Cyril Bateman looks at measuring capacitors at rf via the reflection bridge and discusses fault finding, handling and dielectric absorption in this final article.

Understanding capacitors

Conventional capacitor bridge measurement techniques were described in my last article. These techniques are useful to 10MHz, although there are specialised *LCR* meters capable of measuring at higher frequencies. There's more on this in the panel entitled 'Capacitor bridge.'

Measurements at higher frequencies can be made using the reflection bridge technique with a vector network analyser to measure the 'S' parameters of a capacitor. Developed in the sixties, this technique was intended for characterising high-frequency semiconductors. With suitable jigs, reflection bridge techniques can be used at up to at least 40GHz using an *HP8510* or 6GHz using the *HP8753*.

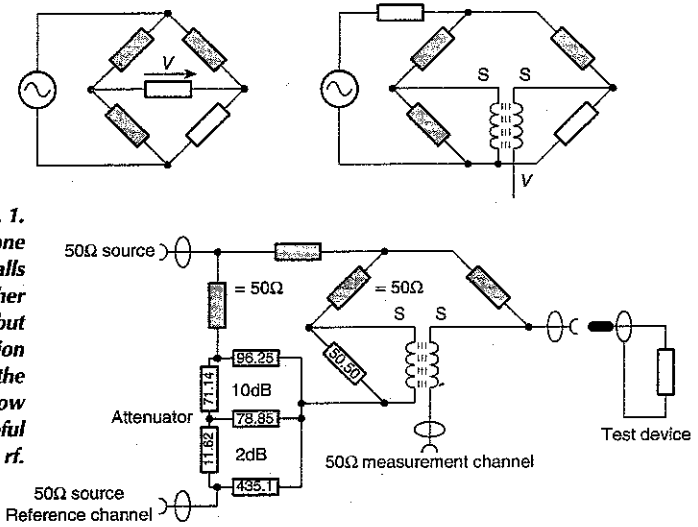

***Fig. 1.** Wheatstone bridge, left, falls down at higher frequencies but the reflection bridge on the right and below produces useful readings at rf.*

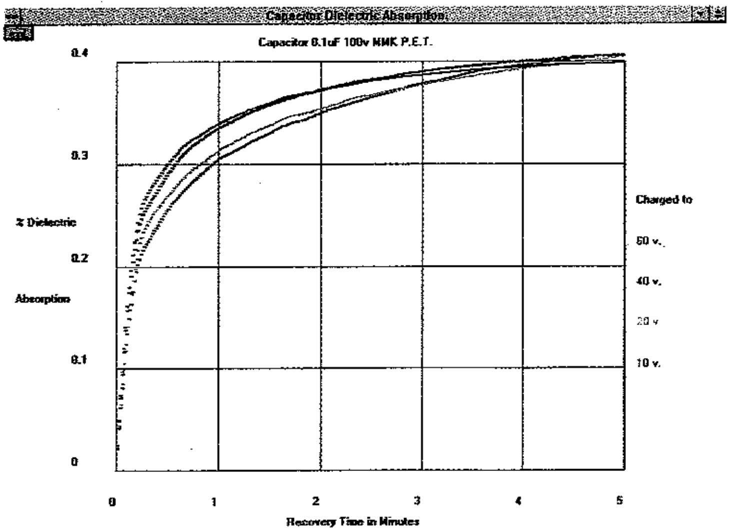

***Fig. 2.** Dielectric absorption is not a fixed number, it varies according to measurement method. With any given capacitor, dielectric absorption also varies according to the 'volts per micron' stress applied.*

Reflection-bridge measurement

For many years, the reflection bridge[1] was the only practical method for making precision measurements at frequencies above 30MHz.

Based on 50Ω standards, such reflection bridge measurements provided excellent accuracy for medium impedances. But accuracy suffered when measuring very high or low impedances. Since many design and measurement laboratories already had access to an *HP8753* though, this method was popular.

I have assumed use of either the *HP8510* or *HP8753* analysers, since I am familiar with them and both include 12-term accuracy enhancement as standard. Other similar instruments – provided they include 12-term accuracy enhancement, sometimes known as 'full 2-port correction' – should also be suitable.

Why this emphasis on 12-term accuracy enhancement ? The accuracy of vector network analyser measurement systems is specified assuming 'well matched' test devices. When used to measure a severely mismatched load, such as a capacitor, the source generator has to drive into effectively a short circuit, but having a mismatched phase. The 12-term accuracy enhancement method corrects for this. Analysers having less than 12-term accuracy enhancement result in increased measurement error.[2]

As frequency increases, it becomes more difficult to measure the test currents and voltages applied to the component being measured, at the exact point where the component has been inserted. Even small changes in electrical length when connecting components, cause considerable measurement phase changes – hence major errors – at high frequencies.

Reflection bridge in practice

A reflection or directional bridge, comprising three 50Ω precision resistors with a wideband 1:1 balun, has the ability to discriminate between signals passing to, and reflected from, a transmission line.[1]

A loss-free transmission line having a matched load absorbs all incident power and reflects nothing. Terminated with anything other than this matched load, a reflected signal is returned to the signal source. This reflected signal, which is separated from the incident signal in the reflection bridge, can then be measured, **Fig. 1**.

When terminated by an open circuit, the reflected signal is identical in amplitude and phase with the incident signal. Terminated in a short circuit, this reflected signal is identical in amplitude but 180° out of phase with the incident signal.

Measurements of these three 'standards,' i.e. of a known value, of a short and of an open circuit, at each frequency of interest can be used to mathematically define a 'calibration plane.' Subsequent measurements of a test component are then corrected to this exact measurement insertion point in the transmission line, ensuring accuracy.

When the line is terminated in a pure capacitive or inductive load, the phase of the reflected wave depends on the load, but the amplitude of the reflected wave will equal that of the incident wave.

When the line is terminated in a lossy capacitive or inductive load, the phase of the reflected wave depends on the phase of the load. The amplitude of the reflected wave will be dependent on the resistive losses being measured.

These measured reflection values, $\pm\Gamma x$ $\pm\Gamma y$ of a test component, can easily be converted into the conventional $R\pm jX$ format, by substitution into two standard equations,

$$R = Z_o \times \frac{1-(\Gamma x^2+\Gamma y^2)}{1-2\Gamma x+\Gamma x^2+\Gamma y^2}$$

$$jX = Z_o \times \frac{2\Gamma y}{1-2\Gamma x+\Gamma x^2+\Gamma y^2}$$

Once in the $R\pm jX$ format, any other desired parameters can simply be derived.[1] There's more on this in box 'Conversions and equations' in last month's article.

In 1994, Hewlett Packard marketed the first high frequency voltage/current based impedance meter, the *HP4291A*. It offered a basic measurement accuracy of 0.8% and a wider impedance range than was possible for reflection measurements using the *HP8753*. But it had a similar price tag.

Measuring from 1MHz to 1.8GHz and having dedicated capacitor test jigs, this instrument avoided the need to design, make and calibrate, high-quality, low-loss, test jigs.

The *HP4286* meter introduced a year later was the first dedicated radio frequency *LCR* meter capable of measuring from 1MHz to 1GHz. It offered a broadly similar capacitor measurement ability but at lower cost. The panel 'Capacitor test instruments' in last month's article details this topic.

More accessible measurement methods

Experimenters' methods trade off cost for accuracy and measurement speed, but commercial *LCR* meters are able to maintain measurement accuracy even at volume production rates. Perhaps you need an intermediate approach, i.e. better accuracy than is possible with experimenters' methods cheaper than buying state-of-the-art equipment?

Good quality second-hand low frequency *LCR* meters are extremely rare, but higher frequency rf impedance measurement instruments are often available from used equipment suppliers. A typical example is the discontinued *HP4191A*, which measures from 1MHz to 1GHz. Using accuracy enhancement techniques, it is still able to provide a useful measurement capability at low cost.

The companion lower frequency *HP4193A* was equipped with an internal generator and test probe. Components could be measured *in situ* on a circuit board, from 400kHz to 110MHz.

Capacitor bridge

The conventional Wheatstone bridge used to measure the ac impedance of a capacitor involves a fixed known capacitance standard and two calibrated variable resistances, Fig. 1. It measures the unknown capacitor as a ratio of this standard by balancing out the detector voltage to near zero.[1]

This configuration has been used commercially, but it suffers from interaction of the two balance controls when measuring high tanδ capacitors. It needs repeated rebalancing, and achieving a true balance is slow.

The transformer ratio-arm bridge was a successful early attempt to eliminate this interacting balance problem, but it is best suited to values less than 10μF. Venerable examples of Wayne-Kerr bridges often appear at good prices. Replacement of every capacitor in the power supply and detector circuits, followed by routine recalibration, usually restores the bridge to its original accuracy.

One manual capacitor bridge which is most successful for all capacitance values can be easily built. It is a variation on the Wheatstone bridge, but with one balancing arm using a variable capacitor. If care is taken in choosing close tolerance and lowest-loss foil with polypropylene or polystyrene capacitor standards, good basic accuracy can be obtained.

My version is optimised for values of 10μF or above, but it can measure down to 100pF when needed. The arrangement shown in the schematics can be used to measure capacitors having a dc polarisation of up to 100V.

Assuming care is taken to minimise stray capacitances and series resistances in the bridge, good measurement results are possible from 20Hz to 20kHz. Higher frequency measurement is possible, but requires some care in arranging guards and in screening the bridge components, See Fig. 5 of last month's article.

For these reasons, and to minimise noise, the internal untuned detector shown in the schematic has been restricted to audio frequencies. I also have an excellent General Radio Corporation *1232A* tuneable high-Q external detector, measuring up to 100kHz, which can be used with this design. It can also be used with either of my two transformer ratio arm bridges. See Fig. 6 of last month's article.

These three bridges, combined with my reflection bridge/phase meter, an *HP4815* rf vector impedance meter and *HP8405* vector voltmeter, provide good accuracy measurements of an extremely wide range of capacitance values over a range of 20Hz to 1GHz.

Dielectric absorption

A degree of dielectric absorption is exhibited by all solid dielectric capacitors, but just what is dielectric absorption? My first demonstration of dielectric absorption resulted from a colleague saying 'catch' and throwing me a discharged high voltage ceramic capacitor, which gave me a nasty jolt. Between the time it was discharged and my catching it, it had recovered a most noticeable voltage.

This is the practical result of dielectric absorption. The cause is the dielectric's ability to store more charge than can be instantly released. This property is fundamental to the dielectric material and depends on the symmetry of its molecular structure.

A symmetrical-molecule dielectric has electrical characteristics effectively constant regardless of frequency and it exhibits minimal dielectric absorption effects. An asymmetrical molecular structure dielectric has a dipole moment, resulting usually in increased dielectric constant. Such an asymmetrical dielectric's electrical characteristics are frequency dependent and it exhibits notable dielectric absorption effects.[3]

Dielectric absorption obviously depends mainly on choice of dielectric materials, but is also related to the degree the dielectric material is stressed in volts per micron. The thinner the dielectric the greater effect for any one charging voltage, **Fig. 2**.

How is this effect measured? For consistency, the capacitor should be charged to a known voltage for a set time. It is discharged at a known rate using the same resistance value, for a controlled time or to a known voltage. Next it is allowed to rest for a set time with open-circuit terminals. Finally, the recovered voltage is measured using a high impedance voltmeter.

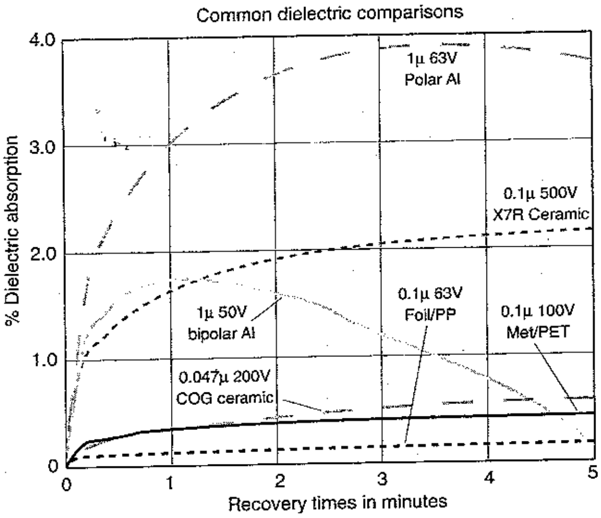

Fig. 3. Measurements using the 100MΩ impedance meter used for Fig. 2. All capacitors were charged to 10V. The effects of self discharging leakage currents can be seen on the two electrolytic capacitor curves. However this plot demonstrates how dielectric absorption varies widely with change of dielectric materials.

Test circuits of various complexity have been defined in national military standards and customer specifications. However, useful comparative tests can be performed using the simplest means of a 9V battery or power supply, a 10 kΩ resistor for charging and 100Ω for discharging, a two-pole three-way rotary switch and a 10MΩ input impedance digital voltmeter.

Using a much higher input impedance meter, the recovered voltage can be observed to rise quickly initially, but continues to increase slowly for several minutes. Many digital voltmeters on their most sensitive range have an input impedance approaching 100MΩ, which is ideal for this experiment, **Fig. 3.**

Practical dielectric absorption testing is best performed in a manner matching your application – especially when choosing a sample and hold or similar capacitor. You might also need to repeat your test sequences at higher ambient temperatures. Many years ago, Bob Pease published a circuit he liked to use for this task. It provided variable charge and discharge rates and completely automated the test switching sequences for you.[4]

Capacitor fault finding

The most common failure mode is that a capacitor fails short circuit. Aluminium electrolytic types are the exception. They usually fail as a higher than normal impedance, when the available oxygen in their electrolyte has been consumed. In such a state, they are commonly referred to as 'dried'.

When measured using the low-frequency charge/discharge capacitance measurement now common in many digital multimeters, capacitance of a 'dried' capacitor may appear unchanged.

A completely open-circuit failure can be exhibited by a fuse protected tantalum. Having blown its fuse, it then becomes an open circuit.

While much less common, a metallised-film capacitor can also fail as a high esr. When subjected to excessive current pulses, the 'schoop' metal spray end connection degrades. Initially, the weakest metallic connection paths burn-out, creating local higher resistance paths. With continued application of current, these high resis-

Table 1a). Typical impedances, in ohms, as measured at 100kHz – low capacitance values.

Capacitor	1μF	2.2μF	4.7μF	10μF	22μF	47μF	100μF
63V polycarb.	0.038Ω	0.018Ω	0.012Ω	0.01Ω			
50V bipolar Al.	2.0Ω	1.5Ω	1.0Ω	0.7Ω	0.25Ω	0.2Ω	0.12Ω
63V polar Al.	2.6Ω	1.9Ω	1.1Ω	0.95Ω	0.4Ω	0.22Ω	0.18Ω
450V polar Al.	24Ω	11Ω	5Ω	3.8Ω	1.5Ω	0.5Ω	

Table 1b). Typical impedances, in ohms, as measured at 100kHz – high capacitance values.

Capacitor	1000μF	2200μF	4700μF	10000μF
25V polar Al.	0.060Ω	0.036Ω	0.024Ω	0.022Ω
63V polar Al.	0.040Ω	0.025Ω	0.011Ω	0.010Ω

The *Capacitor Wizard* esr meter

Independence Electronics[5] has designed a low-cost 100kHz impedance meter aimed at servicing personnel. It simplifies in-circuit capacitor impedance measurements.

Test signal levels have been tailored to permit in-circuit measurement of suspect capacitors without being of sufficient voltage to turn on semiconductor junctions. A supposed 'good' capacitor sounds a beeper. While this beeping impedance level can be adjusted, the factory default sounds the beeper for impedances less than 0.5Ω. A meter scaled from 0.1Ω to 30Ω indicates the approximate impedance measured.

Claimed to be usable for capacitors of 1μF and above, I found some care was needed even with capacitors of 10μF. Many new stocks of modern miniature electrolytics have an impedance near 1Ω, and so did not sound the beeper.[6]

Similarly, some large-value capacitors known to be high esr failures, but having an impedance less than 0.5Ω, sounded the beeper, wrongly suggesting they were still good.

This of course is to be expected.

Unfortunately, the test meter and its accompanying literature incorrectly states that for most capacitors, an impedance less than 0.5Ω indicates a good capacitor.

Putting these problems to one side, does the meter work ? I performed three quite different tests. First of all I compared its readings using electrolytic capacitors previously tested for esr at 100kHz using a capacitance bridge. Capacitance values used, ranged from 1μF to 10000μF

Within the limitations of its meter scale, electrolytic capacitors larger than 1μF, displayed good agreement for both methods.

Using a low loss 1μF polypropylene capacitor in series with a variety of low value non-inductive resistors, I again found good agreement, confirming acceptable factory calibration.

By chance my son arrived with his Grundig tv, which had developed an intermittent colour decoder fault, so I took the opportunity to try this meter on his set. All but two electrolytic capacitors in this chassis caused the beeper to sound. The 'failures' were 0.47μF, 100V and a 4.7μF, 350V components, both of which were in fact good when removed for a bridge measurement.

The user needs to generate a realistic table of expected impedances by capacitor size, capacitance value and voltage rating. Armed with such a table, I consider this meter could then be most useful in a repair workshop with no better facility for measuring esr.

The impedance tabulations supplied with the meter, in my view however, are simplistic in the extreme and so are best ignored.

tance areas grow in size until eventually the capacitor has either a much increased esr, or becomes completely open circuit.

While a completely failed 'open' capacitor is easily identified, a degraded esr, incipient capacitor failure is rather more difficult. How then can a high esr capacitor be quickly identified?

Highly stressed capacitors in power supplies, and in monitor or tv eht and line-scan circuits are obvious first suspects. Another very common failure mode – albeit less well known – is in electrolytics used to block dc while coupling irregular pulse waveforms into the base of a switching transistor. These can become internally reverse polarised and so fail very quickly. Study of the circuit diagram will help you target the most likely suspects.

A dried aluminium electrolytic capacitor usually exhibits clearly visible signs of failure. The most common are deterioration of the end sealing rubber, discoloured insulation sleeve and lead out wires, or signs of leaked electrolyte on the printed circuit board.

Removing a suspect capacitor to test on a capacitance bridge capable of measuring tanδ or esr can be time consuming. Once you have removed the capacitor, it is far easier to simply replace it.

Having assessed the most obvious failure points, can a simple test be applied to check the remaining capacitors *in situ*? Most aluminium electrolytic capacitor impedance curves become a low impedance, almost flat bottomed, curve by 10 or 100kHz, being dominated by the capacitors esr. So a 10 or 100kHz impedance measurement can be used as a rough check on the capacitors high frequency esr. You need only a signal source, a known resistor for comparison and a suitable millivoltmeter or oscilloscope to measure the signal levels.

A practical measurement of this high frequency esr can be made using a 1V signal source fed to the test capacitor via a 1kΩ resistor, giving a direct reading of milliohms, 1mV equalling 1mΩ. With some organisation of leads, etc., this test can be performed while the capacitor is in circuit.

Having measured a capacitor's impedance at 10 or 100kHz, it is essential to compare this result with the maker's claims. Many electrolytic capacitor data books table a maximum 10kHz or 100kHz impedance value for each capacitor. A capacitor exhibiting double this value should certainly be replaced.

A few minutes study of such a databook proves the impossibility of applying any global rule of thumb impedances to judge whether a capacitor is good or bad. The 100kHz esr for a given capacitance value varies according to the capacitor's rated voltage, quality and physical size, **Table 1a)**.

With large-value power supply electrolytics, it is important to ensure accurate measurements down to only a few milliohms. A 10000µF 63V capacitor as used in the power supply of an audio amplifier should have a typical esr at 100Hz around 12mΩ, and at 100kHz around 10mΩ. Increase in

Intermittent failures

Most capacitors failures are identified as a permanent and very low resistance or short circuit. Exceptions are found in aluminium electrolytics which usually fail as a higher than normal impedance and high equivalent series resistance, symptomatic of a 'dried' capacitor. A completely open circuit failure can be demonstrated by a failed, fuse protected, tantalum.

A metallised film capacitor subjected to excessive current pulses can also fail as a high esr. The sprayed metal end connection degrades as the weakest metallic connection paths burn-out, creating local higher resistance paths. With continued application of excess current, these high resistance areas grow in size until eventually the capacitor has either an increased esr, or becomes completely open circuit.

A multilayer ceramic capacitor which has been cracked by handling or soldering, with change of temperature or flexing of the printed board, can sometimes exhibit an intermittent short circuit effect. There's more on this in the panel called 'Capacitor handling.'

A fault location in a metallised film capacitor used at low voltage and with such high circuit impedances that it does not receive sufficient energy to permit self-healing, might exhibit a reduced insulation resistance.

During manufacture, such capacitors are 'cleared' using overvoltage, so should not need to self-heal in normal service. However moisture or solvent ingress during washing, or surface wash residues can contribute a problem. This lower than usual insulation resistance may be intermittent in nature, or vary with temperature or humidity.

One reader who suspected he had a problem with a metallised polycarbonate capacitors possibly having an intermittent lower insulation resistance asked how this might be measured.

An extremely simple test circuit should suffice. Ideally, the test capacitor should be subject to the same voltage as seen in service. Assuming this lies within the range 3V to 15V, an *HEF4044B* set-reset latch can be used to test four capacitors simultaneously.

In **Fig. 4**, I have used 470kΩ resistors to present a high source impedance to the capacitor under test. Higher or lower values could be used, to replicate your circuit conditions.

Having installed the suspect devices, the reset switch is briefly closed to reset the circuit. Any intermittent low insulation resistance in any of the capacitors being tested turns on the respective led. This led remains lit until the reset switch is again activated.

Normally, current drain is extremely small so if necessary, batteries could be used to power the circuit continuously for several months.

It may be that your suspect low insulation resistance is not a capacitor but a track on a printed board. It could have halides remaining on its surface due to improper washing. Change of temperature or humidity can then produce an intermittent low resistance condition. The test circuit is suitable for tracking this problem too.

With suitable matrixing methods, the circuit could be easily expanded to test large numbers of capacitors simultaneously, as a form of low voltage high impedance 'burn in' having automatic indication of failure.

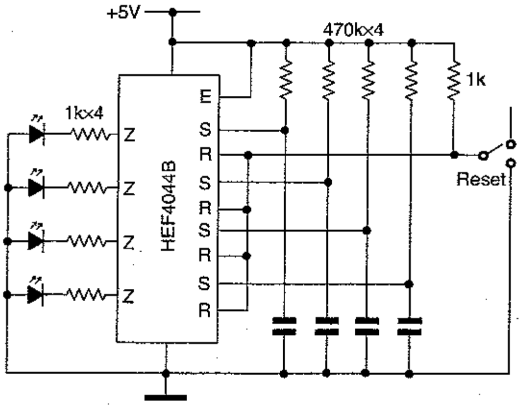

Fig. 4. Simple test circuit designed to indicate an intermittent low insulation resistance at low test voltages in high impedance circuits. While test capacitors are shown, these could in practice easily be suspect printed circuit board tracks.

Capacitor handling

Incorrect soldering methods can damage capacitors, but since most capacitor makers' catalogues specify acceptable soldering times and methods, I do not propose to cover soldering methods in detail.

Remembering that all plastic film dielectrics used to manufacture film capacitors soften and expand at temperatures below that at which solder melts, excessive time and temperature must obviously be avoided.

Ceramic capacitors are probably the most easily damaged by incorrect soldering. Almost all makers specify a pre-heat period sufficient to allow the capacitor dielectric to stabilise at a temperature intermediate between room and soldering temperature. If not observed, thermal shock can cause microscopic or larger cracks which cause the capacitor to fail, usually as a short circuit.

Note that this damage may not result in immediate capacitor failure.

Because many capacitors look mechanically solid or rugged, many users crop or form leads in such way that damage results. If the capacitor maker specifies minimum bending, cropping or soldering distances, these should be strictly observed.

Good practice is to always support the leadwires close to the capacitor body, when bending or cropping leads. Again this is most important with ceramic dielectrics, which can easily become damaged by incorrect handling – especially bare chips intended for surface mounting. Many early failures have resulted from poor handling or cropping methods.

Remember also that humidity protection of encapsulated or 'E' cased capacitors can be seriously reduced by incorrect lead bending or forming. Most lead wires are solder coated or plated with materials not easily 'wetted' by plastic resins and the moisture resisting path lengths may be quite short.

Peculiar early failures can result if handling damage allows the ingress of moisture or board washing solvent.

Should you find early failures occurring, a good rule of thumb is to assume that almost certainly, these will result from poor handling or soldering practices in your assembly.

impedance to 36mΩ at 100Hz obviously triples the power dissipated in the capacitor as heat. In such a case it should be replaced, **Table 1b**).

In summary

Accurate measurements of capacitors – especially of esr at high frequency – requires state of the art equipment and methods. However with these articles, I hope I have been able to encourage experimental measurements using more accessible equipment. ■

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