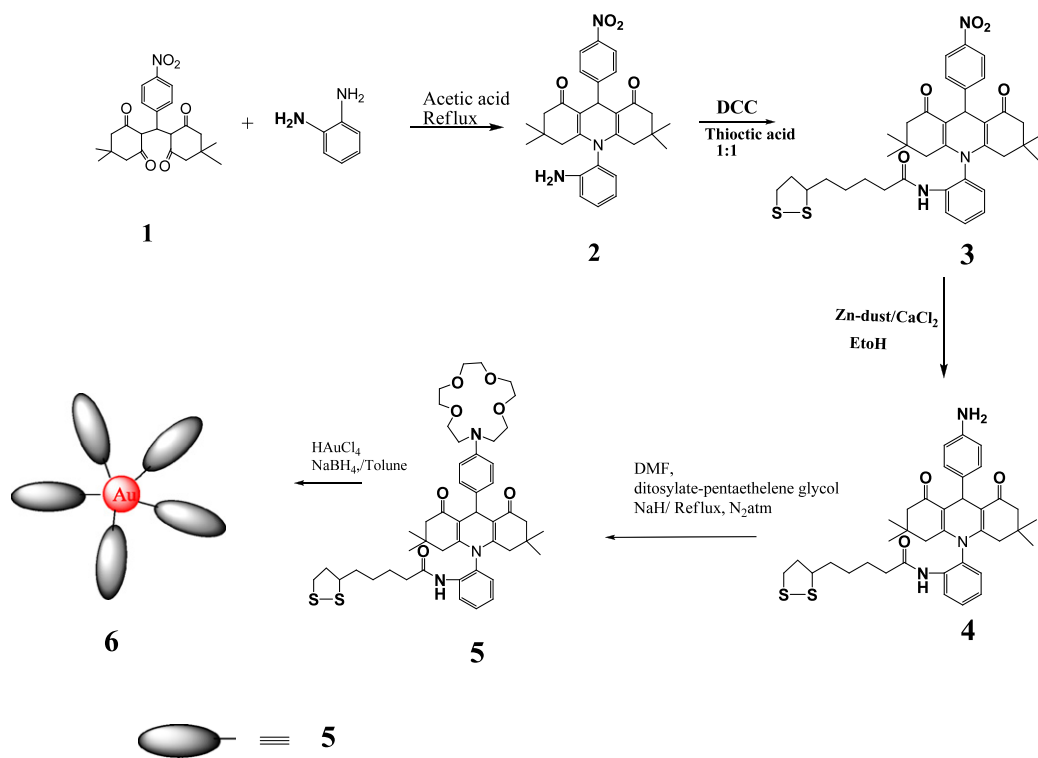
Significant progress has been made in recent years in the development of functional nanomaterials by designing monolayer-protected metal clusters^{10–12} and exploiting them as building blocks for supramolecular structures and sensory applications.¹³ Based on the well-known ability of crown ethers to host *s*-block metals,¹⁴ many fluorescent chemosensors designed in recent years for alkali and alkaline earth ions contain at least one crown ether moiety (or a related derivative) which behaves as a ‘recognition subunit’ connected to one or more fluorophores.¹⁵ In these systems, the output signal following the crown/cation interaction (sandwich complex) involves a change in the emission properties of the fluorophore(s) and is often related to a PET (photoinduced electron transfer) process.¹⁶ Other examples involving different mechanisms, for

example, photoinduced energy transfer¹⁷ excimer or exciplex formation,¹⁸ conformational change,¹⁹ and proton transfer²⁰ have also been reported. Recent development of K^+ sensors has been inspired by the concept of the sandwich complex in which the conformation assembles chromophores in proximity and results in intermolecular interactions that significantly enhance the sensitivity in absorbance or fluorescence.^{21–25}

In this study, we have synthesized aza-crown ether acridinedione-functionalized gold nanoparticles (ACEADD-GNPs) chemosensor, in which through-space PET occurred from the N-atom of the cation receptor (1-aza-15-crown-5) to the fluorophore unit (acridinedione), resulting in the quenching of the fluorescence of the ACEADD unit. Fluorescence titration with different cation salts in an acetonitrile solution of ACEADD showed an increase in the fluorescence intensity due to PET suppression, and the color change is attributed to aggregation of nanoparticles.

The synthetic procedure is shown in Scheme 1. The reaction of tetraketone **1** and 1,2-phenylenediamine in acetic acid on reflux afforded nitroacridinedione **2**. A mixture of **2** and lipoic acid in dry dichloromethane with dicyclohexylcarbodiimide (DCC) on reflux afforded the acridinedione amide derivative **3**. A mixture of **3**, Zn-dust, and CaCl_2 in ethanol on reflux afforded the amino bis-acridinedione derivative **4**. A mixture of **4**, pentaethylene glycol ditosylate, and NaH in DMF on reflux afforded aza-crown ether acridinedione derivative **5**. It was recrystallized from a mixture (9:1) of CHCl_3 and methanol to yield a yellow powder of ACEADD. The synthesis of monolayer-protected clusters (MPCs) adopted the method reported²⁶ by Brust et al. A comparison of

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Scheme 1. Schematic illustration of synthesis and assembly of ACEADD-GNPs via the reaction of HAuCl_4 with ACEADD.

the FT-IR spectra of ACEADD-GNPs resembles that of **5**. NaBH_4 reduces the disulfide moiety of lipoic acid as well as enables the formation of metallic gold nuclei, which leads to the formation

of S-Au bond to produce **6** (Fig. S1) as reported by Zhao et al.²⁷ (detailed synthesis and characterization data are given in the Supplementary data).

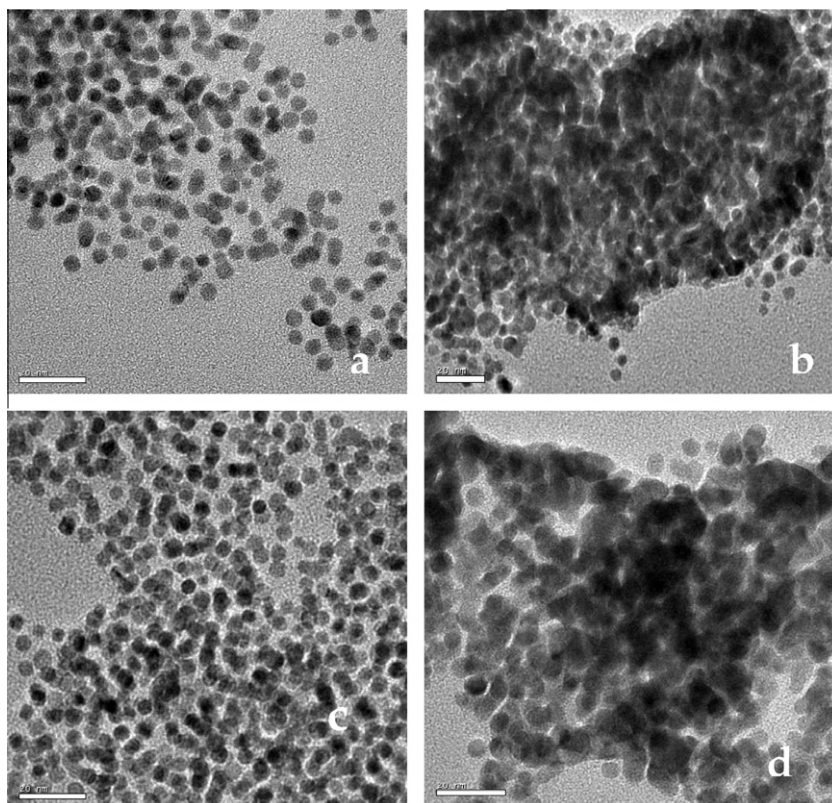


Figure 1. HR-TEM micrographs of ACEADD-functionalized gold nanoparticles (**6**) (a, c) before and (b, d) after addition of 0.081 mM Ca^{2+} and Mg^{2+} to a ACEADD-GNPs solution. (a, c) Spherical shape gold nanoparticles attachment with ACEADD. (b, d) Aggregation in response to addition of Ca^{2+} and Mg^{2+} .

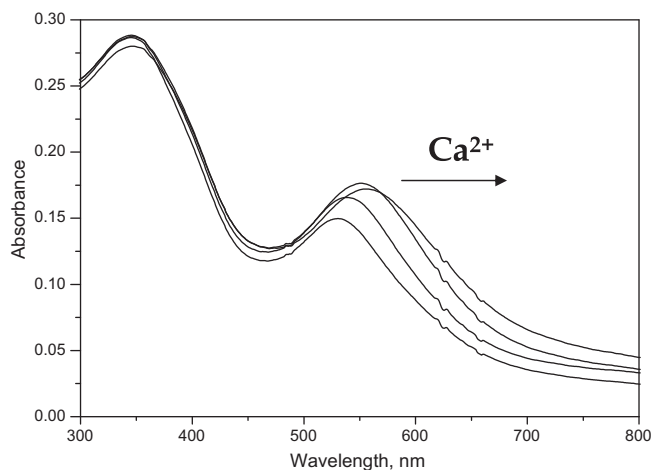


Figure 2. The absorption spectra of **6** upon addition of Ca^{2+} in acetonitrile.

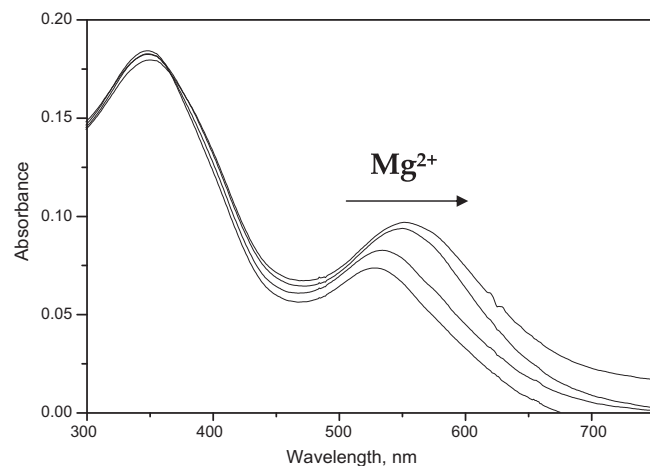
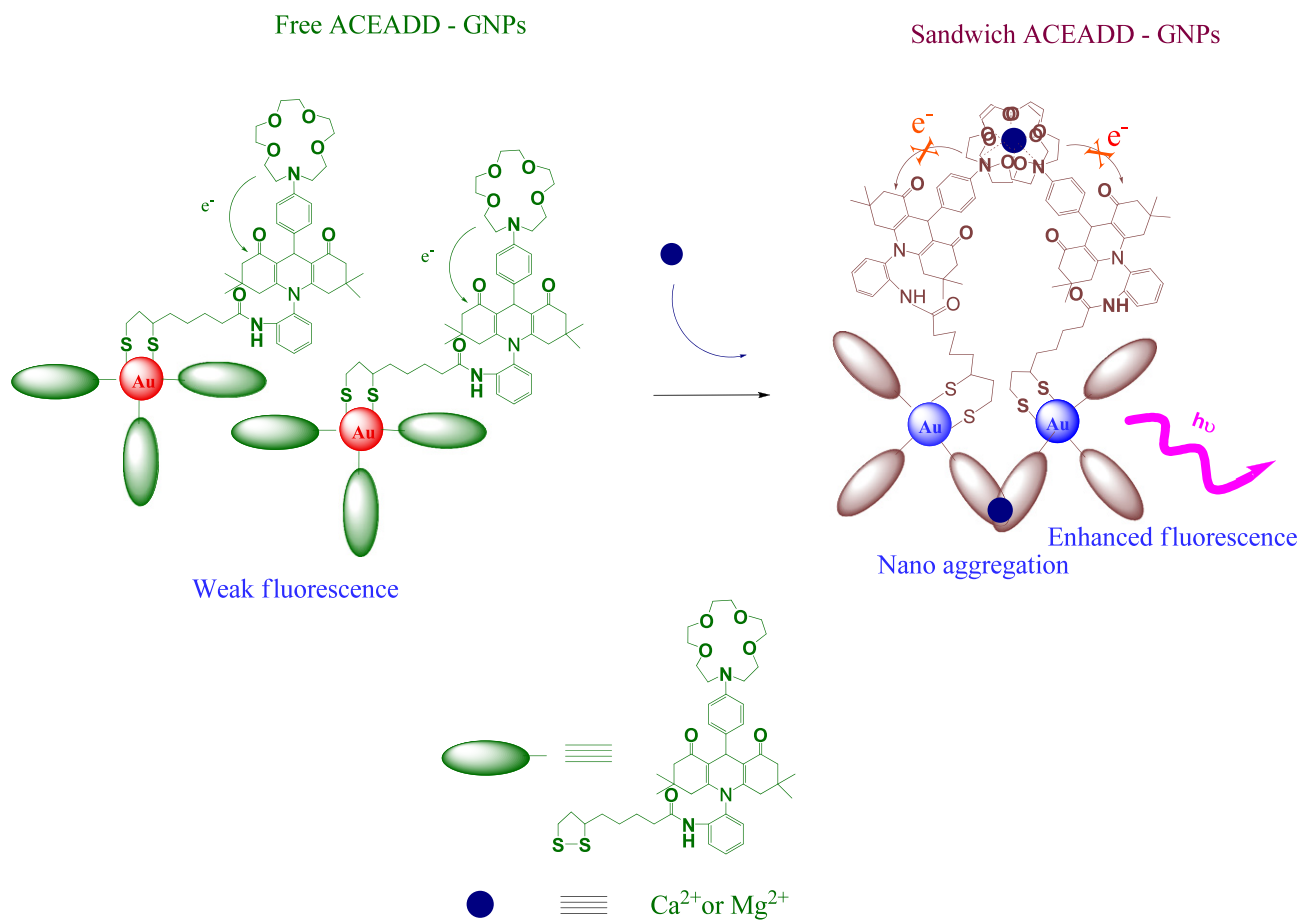


Figure 3. The absorption spectra of **6** upon addition of Mg^{2+} in acetonitrile.

The HR-TEM sample of **6** was prepared by drop-casting a dilute suspension on a carbon-coated copper grid and the images are presented in Figure 1. Three-dimensional approach in TEM images indicate that ACEADD may be anchoring on the surface of the gold nanoparticles (GNPs). The size of GNPs was found to be an average diameter of 4.5 nm. The GNPs are assumed to be spherical; the number of ACEADD molecules capping with one gold nanoparticle of size 4.5 nm can be estimated, if the foot print area of the dithiol molecule is 0.657 nm^2 . This shows that ninety seven (97) dithiol

units will be capping with the nanogold particle having a total surface area of 63.58 nm^2 .

The absorption and emission maxima of acridinedione dyes in acetonitrile centered around 380 and 430 nm, respectively. The absorption at 380 nm is attributed to the intramolecular charge transfer from the nitrogen to the carbonyl oxygen in the acridinedione moiety and the emission at 430 nm to that of the local excited (LE) state.^{28,29} In this study, aza-crown ether acridinedione-GNPs exhibit the absorption spectrum of ACEADD-GNPs **6** that consists



Scheme 2. The possible mechanism of the phenomenon of binding of the free ACEADD-GNPs with Ca^{2+} and Mg^{2+} .

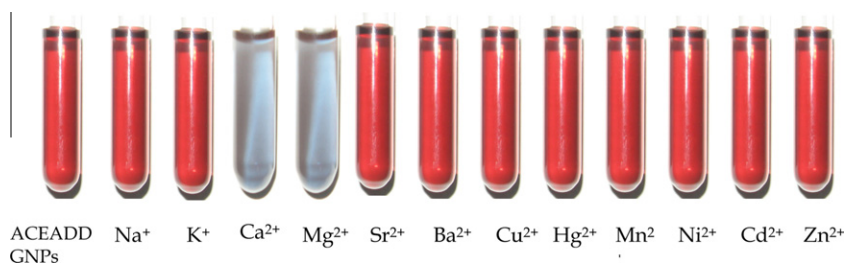


Figure 4. Colorimetric responses of ACEADD-GNPs colloidal solutions appear red. However, upon addition of Ca^{2+} (9.6×10^{-5} M) and Mg^{2+} (9.6×10^{-5} M) the solution immediately turns blue. Addition of other metal ions did not effect the color change.

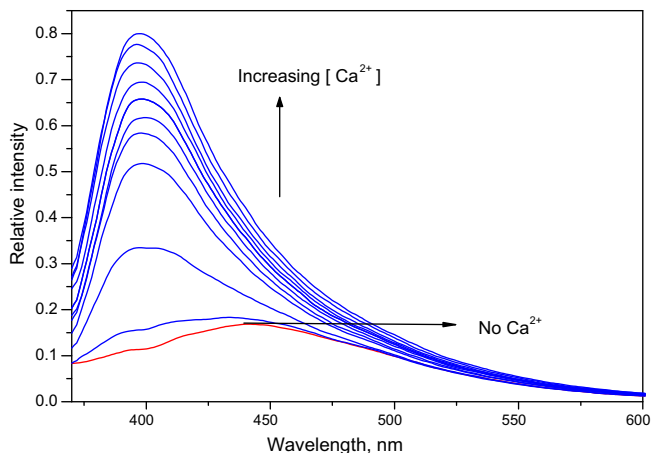


Figure 5. The emission ($\lambda_{\text{ex}} = 360$ nm) spectra of **6** upon addition of Ca^{2+} ($0-9.6 \times 10^{-5}$ M) in acetonitrile.

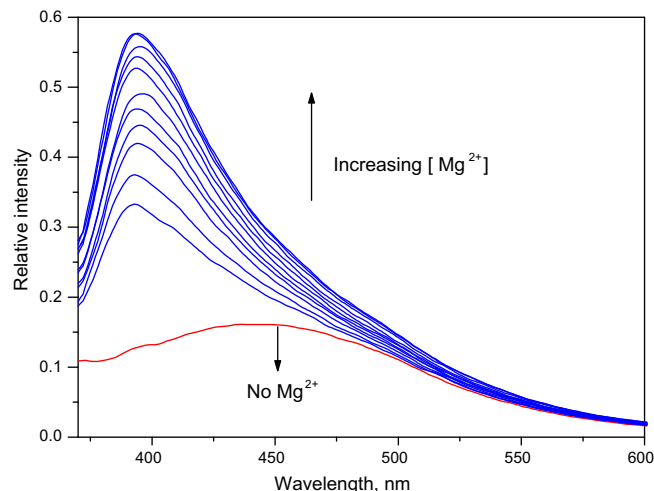


Figure 6. The emission ($\lambda_{\text{ex}} = 360$ nm) spectra of **6** upon addition of Mg^{2+} ($0-9.6 \times 10^{-5}$ M) in acetonitrile.

of two bands: (i) the additive absorption spectrum of ACEADD due to ICT around 360 nm and (ii) a broad band in the visible region around 529 nm, which is attributed to the surface plasmon resonance (SPR) for the stabilized gold nanoparticles.

Crown ethers are known for the unusual property of forming stable complexes with alkali metals. The exceptional stability correlates, to some extent, with the close fit of the cation to the crown cavity where, upon complexation, the oxygen atoms lie in a nearly planar arrangement about the central cation. Although 15-crown-5 complexes best with Na^+ and 18-crown-6 favors K^+ , a sandwich complex of 2:1 between 15-crown-5 and K^+ is also well known.^{30–38}

Interestingly, addition of Na^+ and K^+ ions did not alter the absorption or emission properties of **6** (Figs. S2 and S3). In contrast, on the addition of Ca^{2+} or Mg^{2+} ions ($0-9.6 \times 10^{-5}$ M), the acetonitrile solution of **6** (2.5×10^{-5} M) showed a red shift in the absorption maximum. The significant change in the color visible to the naked eye demonstrates that the ACEADD-GNPs recognize Ca^{2+} and Mg^{2+} and lead to the nano aggregation (Figs. 2 and 3). A highly specific, for both Ca^{2+} and Mg^{2+} ions, binding event is achieved by the cation-induced sandwich-like structure of the aza-crown ether acridinedione-GNPs Scheme 2 and the resultant nano-Au aggregation through colorimetric response that is indicated by broadening and red shifting of surface plasmon resonance peak as reported by Patel et al.³⁹ and Lin et al.⁴⁰ The ACEADD-capped gold nanoparticle's colloidal solution appears red (Fig. 4). However, upon addition of Ca^{2+} and Mg^{2+} the solution immediately turns blue. The significant change in color demonstrates that the ACEADD-GNPs recognize Ca^{2+} and Mg^{2+} . This aggregation was further confirmed by TEM (Fig. 1b and d).

Surprisingly, a pronounced blue shift along with an intensity enhancement of the ACEADD-GNPs emission was observed for **6**

in the presence of Ca^{2+} and Mg^{2+} . An intensity maximum is reached at $[\text{M}^{2+}]/\mathbf{6} = 2.5 \times 10^{-5}$ M, and the emission maximum shifts as much as 40 nm (from 440 to 400 nm), when excited at 360 nm as shown in (Figs. 5 and 6). The corresponding additive absorption spectrum of ACEADD is not affected but SPR peak is shifted. The spectral features of blue shifted and intensity enhanced emission are retained, albeit to a lesser extent, and requiring a higher ratio of metal ion concentration. With lower concentration of metal ion, the emission maximum is at 420 nm. The λ_{max} continues to shift toward blue upon further addition of Ca^{2+} or Mg^{2+} (eg., $\lambda_{\text{max}} = 400$ at $[\text{M}^{2+}]/\mathbf{6} = 2.5 \times 10^{-5}$ M). Apparently, the interactions between **6** and metal ions are weak and the ACEADD-GNPs emission indicates a symmetrical sandwich-like structure; the blue shifted form is generally attributed to partially overlapping crown ether moiety of ACEADD, which might account for the weak emission of blue shifted ACEADD-GNPs and poor sensitivity of the ACEADD emission to the ground state structure. Accordingly, the binding of Ca^{2+} or Mg^{2+} in **6** not only brings the crown group together in the ground state leading to the formation of a sandwich but also prohibits or minimizes such a relaxation event in the excited state leading to a blue shifted emission. The enhancement in fluorescence intensity is attributed to the suppression of the PET process through space. The complexation was established as 2:1 equilibrium from the Benesi–Hindlbrand plot (Figs. S4 and S5). Addition of other metal ions such as Na^+ , K^+ , Sr^{2+} , and Ba^{2+} showed only marginal changes to the absorption and emission of **6** (Figs. S6 and S7), when compared to those with both Ca^{2+} and Mg^{2+} ions.

In summary, we have demonstrated that gold nanoparticles modified with ACEADD in acetonitrile exhibit excellent selectivity toward Ca^{2+} and Mg^{2+} , resulting in the enhanced fluorescence

which is attributed to the photoinduced electron transfer (PET) suppression through space and color change of the suspension from red to blue due to shifted surface plasmon resonance (SPR) with aggregation of nanoparticles by the sandwich complexation.

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Supplementary data

Supplementary data (detailed synthetic procedures, characterization, ¹H NMR, ¹³C NMR data, FT-IR, HR-TEM images and photo-physical studies of compound **6** with other metal ions) associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2010.06.041.

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