Large scale scanning probe microscope: Making the shear-force scanning visible

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We describe a demonstration of a scanning probe microscope with shear-force tuning fork feedback. The tuning fork is several centimeters long, and the rigid fiber is replaced by a toothpick. By scaling this demonstration to visible dimensions the accessibility of shear-force scanning and tuning fork feedback is increased.
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I. INTRODUCTION: SCANNING SURFACES

The function of scientific devices is often not obvious from their appearance. When components are very small and unfamiliar materials are used, many people regard the setup as a black box. An example of black boxes are scanning probe microscopes, which are a family of instruments used to study the surface properties of materials from the atomic to the micron level. The best known are the scanning tunneling microscope[1] (STM) and the atomic force microscope (AFM).[2,3] In STM a voltage is applied between the tip and a surface. When the distance between the tip and the surface is less than 1 nm, electrons will tunnel[4] between the tip and the surface. The closer the tip is to the surface, the larger the current between the tip and the surface. The current can therefore be used to image the surface directly. AFM is based on the attractive van der Waals and repulsive Pauli forces between the tip and the surface. By using AFM nonconducting surfaces can also be imaged because no current is required to flow.

The near-field scanning optical microscope[5] is a version of AFM that uses an optical fiber as the scanning tip. The fiber is pulled or etched and coated with metal except at the very end (see Fig. 1). The use of an optical probe as the scanning tip provides access to simultaneous topographical and optical information on the surface.

For our demonstration this fiber is replaced by a toothpick. Although a toothpick cannot pick up optical information, it can pick up topographical information. A near-field scanning optical microscope constructed this way differs from an AFM by using a stiff probe instead of a flexible cantilever. A stiff probe requires a different feedback system. To measure an optical signal the toothpick could be replaced by an optically transparent material such as polyethylene. The emphasis in this article is on the shear-force feedback.

Conventional optical microscopes are limited by diffraction to a resolution on the order of half of the wavelength of light. As the light propagates from the emitters in the sample to the collection objective, diffraction effectively spreads the signal from the individual emitters over a larger area. The resolution d is given by

$$d = 0.61\frac{\lambda}{\text{NA}}, \tag{1}$$

where λ is the wavelength of the light and NA (Ref. 6) is the numerical aperture of the optical system. For microscopes that use visible light, Eq. (1) results in a resolution of the order of 300 nm. Near-field microscopes capture the evanescent or nonpropagating fields of light before it diffracts by placing a probe tip very close to the surface.[7] In this way the optical resolution is not limited by diffraction but is determined by the opening in the tip, which is typically 50 nm. Different techniques are used to control the distance between the tip and the surface. For rigid tips, shear-force tuning fork feedback is the preferred choice.

To image a surface using a scanning microscope, the tip is moved over the surface of the sample using piezoelectric elements. Piezoelectrics have the ability to create an electric potential when stress is applied or can deform when a potential is applied[8] so that high precision movement can be coupled to electrical control. To prevent the tip from crashing into the surface, the distance between the tip and the surface has to be regulated using some kind of feedback such as the shear force.[9–12] In a regular setup the typical length of the prongs of the tuning fork is 3.2 mm and the fiber has a diameter of 125 μm.

The small dimensions of these elements are an obstacle when demonstrating the device to people who are not familiar with scanning probes. To increase the accessibility of the technique, we constructed an enlarged demo of the topographical imaging part. Our goal was that the demonstration would have the following desired characteristics. (1) The resonance frequency of the tuning fork should be in the audible range. (2) The tip must be of a macroscopic scale (for example, centimeters). (3) The scan speed for an image must be acceptable, for example, an image must be scanned within 5 min. (4) The scanned sample area (for example, a coin) should be clearly visible by eye. (5) The image produced should be of reasonable quality. (6) The feedback system must be comparable to the original setup. (7) The setup must be robust and allow for transport. (8) Finally, the software used to control the position of the tip relative to the sample must be the same as the original near-field scanning optical microscopy software.

The near-field scanning optical microscopy software is available from our group on request. It has been used by students for more than a decade. The program is not tailored to this application, but it is a big time saver in building the instrument.

II. SHEAR-FORCE FEEDBACK

In shear-force feedback the tip is connected to a tuning fork and changes in the resonance of the fork are used for feedback. The tuning fork in a conventional near-field scanning optical microscopy setup is the same tuning fork as

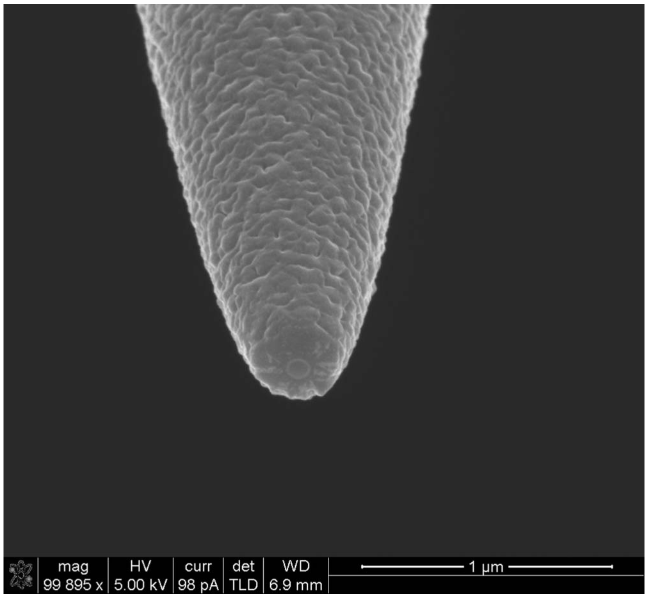


Fig. 1. In-house near-field scanning optical microscopy tip with an opening of 75 nm.

used in ordinary wrist watches. The resonance frequency of this tuning fork is 2^{15}(=32768)Hz. Because the tuning fork is made of piezoelectric material, the vibration of the tuning fork can be excited and measured by applying a voltage across the electrodes. Alternatively, the tuning fork can be driven by a separate piezoelectric element called a dither.

A tuning fork can be described as a driven damped harmonic oscillator with spring constant k, damping constant γ, and effective mass m.[11,12] These parameters yield a resonance frequency and Q factor.[13] For $Q \gg 1$, Q can be approximated as

$$Q = \frac{f_{\text{res}}}{f_{\text{FWHM}}}, \tag{2}$$

where f_{res} is the resonance frequency and f_{FWHM} is the full width of the resonance peak at half the maximum amplitude of the power spectrum. A vibration mode with a high Q factor shows a high and narrow resonance peak. When the tip is brought close to a surface, an extra damping factor $\Delta\gamma$ and an extra spring constant Δk are introduced. The $\Delta\gamma$ results in a decrease of Q or a smaller vibration amplitude. The resonance frequency shifts slightly to a lower frequency, but this effect is very small if $Q \gg 1$ and $\Delta\gamma \ll \gamma$. The shift Δk results in a phase shift because it affects the resonance frequency. These effects are shown in Figs. 2 and 3. The phase is generally used as a feedback signal because it is more sensitive to changes. The linear region around the 90° phase shift is used for the feedback. When the distance between the tip and surface decreases, the interaction between the tip and the surface increases and results in a positive Δk. The stiffer fork has a higher resonance frequency. Because the driving frequency remains the same, the phase difference decreases. The feedback system restores this phase difference by increasing the distance between the tip and the surface. This feedback signal therefore contains topographical information of the surface. High Q modes are ideal for the detection of small changes in the resonance frequency but are slow to respond to changes. The combination of detection precision and adaptation determines the speed at which the tip can be scanned safely over the surface.

III. GIANT SCANNING PROBE MICROSCOPE

The demonstration setup is very similar to the near-field scanning optical microscope setup, except for the size of the components. The tuning fork has to be several centimeters long. A standard tuning fork of 440 Hz used for tuning musical instruments cannot be used because the scanning speed is limited by the relaxation time of the tuning fork. For $Q = 400$ and $f_{\text{res}} = 450$ Hz, the scanning speed is limited to the order of 1 Hz (1 pixel/s) because 400 cycles are required to achieve a steady state amplitude. A 64×64 pixel image would take $64 \times 64 = 4096$ s, or 68 min. By increasing the resonance frequency, it is possible to scan more quickly. The demonstration version requires a frequency in the audible range and a macroscopic size. Different tuning forks were

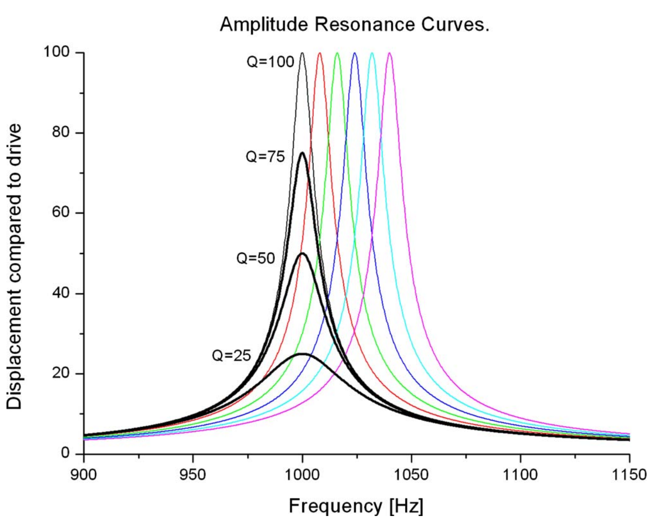


Fig. 2. Amplitude resonance curves for four values of Q (same k) and six values of k (same Q) increasing from left to right.

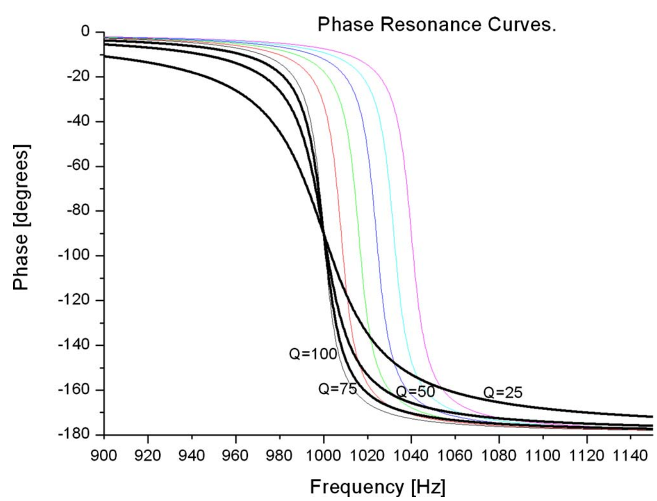


Fig. 3. Phase resonance curves for four values of Q (same k) and six values of k (same Q) increasing from left to right.

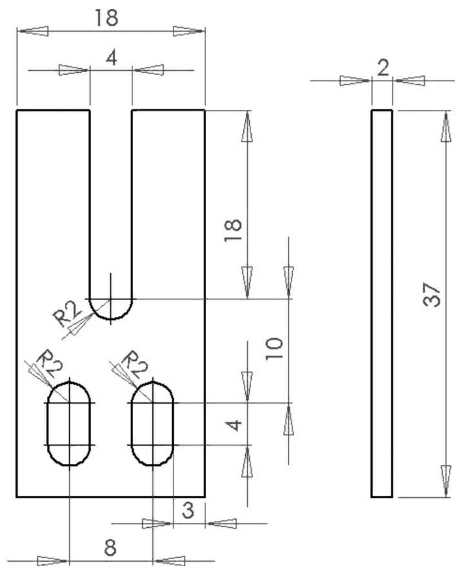


Fig. 4. Dimensions in millimeter of the tuning fork.

designed and tested, yielding the basic design shown in Fig. 4.

Tuning forks generally have multiple modes of vibration with different resonance frequencies. Figure 5 shows our results for the first four resonances of a large metal tuning fork, obtained from simulations using a finite element method. The modes shown are fundamental vibration modes. Higher order modes with higher resonance frequencies consisting of overtones are also possible. The Q factors are different for each mode and depend on the material properties and dimensions.

For the demonstration setup shown in Fig. 7, the fourth resonance mode of the tuning fork is used because it has the appropriate Q factor and the prongs move in a convenient way. The center of mass does not move, which avoids strain on the connecting parts, and the prongs move only in the x-direction, which avoids coupling to other movements.

The resonance of the tuning fork is monitored using a beam deflection method often used in AFM in which a laser beam is reflected by a little mirror on the tuning fork and positioned on a split detector, as indicated in Fig. 6. The vibrational movement of the tuning fork results in an oscillating voltage. The tuning fork can be driven by a piezoelectric element as in Fig. 7(c). The excitation of the tuning fork by magnetic excitation (by attaching a permanent magnet on the base of the tuning fork and applying an alternating magnetic field) is also possible [see Fig. 7(d)]. The frequency response of the tuning fork can be measured by applying a white noise signal that covers all frequencies on the dither and measuring the response of the tuning fork. The transformation of the time-response to the frequency-domain shows the tuning fork resonances. The measured response (not shown) differs slightly from the simulated values, which is attributed to the addition of the toothpick and mirror on the tuning fork.

The phase difference between the driving signal and the detector signal is measured and used for feedback on the height positioning. The height positioning was achieved through a voice-coil actuator. To avoid a slow response of the actuator, the mass of the moving parts of the voice-coil actuator must be kept small, and thus the weight of the samples should be limited. The optical fiber of the near-field scanning optical microscopy is replaced by a toothpick glued to the side of the tuning fork. The stiffness of the tuning fork dominates the Q factor of the system. Actual values are obtained from the tuning fork transfer measurement, as described in Sec. III. Friction between the toothpick and the surface introduces the $\Delta\gamma$ needed for feedback. Instead of the toothpick, an optical tip/rod made from polyethylene can also be used, for example. The XY-positioning on the surface is achieved by an XY-plotter. Just as in the near-field scanning

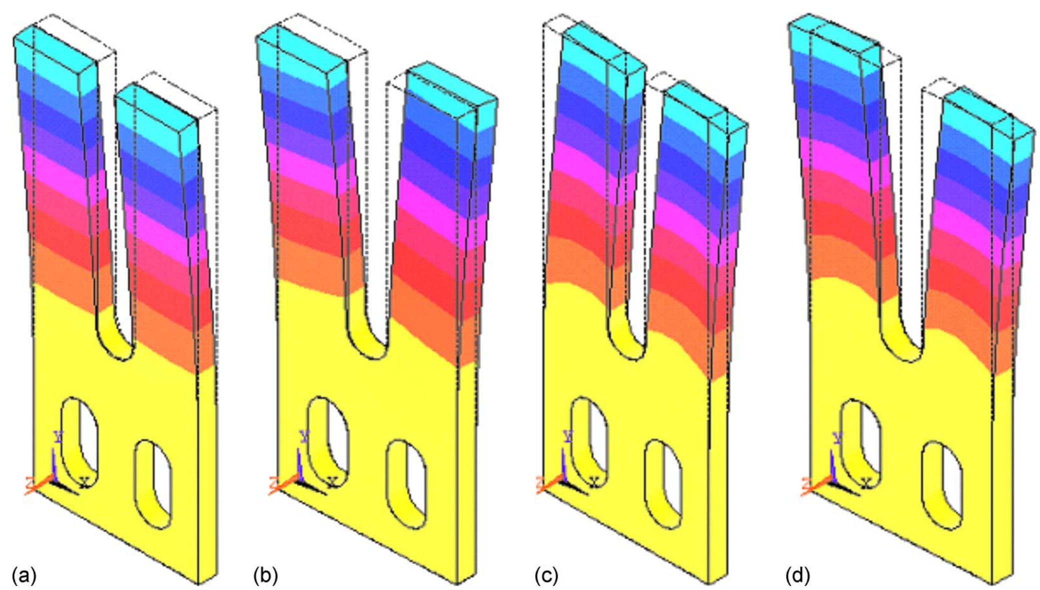


Fig. 5. Simulations of the first four vibration modes of a tuning fork. (a) Mode 1, $f_{\text{res}}=1622$ Hz. (b) Mode 2, $f_{\text{res}}=1765$ Hz. (c) Mode 3, $f_{\text{res}}=6255$ Hz. (d) Mode 4, $f_{\text{res}}=6360$ Hz.

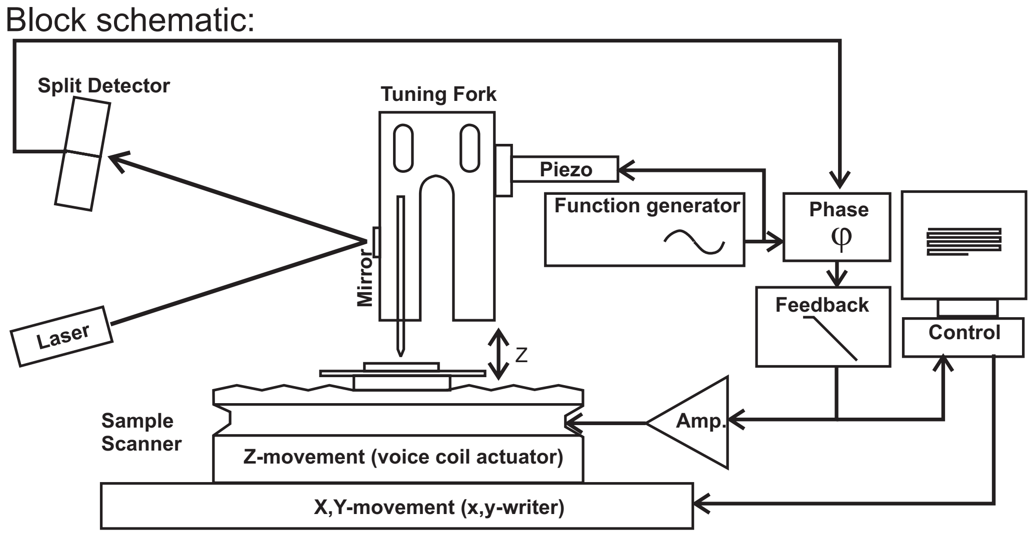


Fig. 6. Schematic overview of the demonstration setup.

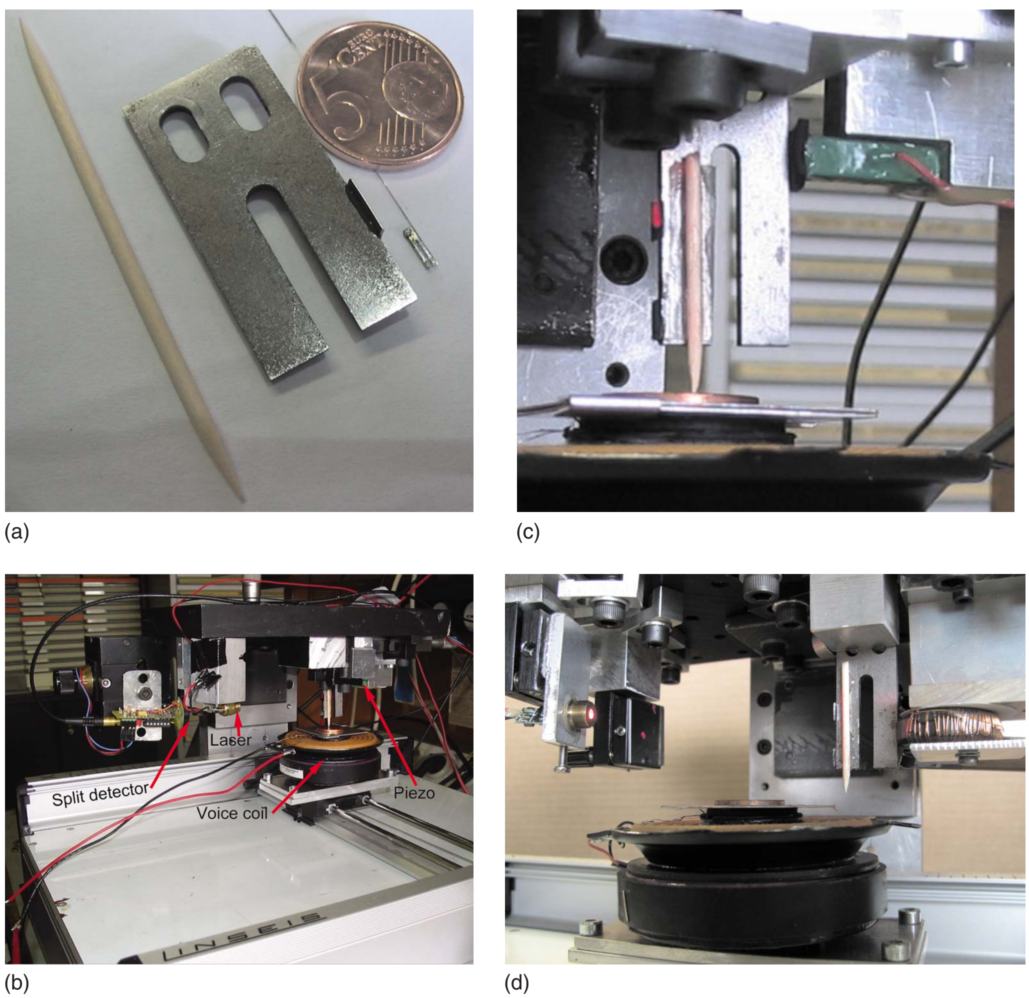
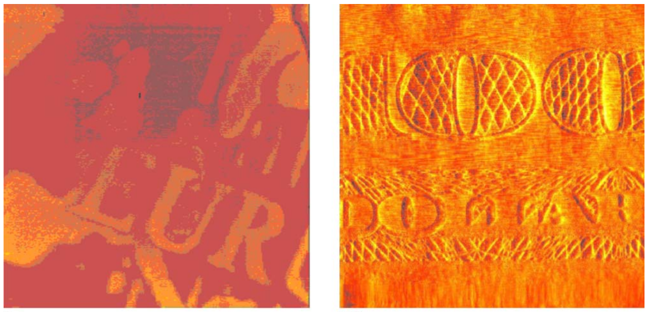


Fig. 7. Pictures of the giant scanning probe microscope. (a) Toothpick and tuning fork compared to a real near-field scanning optical microscopy tuning fork with glass fiber. (b) Overview of the basic setup with excitation by a piezoelectric element. (c) Close-up of excitation with a piezoelectric element. (d) Alternative setup with magnetic excitation and angular adjustments.



(a) (b)

Fig. 8. Images obtained with the giant scanning probe microscope using a toothpick. (a) Scan of a 2 Euro coin. (b) Scan of a 100 dollar banknote.

optical microscopy setup, the setup is sensitive to vibrations and thermal drift. By placing a transparent casing around the setup, influences from the environment were reduced.

IV. RESULTS

Figure 8(a) shows a scan of a 2 Euro coin where the brightness depicts the height. The darkened square on the Euro coin shows the damage caused by a sharp metal tip and feedback that was set too tight, resulting in a tip that scraped over the surface. Figure 8(b) shows a scan of a $100 dollar note. The height resolution is sufficient to measure the thickness of ink on the notes, which is of the order of several tens of microns.

The in-plane resolution (x-y) is determined not only by the number of measurement points but also by the convolution between the tip and the surface. The measured signal is the convolution of the tip function and surface function. To reduce the convolution the tip can be made sharper or replaced by a diamond tip, but the toothpick was used for its entertainment value. The height (z) resolution is less dependent on the surface of the tip because the change of the resonance is determined mostly by the part of the tip that is closest to the surface.

To specify the similarities and differences between our demo and the real thing, some characteristics of a near-field scanning optical microscopy setup and the demo-setup are compared in Table I.

V. CONCLUSIONS

A demonstration model of a near-field scanning optical microscopy with shear-force tuning fork feedback was constructed and operated. It provides a visible version of how real scanning probes work. The setup has already served at various occasions for promotional purposes. Improvements can be made to make the setup more mobile: The base could be reduced and the wiring optimized. The material costs of this setup (assuming a standard laboratory infrastructure) are estimated to be 2000 Euros.

Table I. Comparison of demonstration and real near-field scanning optical microscopy setups. Note that many of the operating characteristics are similar except for the scale of the tip and the scanning area. For one-fiftieth of the cost you can scan an area that is 200 times larger.

Characteristics	Near-field scanning optical microscopy	Demonstration
Frequency	32 kHz	6 kHz
Prong length	3.2 mm	18 mm
Tip	Optical fiber	Toothpick
Scan time	5 min	5 min
Scanned area	$20\times 20\ \mu m^2$	Euro coin
Height resolution	2–5 nm	1 μm
In-plane resolution	50 nm	100 μm
Q factor	300–600	150–300
Tuning fork mass (normalized)	1	1000
Costs	100000 Euros	2000 Euros

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