THE General Radio EXPERIMENTER

VOLUME XVIII No. 11 APRIL, 1944

ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

Also

IN THIS ISSUE

A BRIDGE-CONTROLLED OSCILLATOR

● A BRIDGE-CONTROLLED OSCILLATOR, having particular advantages in use with low-frequency quartz crystals and low-frequency narrow-range tuned circuits, is shown schematically in Figure 1. The diagram indicates the arrangement for use with a 50- or 100-kc quartz crystal. A single-stage high-gain tuned amplifier is followed by a triode used as a phase-inverter. The inverter is connected to the bridge input terminals; the bridge output terminals are connected back to the input of the high-gain amplifier.[1]

First, consider the conditions for balance of the bridge; these are

$$R_1/R_2 = R_3/R_4$$

and

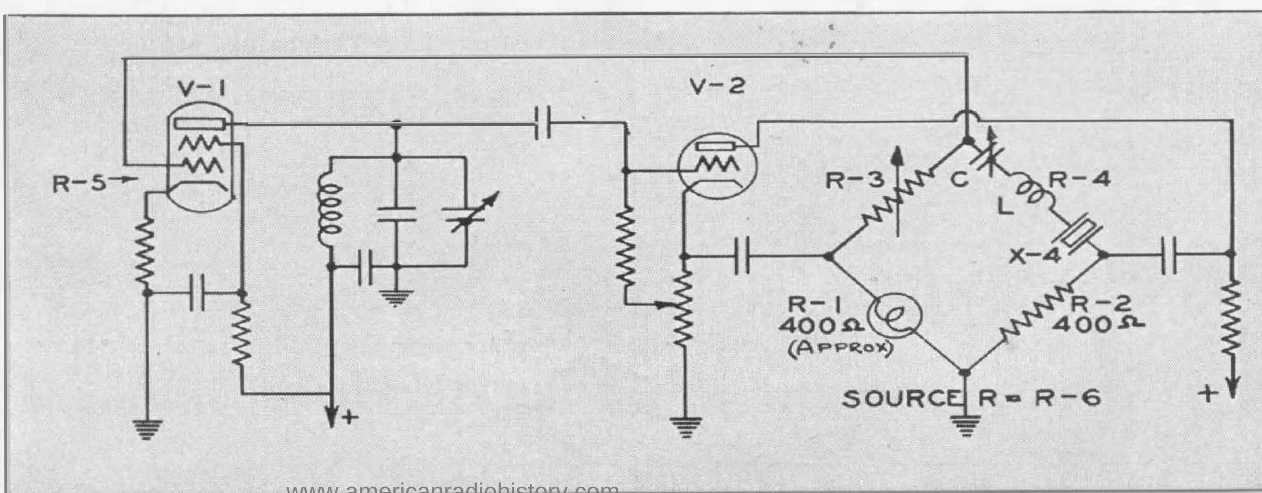
$$X_4 = 0.$$

At balance, the bridge output voltage is zero and the crystal reactance is zero, indicating that the crystal operates at exact series-resonance. Obviously no oscillations could be maintained under these conditions.

Next, if the ratio arm R-1 be given a value of resistance slightly less than that of the arm R-2, there will be a small output voltage from the bridge in the correct phase to maintain oscillations.

[1]This is a substantially simplified modification of Meacham's oscillator. It is also readily adapted to operation over a narrow band of frequencies. "A Bridge-Stabilized Oscillator," L. A. Meacham, *Proc. I.R.E.*, Vol. 26, No. 10, Oct. 1938, p. 1278.

FIGURE 1. Schematic circuit diagram of the bridge-controlled oscillator.



This condition is not stable; the slightest change in bridge balance conditions or in the gain of the amplifier would cause the amplitude of oscillation to increase or decrease. If the value of resistance of the arm R-1 be made dependent on the voltage across it, then stable amplitude conditions will be maintained. In this case, the value of R-1 must increase if the voltage across R-1 increases. If R-1 is a tungsten filament lamp this condition is realizable. (In other arrangements of the bridge, a resistance whose value decreases with increasing voltage may be necessary. In such case a carbon filament lamp could be used.)

With a 115-volt 6-watt tungsten filament lamp operated at 0.6 to 3.0 volts, resistances from about 300 to 600 ohms will be obtained. In the region of 1.0 volt the resistance is near 400 ohms. Therefore, if $R_3 = R_4$ and if a voltage of approximately 2.0 volts is impressed on the bridge input terminals, a resistance balance will be reached.

As an oscillator, assuming first that the amplifier is tuned for zero phase-shift, the system will operate so that the lamp resistance is not quite equal to R-2. The equilibrium value will be such that the loss from the input terminals through the bridge to the output terminals is exactly equal to the gain from the bridge output terminals through the amplifier to the bridge input terminals. It is evident that very slight changes in the lamp resistance will very greatly affect the magnitude of the bridge output. A change in gain of the amplifier is then immediately compensated for by a very slight change in lamp resistance, which, in turn, is produced by an inappreciable change in the voltage across the bridge input terminals, or the level of operation of the oscillator.

The lamp-controlled bridge is therefore a form of automatic level (or "volume") control. In contrast to the usual forms of A.V.C. circuits it has several interesting and important properties. It has infinite cut-off, at balance, whereas A.V.C. circuits have restricted ranges. Also, since the lamp resistance cannot change materially over the time of one cycle of the oscillation frequency, the lamp-controlled bridge introduces no distortion or phase-shift as regulation takes place, with the consequent alterations of the frequency of oscillation.[2]

With conditions outlined above, the amplitude performance of the oscillator can be calculated completely since the system is entirely linear. With the bridge near balance, and with $R_3 = R_4 = 3000$ ohms (which would represent operation with a particular 50-kc plated quartz bar), the net load on each half of the phase-inverter would be slightly less than 400 ohms. The gain of the phase-inverter is:

$$A = \frac{E_{\text{out}}}{E_{\text{in}}} = \frac{2\mu}{r_P/R + \mu + 2}$$

where R is the net resistance of each half of the bridge load. The internal resistance of the phase-inverter stage is:

$$R_0 = \frac{r_P}{\mu/2 + 1}$$

With a tube such as the 6J5–G, $\mu = 20$, $r_P = 7600$ ohms and we find $A = 0.92$, $R_0 = 690$ ohms.

If we have nearly 2.0 volts across the bridge input terminals (to bring the bridge near balance), the input voltage to the phase-inverter stage will be $2 \div 0.92 = 2.17$ volts. If the gain of the tuned amplifier is 400 (which can easily be realized), then the input voltage

[2] "Constant Frequency Oscillators," F. B. Lewellyn, PROC. I.R.E., Vol. 19, p. 2063, December, 1931.

would be 2.17/400 = 0.0055 volts. This voltage is obtained from the bridge output when the lamp resistance is approximately one per cent lower than the resistance of the fixed ratio arm, or 396.0 ohms. Each half of the bridge, consisting of 3000 ohms in parallel with 400 ohms, presents a load of 355 ohms to each half of the phase-inverter, or a total load of 710 ohms. With the internal resistance of the phase-inverter, R_0, at 690 ohms, a very good power match is obtained from the inverter to the bridge.

The conditions outlined so far can be represented in a vector diagram as shown in Figure 2. To avoid confusion, the voltages across the upper and lower bridge arms, and the bridge output voltage, are shown on separate lines.

If next we consider that the amplifier phase-shift is not zero, then the crystal phase-angle must assume such a value that the phase-shift through the bridge is equal and opposite to the phase-shift in the amplifier, or the total phase-shift around the entire loop is zero. These conditions are outlined in the diagram of Figure 3.

From the diagram, even though it is not to scale, it is evident that a given amplifier phase-shift is compensated by the bridge with the crystal phase-shift much smaller than that of the bridge. Since the crystal phase-shift is brought about by a change in operating frequency, the small value of phase-shift means a correspondingly small change in frequency.

Finally, in practice, we require a means of adjusting the operating frequency over a small range around the true crystal series-resonant frequency. This is accomplished by placing a series-tuned L-C circuit in series with the crystal. When this circuit is tuned so that its reactance is zero at the crystal

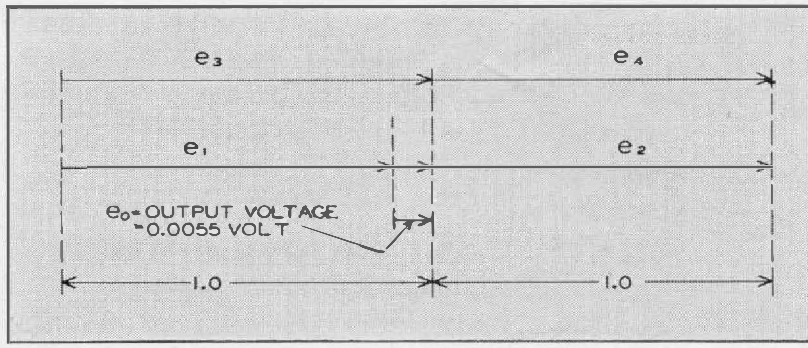


FIGURE 2. Vector diagram for operation with zero phase-shift in amplifier.

frequency, and the amplifier is adjusted by test for zero phase-shift, then the operating frequency is the series-resonant frequency of the crystal. If the capacitance of the tuned circuit is made larger than the resonant value, the operating frequency is reduced; if smaller, it is increased.

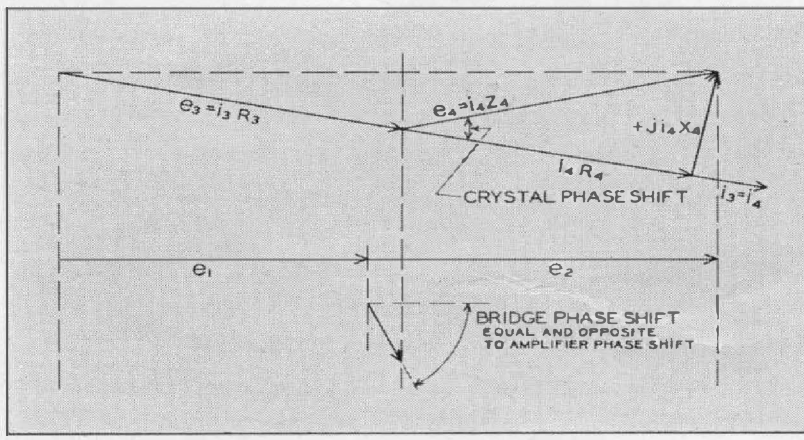
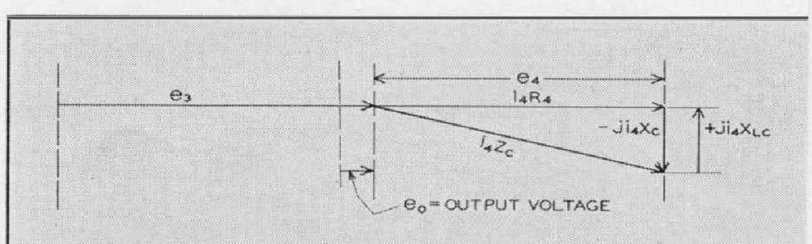


FIGURE 3. Vector diagram for operation with amplifier phase-shift equal and opposite to bridge phase-shift.

These conditions are shown in Figure 4, where the *net* reactance of the series tuned L-C circuit is X_{LC} and the *net* reactance of the crystal is X_C.

In actual operation, the resistance of the crystal is generally unknown, so that

FIGURE 4. Vector diagram for operation with reactance added in series with the crystal.



the adjustment of R_3 to equal R_4 cannot be made in advance. Consequently, it is convenient to operate the system so that $e_1 = e_2$, which can be checked experimentally, adjusting R_3 to obtain this condition. Since the resistances of the arms R-3 and R-4 are substantially higher than those of the ratio arms R-1 and R-2, considerable latitude in the values of R-3 and R-4 is possible without substantially altering the voltage developed across the ratio arms. Consequently, a rudimentary vacuum-tube voltmeter can be built into the system indicating the voltage at the grid of the phase-inverter. Such a voltmeter is also necessary to indicate when oscillations take place. Since the system is linear, plate- or grid-current meters are of no value for this purpose. A particular reading of this voltmeter then corresponds to the condition that $e_1 = e_2$. Whatever the value of the crystal resistance R-4, within reasonable limits for similar crystals, R-3 is adjusted to obtain the proper reading of the voltmeter.[3] When this is done, the value of R-3 exceeds the value of R-4 by a very small amount, the amount being inversely dependent on the gain of the amplifier.

Operation by this method opens up the possibility of measuring the characteristics of the crystal. From the above, the value of R-3 slightly exceeds the resistance of the crystal plus the resistance of the inductor. For comparative purposes these need not be separated.

To determine the crystal reactance, we adjust the L-C circuit to introduce known values of reactance X-1 and X-2. Then:

$$X_1 + X_C = 0 = X_1 + 2\Delta_1 X_0$$
$$X_2 + X_C = 0 = X_2 + 2\Delta_2 X_0$$

Where $\triangle_1$ and $\triangle_2$ are the resulting frequency deviations and X_0 is the resonant reactance of the crystal. Then

$$X_0 = \frac{X_2 - X_1}{2(\Delta_2 - \Delta_1)}$$

Using this method, the resistance of a particular type of 50-kc quartz bar was 2700 ohms, its resonant reactance was 228×10^6 ohms. The "Q" of the bar, X_0/R, was 84,500.

The method is very useful in comparing the performance of bars in production. The resonant reactances of such bars are all the same, since the reactance depends on the cut and dimensions. The effective resistance of the bars is also determined by the cut and dimensions, but *in addition* depends upon many other factors such as the type and condition of the mounting device, supersonic radiation and reflections. Where identical bars are being processed, these factors can be controlled so that the observed resistances are closely the same.

J. K. Clapp

[3] As in the Types 675-P and 690-D Piezo-Electric Oscillators.

THE EFFECT OF HUMIDITY ON ELECTRICAL MEASUREMENTS*

● AS SUMMER APPROACHES, we prepare for the usual crop of complaints that come in regarding the erratic behavior of electrical measuring equipment, particularly precision impedance bridges. The various stories conflict. Sometimes the bridge seems to read high, sometimes low; the balance may drift badly or suddenly jump to a new value; it may show increasing errors as the frequency is lowered, or the balance may shift with applied voltage. At first glance it seems that there must be as

*Reprinted from the August, 1943, issue of the *Experimenter*.

many causes as kinds of error. Actually, there is just one cause, high relative humidity.

High relative humidity affects insulation in two ways. If the insulation is porous, moisture will be absorbed into the volume of the material, while if moisture wets the surface, a thin film of water is formed covering the whole surface. Water distributed throughout the interior of an insulator produces interfacial polarization which causes an increase in capacitance, dissipation factor, and volume conductivity. The amounts of these increases vary with the relative humidity and inversely with the frequency.[1] At 100% relative humidity and a frequency of 60 cycles, increases as much as 50% in capacitance, of a millionfold in conductivity, and up to a dissipation factor of 1.0, are quite possible for such porous materials as filled and laminated thermo-setting plastics, many thermoplastics and natural fibers like cotton, wool, and silk. The rate at which a porous material absorbs water and the tenacity with which it holds it depend greatly on the cross section of the pores. When these approach molecular dimensions, as in silica gel, which is a silicate having microscopic pores produced by suitable heat treatment, the material acts as a desiccant, and the absorbed water can be removed only by heating above the boiling point. Mica and some ceramics act in this manner. Only quartz and most glasses, some steatites, polystyrene, and a few other polymers are free from volume absorption and the accompanying deterioration of dielectric properties.

The formation of a surface film of water on an insulator is determined by the ease with which water wets the surface, which in turn is measured by the contact angle between the surface and a drop of water on the surface.[2] Most of the porous materials that show large volume absorption also wet very easily. A microscopic roughness of the surface helps film formation. Quartz, glass, and steatite also wet easily. Only wax, polystyrene, and some other polymers successfully prevent the formation of a continuous film. The condition of the surface is also important. Dust and particularly acid perspiration from handling greatly aid wetting. The conductivity of even a thin film is enormous. Merely breathing on the surface of a good insulator like quartz will lower the insulation resistance between terminals spaced ¾ inch apart from above 10 MM Ω to below 1 M Ω. A film so formed will vanish rapidly if the surface is chemically clean and the relative humidity low. On a dirty surface, however, the film persists and can be removed only by thorough cleaning or by heating.

Because there are no rigid stable insulators which are unaffected by moisture, it is customary to impregnate them or at least to coat their surfaces with one of the water-repellent substances such as wax, polystyrene, or the newer silicon resins. Any of these materials operates successfully on the non-porous insulators, such as glass and steatite, so long as perfect adhesion is maintained. Large changes in temperature, particularly toward freezing, will produce cracking and chipping of the surface material because of the differences in temperature coefficients of linear expansion, and because most coatings, the waxes in particular, become brittle at the lower temperatures. Any moisture film which

[1] R. F. Field, "Frequency Characteristics of Decade Condensers," General Radio *Experimenter*, Vol. XVII, No. 5, Oct., 1942, pp. 1-7.

[2] On the well waxed surface of an automobile during a rain, large drops stand with a small re-entrant angle, the area of contact being smaller than the maximum section of the drop.

then forms between the insulation and the coating persists and can be removed only by complete cleaning of the surface or by heating.

On porous materials a thin protective coating is of no value because even the waxes are themselves somewhat porous. Such a coating decreases the rate at which moisture penetrates to the inner material, but continued exposure to high relative humidity will eventually result in the same equilibrium conditions. For reasonable success, wax coatings must be heavy, the result of multiple dippings, and of the order of 0.1 inch.

In all General Radio instruments great care has been taken to provide adequate protection against high relative humidity. All solid dielectric condensers are hermetically sealed or heavily waxed. All high-valued resistors are waxed or similarly protected. All steatite insulation is protected by a surface coating by the manufacturer. Mica-filled phenolic or polystyrene is used as insulation for mounting all high impedances. Wires for cables are insulated with rubber or a synthetic, with a lacquered identifying braid. These precautions are sufficient to allow normal operation under 90% relative humidity at 90° F. of all instruments except the 0.1% impedance bridges. An even more severe test occurs when, at 90% relative humidity, the temperature fluctuates sufficiently to reach the dew point and cause direct moisture condensation. Under these conditions the operation of an instrument may not meet catalog specifications. If power is dissipated inside the instrument, the heat generated will quickly evaporate the conducting moisture films. Otherwise some time must elapse to allow natural evaporation. A 40-watt lamp or other resistive load maintained inside the case will usually prevent condensation. It will have, however, little effect on moisture absorption.

The TYPE 716-B Capacitance Bridge is probably as greatly affected by moisture as any of our instruments. All steatite insulated terminals are wax coated, the input transformer is wax sealed, and the bridge wiring is open bus. Only the TYPE 722 Precision Condenser, used on the capacitance standard, is affected by moisture, and that only in its dielectric losses, not in its capacitance. Its own dissipation factor is defined by its figure of merit $F = DC = 0.04\ \mu\mu f$, corresponding to a dissipation factor of the steatite stator support of 0.004. At about 60% relative humidity, moisture absorption through the wax coating on these bars causes their dissipation factor to rise. A tenfold increase at 90% relative humidity must be expected. This will produce a negative error in the direct reading of dissipation factor exactly equal to the increase in dissipation factor of the precision condenser. No error will appear in parallel substitution measurements.

Another dielectric loss occurs in aluminum-plate air condensers under high humidity conditions from the absorption of moisture by the aluminum oxide on the surface of all the plates. In its dry state aluminum oxide has a small dissipation factor and imparts to the whole condenser a dissipation factor of only 0.0000001, since its contribution is proportional to the ratio of the thickness of the oxide film, about 10 millionths of an inch, to the plate spacing of 30 mils. When exposed to moisture the dissipation factor of the oxide is an exponential function of the relative humidity,[3] increasing a decade of dissipation factor for every 15% rise in relative humidity.

[3]A. V. Astin, "Nature of Energy Losses in Air Capacitors at Low Frequencies," *Journal of Research of the National Bureau of Standards*, Vol. 22, No. 6, June, 1939, pp. 673-695.

At 90% the air condenser has a dissipation factor of about 0.01. Since the dielectric loss occurs on the surfaces of all the plates, the air condenser behaves like a variable solid dielectric condenser, and its dissipation factor does not cancel out even in parallel substitution measurements. As before, the error in the bridge reading is negative.

Both of these kinds of moisture absorption in steatite and in aluminum oxide are troublesome when the relative humidity stays at 60% throughout the day, since at this level only a half day is required to attain equilibrium. A relative humidity of 40% causes no appreciable error, and even a rise to 60% followed by a drop back to 40% within six hours will cause little trouble. The time needed to attain equilibrium increases with the relative humidity and is at least three days at 90%.

Every laboratory should be equipped with some type of hygrometer in order that the possibility of errors in bridge measurements may be anticipated. The ordinary hair hygrometer is very useful in spite of its large errors because it is of the indicating type. A wet and dry bulb hygrometer should be available as a check under extreme conditions. Regular readings of relative humidity during the summer months are fully as important as are those of temperature, for the units being measured are in many cases more liable to be affected by high humidity than the measuring equipment itself. This fact indicates that the bridge readings of dissipation factor may appear to be high or low dependent upon the relative rates at which the unknown condenser and the standard condenser in the bridge change their dissipation factors with humidity. Without a hygrometer this situation cannot be definitely recognized except as the reading of dissipation factor becomes ridiculously low or actually negative. A certain instability of bridge balance will appear at relative humidities above perhaps 70%, as indicated by a more or less steady drift of both capacitance and dissipation factor balance points.

There is little that can be done with existing measuring instruments to eliminate this type of error, short of air conditioning. This should preferably apply to the entire room containing measuring equipment. Then the unknown unit is measured under standard conditions. It is also possible to dry out the measuring instrument by placing a desiccant, such as silica gel, inside its case. However, the amount of moisture which can seep through the joints between panel and case and around the control shaft is amazing. Unless unusual care is taken, it will be necessary to renew the desiccant each working day whenever the relative humidity is above 70%.

— ROBERT F. FIELD

SCHEDULED DELIVERY DATES

● MOST OF OUR CUSTOMERS who have to deal directly with procurement are familiar with the scheduling system under which electronic test equipment is now delivered. To our engineering customers whose principal interest is "when do I get it" rather than a detailed explanation of delays in deliveries, several words to clarify the predicament of General Radio seem to be in order.

Early in the war it became apparent that there would be severe shortages of manpower and materials and that test instrument manufacturers, sooner or later, would develop large shortage lists.

The materials shortage was due not only to a scarcity of certain basic raw materials and the necessary manpower to process them, but also to an even greater shortage of a considerable number of finished components which instrument contractors purchase from subcontractors.

At first manufacturers attempted to establish the delivery sequence of orders from the urgency statements of the customer. The priority system set up at the beginning did not cover test equipment and some other tools of production. Often the axle which squeaked the loudest got the most oil, since the manufacturer had no inside knowledge of the basic war plan nor any information as to how an order for a particular instrument fitted into the war picture. It became necessary for closer supervision by the governmental agency which had been set up to determine the priority of orders for test equipment. This function is now administered by the War Production Board, in collaboration with the procurement agencies, which decides the relative importance of orders placed by the Army, Navy, Maritime Commission, the British, Russian and Chinese Governments, and all other branches of the United Nations war effort.

For some time the sequence of shipments to these agencies has been decided solely by the tactical urgency of the war problem involved. Sub-divisions of each agency set the urgency of orders within the agency.

When anyone places an order for electronic test equipment it is now required that very complete supporting information be supplied to the WPB as to the tactical urgency in order that the proper delivery schedule may be established. This schedule is based upon two things: the production capacity of the manufacturer (already expanded to the limit) and the urgency of the war problem involved.

After a delivery date has been set by WPB, the customer and the supplier are notified. The order then takes its place in the manufacturer's delivery schedule. The manufacturer makes every effort to meet the delivery date and his efforts are supplemented by those of the Army-Navy Electronics Production Agency, which is in close touch with changes in urgency and with any shortages and bottlenecks which may develop. All changes in scheduled deliveries are controlled by the WPB, and become necessary principally from two causes:

(1) From frequent changes in the war plan, the urgency standing of many orders changes from day to day.

(2) Due to shortages of raw materials, finished components, and manpower, the manufacturer's production schedule lags.

When it becomes necessary for WPB to change a delivery date, the manufacturer has no prior knowledge of that fact, nor any information as to the reason for the change. He is required by law to fill all orders in the sequence decided upon by the WPB schedules. Appeals directly to the manufacturer to reshuffle deliveries accordingly cannot be acted upon.

The present scheduling system at times results in repeated disappointments to our customers. Its whole purpose, however, is to supply war materials when and where they are most urgently needed. This, after all, seems to be the basic aim of war production.

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