Stompboxology™

Volume 13, Number 2

Going Discrete

Discrete-transistor circuits tend to be quiet, simple, and cheap. Yet to a generation raised on chips, transistors might as well be a lost art. This issue explores transistor function in simple terms that open a host of tonal doors.

Bipolar Transistors

Q. What's a bipolar transistor (BPT)?

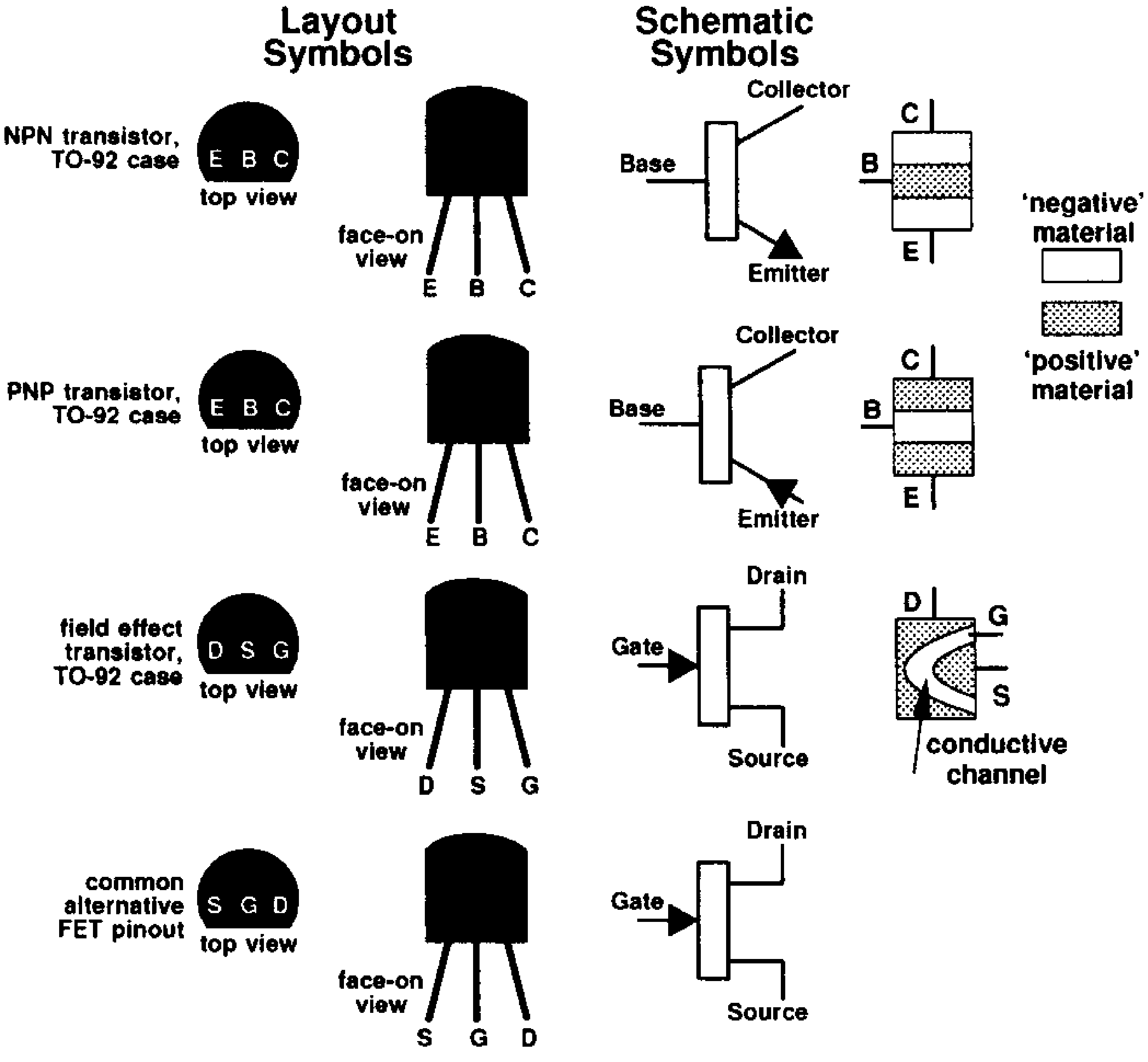
A. A BPT is a component that has three leads: emitter (E), base (B), and collector (C). Fig. 1 shows the schematic symbol, layout symbol, and pinout of a common type.

American transistor part numbers begin *2N*, followed by three or four digits and occasionally a letter, such as 2N107, 2N3904, or 2N2369A. Transistors come in cases designated *TO* for *transistor outline*. Small-signal transistors come in TO-5, TO-8, and TO-92 cases, the latter a 1/8" black plastic cylinder flattened on one side. TO-92 is the commonest case style for small-signal transistors found in stompboxes.

Early transistors were made of germanium. Pure germanium is an insulator, but the addition of impurities allows it to conduct current in specific circumstances. This explains the origin of the term semiconductor. Germanium transistors were used in several early pedals that became classics. While a few germanium transistors can still be had, (e.g., in the NTE line of replacement parts, and the occasional 2N part stocked by a major supplier), most modern transistors are made of silicon.

BPTs are further categorized as NPN or PNP, *N* standing for *negative layer*, *P* standing for *positive layer*, as in Fig. 1. To avoid confusion, the following discussion deals only with NPN types. PNP transistors are detailed later in the issue.

Fig. 1. Common transistor layout & schematic symbols.



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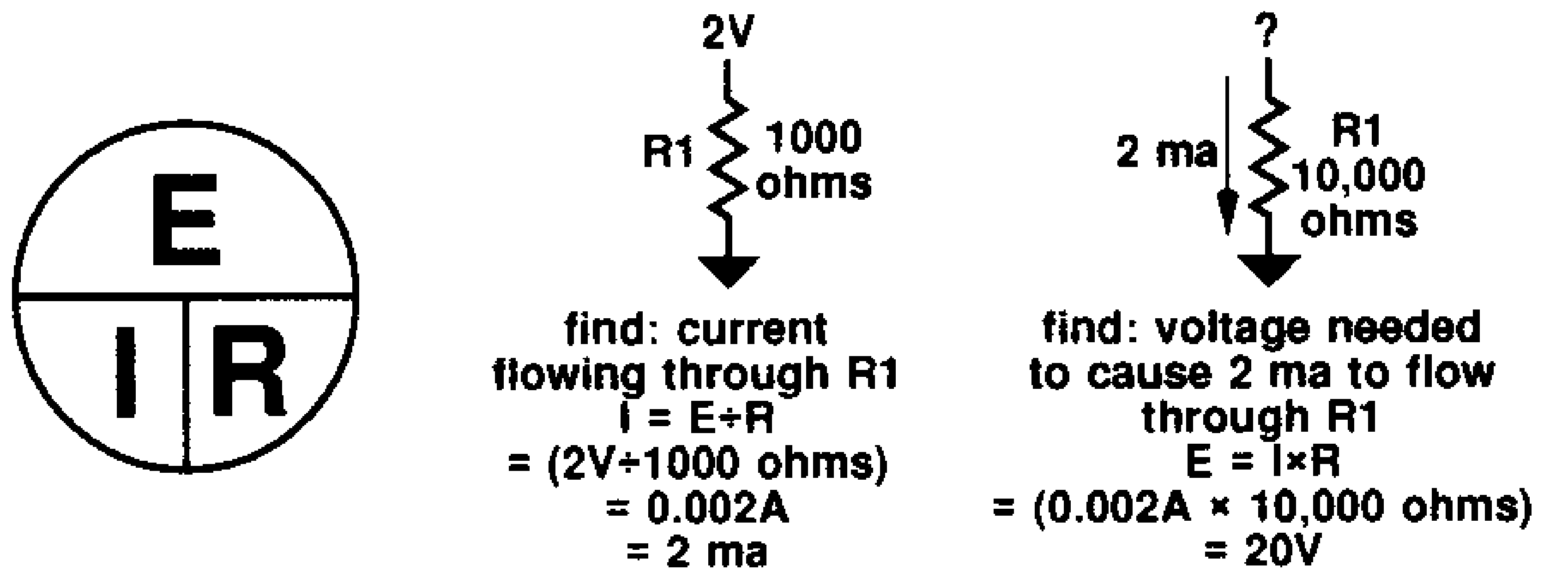
Explanations of transistor function usually employ a model. But the model demands knowledge of certain basic concepts. Our model treats a BPT as a current-controlled resistor—

Q. Let's stop and pick up a few of those basic concepts, like current and

Fig. 2. Ohm's law and two simple examples. Applies equally to impedances and audio signals.

E = electromotive force (volts, millivolts, microvolts)
I = current (amps, milliamps, microamps)
R = resistance (ohms)



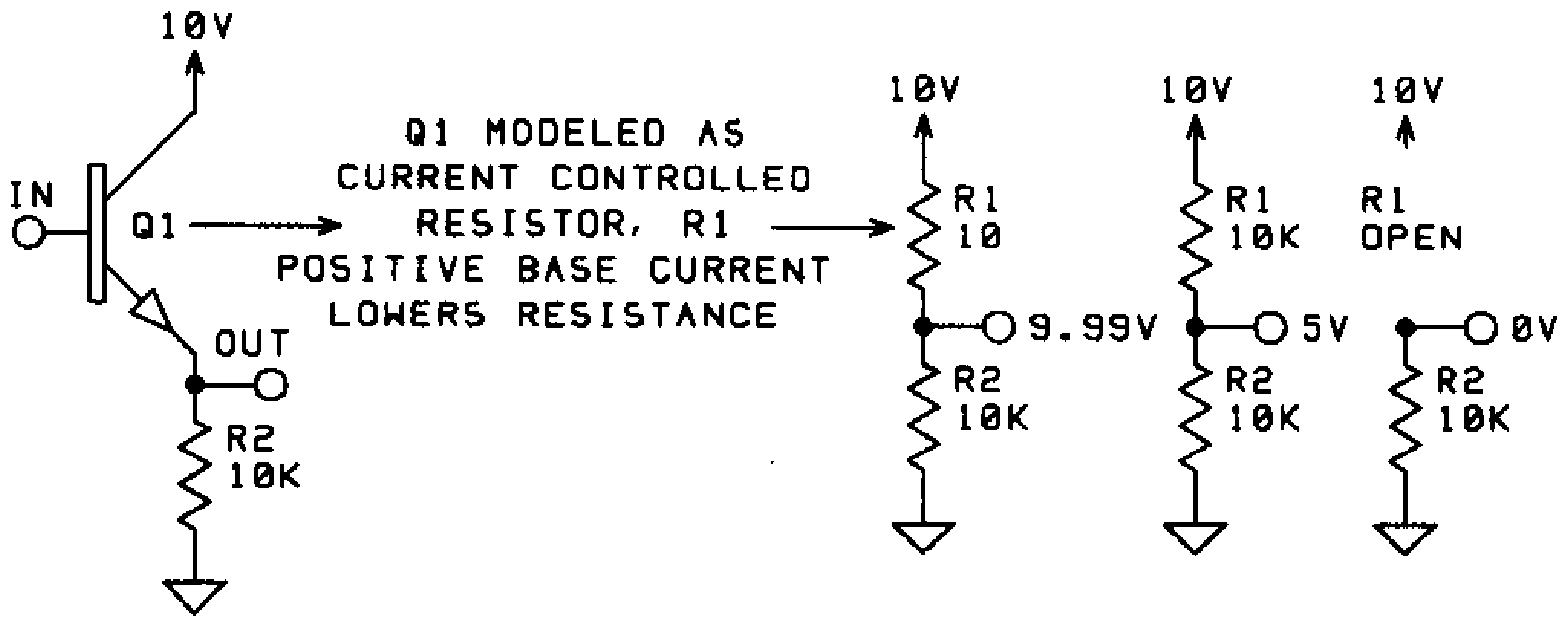


Fig. 3. NPN BPT modeled as current-controlled resistance. As this resistance changes, so does emitter voltage.

resistance.

A. Current is the rate of flow of electrons. Its unit of measure is the ampere, milliampere (one-thousandth of an amp), or microampere (one-millionth of an amp).

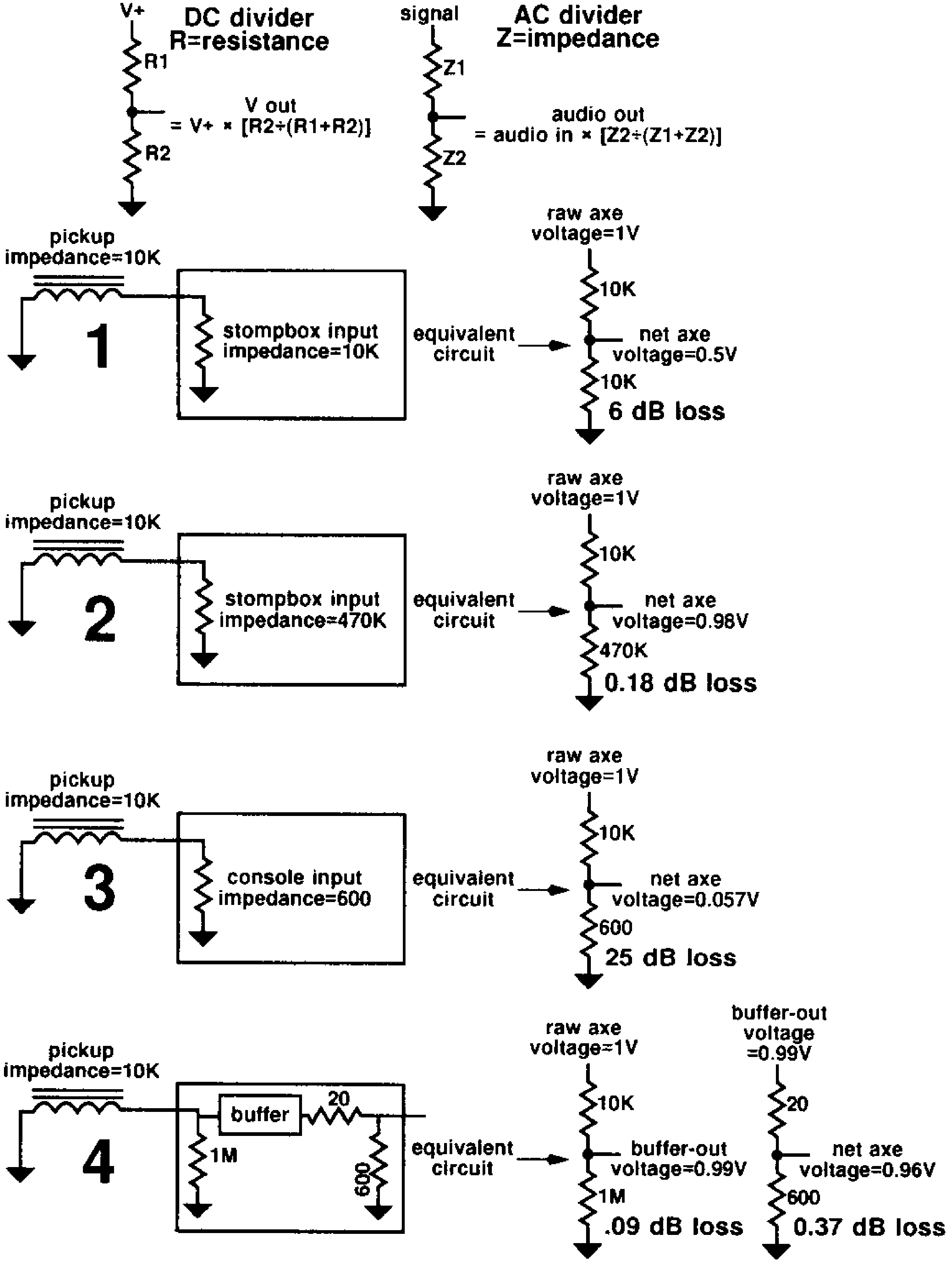
Resistance is the property of opposing the flow of electrons. Its unit is the ohm.

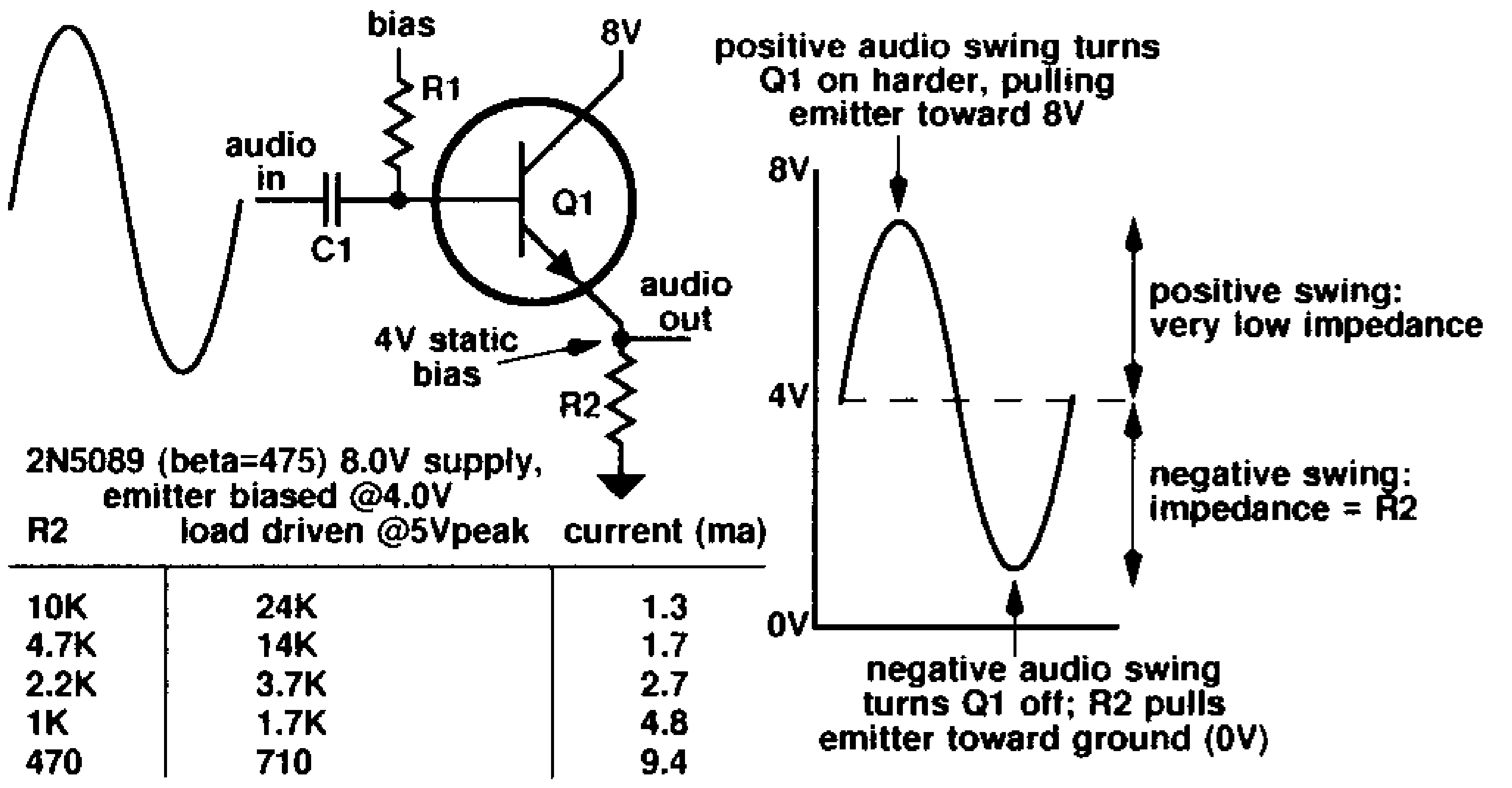
Current and resistance are related by a third quantity, voltage, which indicates the potential difference between two points, and which causes current to flow. Its unit is the volt, millivolt (one-thousandth of a volt), or microvolt (one-millionth of a volt). Voltage is also referred to as electromotive force (E). The relationship among these three is defined by Ohm's law (Fig. 2)

Q. What does the circle in Fig. 2 mean?

A. Covering the quantity you want to find leaves the remaining parts in the proper form. If you want to find voltage, cover E; that shows IxR. If you want current, cover I; that leaves E÷R. If you want resistance, cover R, leaving E÷I. This diagram is an old mnemonic aid.

Fig. 4. Loading losses involve DC or AC voltage dividers, which follow a simple formula. 1—Axe feeding poorly designed stompbox with 10K input impedance; loading results in 6 dB signal loss. 2—Better design sports 470K input impedance; loading loss is negligible. 3—A worst-case scenario, feeding axe directly into 600-ohm studio console. Loading loss is enormous. 4—Proper interfacing requires the interposition of a buffer with very high input impedance, very low output impedance. Buffering reduces net loading losses to negligible levels.





2N5089 (beta=475) 8.0V supply,
emitter biased @4.0V

R2	load driven @5Vpeak	current (ma)
10K	24K	1.3
4.7K	14K	1.7
2.2K	3.7K	2.7
1K	1.7K	4.8
470	710	9.4

Fig. 5. Emitter follower for audio signals requires a DC bias through R1, such that emitter voltage settles near half the supply voltage. Audio couples through C1 to base. Positive voltage swing causes Q1 to conduct harder, pulling the emitter voltage toward V+. The impedance of this half-cycle is low, because positive input voltage can make Q1 appear as a resistance of 10 ohms or so, which easily drives a 600-ohm load. Negative audio swing makes Q1 appear as a larger resistance. The only force pulling the emitter voltage down is R2. Thus, NPN emitter follower exhibits a low output impedance only for the positive portion of the audio cycle. The value of the emitter resistor determines the impedance for the negative audio swing. Table shows values for resting current drain vs. load driven @5V peak for a 2N5089 with a beta of 475. This simple follower can drive internal stompbox stages, and practically all stompbox and amp inputs, while drawing negligible current. Rising current drain with falling value of R2 makes other approaches more practical for driving difficult loads.

Always use the same units to get the correct answer. You can't divide millivolts by amps; you have to convert millivolts to volts, then divide by amps; or keep millivolts and convert amps to milliamps, then divide.

Q. I understand voltage, resistance, current, and Ohm's law. You were saying that you had modeled a BPT as a current-controlled resistor.

A. Right (Fig. 3). The electrical path exists between the collector and the emitter. Current applied to the base controls the conduction state of the C-E channel. NPN transistors increase conductivity as the current applied to the base moves from negative to positive. The fact that a change in base current causes much greater change in C-E current is what allows a transistor to amplify.

Q. What can I build with one transistor that's useful in stompboxes?

A. The simplest circuit is called an emitter follower (Fig. 5). It's a common stompbox input buffer, and may be an even more common output buffer.

Q. What's a buffer?

A. In audio, a buffer is a circuit that conveys audio from one stage to another, the point being to prevent loading losses.

Q. What are loading losses?

A. Loading losses bring up another basic concept: voltage dividers. Two connected resistances (or impedances) form a voltage divider. The function follows a formula shown in Fig. 4.

A signal source, such as a guitar pickup, exhibits a specific impedance. So does the stompbox input fed by the pickup. Plugging the pickup into the box creates a voltage divider. Given a 10K pickup plugging into a 10K stompbox input, half the voltage is lost to divider action. This is called a *loading loss*, because the stompbox input loads the signal source. If the stompbox input impedance were 470,000 ohms, the loading loss falls to negligible levels.

Plugging that same 10K pickup into a 600-ohm input found in some studio gear loses about 94% of the signal. Interposition of a buffer with a 1M input impedance and a 20-ohm output impedance reduces losses to negligible levels.

Q. Why not make all inputs high impedance, to avoid loading losses?

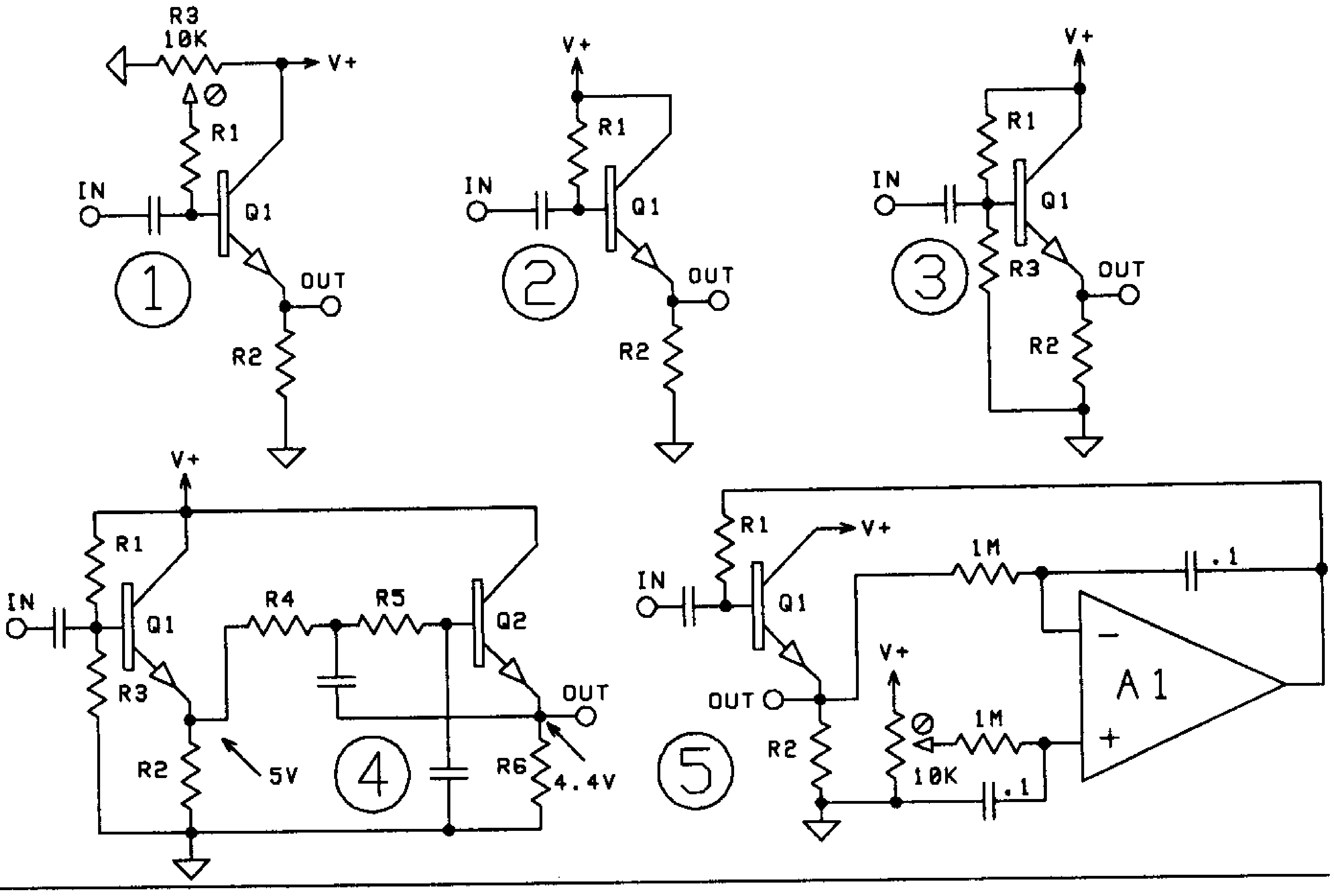
A. That's not always practical. Some chips are internally configured with low-to-medium impedances. In those cases place a buffer between the signal source and the load.

Q. How do I design and use emitter followers?

A. Copy the circuit in Fig. 5.

Q. Three obvious questions about that circuit: (1) How do I choose the tran-

Fig. 6. Common means of biasing an emitter follower. 1—Trimpot biasing varies voltage applied to one end of fixed bias resistor R1; trim R3 to give desired emitter voltage. 2—Single resistor to V+; R1 must be chosen to conduct correct current to base. Though proper value can be calculated from supply voltage, transistor beta, and R2, it's just as easy to replace R1 with a 5M pot; trim for desired emitter bias; measure value of pot resistance, replace pot with nearest-value fixed resistor. In circuits #1 and #2, input impedance approximates the value of R1. 3—Divider biasing uses resistive voltage divider R1-R3 tied to base. Input impedance approximates the value of R1 in parallel with R3. 4—DC coupling lets follower get bias from preceding stage. In this case, 2nd follower is a simple active filter. Using NPN transistors, Q2's emitter voltage will be ~0.6V less than Q1's emitter voltage. 5—Servo amp A1 automatically biases emitter at voltage set by trimpot.



sistor? (2) What's the value of R1? and (3) What's the value of R2?

A. In choosing a transistor you'll be concerned mainly with a property that goes under various names, but which we'll call *beta*. Beta measures the sensitivity to base current, and is stated as a number that ranges from 10 to 1000 for common transistors. Less than 100 is low; 100 to 350 is medium; above 350 is high. Many digital multimeters will measure the beta of NPN and PNP transistors.

The value of R1 pretty much sets the buffer's input impedance, so you want to make it as high as possible, but not so high that it can't pass enough current to bias the transistor; 470K makes a good choice.

The value of R2 sets the impedance of the negative output swing; use 10K for typical stompbox loads of 25K and up.

Q. Could you explain that?

A. Check out Fig. 5. When Q1 is biased at 1/2V+, audio applied to the base through C1 adds to, or subtracts from, the static bias current applied through R1. When audio swings positive, Q1 turns on harder, pulling the emitter up toward V+ —

Q. By divider action with R2.

A. Right.

Q. How hard can Q1 pull?

A. Ten ohms or less for a beta of 450. This makes the impedance of the top half of the audio swing very low, easily able to drive 600 ohms.

When the audio swings negative, Q1 turns off; its resistance rises. The only force pulling the emitter down toward ground is R2. So, simple emitter followers exhibit asymmetrical output impedance. The value of R2 sets the impedance of the negative swing.

Q. It appears that R1, R2, and Q1's beta are interactive variables. How about giving me a few guidelines to simplify the choices.

A. (1) Make R1 at least 10 times the expected source impedance. (2) Make R2 no more than 1/3 the expected load impedance. (3) Use a transistor with a beta of at least 250; 2N5088, 5089, 2484, and 3565 types should work fine.

Q. So, if I wanted a buffer for a stompbox input driving a 50K second stage, I could use 470K for R1, 10K for R2, and a 2N5089 transistor?

A. Yes.

Q. Why does the axe feed couple to Q1 through a capacitor?

A. With its volume knob turned all the way up, the axe appears as a 10K resistor tied to ground. Connecting a 10K resistor directly to Q1's base would upset the bias current flowing in R1.

Q. Could you explain *bias* in more detail?

A. The meaning of the term changes with context. Generally, transistor bias refers to a constant conduction state maintained to achieve some desired result. In audio, to *bias* a bipolar transistor means *to apply a current to the base that puts the transistor in a conduction state that allows it to respond linearly to audio signals.*

Q. What is that state? In other words, what can I measure to tell that the transistor is properly biased?

A. With an emitter follower, measure the emitter voltage, which should be close to 1/2V+.

Q. How can I bias an emitter follower?

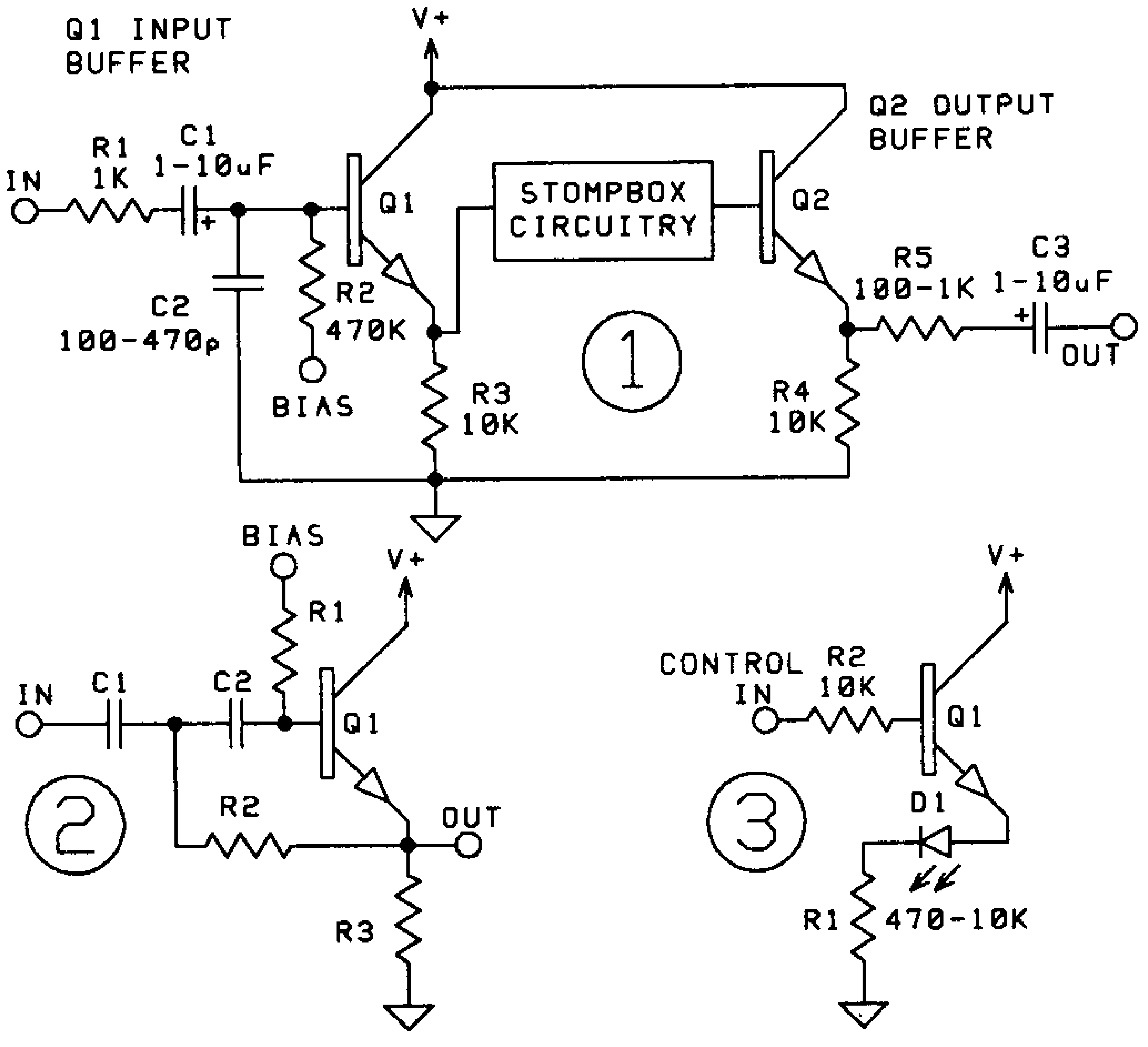
A. These methods are most useful in stompboxes:

- trimpot
- single resistor to V+
- fixed divider
- from preceding stage
- servo

Referring to Fig. 6, trimpot biasing applies to any transistor and lets you compensate for differences in beta. The drawback is the extra setup step.

Fig. 6–2 illustrates biasing through a resistor tied to V+. Formulas exist

Fig. 7. 1—Input and output buffers are the most common stompbox uses for emitter followers. Followers often add a small series resistance, R1; an RF shunt capacitance, C2; and, at the output buffer, a small series resistance, R5. 2—Emitter follower used in simple active highpass filter; emitter resistance should be about 1/10 the value of R1 & R2. 3—Emitter follower used as LED driver; high base impedance shows driving stage an easy load.



Project No. G287

Split-O-Matic V

FET-input four-output noninverting splitter with individually variable output levels.

Circuit Function

Axe feed couples through C1-R1 to source follower Q1, whose output couples to the bases of emitter followers Q2–5, each of whose emitter resistor is a 10K audio-taper pot whose wiper ties through a 470-ohm resistor and a 10μF cap to the output path. The net signal paths are noninverting.

Trimpot R13 is used to adjust the output bias.

Use

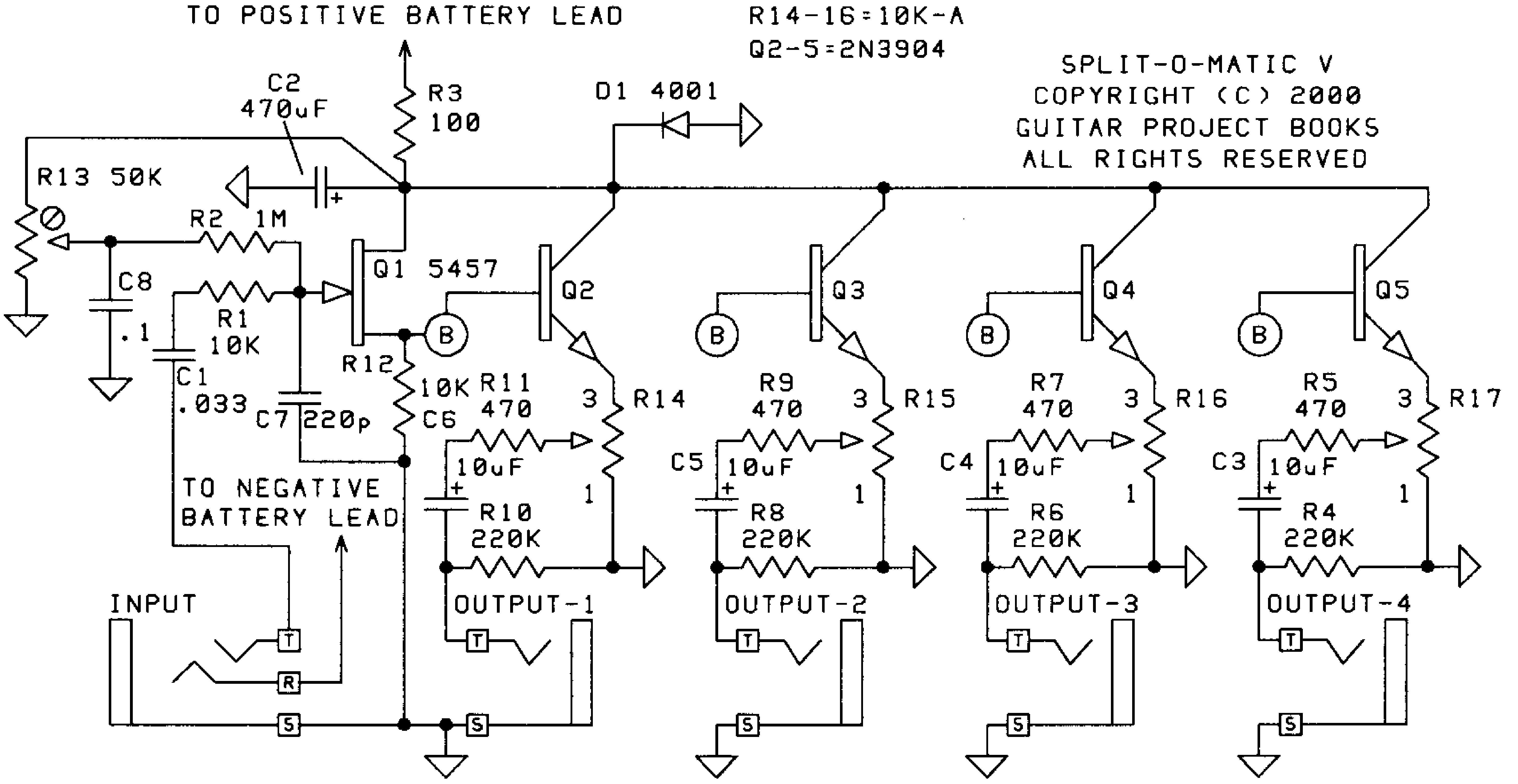
Pots have these functions:

R13	output bias trim
R14	output-1 level
R15	output-2 level
R16	output-3 level
R17	output-4 level

Center R13, connect battery, insert plug into input jack (cord should be plugged into axe whose volume pot is turned all the way down). Measure V+, the voltage present at jumper J1; trim R13 so that terminal-3 of R14 is at 1/2V+.

Use is self-explanatory. Circuit provides about 5V of headroom running at 7.5V.

Split-O-Matic V schematic.



to calculate bias resistance given V+, beta, and emitter resistance; in practice, tie a large pot to V+, trim to give the desired emitter bias, then substitute the nearest standard-value resistor for the pot. The drawback of this approach is that emitter bias shifts with battery aging, and the bias resistance applies only to another transistor having a similar beta.

Fig. 6–3 illustrates fixed-divider biasing. The quick way to achieve this is to tie the end-terminals of a 1M pot across V+ and ground; tie the wiper to the transistor's base. Trim the pot for the desired emitter bias. Remove the pot, measure the resistances of the two arms, substitute the nearest value fixed resistors. The net impedance then approximates those two resistances in parallel.

Q. Can the preceding stage bias a transistor directly?

A. Yes, as in Fig. 6–4. But here we find that a BPT isn't a perfect current-controlled resistor. If you show 5V at Q1's emitter, the voltage at Q2's emitter settles at ~4.4V due to the forward drop across the base-emitter junction.

Q. What's forward drop?

A. Semiconductors don't behave as pure resistance. To get a diode or

Fig. 8. Emitter follower used to illustrate the importance of the output bias point. Greatest headroom generally coincides with the output being biased close to 1/2V+. If output bias rises above this point, positive audio excursion is limited; if output bias falls below this point, negative audio excursion is limited. Altered bias can be used to generate even harmonics.

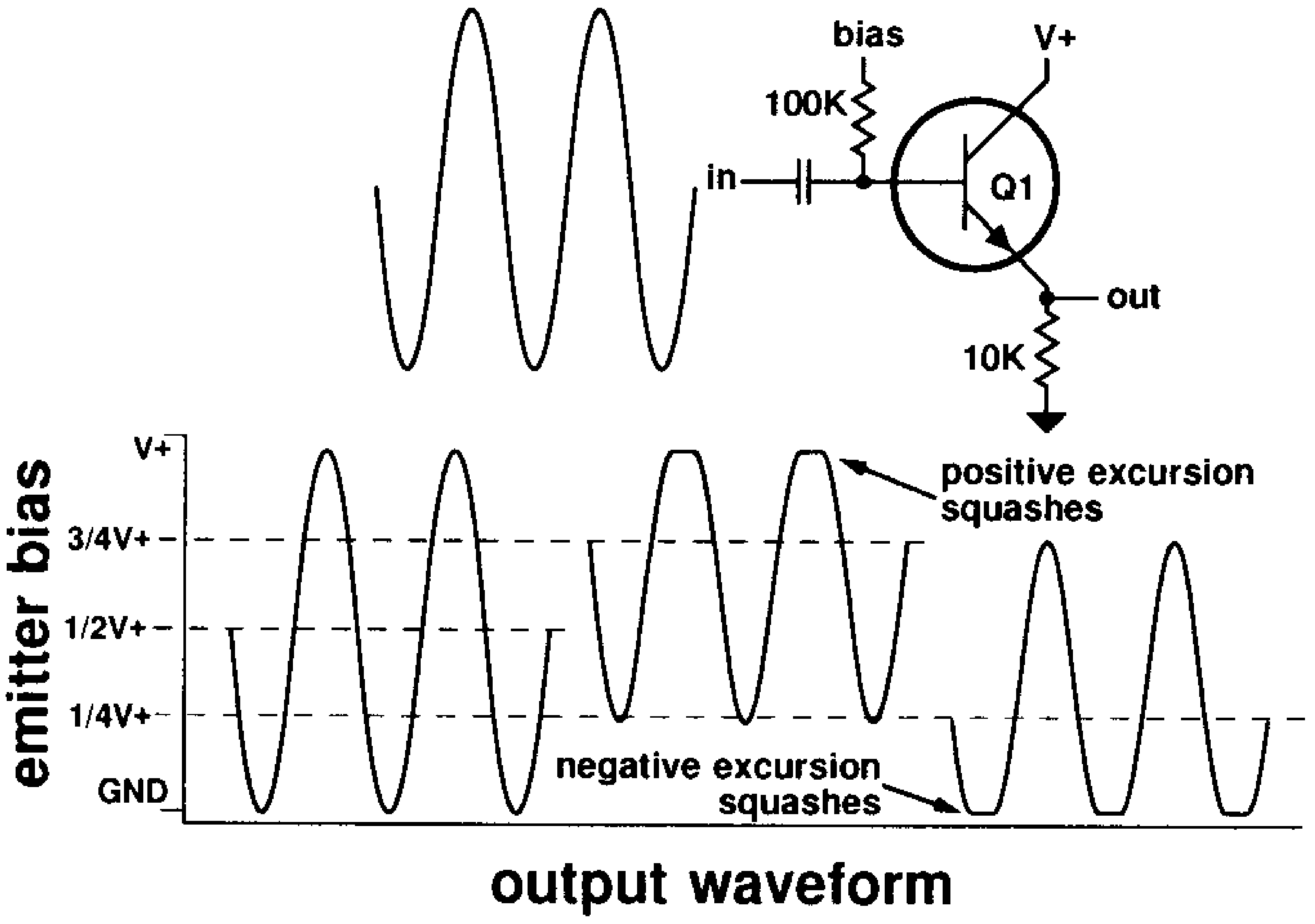
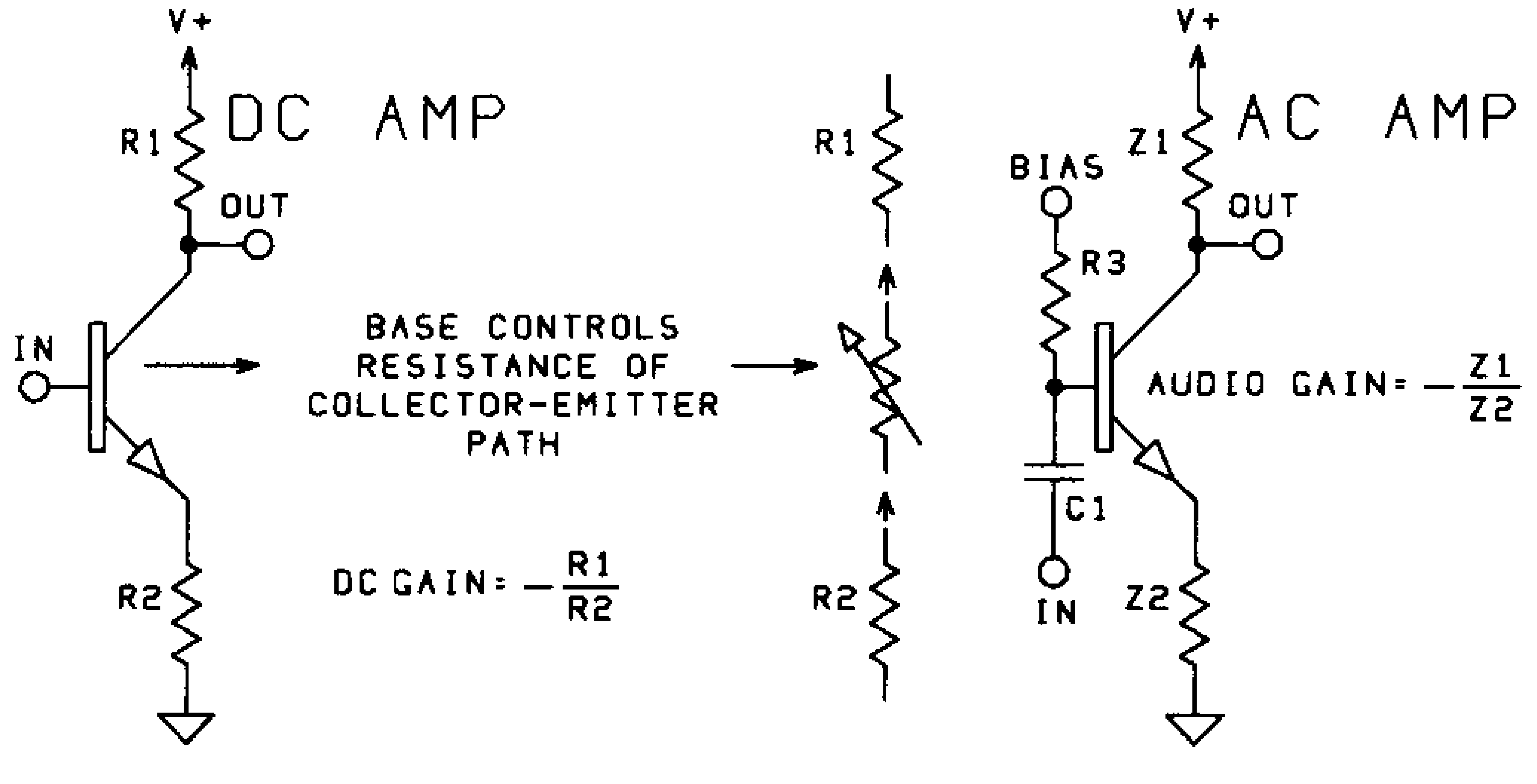
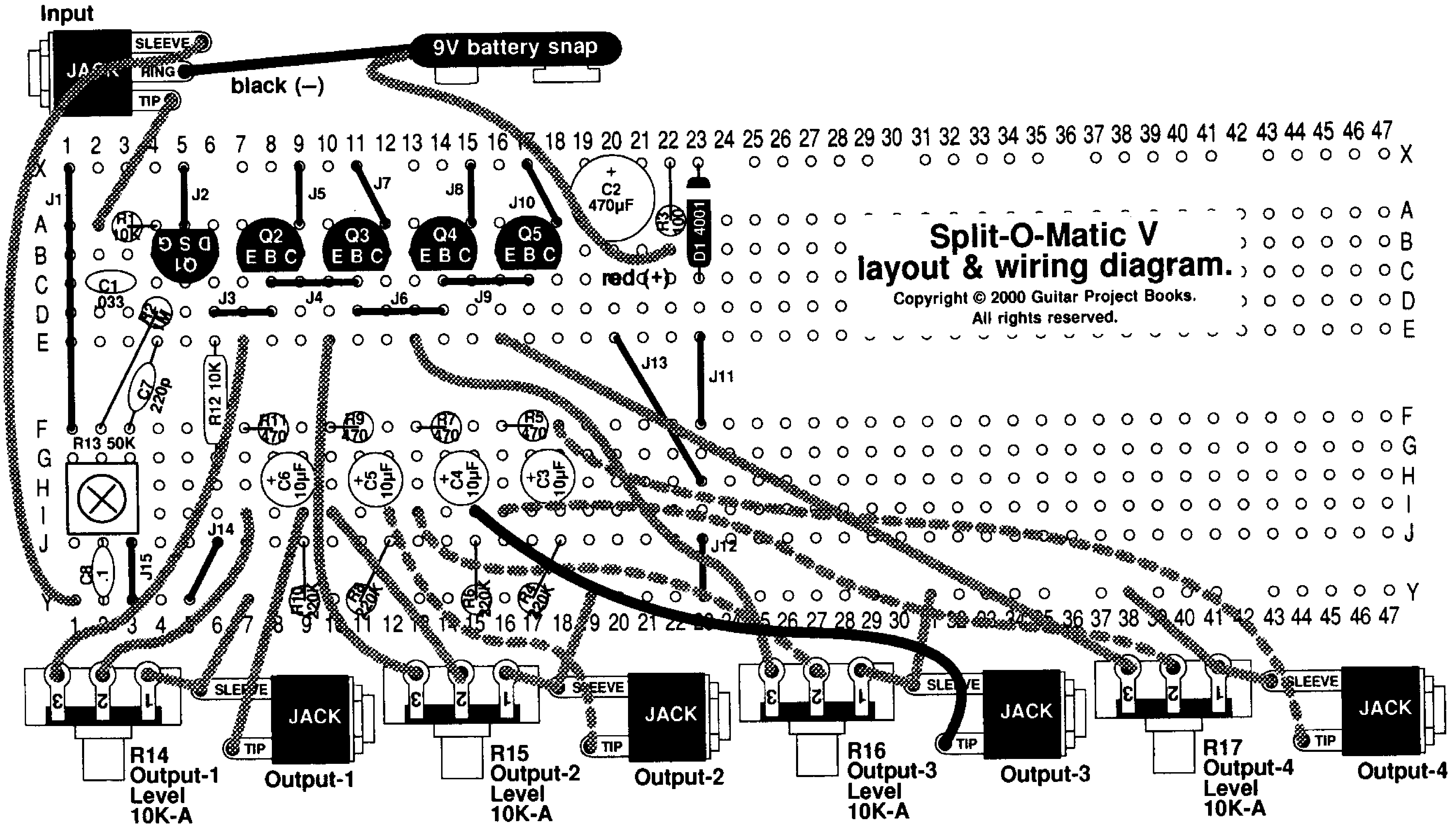


Fig. 9. Basic inverting amplifier, also called common-emitter amplifier. Using current-controlled resistor model, application of positive current to base turns Q1 on, pulling collector down toward R2; if R1=R2, then gain = 1; if R2<R1, then gain approximates R1÷R2. Important to remember that output is inverted. AC version biases base using methods similar to those for emitter follower; audio couples through C1. Positive audio swing turns Q1 on, pulling collector down toward R2. For audio signals, the ratio of impedances, rather than pure resistance. This gives a convenient way to alter tone.





Split-O-Matic V layout & wiring diagram.

Parts List/Soldering Checklist

Circuit Board Radio Shack p/n 276-170; Hosfelt p/n 42-183; or DC Electronics p/n J4-404

Resistors

☐	R1	10K	(brn-blk-org)	A3-A4
☐	R2	1M	(brn-blk-grn)	D4-F2
☐	R3	100	(brn-blk-brn)	X22-A22
☐	R4	220K	(red-red-yel)	J18-Y17
☐	R5	470	(yel-vio-brn)	F16-F17
☐	R6	220K	(red-red-yel)	J15-Y15
☐	R7	470	(yel-vio-brn)	F13-F14
☐	R8	220K	(red-red-yel)	J12-Y11
☐	R9	470	(yel-vio-brn)	F10-F11
☐	R10	220K	(red-red-yel)	J9-Y9
☐	R11	470	(yel-vio-brn)	F7-F8
☐	R12	10K	(brn-blk-org)	E6-G6

Bare Wire Jumpers

☐	J1	X1-F1
☐	J2	X5-A5
☐	J3	D6-D8
☐	J4	C8-C11
☐	J5	X9-A9
☐	J6	D11-D14
☐	J7	X11-A12
☐	J8	X15-A15
☐	J9	C14-C17
☐	J10	X17-A18
☐	J11	E23-F23
☐	J12	J23-Y23
☐	J13	E20-H23
☐	J14	J6-Y5
☐	J15	J3-Y3

Capacitors

☐	C1	0.033	C2-C3
☐	C2	470µF	X20-A20 ('+' lead to X20)
☐	C3	10µF	H17-H18 ('+' lead to H17)
☐	C4	10µF	H14-H15 ('+' lead to H14)
☐	C5	10µF	H11-H12 ('+' lead to H11)
☐	C6	10µF	H8-H9 ('+' lead to H8)
☐	C7	220pF	E4-F3
☐	C8	0.1	J2-Y2

Semiconductors

☐	D1	1N4001	X23-C23 (banded end to X23)
☐	Q1	2N5457	drain (D) to B6, source (S) to B5, gate (G) to B4
☐	Q2	2N3904	emitter (E) to B7, base (B) to B8, collector (C) to B9
☐	Q3	2N3904	emitter (E) to B10, base (B) to B11, collector (C) to B12
☐	Q4	2N3904	emitter (E) to B13, base (B) to B14, collector (C) to B15
☐	Q5	2N3904	emitter (E) to B16, base (B) to B17, collector (C) to B18

Trimpot

☐	R13	50K single-turn trimpot; leads go in I1-H2-I3

Potentiometers (T=terminal)

☐	R14	10K audio-taper	T1 to sleeve of output-1 jack and to Y7, T2 to I7, T3 to E7
☐	R15	10K audio-taper	T1 to sleeve of output-2 jack and to Y19, T2 to I10, T3 to E10
☐	R16	10K audio-taper	T1 to sleeve of output-3 jack and to Y31, T2 to I13, T3 to E13
☐	R17	10K audio-taper	T1 to sleeve of output-4 jack and to Y38, T2 to I16, T3 to E16

Jacks (T=terminal)

☐	input jack (1/4" 3-terminal/stereo): tip to A2, ring to negative (–) battery lead, sleeve to Y1
☐	output-1 jack (1/4" 2-terminal/mono): tip to I9, sleeve as noted above
☐	output-2 jack (1/4" 2-terminal/mono): tip to I12, sleeve as noted above
☐	output-3 jack (1/4" 2-terminal/mono): tip to I15, sleeve as noted above
☐	output-4 jack (1/4" 2-terminal/mono): tip to I18, sleeve as noted above

9V Battery Leads

☐	black (negative, –) to ring of input jack
☐	red (positive, +) to B22

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transistor to conduct current, you have to apply enough voltage to overcome a native property called forward drop. For a silicon diode this is about 0.6V. The base-emitter junction inside a transistor is equivalent to a silicon diode, with the base being the anode and the emitter the cathode.

Forward drop is no big deal when you control the bias and couple through a capacitor. But when DC coupling to the base of an NPN emitter follower, the output is always one diode drop below the input. For maximum headroom—

Q. What's headroom?

A. The greatest undistorted signal amplitude that a stage can pass. For maximum headroom, bias the voltage follower such that the emitter voltage falls close to 1/2V+. Fig. 8 illustrates the concept.

It's important to remember that a given bias applies only to other transistors having identical beta, and at substantially the same temperature.

Q. What else can I build using emitter followers?

A. Simple active filters (e.g., Figs. 6–4 and 7–2). Use the follower in place of an op-amp voltage follower. Also, a follower makes an LED driver (Fig. 7–3)

Q. If I understand emitter followers correctly, they're used mainly as input and output buffers, to prevent loading losses, out of their high input impedance and low (but asymmetrical) output impedance. In order to get them to pass audio without distortion, they have to be biased in a particular state of

Project No. G288

Distort-O-Matic XI

All-transistor distortion box with aggressive tone controls.

Circuit Function

Axe feed couples through C14-R2 to a noninverting amplifier made up of Q1-Q2, which applies ~40 dB of broadband gain; R18 trims preamp bias. Output is taken off Q2's collector and couples through C2 to phase splitter Q3, thence through C3 and C4 to an amplifying positive fullwave rectifier comprised of Q4 & Q5. Output is taken at the collectors of Q4-Q5 and couples directly to terminal-3 of edge control pot R19. Terminal-1 of R19 gets the raw preamp output through C12; terminal-2 feeds germanium diode clipper D4-5, whose output feeds inverting amp Q6, whose nominal gain is 1; however, pots R21 and R22 allow Q6 to generate bass/treble boost/cut in excess of 30 dB. Output is taken off the wiper of R20, which serves as Q6's collector load.

Use

Pots and switch have these functions:

R18	preamp bias trim
R19	edge (hard/soft)
R20	output level
R21	treble boost/cut
R22	bass boost/cut
S1	effect/bypass

Center R18, R20, R21, and R22; turn R19 fully CCW; toggle S1 to effect. Connect unit to an axe whose volume pot is turned all the way down. Trim R18 to give 1/2V+ at the collector of Q2.

Next, attach unit to amp, establish desired listening level. In this state modest distortion should be noted. Take the bass/treble controls through their ranges and note the effect on tone. Take edge control R19 to its clockwise limit and note the change in sound.

Notes

High gain demands a neat layout and short pot-leads to prevent oscillation.

L1 was salvaged from a Dunlop® Crybaby® manufactured in 1989; it has a nominal value of ~0.5H. Dimensions may vary, requiring added connectors or alternative mounting. Several small audio transformers sold by Mouser® also exhibit ~0.5H of inductance, but proved unsuitable in this application due to their low Q. The adjustable preamp bias lets the player move bias closer to V+. This lowers the threshold of unipolar clipping, giving earlier onset of mild distortion.

Distort-O-Matic XI schematic.

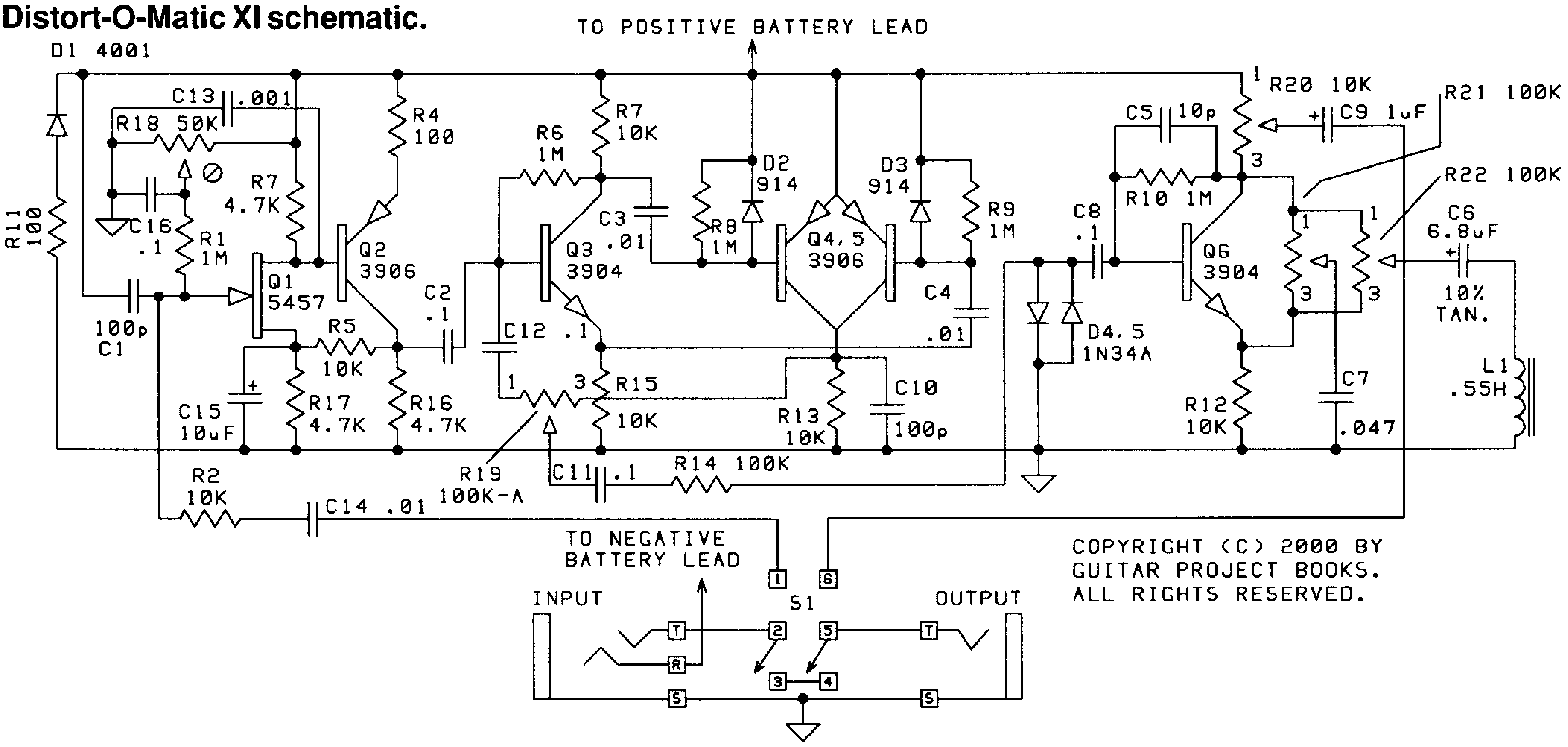
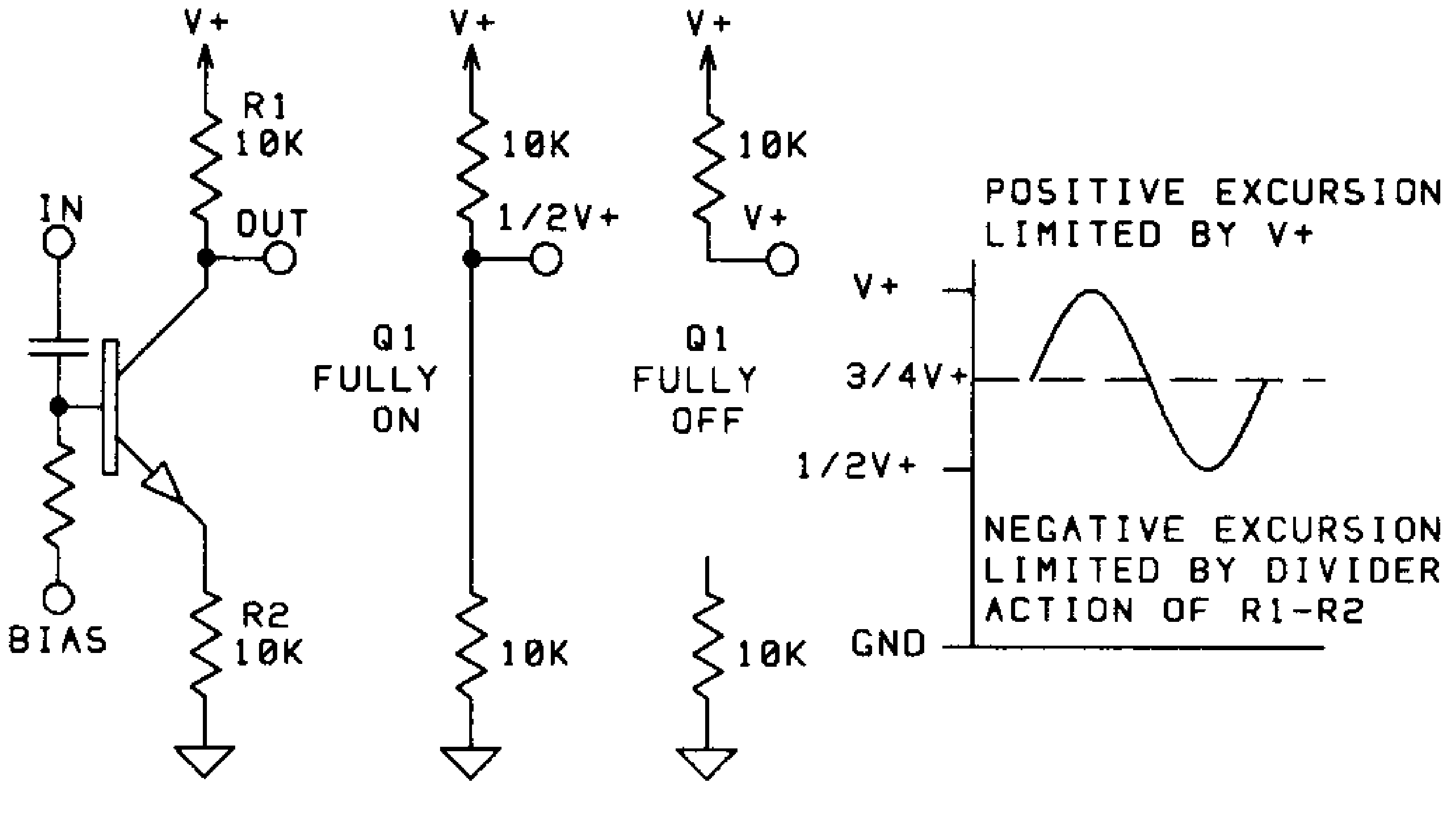


Fig. 10. Unity-gain inverting amp's maximum headroom is limited to just under 1/2V+. When Q1 turns fully on, it acts as a short; collector swings near 1/2+ by divider action of R1-R2. When Q1 turns off, it acts as an open circuit; R1 pulls collector near V+. Optimum headroom occurs with collector bias at 3/4V+.



conduction, achieved by applying a current to the base such that the emitter voltage settles close to 1/2V+.

A. Right.

Inverting Amplifiers

Q. Let's move on to discrete-transistor gain stages.

A. The first of these is the inverting amplifier, also referred to as a common-emitter amplifier. Fig. 9 shows the typical circuit. Gain approximates the ratio of collector impedance to emitter impedance.

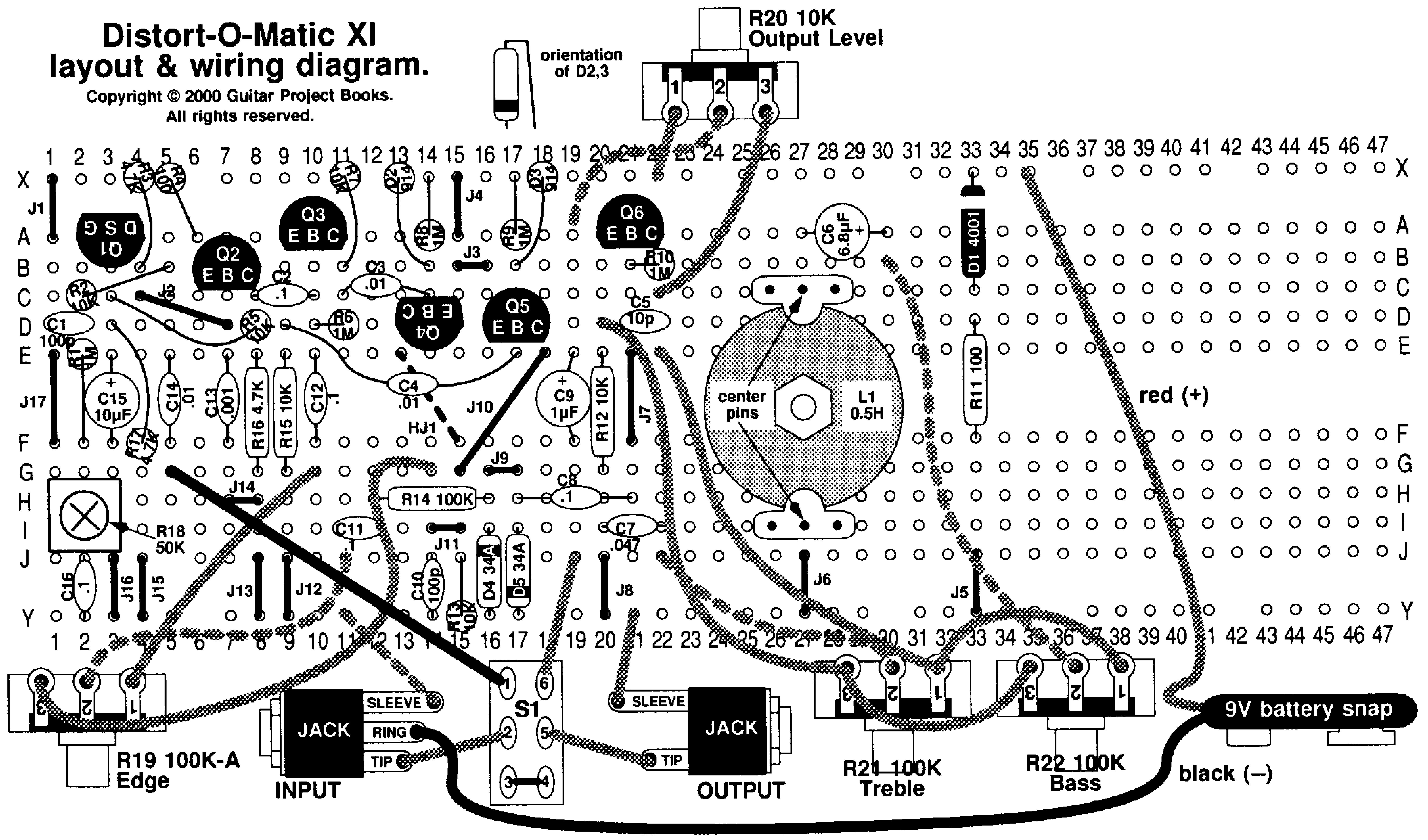
Q. Why is this called this an inverting amplifier?

A. The polarity of the output signal is inverted relative to the input. The positive audio swing turns Q1 on harder, which pulls the collector down toward the emitter. When the negative audio swing turns Q1 off, the collector resistor pulls the collector up toward V+.

Q. How much gain can I get from a single transistor?

A. Maximum gain varies with beta and supply voltage; it rarely reaches the theoretical maximum. Using a BPT with a beta of 450 or more, you can get

Distort-O-Matic XI layout & wiring diagram.



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Resistors

[ ]	R1	1M	(brn-blk-grn)	E2-F2
[ ]	R2	10K	(brn-blk-org)	C2-B5
[ ]	R3	4.7K	(yel-vio-red)	X4-B4
[ ]	R4	100	(brn-blk-brn)	X5-A6
[ ]	R5	10K	(brn-blk-org)	C3-D8
[ ]	R6	1M	(brn-blk-grn)	D10-D11
[ ]	R7	10K	(brn-blk-org)	X11-B11
[ ]	R8	1M	(brn-blk-grn)	X14-A14
[ ]	R9	1M	(brn-blk-grn)	X17-A17
[ ]	R10	1M	(brn-blk-grn)	B21-B22
[ ]	R11	100	(brn-blk-brn)	D33-F33
[ ]	R12	10K	(brn-blk-org)	E20-G20
[ ]	R13	10K	(brn-blk-org)	J15-Y15
[ ]	R14	100K	(brn-blk-yel)	H12-H16
[ ]	R15	10K	(brn-blk-org)	E9-G9
[ ]	R16	4.7K	(yel-vio-red)	E8-G8
[ ]	R17	4.7K	(yel-vio-red)	D3-F4

Bare Wire Jumpers

[ ]	J1	X1-A1
[ ]	J2	C4-D7
[ ]	J3	B15-B16
[ ]	J4	X15-A15
[ ]	J5	J33-Y33
[ ]	J6	J27-Y27
[ ]	J7	E21-F21
[ ]	J8	J20-Y20
[ ]	J9	G16-G17
[ ]	J10	E18-G15
[ ]	J11	I14-I15
[ ]	J12	J9-Y9
[ ]	J13	J8-Y8
[ ]	J14	H7-H8
[ ]	J15	J4-Y4
[ ]	J16	J3-Y3
[ ]	J17	E1-F1

Capacitors

[ ]	C1	100pF	D1-D2
[ ]	C2	0.1	C8-C10
[ ]	C3	0.01	C11-C14
	(install hidden jumper HJ1 [E13-F15] before soldering C4)		
[ ]	C4	0.01	D9-E17
[ ]	C5	10pF	D21-D22
[ ]	C6	6.8µF 10% tantalum	A27-A30 ('+' lead to A30)
[ ]	C7	0.047	I20-I22
[ ]	C8	0.1	H17-H21
[ ]	C9	1µF	E19-F19 ('+' lead to E19)
[ ]	C10	100pF	J14-Y14
[ ]	C11	0.1	I11-I12
[ ]	C12	0.1	E10-F10
[ ]	C13	0.001	E7-F7
[ ]	C14	0.01	E5-F5
[ ]	C15	10µF	E3-F3 ('+' lead to E3)
[ ]	C16	0.1	J2-Y2

Semiconductors

[ ]	D1	1N4001	X33-C33 (banded end to X33)
[ ]	D2	1N914	X13-B14 (banded end to X13)
[ ]	D3	1N914	X18-B17 (banded end to X18)
[ ]	D4	1N34A	I16-Y16 (banded end to I16)
[ ]	D5	1N34A	I17-Y17 (banded end to Y17)
[ ]	Q1	2N5457	drain (D) to A4, source (S) to A3, gate (G) to A2
[ ]	Q2	2N3906	emitter (E) to B6, base (B) to B7, collector (C) to B8
[ ]	Q3	2N3904	emitter (E) to A9, base (B) to A10, collector (C) to A11
[ ]	Q4	2N3906	emitter (E) to D15, base (B) to D14, collector (C) to D13
[ ]	Q5	2N3906	emitter (E) to D16, base (B) to D17, collector (C) to D18
[ ]	Q6	2N3904	emitter (E) to A20, base (B) to A21, collector (C) to A22

Inductor

[ ] L1 0.5H one terminal to C27, other terminal to I27; see text

Trimpot

[ ] R18 50K single-turn trimpot; terminals go in I1-H2-I3

Potentiometers (T=terminal)

[ ] R19 100K audio-taper T1 to G10, T2 to J11, T3 to G14

[ ] R20 10K T1 to X22, T2 to A19, T3 to C22

[ ] R21 100K T1 to T1 of R22 and to E22, T2 to J22, T3 to T3 of R22 and to D20

[ ] R22 100K T2 to B30; T1 & T3 described with R21

Jacks (T=terminal)

[ ] input jack (1/4" 3-terminal/stereo): tip to T2 of S1, ring to negative battery lead, sleeve to Y11

[ ] output jack (1/4" 2-terminal/mono): tip to T5 of S1; sleeve to Y21

Switches (T=terminal)

[ ] S1 (DPDT stomp switch): T1 to G5, T2 to tip of input jack, T3 to T4, T5 to tip of output jack, T6 to J19

9V Battery Leads

[ ] black (negative, –) to ring of input jack

[ ] red (positive, +) to X35

Project No. 289

Tremolo-Matic XVIII

Something a little different.

Circuit Function

Signal path: Axe feed couples directly to the primary winding of T1, a 10K:10K transformer, one of whose secondary outputs ties to the gate of Q1, the other secondary output tying to the gate of Q2. The secondary's center tap ties to the output of a soft triangle oscillator. Q1 and Q2 form a differential amplifier; the 10K winding of T2 serves as the drain loads of both transistors; the center tap of this winding ties to positive supply through supplemental decoupling network R6-C3. Signal output is taken off the 600-ohm winding of T2 and couples directly to the output path. The signal path is noninverting.

Control path: IC1-c, -d, and their associated components form a soft triangle oscillator whose rate varies under control of R14 and whose depth varies with the setting of R15. Trimpot R13 varies the DC offset at the output of IC1-a, which ties to the center tap of T1's secondary winding.

Use

Pots and switch have these functions:

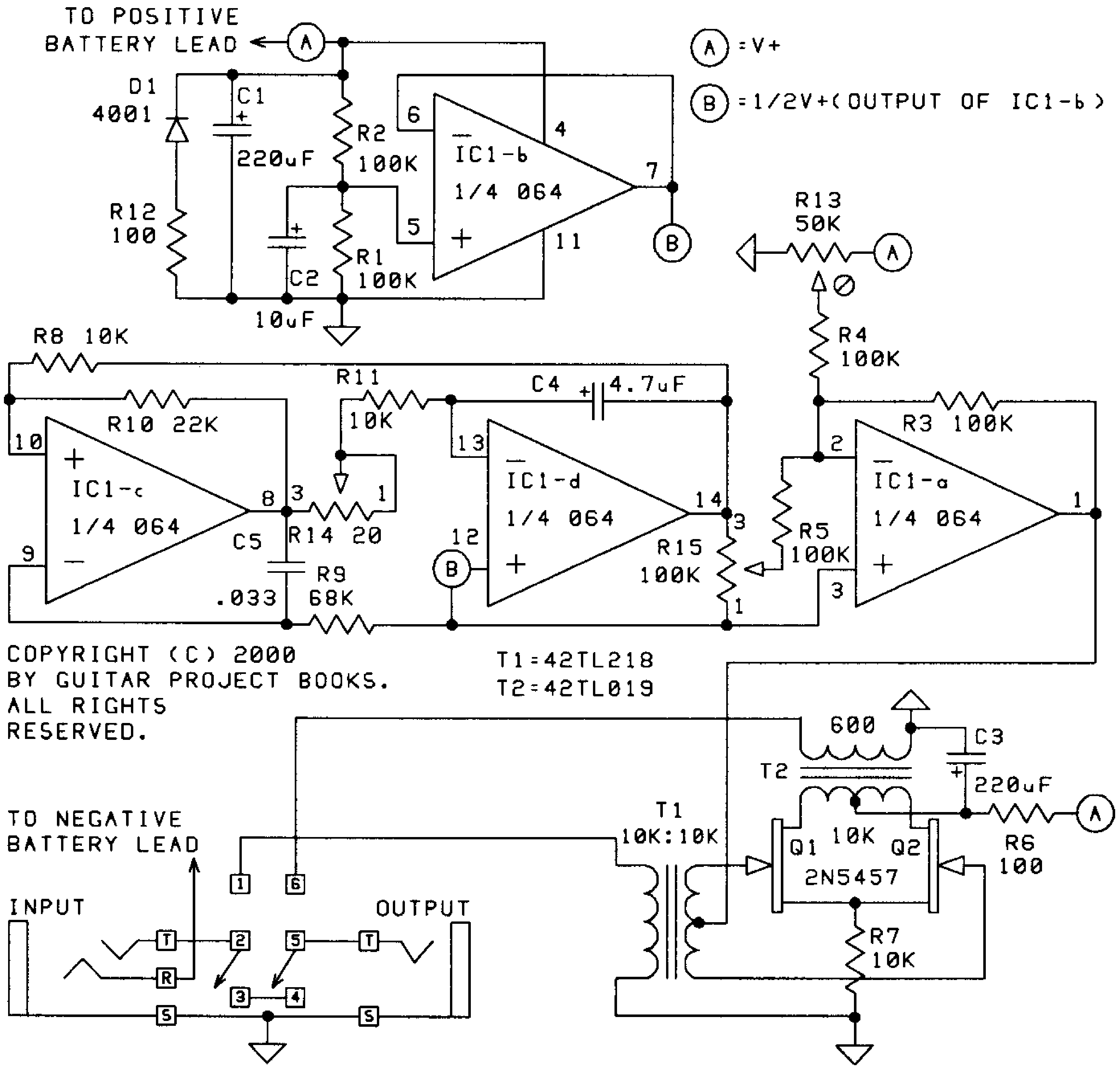
R13	depth trim
R14	tremolo rate
R15	tremolo depth
S1	effect/bypass

Initial settings: center R13, R14, and R15. Connect unit to axe and amp, establish desired listening level. In this state tremolo might of might not be present. Take the depth trimpot R13 through its range to get a feel for the range of sounds possible; set R13 for the most pleasing sound. Take R15 through its range; re-trim if needed to get the desired sound.

Notes

T1 can be oriented either way, as both windings have 10K impedance. T2's 10K winding is marked with a 'P' on the body; if doubt exists as to windings, the winding with the greater resistance is the 10K winding. Both transformers have been left unloaded to facilitate increased gain and ringing. This alters the box's tonal balance toward the mid-treble. TM18's mechanism compares to that found in pentode bias modulators in tube amps, but in this case gate bias modulation results in cyclical distortion.

Tremolo-Matic XVIII schematic.



voltage gain of 100, or 40 dB, from one transistor.

Q. I take it we have to bias the inverting amplifier, just as we did the emitter follower.

A. Yes, and the same methods apply, plus a new one, feedback biasing (Fig. 11–1). The empiric way to find the feedback bias resistance is to wire a 5M or 10M pot between collector and base; trim the pot to give the desired collector voltage, substitute the nearest fixed resistor for the pot.

Q. What's the optimum bias point?

A. In most cases the collector should settle near 3/4V+.

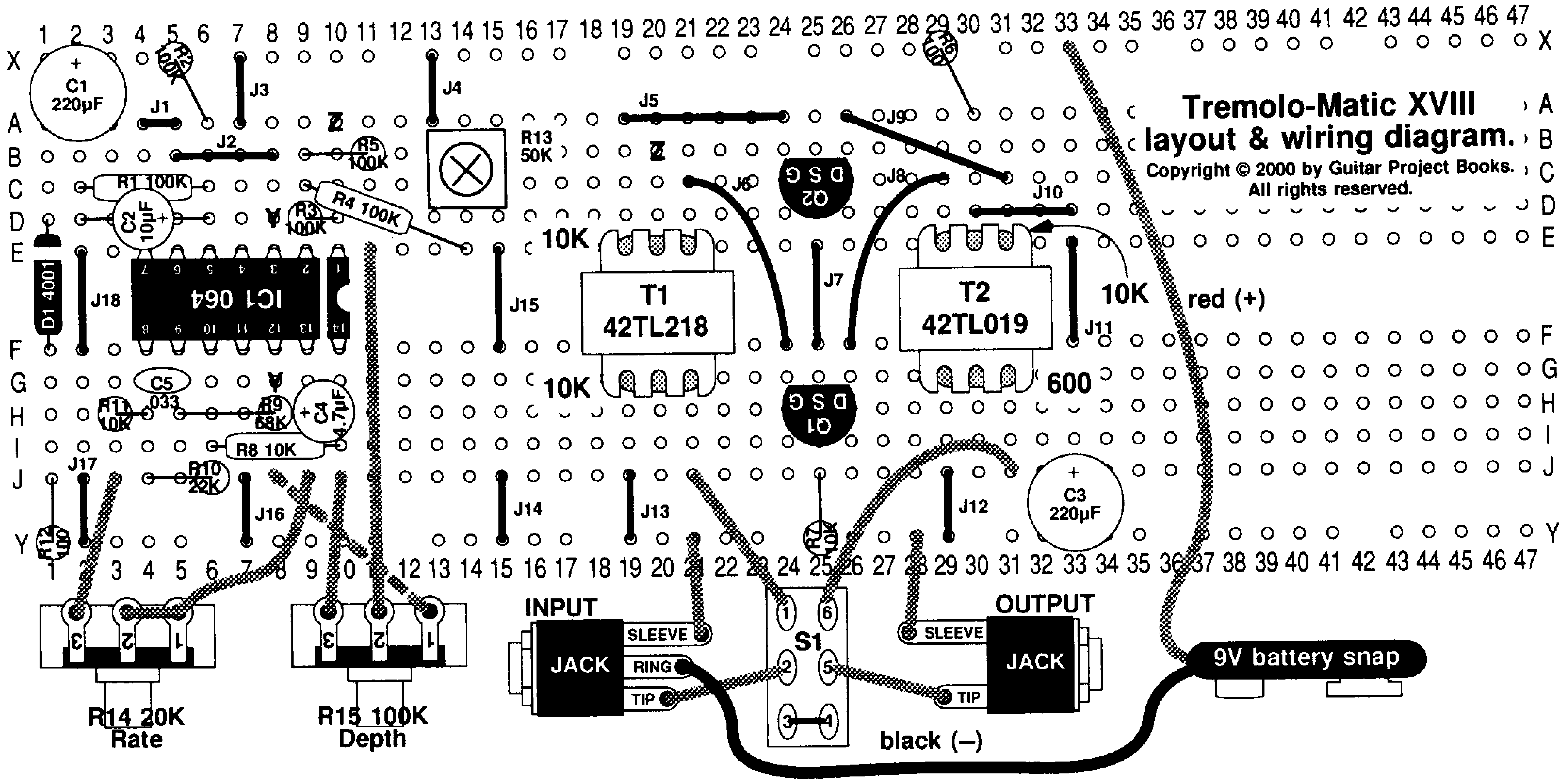
Q. What is the inverting amp's output impedance?

A. It's asymmetrical, like that of an emitter follower. The collector load determines the impedance of the upward swing; the value of the emitter impedance, and to some extent Q1's beta, determines the impedance of the downward swing. Generally, take the value of the collector load as the output impedance.

Q. What good are inverting amps?

A. These are the most useful stompbox functions:

- unity-gain inversion
- inverting boost
- tone networks



Tremolo-Matic XVIII layout & wiring diagram.

Parts List/Soldering Checklist

Circuit Board Radio Shack p/n 276-170; Hosfelt p/n 42-183; or DC Electronics p/n J4-404

IC Sockets

[ ] 14-pin for IC1; pin-1 to E10

Resistors

[ ] R1 100K (brn-blk-yel) C2-C6
[ ] R2 100K (brn-blk-yel) X5-A6
[ ] R3 100K (brn-blk-yel) D9-D10
[ ] R4 100K (brn-blk-yel) C9-E14
[ ] R5 100K ((brn-blk-yel) B9-B11
[ ] R6 100 (brn-blk-brn) X29-A30
[ ] R7 10K (brn-blk-org) J25-Y25
[ ] R8 10K (brn-blk-org) I6-I10
[ ] R9 68K (blu-gry-org) H5-H8
[ ] R10 22K (red-red-org) J4-J6
[ ] R11 10K (brn-blk-org) H3-H4
[ ] R12 100 (brn-blk-brn) J1-Y1

Bare Wire Jumpers

[ ] J1 A4-A5
[ ] J2 B5-B8
[ ] J3 X7-A7
[ ] J4 X13-A13
[ ] J5 A19-A24
[ ] J6 C21-F24
[ ] J7 E25-F25
[ ] J8 C29-F26
[ ] J9 A26-C31
[ ] J10 D30-D33
[ ] J11 E33-F33
[ ] J12 J29-Y29
[ ] J13 J19-Y19
[ ] J14 J15-Y15
[ ] J15 E15-F15
[ ] J16 J7-Y7
[ ] J17 J2-Y2
[ ] J18 E2-F2

Capacitors

[ ] C1 220µF X2-A2 ('+' lead to X2)
[ ] C2 10µF D2-D6 ('+' lead to D6)
[ ] C3 220µF J33-Y33 ('+' lead to J33)
[ ] C4 4.7µF H9-H10 (polarity irrelevant)
[ ] C5 0.033 G4-G5

Flying Jumpers (<u>insulated</u> wire)

[ ] YY D8-G8
[ ] ZZ A10-B20

Semiconductors

[ ] D1 1N4001 D1-F1 (banded end to D1)
[ ] IC1 TL064 quad op amp; pin-1 to E10
[ ] Q1 2N5457gate (G) to H24, source (S) to H25, drain (D) to H26
[ ] Q2 2N5457gate (G) to C24, source (S) to C25, drain (D) to C26

Trimpot

[ ] R13 50K single turn trimpot; terminals go in C13-B14-C15

Transformers

[ ] T1 10K:10K Mouser Electronics p/n 42TL218; pins go in E19-20-21 and G19-20-21; can be oriented either way
[ ] T2 10K:600 Mouser Electronics p/n 42TL019; 10K winding pins go in E29-30-31; 600-ohm winding pins go in G29-30-31

Potentiometers (T=terminal)

[ ] R14 20K or 25K T1 to T2 and to J9, T3 to J3
[ ] R15 100K T1 to J8, T2 to E11, T3 to J10

Jacks (T=terminal)

[ ] input jack (1/4" 3-terminal/stereo): tip to T2 of S1, ring to negative (–) battery lead, sleeve to Y21
[ ] output jack (1/4" 2-terminal/mono): tip to T5 of S1, sleeve to Y28

Switches (T=terminal)

[ ] S1 (DPDT stomp switch): T1 to J21; T2 to tip of input jack; T3 to T4; T5 to tip of output jack; T6 J31

9V Battery Leads

[ ] negative (black, –) to ring of input jack
[ ] red (positive, +) to X33

- phase splitting/phase shifting
- distortion
- LED drivers

Q. What is "unity-gain inversion"?

A. Inverting the signal with a gain of 1. It's valuable because circuits often demand an inverting step to keep a noninverting signal path. Unlike an emitter follower, whose headroom approaches 90% of the supply voltage, unity-gain inversion is limited to less than 50% of the available voltage.

Q. Why?

A. Check out Fig. 10. Because emitter resistance equals collector resistance, the collector can never swing below 1/2V+. This makes 3/4V+ the optimum bias point.

A unity-gain inverter also supplies an equal but noninverted output from the emitter. This function compares to the phase splitter found in many tube amps. It's useful to generate a balanced signal from an unbalanced one, and as a variable phase-shift network in vibrato and phase boxes.

The inverting amplifier can alter tone in many ways (Fig. 11–1, 2, 3, & 5). Our initial model assumed pure resistance tied to emitter and collector. In fact, simple and compound impedances can be tied to these points, giving boost, cut, or mixed functions.

Driving one or more inverting gain stages to clipping is a common

Project No. G290

Boost-O-Matic IV

Discrete-FET treble booster.

Circuit Function

Axe feed couples through R10-C2 to Q1, a FET configured as an inverting amplifier whose gain and frequency contour depends on the setting of R12-a; Q1's output couples through C5 to Q1, configured as Q1 but for use of 10K audio-taper pot for Q2's drain resistor. Q2's treble gain depends on the setting of R12-b. Signal output is taken off the wiper of R13, thence through C8-R4 to the output path. The net signal path is noninverting.

Use

Pots and switch have these functions:

R11	bias trim
R12	treble boost
R13	output level
S1	effect/bypass

Initial settings: R11 centered, R12, R13 fully CCW; S1 effect in. Connect unit to axe whose volume pot is turned all the way down; do not connect unit to amp at this point. Connect voltmeter leads to jumpers J1 and J10; this measures the positive supply voltage. Multiply this voltage by 0.75, then trim R11 to give this voltage at jumper J2, the drain of Q1.

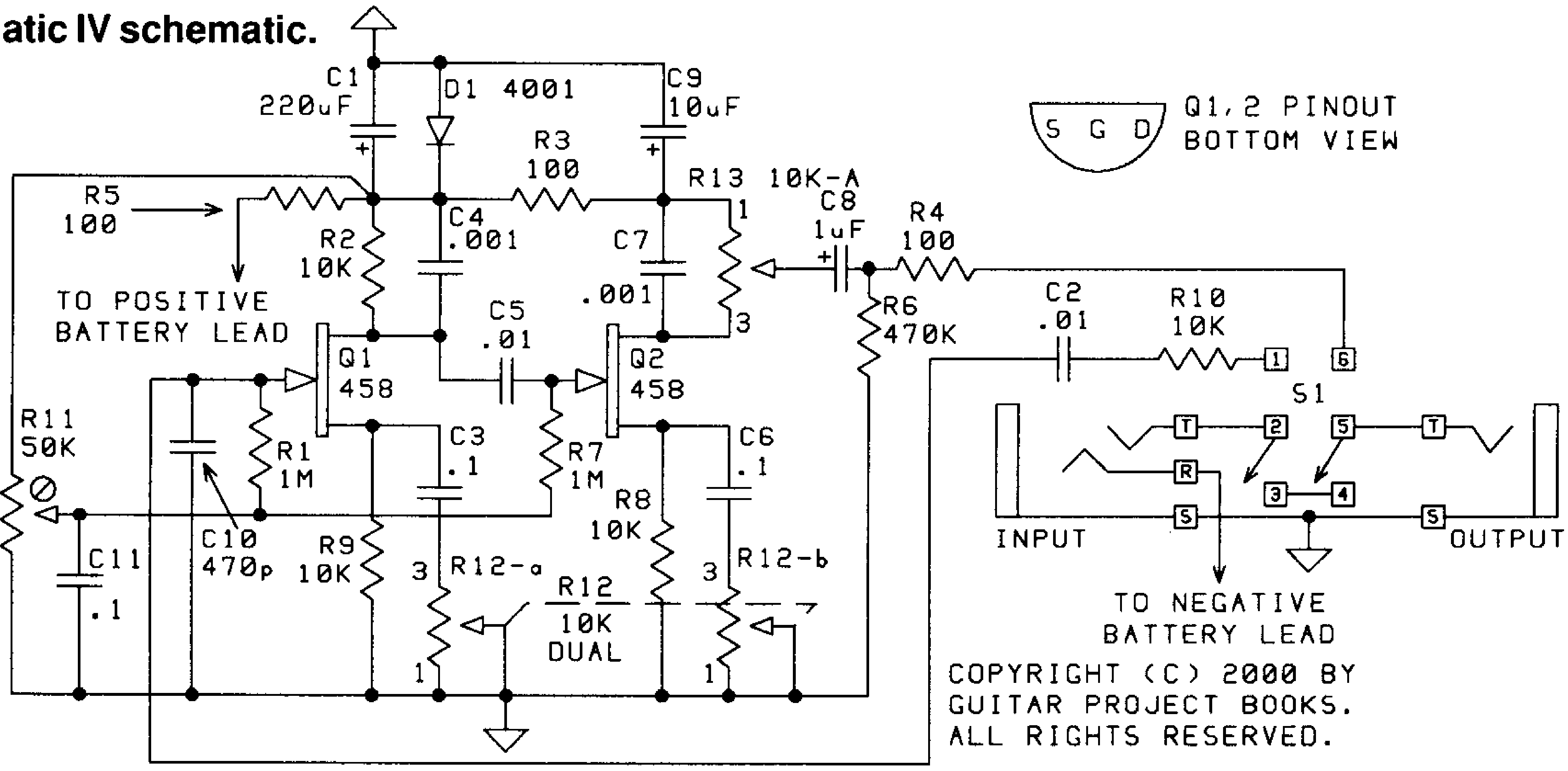
Next, connect unit to amp, establish desired listening level. Take treble boost control through its range and note the effect on sound.

Notes

The NTE458 is a high-transconductance FET, which gives higher gain than do medium- and low-transconductance FETs. Here gain tops out at about 40 dB at 8 KHz. Although distortion supervenes at the higher gain levels, FETs allow aggressive boost without sounding harsh.

Because the FETs' frequency response extends well into VHF, C4, C7, and C10 are used to limit the unit's frequency response. A metal case is recommended.

Boost-O-Matic IV schematic.



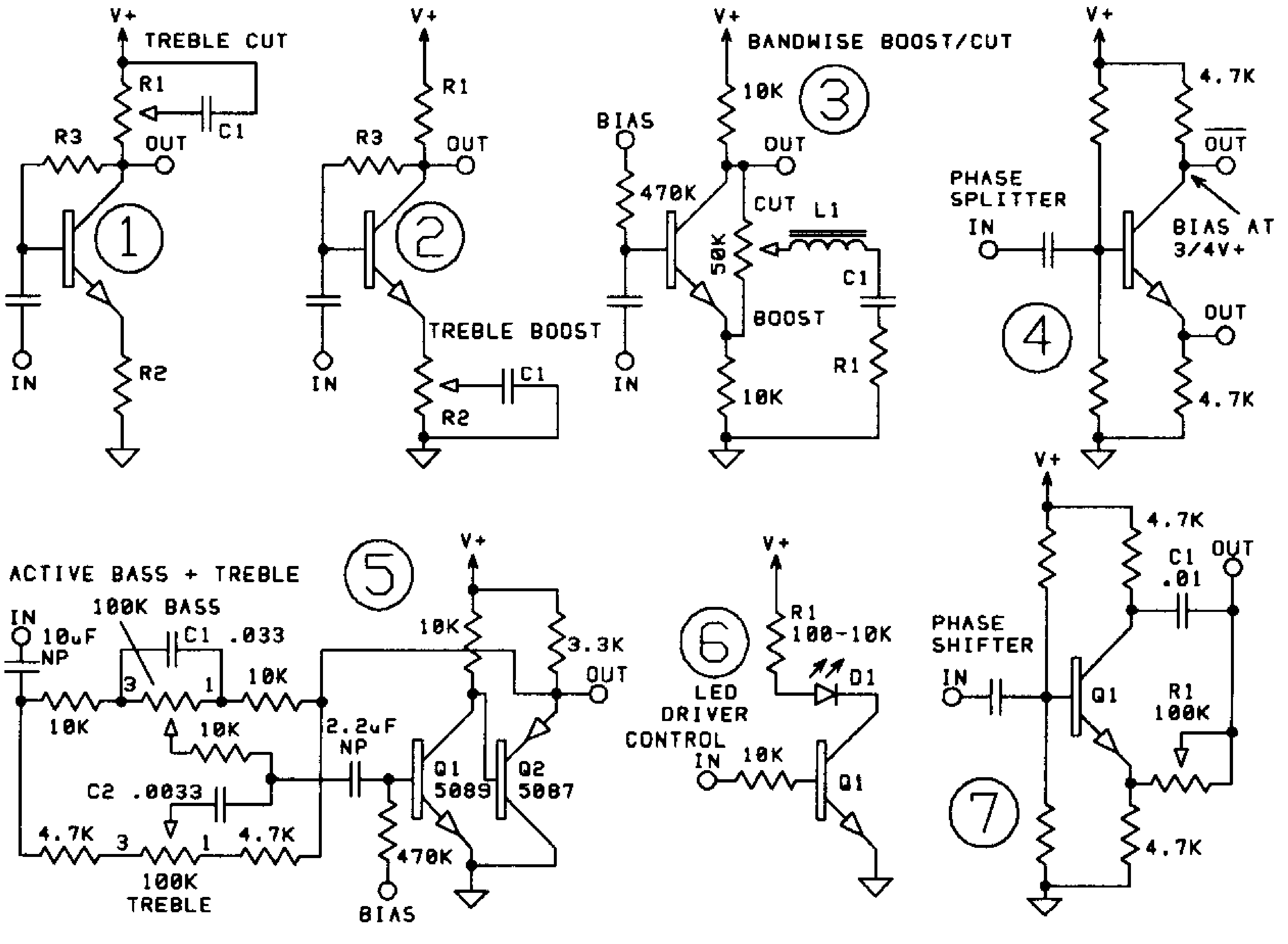
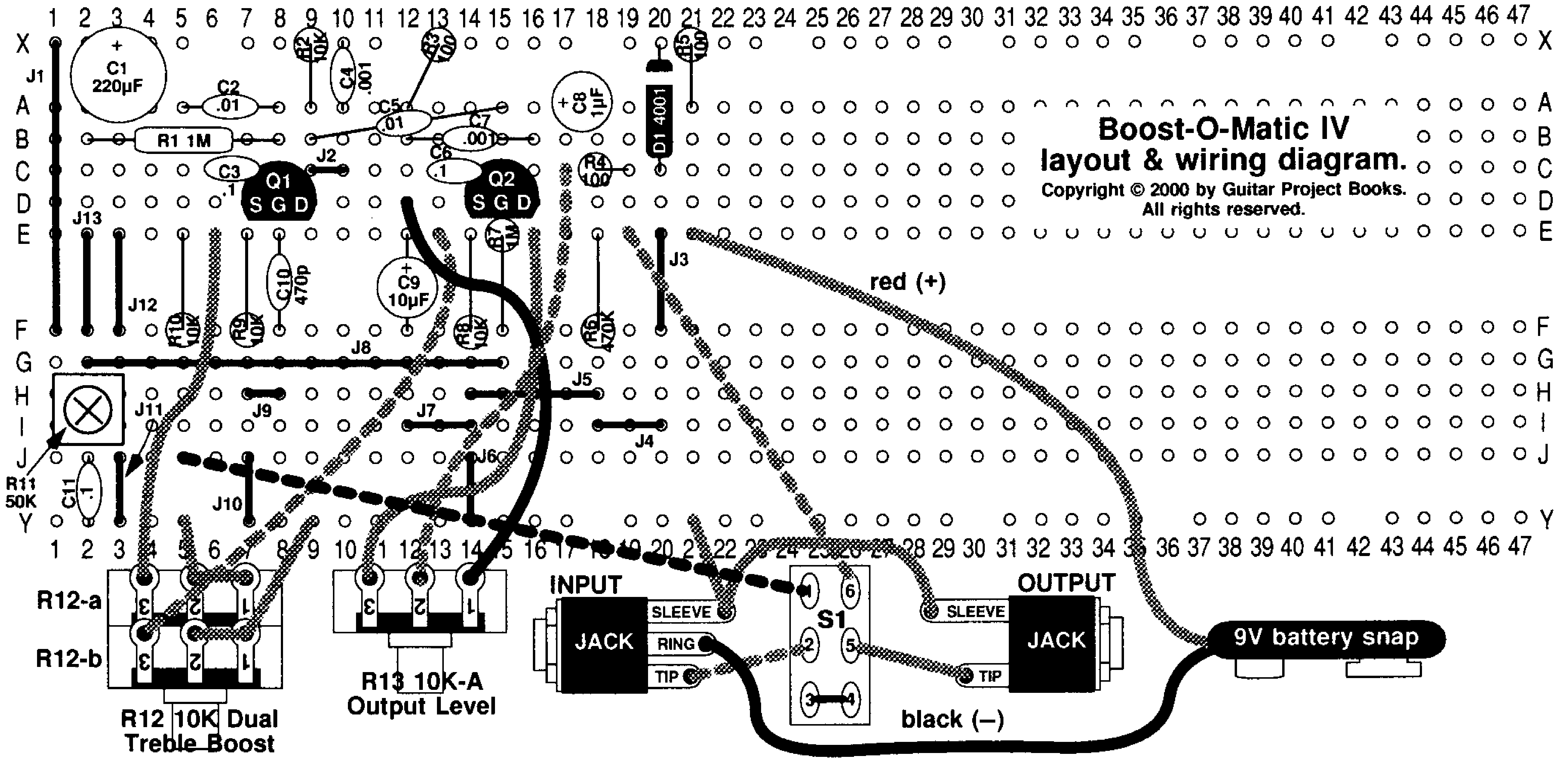


Fig. 11. A few examples of what the one-transistor inverting amp can do in a stompbox. 1—Substituting a potentiometer for collector load resistor enables treble cut, variable from none to severe; choice of C1 and R1-R2 determines range. 2—Same concept adapted to treble boost, variable from none to extreme; frequencies covered depend on relative values; stability may demand a small cap in parallel with collector resistor. Q1 and Q2 are biased by negative feedback off the collector (R3). This partly compensates for differences is transistor beta and changes in supply voltage. 3—Bandwise boost cut uses series resonance formed by L1-C1; R1 limits maximum boost/cut. 4—Phase splitter provides unity-gain, in-phase and antiphase outputs from one input; could drive balanced line directly. 5—Active bass & treble circuit uses Q1 as gain block, Q2 as buffer to reduce loading effects with tone shaping network. Input impedance is low enough that it, too, should be buffered. Change C1 and C2 to change frequency range of bass & treble pots. 6—LED driver differs from follower driver in that Q1 applies gain, so very little voltage will be needed to turn Q1 on. 7—Variable phase shifter. In practice, R1 is made an LDR-based optocoupler; output needs buffering.



Parts List/Soldering Checklist

Circuit Board Radio Shack p/n 276-170; Hosfelt p/n 42-183; or DC Electronics p/n J4-404

Resistors

[ ] R1 1M (brn-blk-grn) B2-B8
[ ] R2 10K (brn-blk-org) X9-A9
[ ] R3 100 (brn-blk-brn) X13-A12
[ ] R4 100 (brn-blk-brn) C18-C19
[ ] R5 100 (brn-blk-brn) X21-A21
[ ] R6 470K (yel-vio-yel) E18-F18
[ ] R7 1M (brn-blk-grn) E15-F15
[ ] R8 10K (brn-blk-org) E14-F14
[ ] R9 10K (brn-blk-org) E7-F7
[ ] R10 10K (brn-blk-org) E5-F5

Bare Wire Jumpers

[ ] J1 X1-F1
[ ] J2 C9-C10
[ ] J3 E20-F20
[ ] J4 I18-I20
[ ] J5 H14-H18
[ ] J6 J14-Y14
[ ] J7 I12-I14
[ ] J8 G2-G15
[ ] J9 H7-H8
[ ] J10 J7-Y7
[ ] J11 J3-Y3
[ ] J12 E3-F3
[ ] J13 E2-F2

Capacitors

[ ] C1 220µF X3-A3 ('+' lead to X3)
[ ] C2 0.01 A5-A8
[ ] C3 0.1 C6-C7
[ ] C4 0.001 X10-A10
[ ] C5 0.01 B9-A15
[ ] C6 0.1 C13-C14
[ ] C7 0.001 B12-B16
[ ] C8 1µF A17-A18 ('+' lead to A17)
[ ] C9 10µF E12-F12 ('+' lead to E12)
[ ] C10 470pF E8-F8
[ ] C11 0.1 J2-Y2

Semiconductors

[ ] D1 1N4001 X20-C20 (banded end to X20)
[ ] Q1 NTE458 FET source (S) to D7, gate (G) to D8, drain (D) to D9
[ ] Q2 NTE458 FET source (S) to D14, gate (G) to D15, drain (D) to D16

Trimpot

[ ] R11 50K single turn trimpot; terminals go in I1-H2-I3

Potentiometers (T=terminal)

R12 10K dual pot
[ ] R12-a T1 to T2 and to Y5, T3 to E6
[ ] R12-b T1 to T2 and to Y9, T3 to E13
[ ] R13 10K audio taper T1 to D12, T2 to C17, T3 to E16

Jacks (T=terminal)

[ ] input jack (1/4" 3-terminal/stereo): tip to T2 of S1; ring to negative (–) battery lead, sleeve to Y21 and to sleeve of output jack
[ ] output jack (1/4" 2-terminal/mono): tip to T5 of S1, sleeve to sleeve of input jack

Switches (T=terminal)

[ ] S1 (DPDT stomp switch): T1 to J5, T2 to tip of input jack, T3 to T4, T5 to tip of output jack, T6 to E19

9V Battery Leads

[ ] negative (black, –) lead to ring of input jack
[ ] positive (red, +) lead to E21

stompbox distortion mode. Gain, frequency contour, and the resting bias point control the harmonic profile.

Finally, like a follower, an inverting amp can serve as an LED driver. The difference is that gain makes the amp respond more vigorously to the control signal.

Q. What's an LED driver?

A. A circuit that controls the flow of current through an LED.

Q. Why not drive the LED directly off the primary controlling voltage?

A. In some applications you can. But an LED typically draws a milliamp or more, which is enough to load some circuit segments. The driver isolates the load from the control source.

Field-Effect Transistors

Q. I believe we have enough information to bring field-effect transistors into the picture.

A. A FET's three terminals are called drain, source, and gate, corresponding to a BPT's collector, emitter, and base. While the drain and source terminals are interchangeable, it's customary to call the terminal tied to V+ the drain, and the terminal tied to ground or V– the source. We'll speak initially only of N-channel FETs, which correspond to NPN BPTs.

FETs respond to voltage rather than current. Application of a voltage to the gate alters the resistance between drain and source, so our FET model is a voltage controlled resistor. Because the gate is practically an open circuit, no significant current flows into it.

FETs come in fewer part numbers than BPTs. For every 10 different BPTs, you might find one or two FETs.

Q. Do FETs have a beta?

A. They have a similar property, called transconductance. This can be viewed as the change in drain-source resistance produced per unit of voltage applied to the gate. Common FETs cannot conduct as hard as BPTs,

Project No. G291

Split-O-Matic VI

Noninverting quad splitter features high-impedance input, easily drives four 600-ohm loads simultaneously, with low distortion and voltage gain of about 0.95.

Circuit Function

Audio feed couples through R15-C1 to the bases of Q1-Q2, which form a bias network for driver-transistor pairs Q3-4, Q5-6, Q7-8, and Q9-10. Each driver's output is taken at the juncture of 10-ohm emitter resistors, and couples through a 10µF cap to an output.

R18 allows fine tuning of the output offset.

Use

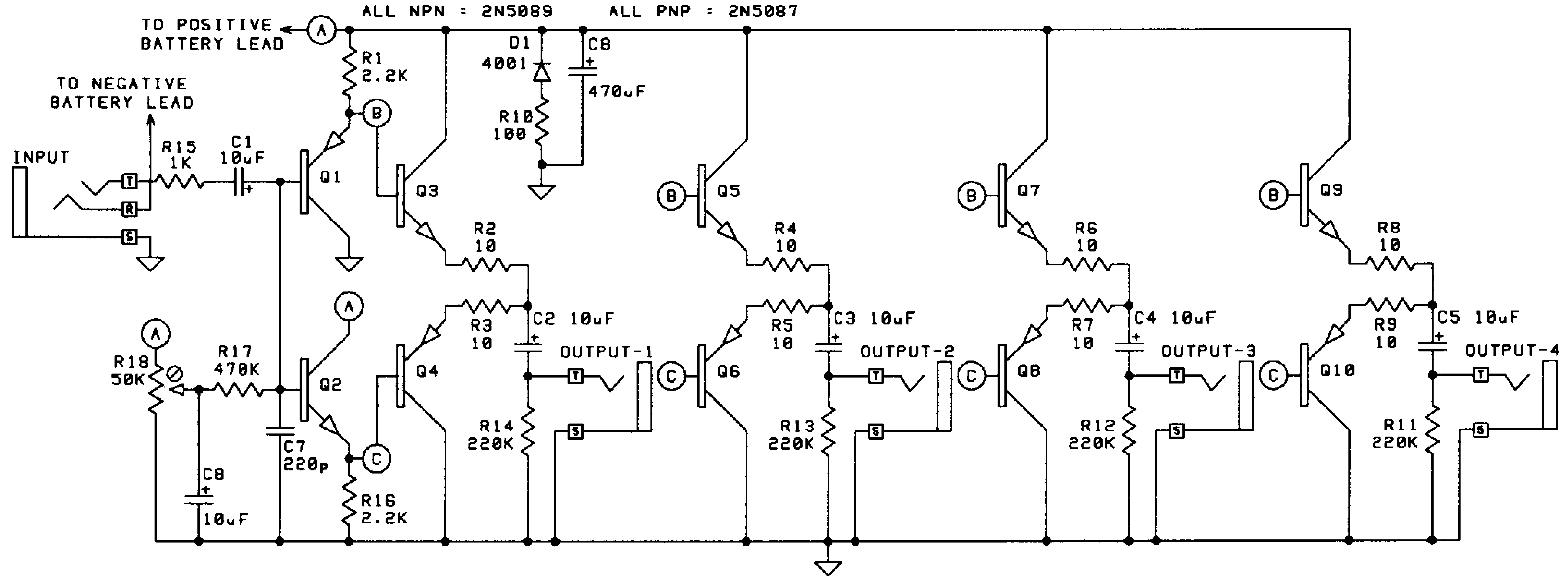
Center R18, then connect a 9V battery and insert a plug into the input jack. Measure the battery voltage; trim R18 to give 1/2V+ at the juncture of R2 and R3, most conveniently accessible as the positive lead of C2.

Use is self-explanatory.

Notes

Running @ 7.5V the prototype drew ~6 ma unloaded, ~10ma with all four outputs driving individual 470-ohm loads. Voltage gain under this load was ~0.95 with no crossover distortion. Undistorted headroom at this supply voltage is about 5V peak. Response is essentially flat over the audio spectrum.

Split-O-Matic VI schematic.



so we can't get as much gain from a single FET as from a single BPT.

Q. What can I build with FETs?

A. Followers and inverting amplifiers, very similar to the BPT circuits just covered. Fig. 12 shows a few examples. Also, FETs form the mainstay of electronic switching in stompboxes [*FET switches are covered in depth in Vol. 5, No. 4—Ed.*].

Q. How do I bias a FET?

A. Most methods used for BPTs apply to FETs. In practice, the bias resistor is usually a million ohms or more. The value of this resistor sets the input impedance, because the gate itself is practically an open circuit. It's often best to individualize the bias, because individual FETs of the same number differ in transconductance, just as BPTs differ in beta.

Noninverting Amplifiers

Q. What about noninverting amps?

A. These are necessarily two-stage devices; two inverting amps in series, in fact. Fig. 13 shows a couple of examples.

Q. Why do I need noninverting amps? Why can't I use inverting amps all the time?

A. Noninverting gain stages simplify some circuits, because it's desirable

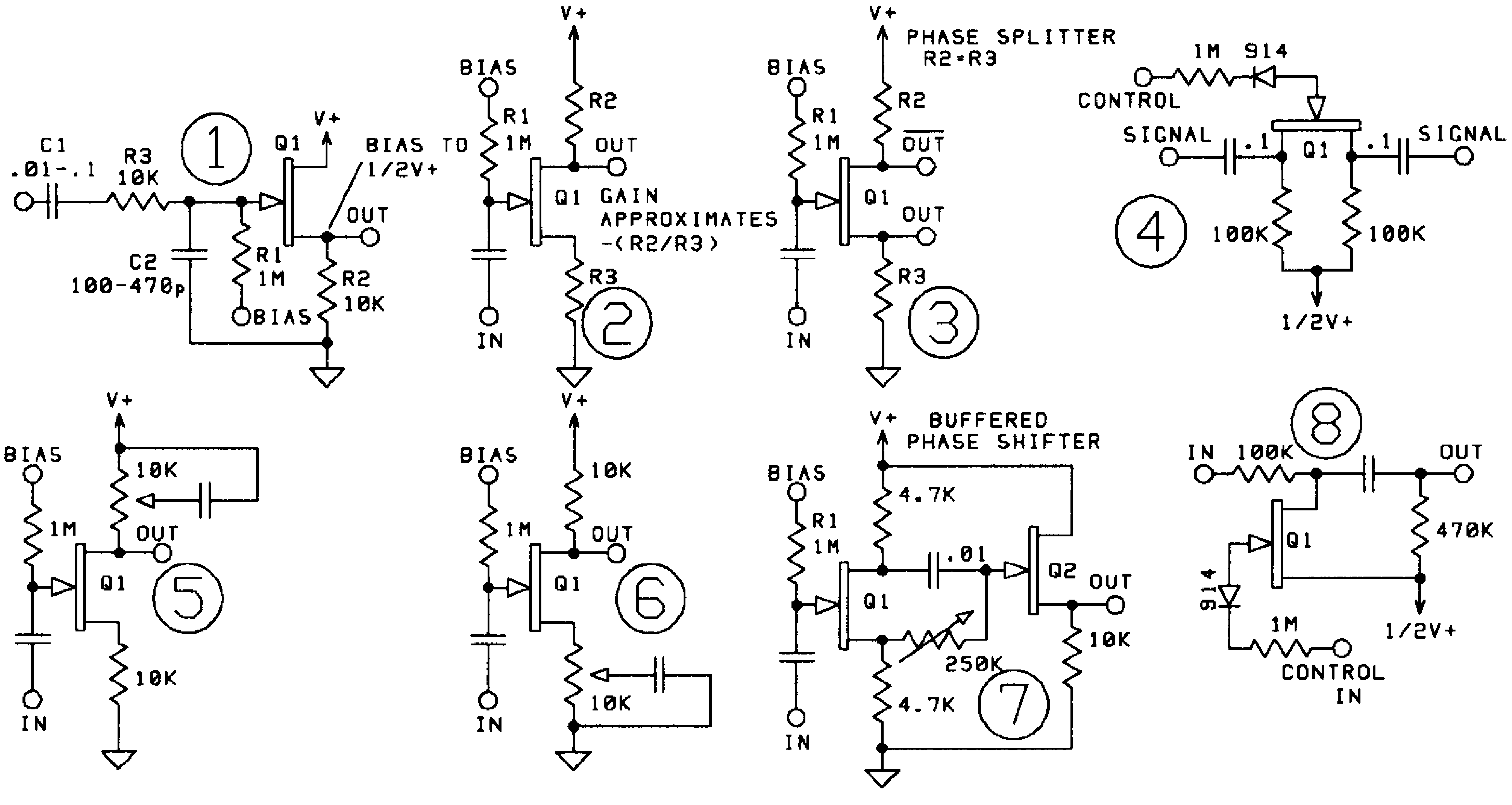
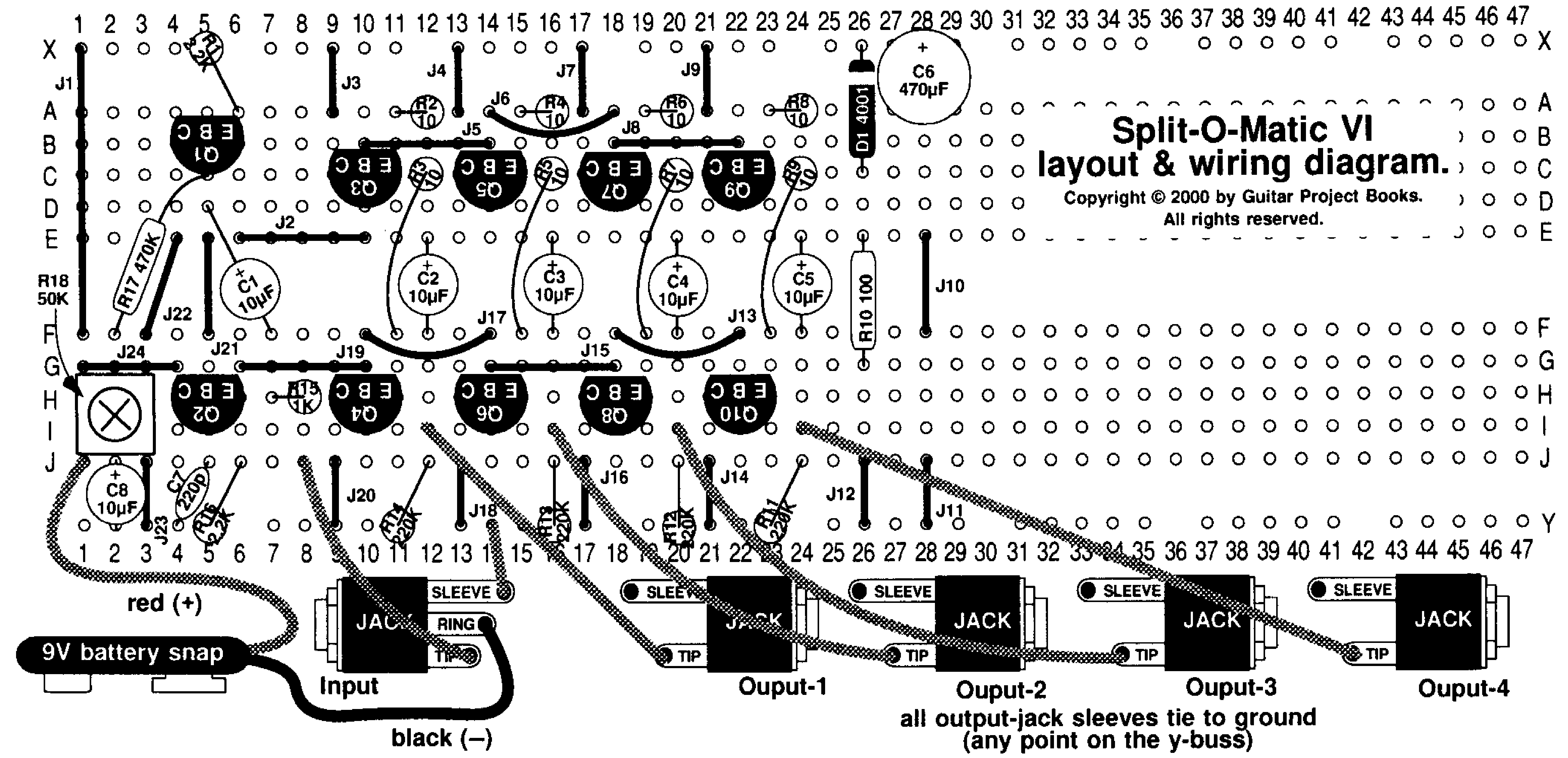


Fig.12. A few stompbox applications for field effect transistors. 1—FET source follower performs same role as BPT emitter follower. Many input stages include R3-C2 as an RF shunt network. 2—FET common-source amp acts similarly to BPT common-emitter amp; FET's lower transconductance means less maximum gain per stage than BPT. 3—FET phase splitter. 4—FET used as bidirectional signal switch. When control input is low, FET pinches off. When control input is high, D-S path acts as a few hundred ohms of resistance. 5—FET common-source amp with variable treble cut. 6—Same as #5, with variable treble boost. 7—Buffered FET phase shifter. 8—FET used as shunt switch.



Split-O-Matic VI layout & wiring diagram.

Parts List/Soldering Checklist

Circuit board Radio Shack p/n 276-170; Hosfelt p/n 42-183; or DC Electronics p/n J4-404

Resistors

[ ] R1	2.2K	(red-red-red)	X5-A6
[ ] R2	10	(brn-blk-blk)	A11-A12
[ ] R3	10	(brn-blk-blk)	C12-F11
[ ] R4	10	(brn-blk-blk)	A15-A16
[ ] R5	10	(brn-blk-blk)	C16-F15
[ ] R6	10	(brn-blk-blk)	A19-A20
[ ] R7	10	(brn-blk-blk)	C20-F19
[ ] R8	10	(brn-blk-blk)	A23-A24
[ ] R9	10	(brn-blk-blk)	C24-F23
[ ] R10	100	(brn-blk-brn)	E26-G26
[ ] R11	220K	(red-red-yel)	J24-Y23
[ ] R12	220K	(red-red-yel)	J20-Y20
[ ] R13	220K	(red-red-yel)	J16-Y16
[ ] R14	220K	(red-red-yel)	J12-Y11
[ ] R15	1K	(brn-blk-red)	H7-H8
[ ] R16	2.2K	(red-red-red)	J6-Y5
[ ] R17	470K	(yel-vio-yel)	C5-F2

Bare Wire Jumpers

[ ] J1	X1-F1
[ ] J2	E6-E10
[ ] J3	X9-A9
[ ] J4	X13-A13
[ ] J5	B10-B14
[ ] J6	A14-A18
[ ] J7	X17-A17
[ ] J8	B18-B22
[ ] J9	X21-A21
[ ] J10	E28-F28
[ ] J11	J28-Y28
[ ] J12	J26-Y26
[ ] J13	F18-F22
[ ] J14	J21-Y21
[ ] J15	G14-G18
[ ] J16	J17-Y17
[ ] J17	F10-F14
[ ] J18	J13-Y13
[ ] J19	G6-G10
[ ] J20	J9-Y9
[ ] J21	E5-F5
[ ] J22	E4-F3
[ ] J23	J3-Y3
[ ] J24	G1-G4

Capacitors

[ ] C1	10µF	D5-F7 ('+' lead to D5)
[ ] C2	10µF	E12-F12 ('+' lead to E12)
[ ] C3	10µF	E16-F16 ('+' lead to E16)
[ ] C4	10µF	E20-F20 ('+' lead to E20)
[ ] C5	10µF	E24-F24 ('+' lead to E24)
[ ] C6	470µF	X28-A28 ('+' lead to X28)
[ ] C7	220pF	J5-Y4
[ ] C8	10µF	J2-Y2 ('+' lead to J2)

Semiconductors

[ ] D1 1N4001 X26-C26 (banded end to X26)

[ ] Q1 2N5087 collector (C) to B4, base (B) to B5, emitter (E) to B6

[ ] Q2 2N5089 collector (C) to H4, base (B) to H5, emitter (E) to H6

[ ] Q3 2N5089 collector (C) to C9, base (B) to C10, emitter (E) to C11

[ ] Q4 2N5087 collector (C) to H9, base (B) to H10, emitter (E) to H11

[ ] Q5 2N5089 collector (C) to C13, base (B) to C14, emitter (E) to C15

[ ] Q6 2N5087 collector (C) to H13, base (B) to H14, emitter (E) to H15

[ ] Q7 2N5089 collector (C) to C17, base (B) to C18, emitter (E) to C19

[ ] Q8 2N5087 collector (C) to H17, base (B) to H18, emitter (E) to H19

[ ] Q9 2N5089 collector (C) to C21, base (B) to C22, emitter (E) to C23

[ ] Q10 2N5087 collector (C) to H21, base (B) to H22, emitter (E) to H23

Trimpot

[ ] R18 50K single-turn trimpot; terminals go in I1-H2-I3

Jacks (T=terminal)

[ ] input jack (1/4" 3-terminal/stereo): tip to J8, ring to negative (–) battery lead, sleeve to Y14

[ ] output-1 jack (1/4" 2-terminal/mono): tip to I12, sleeve to any point on the Y-buss

[ ] output-2 jack (1/4" 2-terminal/mono): tip to I16, sleeve to any point on the Y-buss

[ ] output-3 jack (1/4" 2-terminal/mono): tip to I20, sleeve to any point on the Y-buss

[ ] output-4 jack (1/4" 2-terminal/mono): tip to I24, sleeve to any point on the Y-buss

9V Battery Leads

[ ] negative (black, –) lead to input jack ring

[ ] positive (red, +) lead to J1

that the stompbox's net signal path not invert.

Q. What is "net signal path"?

A. Signal path taken from input to output. The signal may undergo several inversions inside the box, but the final inversion must return the signal to its original polarity.

Q. Why shouldn't the box invert?

A. Stompbox signals often get split and remixed. Mixing inverted and noninverted signals results in cancellation. The signal level drops and sounds hollow and thin.

Discrete-Transistor Operational Amplifiers

Q. What exactly is an op amp?

A. An operational amplifier is a gain block that has an inverting input, a noninverting input, and an output. The perfect op amp exhibits infinite input impedance, zero output impedance, and infinite gain. Real-world op

Project No. G292

Tremolo-Matic XXII

Variable-waveform tremolo uses discrete-transistor VCA.

Circuit Function

Signal path: Axe feed couples through C5-R9 to Q1, an inverting amplifier with bass & midrange gain of 1, plus ~25 dB of treble boost that kicks in above ~300 Hz. Q1's output couples through C10-R22 to a VCA made up of Q2-6 (matched transistors Q2–5 are contained in IC3). VCA output is taken at the collector of Q6, coupling through C8 to a de-emphasis network comprised of R14-15-16 and C9. The nominal signal path is noninverting.

Control path: IC-c, -d, and their associated components form an oscillator whose rate varies under control of R24, and whose waveform shape varies under control of R35. When S2 selects triangle, R35 varies shape from ramp to triangle to negative ramp; when S2 selects squarewave, R35 varies the duty cycle from ~15% to ~85%. R36 controls the amplitude of the voltage feeding R8, which varies VCA gain from 0 to ~1.

Use

Switches and pots have these functions:

R33	feedthrough trim
R34	tremolo rate
R35	waveform shape/duty cycle
R36	tremolo depth
S1	effect/bypass
S2	waveform select triangle/squarewave

Initial settings: R34, R35, R36 fully CW; S1 effect in, S2 triangle. Connect unit to axe whose volume is turned all the way down; and to amp whose volume is turned all the way down. Slowly advance amp volume until feedthrough pulses are heard. Trim R33 for minimum feedthrough.

Next, center R34-35-36 and establish a desired listening level. Take the controls through their ranges and note the sounds possible; toggle S2 to square and repeat the checkout sequence.

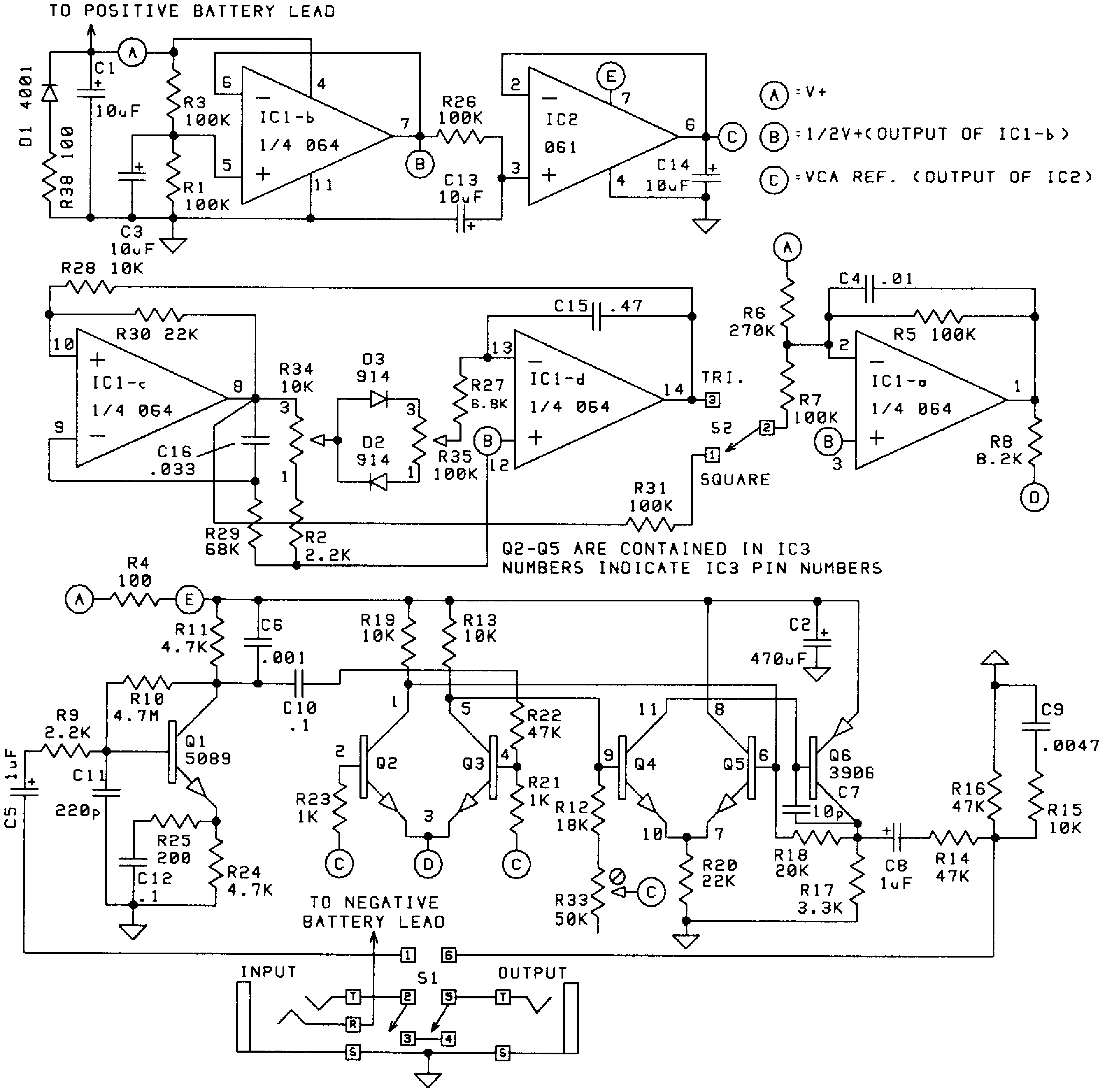
Notes

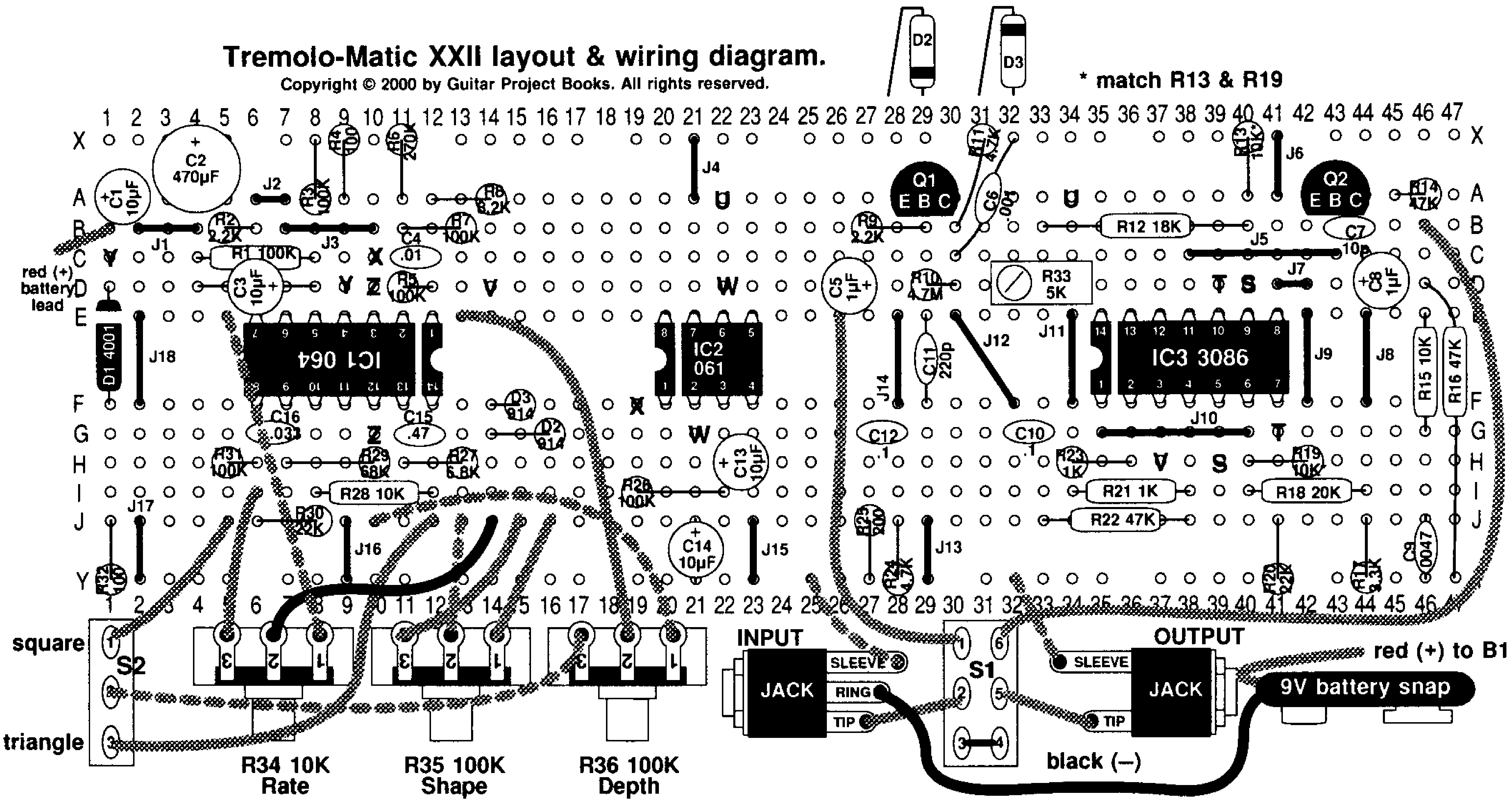
This box has deliberately been given a bright tone, plus smooth distortion that's almost imperceptible at low input levels.

Close matching of R13 and R19 helps feedthrough trim ignore changes in supply voltage. Choose 20 or so 10K resistors, measure each on a digital ohmmeter; select the pair that match best, use these for R13 and R19.

The prototype drew less than 3 ma from a 7.5V nicad.

Tremolo-Matic XXII schematic.





Tremolo-Matic XXII layout & wiring diagram.

Parts List/Soldering Checklist

Circuit Board Radio Shack p/n 276-170; Hosfelt p/n 42-183; or DC Electronics p/n J4-404

IC Sockets

- [ ] 14-pin for IC1; pin-1 to E12
- [ ] 8-pin for IC2; pin-1 to F20
- [ ] 14-pin for IC3; pin-1 to F35

Resistors

[ ]	R1	100K	(brn-blk-yel)	C4-C8
[ ]	R2	2.2K	(red-red-red)	B5-B6
[ ]	R3	100K	(brn-blk-yel)	X8-A8
[ ]	R4	100	(brn-blk-brn)	X9-A9
[ ]	R5	100K	(brn-blk-yel)	D11-D12
[ ]	R6	270K	(red-vio-yel)	X11-A11
[ ]	R7	100K	(brn-blk-yel)	B11-B13
[ ]	R8	8.2K	(gry-red-red)	A12-A14
[ ]	R9	2.2K	(red-red-red)	B27-B29
[ ]	R10	4.7M	(yel-vio-grn)	D29-D30
[ ]	R11	4.7K	(yel-vio-red)	X31-B30
[ ]	R12	18K	(brn-gry-org)	B33-B40
[ ]	R13	10K	(brn-blk-org)	X40-A40
	[match R13 and R19]			
[ ]	R14	47K	(yel-vio-org)	A45-A46
[ ]	R15	10K	(brn-blk-org)	E46-G46
[ ]	R16	47K	(yel-vio-org)	D46-Y47
[ ]	R17	3.3K	(org-org-red)	J44-Y44
[ ]	R18	20K	(red-blk-org)	I40-I44
[ ]	R19	10K	(brn-blk-org)	H40-H42
[ ]	R20	22K	(red-red-org)	J41-Y41
[ ]	R21	1K	(brn-blk-red)	I34-I38
[ ]	R22	47K	(yel-vio-org)	J33-J38
[ ]	R23	1K	(brn-blk-red)	H34-H36
[ ]	R24	4.7K	(yel-vio-red)	J28-Y28
[ ]	R25	200	(red-blk-brn)	J27-Y27
[ ]	R26	100K	(brn-blk-yel)	I19-I22
[ ]	R27	6.8K	(blu-gry-red)	H11-H13
[ ]	R28	10K	(brn-blk-org)	I8-I12
[ ]	R29	68K	(blu-gry-org)	H7-H10
[ ]	R30	22K	(red-red-org)	J6-J8
[ ]	R31	100K	(brn-blk-yel)	H5-H6
[ ]	R32	100	(brn-blk-brn)	J1-Y1

Bare Wire Jumpers

[ ]	J1	B2-B4
[ ]	J2	A6-A7
[ ]	J3	B7-B10
[ ]	J4	X21-A21
[ ]	J5	C38-C43
[ ]	J6	X41-A41
[ ]	J7	D41-D42
[ ]	J8	E44-F44
[ ]	J9	E42-F42
[ ]	J10	G35-G40
[ ]	J11	E34-F34
[ ]	J12	E30-F32
[ ]	J13	J29-Y29
[ ]	J14	E28-F28
[ ]	J15	J23-Y23
[ ]	J16	J9-Y9
[ ]	J17	J2-Y2
[ ]	J18	E2-F2

Capacitors

[ ]	C1	10µF	A1-A2 ('+' lead to A1)
[ ]	C2	470µF	X4-A4 ('+' lead to X4)
[ ]	C3	10µF	D4-D8 ('+' lead to D8)
[ ]	C4	0.01	C11-C12
[ ]	C5	1µF	D26-D27 ('+' lead to D27)
[ ]	C6	0.001	X32-C30
[ ]	C7	10pF	B43-B44
[ ]	C8	1µF	D44-D45 ('+' lead to D44)
[ ]	C9	0.0047	J46-Y46
[ ]	C10	0.1	G32-G33
[ ]	C11	220pF	E29-F29
[ ]	C12	0.1	G27-G28
[ ]	C13	10µF	H22-H23 ('+' lead to H22)
[ ]	C14	10µF	J21-Y21 ('+' lead to J21)
[ ]	C15	0.47	G11-G12
[ ]	C16	0.033	G6-G7

Flying Jumpers (<u>insulated</u> wire)

[ ]	SS	D40-H39
[ ]	TT	D39-G41
[ ]	UU	A22-A34
[ ]	VV	D14-H37
[ ]	WW	D22-G21
[ ]	XX	C10-F19
[ ]	YY	C1-D9
[ ]	ZZ	D10-G10

Semiconductors

[ ]	D1	1N4001	D1-F1 (banded end to D1)
[ ]	D2	1N914	G14-G16 (banded end to G16)
[ ]	D3	1N914	F14-F15 (banded end to F14)
[ ]	IC1	TL064 quad op amp; pin-1 to E12	
[ ]	IC2	TL061 op amp; pin-1 to F20	
[ ]	IC3	LM3086 transistor array (contains Q2–Q5); pin-1 to F35	
[ ]	Q1	2N5089 emitter (E) to A28, base (B) to A29, collector (C) to A30	
[ ]	Q6	2N3906 emitter (E) to A42, base (B) to A43, collector (C) to A44	

Trimpot

- [ ] R33 5K multiturn trimpot; leads go in D32-33-34

Potentiometers (T=terminal)

- [ ] R34 10K T1 to E5, T2 to J14, T3 to I6
- [ ] R35 100K T1 to J16, T2 to J13, T3 to J15
- [ ] R36 100K T1 to J10, T2 to E13, T3 to terminal-2 of S2

Jacks (T=terminal)

- [ ] input jack (1/4" 3-terminal/stereo): tip to T2 of S1, ring to negative (–) battery lead, sleeve to Y25
- [ ] output jack (1/4" 2-terminal/mono): tip to T5 of S1, sleeve to Y32

Switches (T=terminal)

- [ ] S1 (DPDT stomp switch): T1 to E26; T2 to tip of input jack; T3 to T4; T5 to tip of output jack; T6 to B46
- [ ] S2 (SPDT slide or toggle switch): T1 to J5, T2 to terminal-3 of R36, T3 to J12

9V Battery Leads

- [ ] black (negative, –) to ring of input jack
- [ ] red (positive, +) to B1

Project No. G293
Tone-O-Matic XI

One of the most popular and sweet-sounding equalizers found in guitar amps, adapted from BPTs to FETs..

Circuit Function

Axe feed couples through C1-R1 to Q1, a FET source follower biased through trimpot R3. Q1's output ties through R28 to a discrete-transistor op amp comprised of Q2-3-4. Output is taken at the collector of Q4 and couples through C3-R4 to the output path. The net signal path is noninverting.

Pots R31-R35 are connected to simulated impedances (Q5-8 and their associated components), allowing in excess of 15 dB of boost or cut at 80 Hz, 480 Hz, 1.5 KHz, & 4 KHz; and above 4 KHz.

Use

Pots and switch have these functions:

R30	bias trim
R31	80 Hz boost/cut
R32	480 Hz boost/cut
R33	1.5 KHz boost/cut
R34	4 KHz boost/cut
R35	presence boost/cut (above 4 KHz)
S1	effect in/out

Before powering up the unit for the first time, rotate R30 fully CCW; center all panel pots. Apply power to unit, measure the supply voltage. Trim R30 to give 1/2V+ at the collector of Q4.

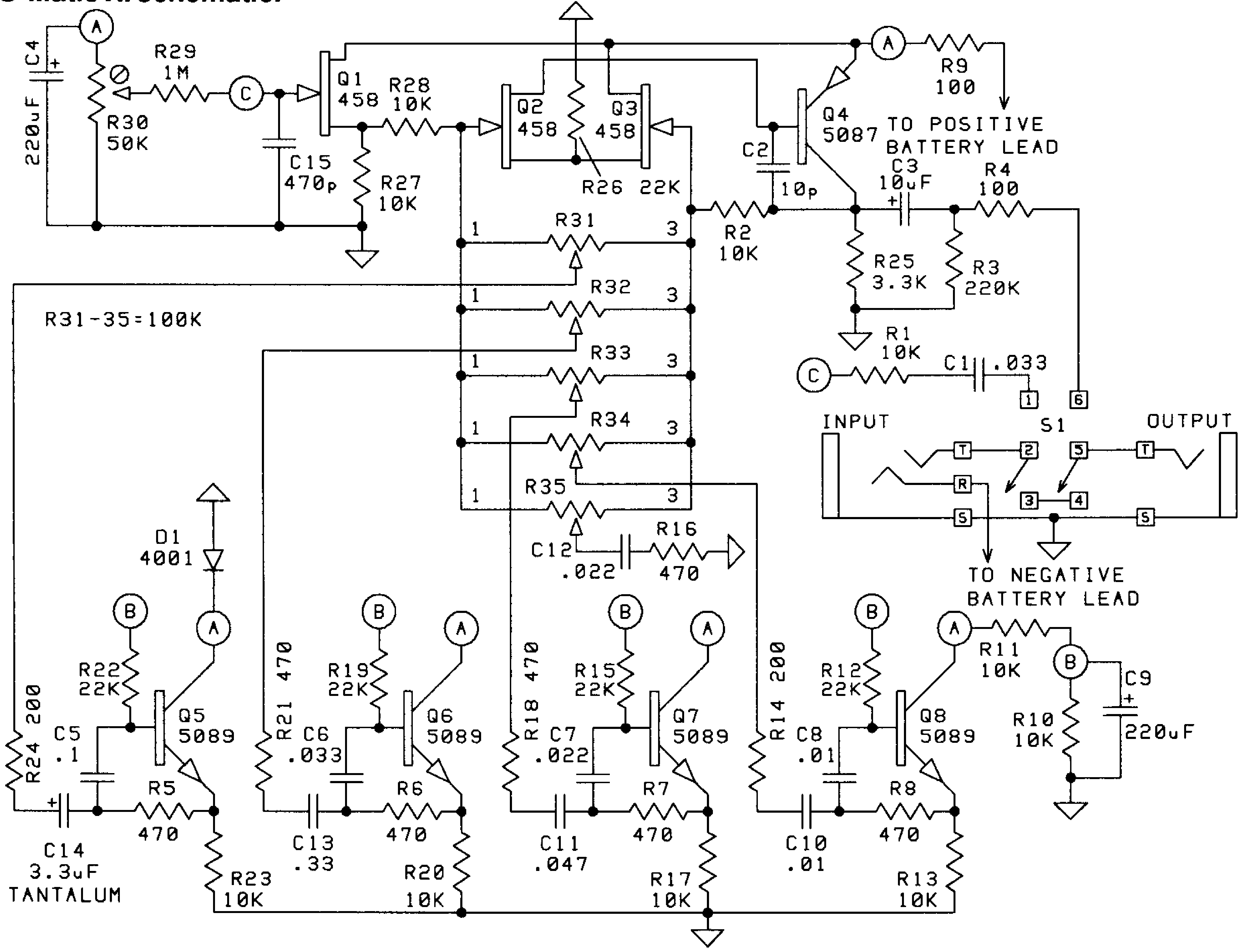
Take the pots through their ranges and note the effect on sound.

Notes

TOM11 will run off 9V but needs at least 15V to breathe; performs splendidly at 30V (be certain that capacitors' rated voltage exceeds the maximum supply voltage). A metal box is recommended.

To realize the rated boost/cut, Q5–Q8 must be high-beta types, such as 2N5089 or MPSA18. A significant fall in gain was noted using 2N3904s.

Tone-O-Matic XI schematic.



amps don't meet these ideals, but chip versions come close enough to treat as them as ideal in some cases. Op amps originated as building blocks for analog computers, to perform simple mathematical operations. Vacuum tube versions date back to the 1930s.

Q. Why would anyone want to make op amps from discrete transistors, given the huge selection and low cost of IC op amps?

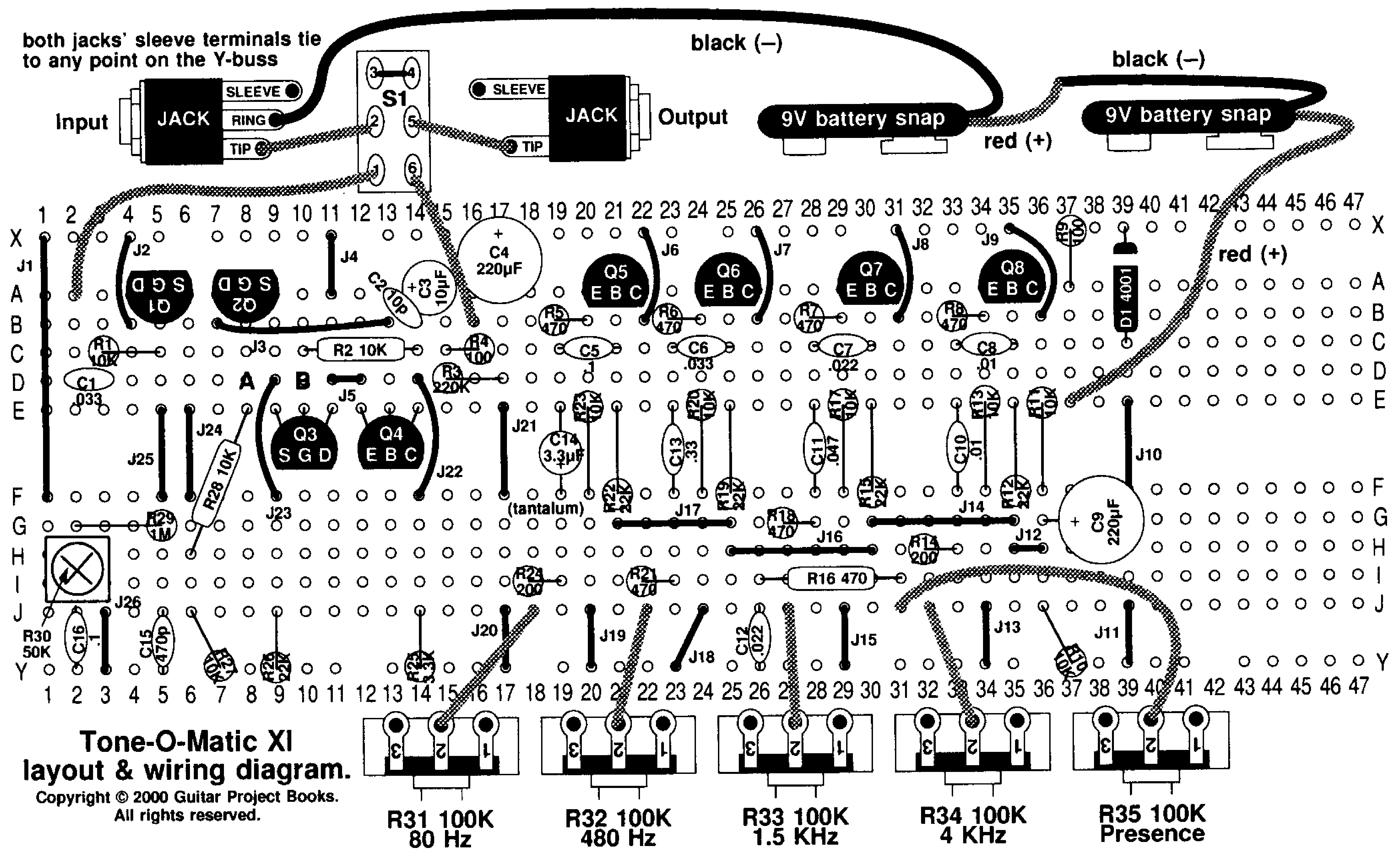
A. Fewer active devices in the signal path mean lower noise. Discrete-transistor amps tend less to overload by hard clipping than do IC op amps. And some players simply prefer the sound of discrete transistors to that of chips.

Q. How do discrete op amps differ from chip versions?

A. A discrete-transistor op amp's output impedance is higher, several thousand ohms compared to a few hundred ohms for IC amps; the maximum gain—referred to in op-amp data sheets as open-loop gain—is much lower; and, often, there's a considerable DC offset at the output.

Q. What's a DC offset?

A. Like bias, the meaning of DC offset varies with context. A *DC offset* can be thought of as the voltage at a given circuit point. Offset sometimes im-



Tone-O-Matic XI layout & wiring diagram.

all pots' terminal-1 ties to circuit board point 'A' (hole D8)
all pots' terminal-3 ties to circuit board point 'B' (hole D10)

Parts List/Soldering Checklist

Circuit Board Radio Shack p/n 276-170; Hosfelt p/n 42-183; or DC Electronics p/n J4-404

Resistors

[ ]	R1	10K	(brn-blk-org)	C3-C5
[ ]	R2	10K	(brn-blk-org)	C10-C14
[ ]	R3	220K	(red-red-yel)	D15-D17
[ ]	R4	100	(brn-blk-brn)	C15-C16
[ ]	R5	470	(yel-vio-brn)	B19-B20
[ ]	R6	470	(yel-vio-brn)	B23-B24
[ ]	R7	470	(yel-vio-brn)	B28-B29
[ ]	R8	470	(yel-vio-brn)	B33-B34
[ ]	R9	100	(brn-blk-brn)	X37-A37
[ ]	R10	10K	(brn-blk-org)	J36-Y37
[ ]	R11	10K	(brn-blk-org)	E36-F36
[ ]	R12	22K	(red-red-yel)	E35-F35
[ ]	R13	10K	(brn-blk-org)	E34-F34
[ ]	R14	200	(red-blk-brn)	H32-H33
[ ]	R15	22K	(red-red-yel)	E30-F30
[ ]	R16	470	(yel-vio-brn)	I26-I31
[ ]	R17	10K	(brn-blk-org)	E29-F29
[ ]	R18	470	(yel-vio-brn)	G27-G28
[ ]	R19	22K	(red-red-yel)	E25-F25
[ ]	R20	10K	(brn-blk-org)	E24-F24
[ ]	R21	470	(yel-vio-brn)	I22-I23
[ ]	R22	22K	(red-red-yel)	E21-F21
[ ]	R23	10K	(brn-blk-org)	E20-F20
[ ]	R24	200	(red-blk-brn)	H18-H19
[ ]	R25	3.3K	(org-org-red)	J14-Y14
[ ]	R26	22K	(red-red-org)	J9-Y9
[ ]	R27	10K	(brn-blk-org)	J6-Y7
[ ]	R28	10K	(brn-blk-org)	E8-H6
[ ]	R29	1M	(brn-blk-grn)	G2-G5

Bare Wire Jumpers

[ ]	J1	X1-F1
[ ]	J2	X4-B4
[ ]	J3	B7-B13
[ ]	J4	X11-A11
[ ]	J5	D11-D12
[ ]	J6	X22-B22
[ ]	J7	X26-B26
[ ]	J8	X31-B31
[ ]	J9	X35-B36
[ ]	J10	E39-F39
[ ]	J11	J39-Y39
[ ]	J12	H35-H36
[ ]	J13	J34-Y34
[ ]	J14	G30-G35
[ ]	J15	J29-Y29
[ ]	J16	H25-H30
[ ]	J17	G21-G25
[ ]	J18	J24-Y23
[ ]	J19	J20-Y20
[ ]	J20	J17-Y17
[ ]	J21	E17-F17
[ ]	J22	D14-F14
[ ]	J23	D9-F9
[ ]	J24	E6-F6
[ ]	J25	E5-F5
[ ]	J26	J3-Y3

Capacitors

[ ]	C1	0.033	D2-D3
[ ]	C2	10pF	A13-B14
[ ]	C3	10µF	A14-A15 ('+' lead to A14)
[ ]	C4	220µF	X17-A17 ('+' lead to X17)
[ ]	C5	0.1	C19-C21
[ ]	C6	0.033	C23-C25
[ ]	C7	0.022	C28-C30
[ ]	C8	0.01	C33-C35
[ ]	C9	220µF	G36-G39 ('+' lead to G36)
[ ]	C10	0.01	E33-F33
[ ]	C11	0.047	E28-F28
[ ]	C12	0.022	J26-Y26
[ ]	C13	0.33	E23-F23
[ ]	C14	3.3µF 10% tantalum	E19-F19 ('+' lead to F19)
[ ]	C15	470pF	J5-Y5
[ ]	C16	0.1	J2-Y2

Semiconductors

[ ]	D1	1N4001	X39-C39 (banded end to X39)
[ ]	Q1	NTE458	source (S) to A6, gate (G) to A5, drain (D) to A4
[ ]	Q2	NTE458	source (S) to A9, gate (G) to A8, drain (D) to A7
[ ]	Q3	NTE458	source (S) to E9, gate (G) to E10, drain (D) to E11
[ ]	Q4	2N5087	emitter (E) to E12, base (B) to E13, collector (C) to E14
[ ]	Q5	2N5089	emitter (E) to A20, base (B) to A21, collector (C) to A22
[ ]	Q6	2N5089	emitter (E) to A24, base (B) to A25, collector (C) to A26
[ ]	Q7	2N5089	emitter (E) to A29, base (B) to A30, collector (C) to A31
[ ]	Q8	2N5089	emitter (E) to A34, base (B) to A35, collector (C) to A36

Trimpot

[ ] R30 50K single turn trimpot; terminals go in I1-H2-I3

Potentiometers (T=terminal)

[all pots' terminal-1 ties to point 'A' on the circuit board (hole D8); all pots' terminal-3 ties to point 'B' on the circuit board (hole D10)]

[ ]	R31	100K T2 to J18
[ ]	R32	100K T2 to J22
[ ]	R33	100K T2 to J27
[ ]	R34	100K T2 to J32
[ ]	R35	100K T2 to J31

Jacks (T=terminal)

- [ ] input jack (1/4" 3-terminal/stereo): tip to T2 of S1; ring to negative (–) battery lead, sleeve to any point on the Y-buss
- [ ] output jack (1/4" 2-terminal/mono): tip to T5 of S1, sleeve to any point on the Y-buss

Switches (T=terminal)

- [ ] S1 (DPDT stomp switch): T1 to A2; T2 to tip of input jack; T3 to T4; T5 to tip of output jack; T6 to B16

9V Battery Leads

[two 9V batteries in series]

- [ ] black (negative, –) to ring of input jack
- [ ] red (positive, +) to E37

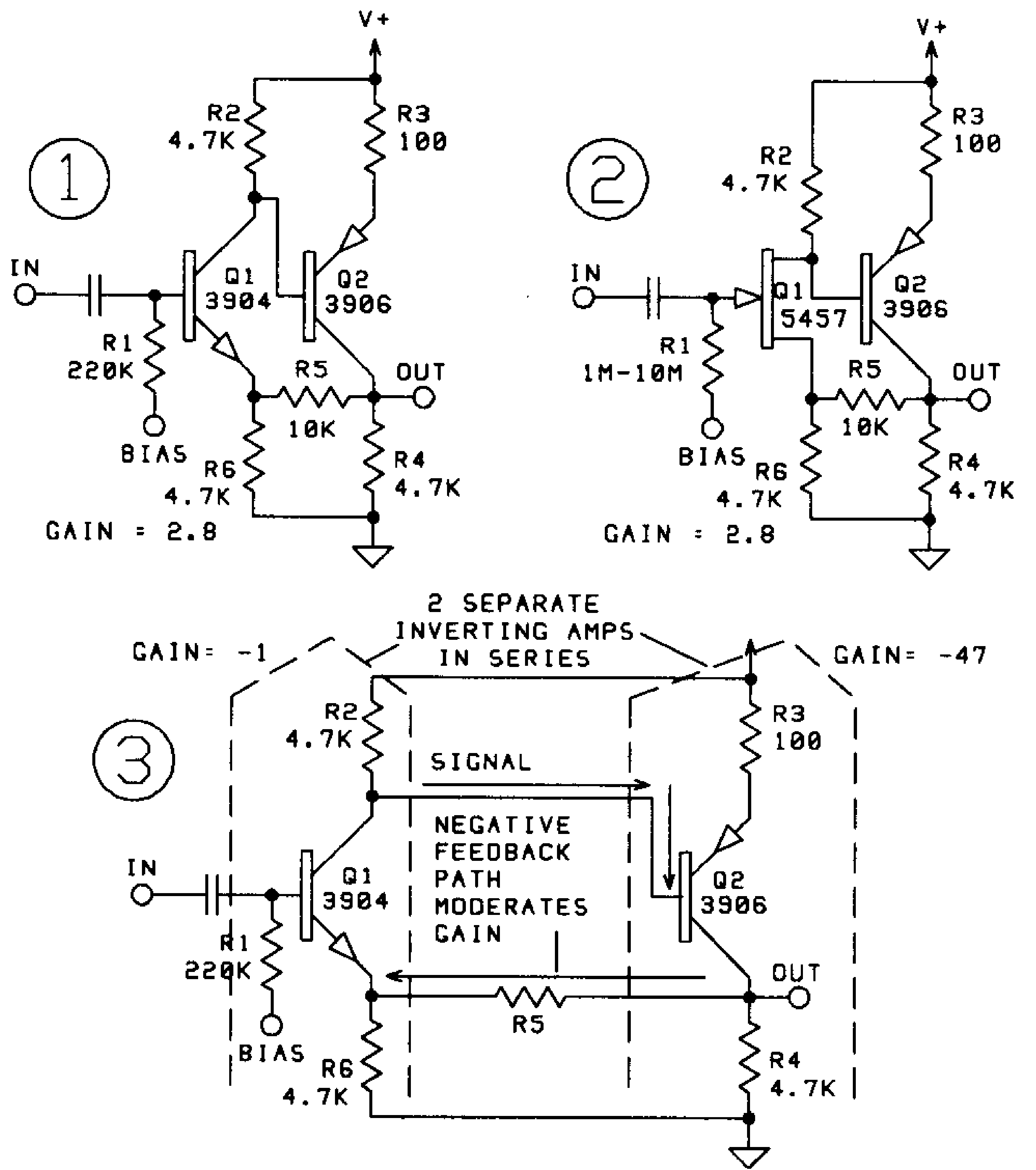


Fig. 13. Noninverting discrete-transistor gain stages suitable for stompbox use. 1—A pair of BPTs give gain of ~2.8. Apply voltage to free end of R1 to give 1/2V+ at output. Running at 7.5V, circuit's headroom approaches 7V. 2—A FET and a BPT, similar to #1 but slightly less headroom. 3—Simple analysis of circuit #1 shows two independent inverting amps in series. Q1 has gain of -1; Q2 has nominal gain of -47, but its output returns through R5 to Q1's emitter; this is effectively a negative feedback path, such that lowering the value of R5 increases negative feedback and lowers net amp gain; raising R5 increases gain; either move will require re-tuning bias. In both circuits, placing cap in parallel with R6 boosts gain by a dual mechanism: First, it raises Q1's treble gain to max. Second, it shunts audio feeding back through R5, but not the necessary DC bias, so Q2's gain kicks up near its theoretical max of 47; gain of circuit #1 exceeds 400, circuit #2 shoots to about 100. Circuit #1 requires additional stability measures when running at high gain.

plies a departure from some expected or desired value. In many circuits, an op amp's output should fall very close to 1/2V+. Significant departure from 1/2V+ would be called a DC offset. Bias and offset sometimes overlap in meaning, in that the DC voltage at the output of an emitter follower or a common-emitter amp is often called the output bias instead of the offset; but either usage is OK. You could say that altering the gate bias of a source follower shifts the DC offset of the source.

Q. What can discrete op amps do for me in building stompboxes?

A. This:

- inverting buffer
- inverting amp

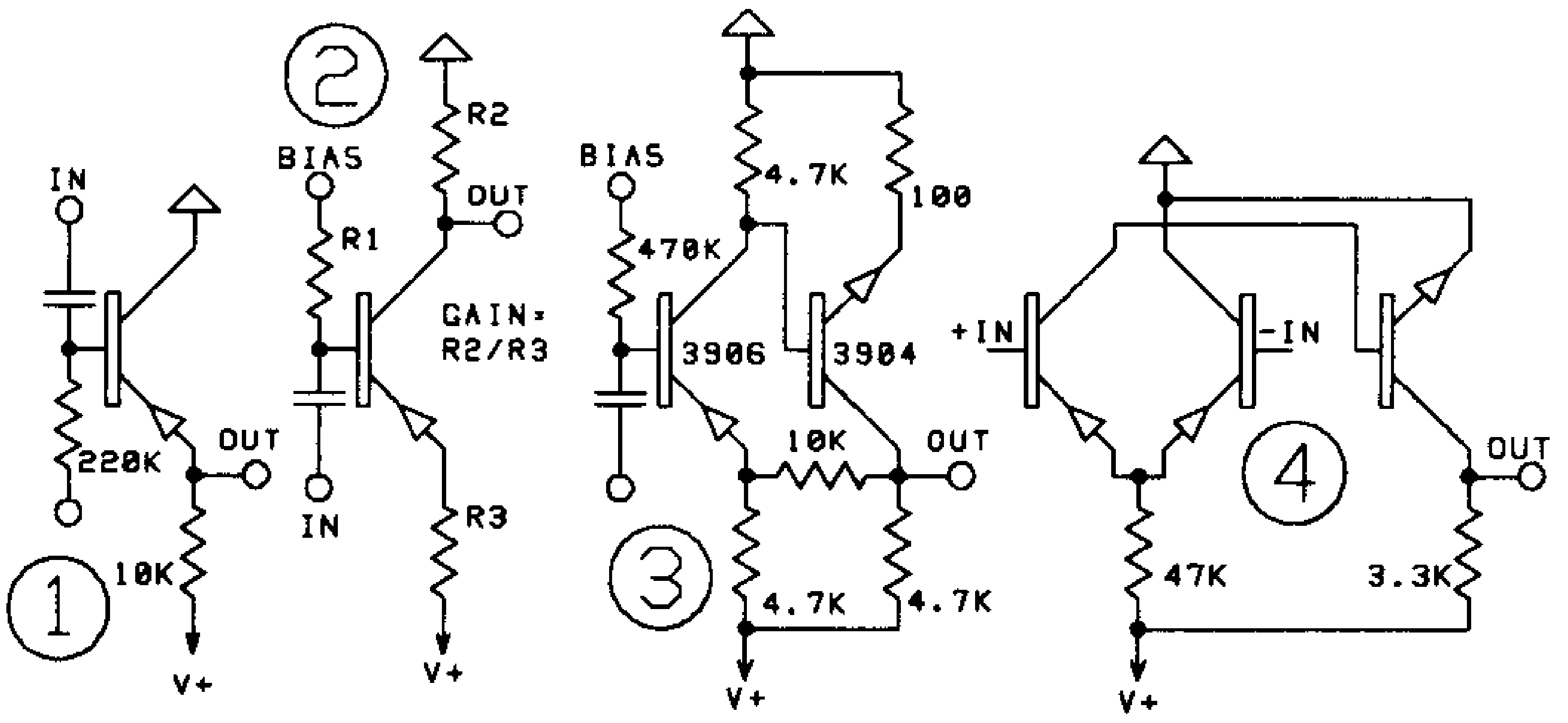


Fig. 15. 1—PNP emitter follower; pulls strongly toward ground. 2—PNP inverting amp. 3—PNP-input noninverting amp. 4—Discrete op amp using PNP differential pair. In all cases, topology is identical to NPN versions, but power polarity is inverted.

- noninverting amp
- mixer (inverting, noninverting)
- equalizer/tone network
- I–V converter
- voltage controlled amplifier

An op-amp inverting buffer is useful because it offers twice the headroom of the single-BPT or single-FET inverting amps we discussed above. Running off 7.5V, it gives nearly 7V of headroom.

Op amp inverting and noninverting amps follow simple gain formulas. These formulas apply to discrete op amps, but they don't follow the formulas as closely as chips do.

One of the most popular equalizers found in guitar amps is based on a discrete-transistor op amp. This circuit made its commercial debut, as far as we can tell, in the autumn of 1976 in the Realistic® model 31-1986. If you find one of these at a garage sale cheap, grab it. It contains two 1.4H and two 0.4H shielded inductors that make fantastic wah/tone parts. It's also an extremely warm EQ to use with a home stereo system.

You can use a discrete op amp as the current-to-voltage converter at the output of, say, an SSM2120 or NE570.

Finally, a discrete op amp forms part of a high-performance VCA, discussed below.

PNP vs. NPN

Q. I have NPN BPTs and N-channel FETs pretty well in focus. What's the difference in using PNP BPTs and P-channel FETs?

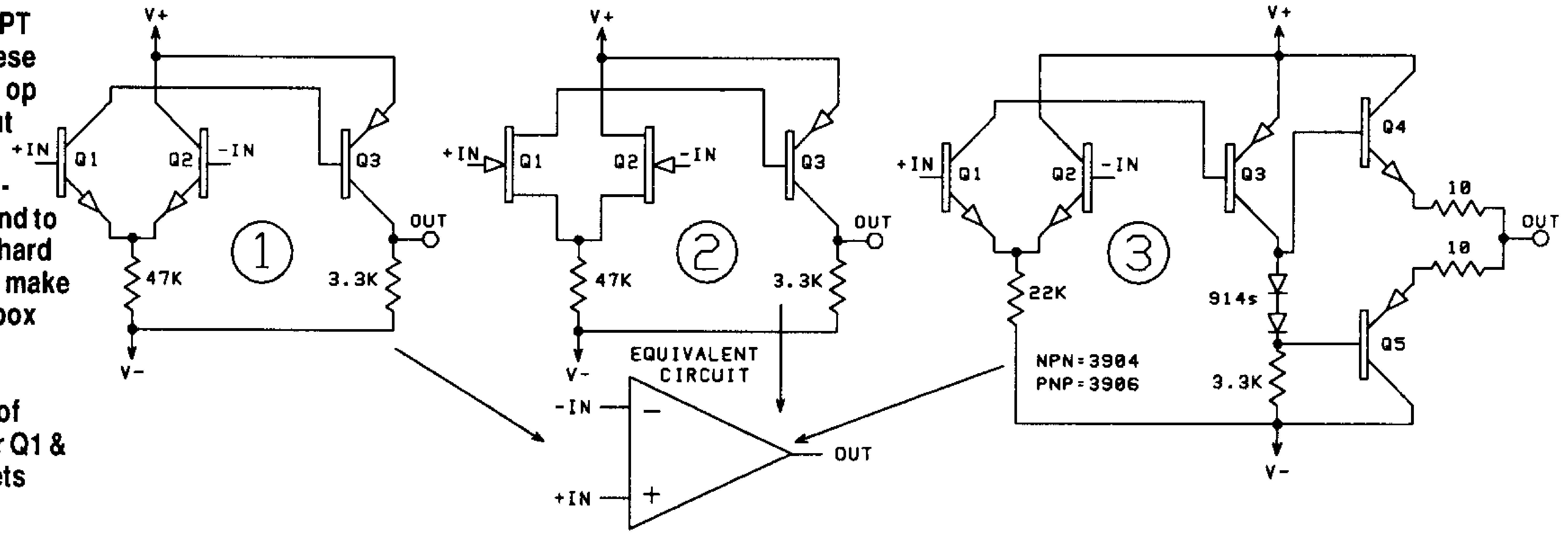
A. PNP transistor circuits are identical to NPN types but require two changes:

- invert the power supply
- invert polarity of supporting components as necessary

Fig. 15 gives examples. Note that a PNP emitter follower pulls hardest on the negative audio swing. The worth of this fact will become evident shortly.

Much the same applies to P-channel FETs: positive voltage pinches off

Fig. 14. Discrete-transistor operational amplifiers. 1—BPT version. 2—FET version. These differ from integrated circuit op amps in having higher output impedance, lower supply rejection and lower common-mode rejection. They also tend to be quieter and less prone to hard clipping with overload. They make terrific performers in stompbox tone networks, mixers, & equalizers. Common-mode rejection improves with use of matched monolithic pairs for Q1 & Q2. 3—Power output stage lets amp drive 600 ohms.



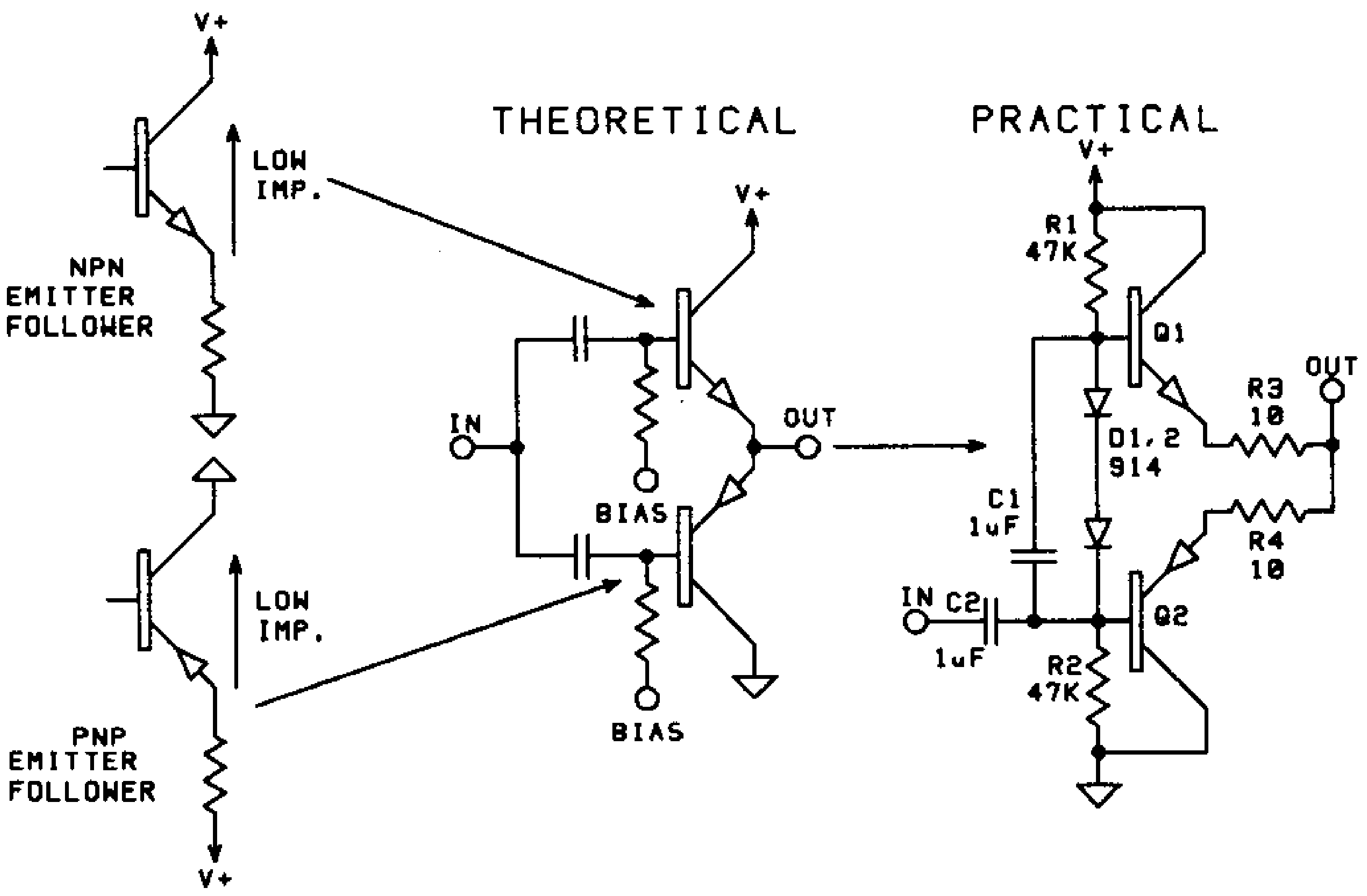


Fig. 16. NPN emitter follower exhibits low impedance for positive half of audio waveform; PNP follower exhibits low impedance for negative half of audio waveform. Combining the two yields a stage that can drive low-impedance loads, yet does not draw excessive current at rest. Theoretical circuit becomes practical by substitution of a network that automatically biases Q1 and Q2 (R1-R2-D1-D2); and by addition of R3 and R4, to help prevent temperature-related instability. Many different bias networks can sub for the one shown.

the drain-source channel. But so few P-channel FETs are available that hobbyists rarely use them.

Line Drivers

Q. When we were discussing emitter followers, you showed that a follower could drive 700 ohms, but at prohibitive cost in battery drain. Is there a way to drive 600-ohm studio loads without paying a penalty in current?

A. Yes. Stages called line drivers combine NPN and PNP emitter followers (Fig. 16). An NPN transistor pulls very hard up toward V+, a PNP transistor pulls very hard down toward ground. Each transistor drives the half of the audio signal that it handles best. Versions of this circuit based on power transistors can source and sink tens of amps.

For this circuit to function, both transistors have to be biased so that they barely conduct in the absence of an audio signal. The networks that achieve this are more complicated than single-resistor biasing; Fig. 16 shows one example, Split-O-Matic VI shows another. This keeps current drain low, while allowing an audio signal to drive the pair.

Q. How do you assess drive capability?

A. Breadboard the circuit, apply a 5V 1KHz sinewave to the input. Couple a 10K audio-taper pot between the output and a 100µF capacitor whose '–' lead ties to ground. Then, observing input and output waveforms on an oscilloscope, lower the pot resistance to the threshold of amplitude loss or distortion. Remove the pot, measure the value.

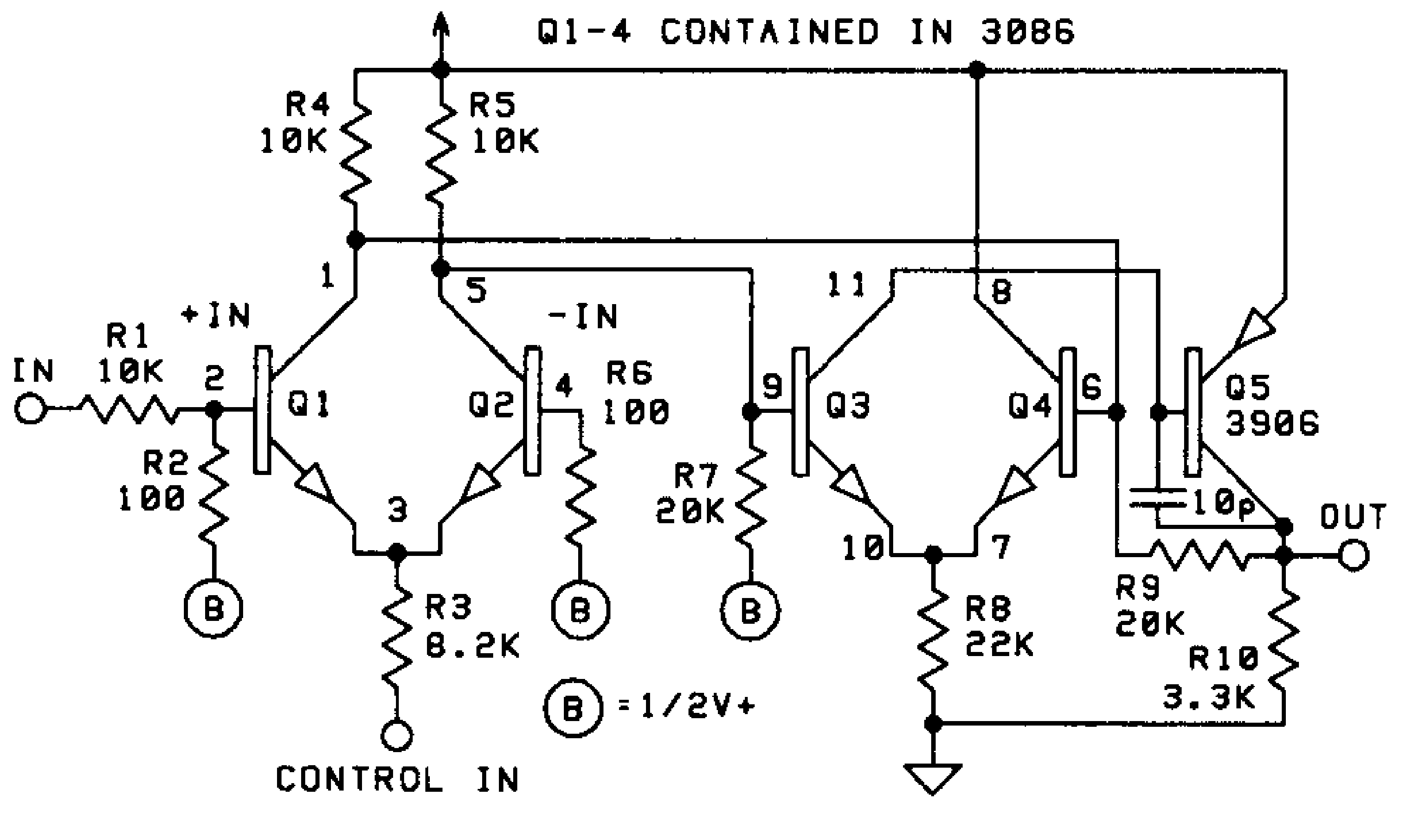
Voltage Controlled Amplifier

Q. What about this discrete-transistor VCA?

A. High-performance chip VCAs, such as those in the SSM2013 and SSM2122, are expensive and available through only a few suppliers. It turns out to be practical to build a VCA similar to chip versions, using discrete transistors. This VCA is as quiet as such circuits go; capable of very low feedthrough that's not particularly sensitive to changes in supply voltage; and can be scaled to run off as little as 5V or more than 30V.

The VCA consists of two subcircuits (Fig. 17). Q1 and Q2 are configured in what's called a differential amplifier. Without going into detail, it reacts to

Fig. 17. Discrete-transistor VCA uses matched transistor pairs. Q1–4 reside in 14-pin DIP LM3086. Several stompbox/tone-friendly traits. First, unit offers noninverting (pin-2) and inverting (pin-4) inputs; both can be used simultaneously. Second, device requires less noise reduction in tremolo than do common chip VCAs. Third, signal inputs respond to overdrive much as OTA inputs do: gentle squashing that can be unipolar or bipolar, depending on base bias. With control input at ground, signal gain approximates one; gain falls as control voltage rises, reaching 0 at one diode drop below 1/2V+. Output will drive 5V peak into a 43K load. Match between R7 & R9 determines control feedthrough cancellation; in practice, R7 is made an 18K fixed resistor in series with 5K multiturn trimpot, which acts as feedthrough trim. Unlike NE570, LM3080, LM13600, & SSM2120, control feedthrough trim of this VCA is not particularly sensitive to changes in supply voltage. Circuit will run off as little as 5V but can be scaled to run off 30V. This VCA uses less than a dollar's worth of semiconductors.



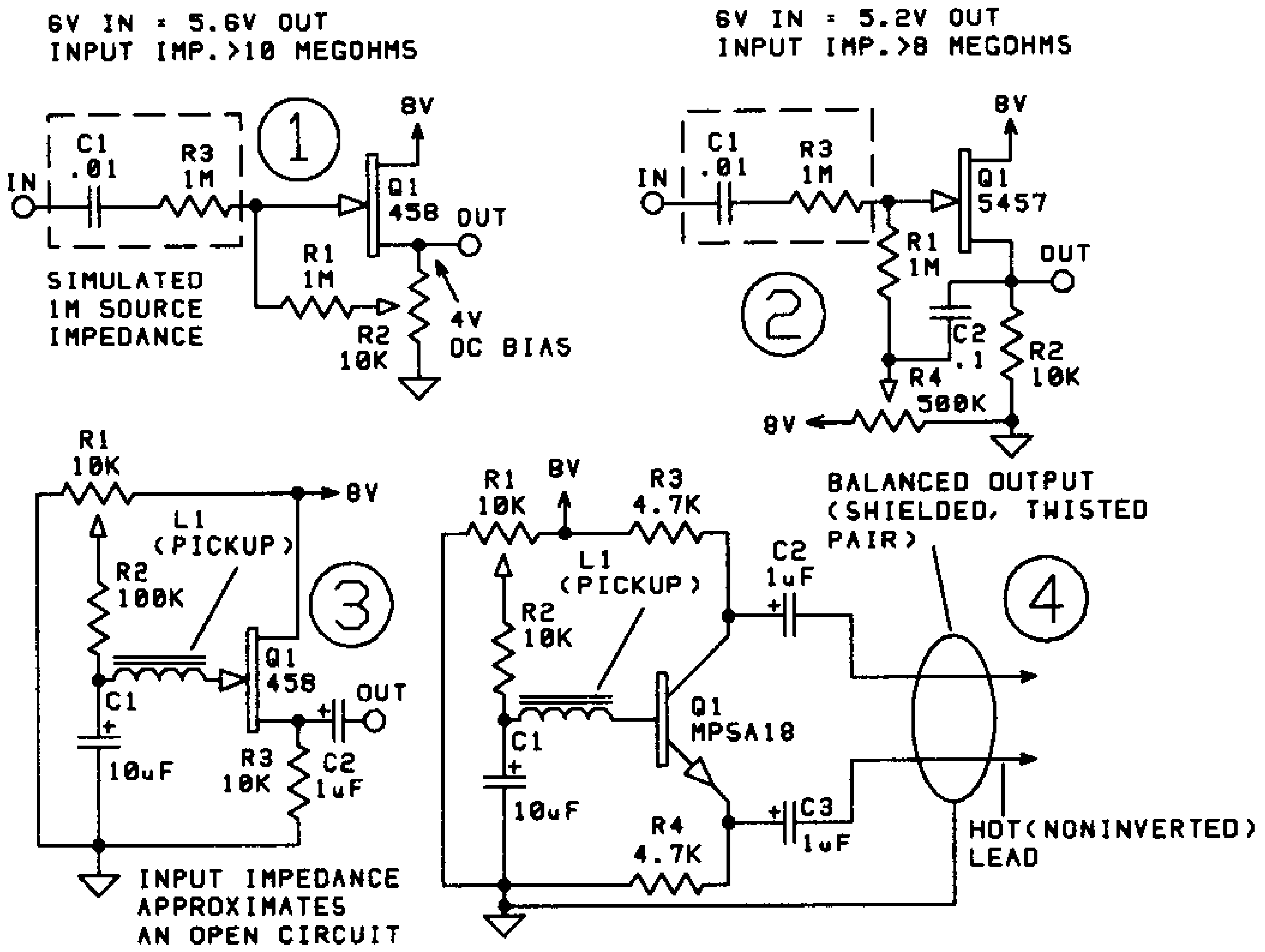
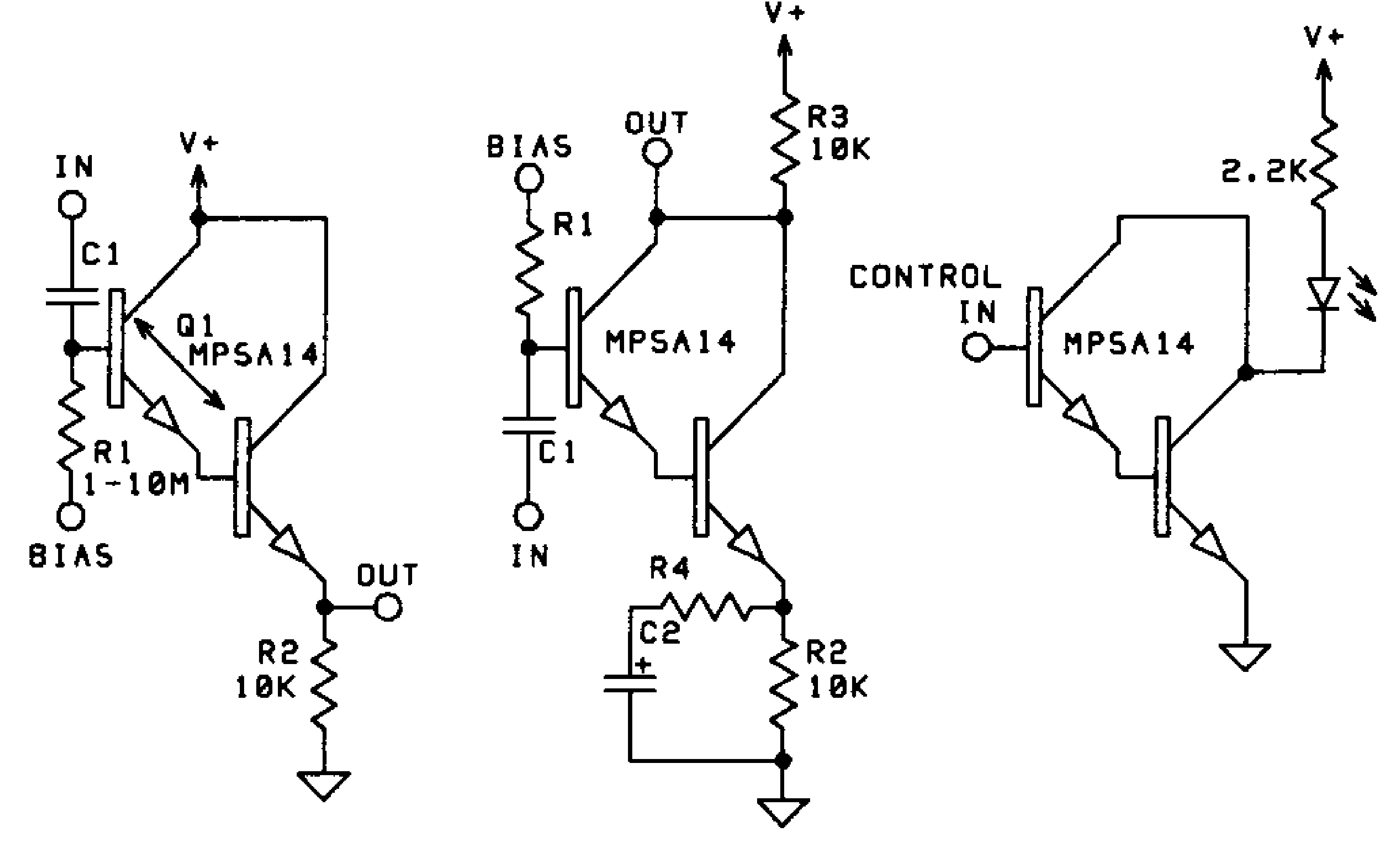


Fig 18. 1—Bootstrapping raises input impedance of FET source follower. Nominal 1M impedance is set by choice of R1. This becomes an effective impedance of >10 megohms by feeding in-phase audio back to input through R1. R3 simulates a 1M source impedance; voltage drop, due mainly to divider action with Q1's input impedance, is less than 10%. 2—Same principle, slightly different embodiment. Trim 500K pot for 4V at source; impedance multiplied by a factor of ~8. In #1 and #2, R3 is used only to demonstrate the change in input impedance; R3 should not be part of the final circuit. 3—Axe-dwelling FET buffer needs no bias resistor because the pickup conveys the bias. Loading effects would probably be difficult to detect, since FET gate appears as an open circuit. 4—Direct base bias through pickup, configured to give balanced output. High-beta transistor shows pickup a very high impedance.

Fig. 19. Darlington transistor, MPSA14. 1—Emitter follower; extremely high DC beta allows use of very large bias resistance, giving high input impedance. 2—Inverting amp resembles that for conventional transistor, but audio response rolls off rapidly as frequency rises. 3—Darlington used as LED driver; main reason to choose such a circuit is very high sensitivity.



the difference between the signals applied to the bases, ignoring identical signals applied to both bases. The differential amp generates two outputs at the collectors of Q1 and Q2, proportional to emitter current. In practice, varying the voltage applied to R3 varies gain. Gain peaks when R3 is at ground; gain falls to 0 when the control voltage reaches one diode drop (0.6V) below 1/2V+.

Q3-4-5 form a discrete op amp configured as a differential current-to-voltage converter that receives the current generated by Q1-2.

Q. What do the 100-ohm resistors, R2 & R6, do?

A. They bias Q1 and Q2.

Q. And the 10K input resistor, R1?

A. Sets the input impedance at 10K ohms, and forms a voltage divider with R2 to reduce the signal voltage by a factor of 100. Another way to look at it is that R1-R2 convert the input from a voltage to a current.

Q. Fig. 17 says that Q1–Q4 reside in a chip, the LM3086. Why not use discrete TO-92 transistors instead of a chip?

A. Transistors created on the same die at the same time match closely. Also, because transistor characteristics change with temperature, close proximity means that all transistors change at the same time. This makes the circuit relatively immune to temperature changes. Matched transistors are essential to peak performance from this VCA. The LM3086 (or CA3086) costs less than $1 from major suppliers.

Q. Why'd you hedge by calling this VCA "as quiet as such circuits go"?

A. Rig an SSM2120, NE570, or this discrete-transistor VCA to vary gain from 0 to 1. Short the audio input with a 10µF capacitor, plug the output into an amp. Now rotate the gain control pot and listen.

Q. I can hear a change in hiss as gain goes from 0 to 1!

A. This property is native to many VCAs. While it isn't usually audible in compressors and gates, rhythmic effects push it to the fore. To use chip VCAs as tremolo modulators you have to incorporate noise reduction measures. This discrete-transistor VCA requires less noise reduction than the 570 or 2120.

Raising Input Impedance

Q. Occasionally I see advertising references to boxes whose input impedance measures millions of ohms. What's the point of such high impedance?

A. One is to render loading losses negligible. A 10K pickup driving a 10M input loses less than 0.1% of its voltage. But what we've called loading losses are actually more complex. Being an inductor, a pickup tends to ring. A 100K input impedance may pass the signal with no audible amplitude loss, yet still dampen the pickup's ringing. Here an input impedance of 1M or more can improve tone.

Q. How do I get multi-megohm input impedance?

A. Any number of ways. With a FET (follower or amp), simply use a 10M bias resistor, and you have an input impedance of about 10 million ohms. Another method of raising input impedance is called *bootstrapping*, a form of positive AC feedback to the input. Fig. 18 gives a few examples.

Raising stompbox input impedance helps, but only to a point. Other factors affect tone. A pickup is a high-value inductor that forms a 12 dB/octave lowpass filter with parasitic capacitance in the axe cord.

Q. What's parasitic capacitance?

A. Capacitance produced by the proximity of two conductors. The center conductor and the outer shield of the axe cord form a capacitor whose value depends on length of the cord, proximity of the two conductors, and the dielectric constant of the insulator. This capacitance forms a lowpass filter that can deplete upper harmonics.

For greatest efficiency, the buffer should mount in the axe (Fig. 18–3). This leaves the pickup virtually unloaded and isolates it from stray capacitance in the axe cord. (**Caution: This option may demand rewiring the axe, or use of a true dual supply to keep the existing ground connections. Don't modify any instrument unless you're adept, and are prepared to sacrifice the axe being modified.**)

Darlington Transistors

Q. What are Darlington transistors?

A. Two conventional transistors wired in series; Fig. 19 shows an example.

Q. What good are they?

A. They're useful in stompboxes because they give the builder more tonal options. They tend to squash rather than clip, though the difference is not dramatic. Second, they exhibit DC beta in the tens of thousands, giving multi-megohm input impedance. On the downside, their beta rolls off rapidly with frequency. A Darlington transistor gives no more audio gain than a conventional transistor. You can use them as LED drivers or emitter followers for cases that need very high input impedance.

Servos

Q. A while back you mentioned servo biasing. Could you explain this in more detail?

A. A servo compares the amp's actual output voltage against a reference voltage. If the two don't match, it generates an error voltage that drives the amp's output voltage toward the reference voltage.

Servos are so simple and well behaved that these circuits (Fig. 20) will need no change in many applications. Remember that an inverting amp needs a noninverting servo; a noninverting amp needs an inverting servo.

Occasionally, an amp-servo combination oscillates. You can test the servo for dynamic stability by subjecting it to a tone burst while observing the output on an oscilloscope. Usually, doubling or halving one of the lowpass caps cures instability.

Buying Transistors

Q. What kind of transistors should I buy, and in what quantity?

A. Initially, buy what are known as *first-quality* or *prime* transistors. These are the ones listed by specific part number in catalogs. Singly, they cost 20–50¢ apiece, with price breaks kicking in at qty. 10 and getting serious at qty. 100. Avoid bargain transistor assortments, because they may contain parts rejected for low beta, high noise, or both; or they may contain first-quality transistors that possess an uncommon pinout, such as E-C-B in a

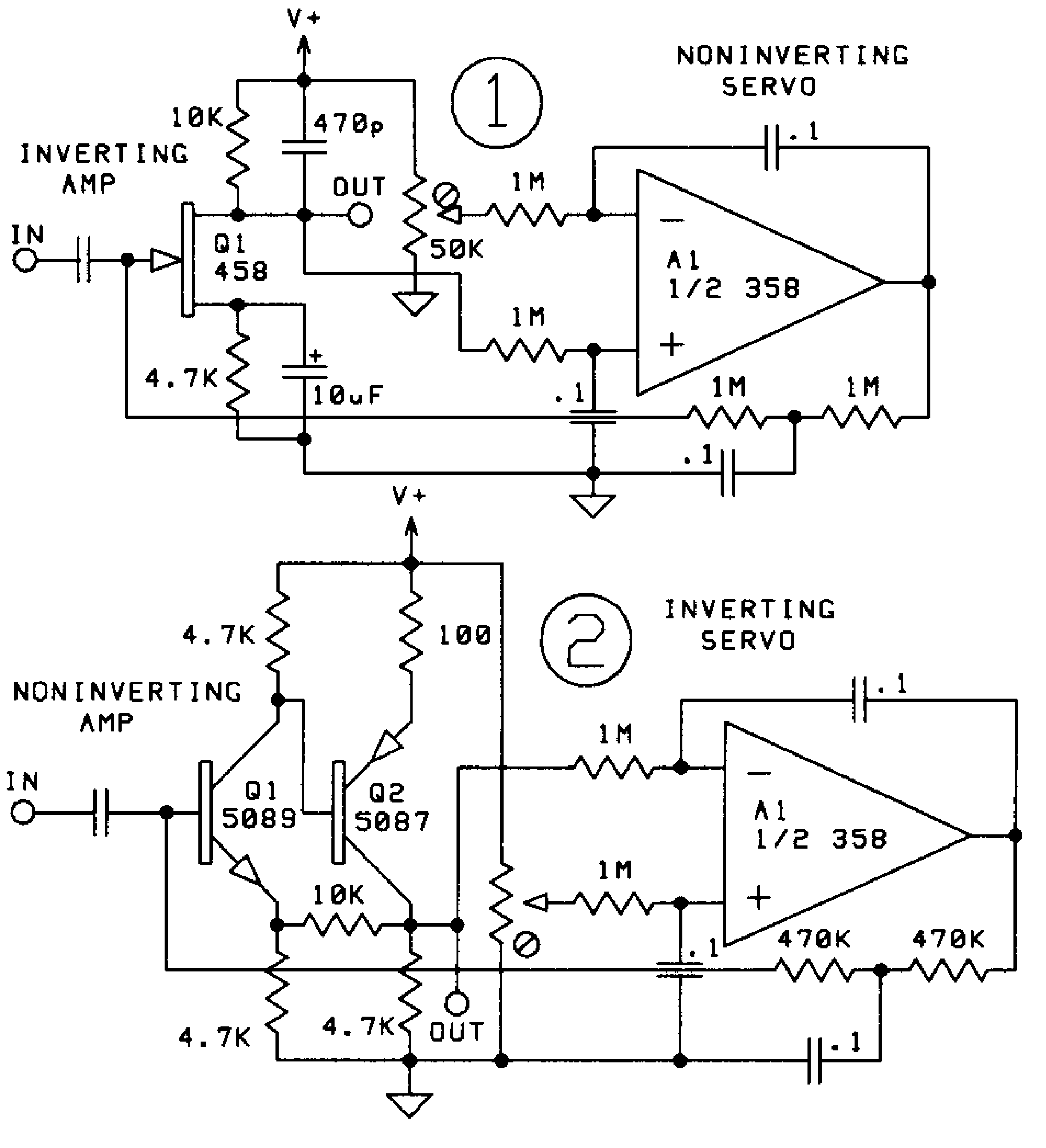


Fig. 20. Servo biasing details. Chip op amps work best here because they approach ideal op amp behavior near DC. 1—An inverting amplifier needs a noninverting servo, such that a rise in output voltage above the desired point feeds back a positive correction voltage to gate, which tends to bring output voltage down to desired level. 2—A noninverting amp needs an inverting servo, such that a rise in output voltage creates a fall in feedback voltage, which tends to bring output voltage back down to desired level. Noise of op amp's output stage will couple to signal path unless shunted by capacitor.

TO-92 case.

A few retailers sell first-quality transistors as loss leaders, e.g., a bag of 100 prime 3904s or 3906s for less than 10¢ each.

Q. Any other benefits to knowing transistors?

A. Transistors open the door to tubes. A triode's cathode, grid, and plate correspond to an NPN BPT's emitter, base, and collector; and to an N-channel FET's source, gate, and drain. In the early 1960s when transistors first penetrated the hobby scene in a big way, veteran tube users had no trouble adapting to them, because they understood tubes. The modern builder who understands transistors will have little difficulty moving over to tubes. Tube circuits demand radically different safety precautions, as they run at voltages high enough to cause death by electrocution.

Project Details

Q. I get the feeling this issues's projects flesh out what we've just discussed.

A. Yes.

Q. The circuits also look more complex than the models on which they're based. How about explaining all seven projects in simple terms, and relating them to their parent circuits?

A. We'll start with—

Split-O-Matic V

A. SOM5 is a one-in/four-out noninverting splitter with individually variable output levels. Referring to the schematic, the circuit consists of source follower Q1 driving four emitter followers, Q2–5. We chose a FET input as a matter of personal taste, and also because FETs are easy to rig for high input impedance, a million ohms in this case. R1-C7 form an lowpass filter that rolls off in the ultrasonic range, to help prevent oscillation and exclude AM radio signals. All four emitter followers couple directly to Q1's source, which also biases them. Trimpot biasing lets us put the output offset dead-on 1/2V+. To save parts we've used 10K pots in place of the BPTs' emitter resistors. R5-7-9-11 help stabilize the followers and, more importantly, keep an accidentally shorted output from taking all the others down with it. The box is designed to drive amp and stompbox inputs, whose impedances typically exceed 30K ohms.

Q. What's the point of R3-C2?

A. If you never use anything but battery power, nothing. If you run the box off a wall wart with a bit of residual ripple, R3-C2 forms a lowpass filter that reduces hum.

Q. How do you choose the value of C3, the input coupling cap?

A. The choice is determined by the amount of low-frequency information we want to enter Q1. The larger C3, the more bass; the lower C3, the less bass. The technical reason involves concepts and math that we've intentionally avoided in this ish, to keep it simple. C3 could be as low as 0.01μF, or as high as 0.1μF. To decide, breadboard the circuit, connect it to axe and amp, and swap out caps while listening to the tone. The nominal 0.033μF value works fine for guitar.

Distort-O-Matic XI

A. DOM11 uses a noninverting preamp with a few additions. First, R2-C1 keeps out RF and aids stability.

Q. Why does C1 tie to V+ instead of ground?

A. Using V+ saved us a jumper. The battery is an AC ground, so shunt caps like this can tie to V+ or ground.

C15 kicks the noninverting amp's nominal gain of 2.8 up to maximum; so much gain that stability required C13 to roll off the ultrasonic response. Q2's output couples through C2 to the base of Q3, which you'll recognize as a unity-gain inverting amp, here used as a phase splitter. Q3 drives Q4-Q5, a couple of PNP transistors configured as a positive fullwave rectifier, with gain.

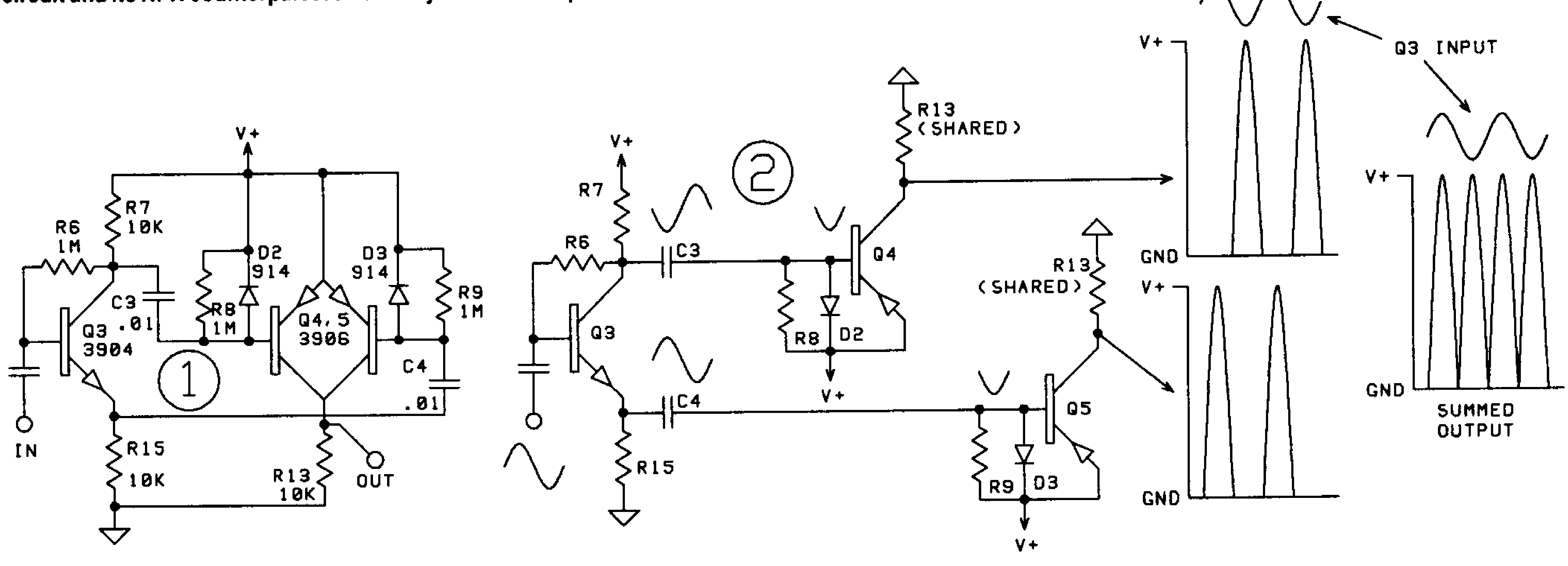
Q. Could you explain that in more detail?

A. Check out Fig. 21. Q3-4-5 form a common circuit in stompbox level detectors. Q3 creates inverted and noninverted replicas of the input signal. Q4 is an inverting amp configured for maximum gain, because the ratio of collector resistance to emitter resistance is as high as it can get. Q4 is biased by R8 such that, in the absence of an audio signal, Q4 is turned off and R13 pulls the collector close to ground. When audio reaches the base, positive audio swings get shunted to V+ through D2. Negative audio swings reach the base and turn Q4 on, which pulls the collector hard toward V+. The same thing happens in Q5, but it sees an audio input inverted relative to Q4's, so Q4 and Q5 trigger on alternate audio cycles. These transistors share a collector resistor, which sums the two outputs. The result is positive fullwave rectification, with quite a bit of gain.

At this point we have the raw preamp output, and the frequency-doubled and boosted output of Q4-5. Edge control pot R19 varies the mix of signal sources. R19's wiper feeds the signal through C11-R14 to germanium diode clipper D4-5. The point of clipping at this stage is less to alter the distortion than to give our post-distortion tone controls room to work.

Audio couples through C8 to Q6, a feedback-biased inverting amp with nominal gain of 1. Q6's gain varies according to the setting of tone control pots R21 and R22. With R21 fully CW, C12 is in parallel with R12; the transistor attempts to deliver maximum treble response. With R21 fully CCW, C12 shunts R20, rolling off the treble gain. R22 ties to the series resonance

Fig. 21. 1—Circuit block from Distort-O-Matic XI. 2—Same circuit with schematic rearranged for clarity. Q3 is a unity-gain phase splitter, providing an inverted output at the collector, a noninverted output at the emitter. Q4 is a PNP inverting amplifier configured for maximum gain (emitter resistance is 0), and biased off in the resting state by R8; Q4's collector is near ground. When audio reaches the base through C3, positive audio swing gets shunted to V+ through D2, negative audio swing turns Q4 on, pulling collector hard toward V+, giving a positive output peak. Q5 is identical, but its audio input is inverted relative to that reaching Q4, so it triggers on peaks ignored by Q4. Q4 and Q5 share a common collector resistor, R13. Net result is positive fullwave rectification of audio, with boost. This circuit and its NPN counterpart are normally used in stompbox level detectors.



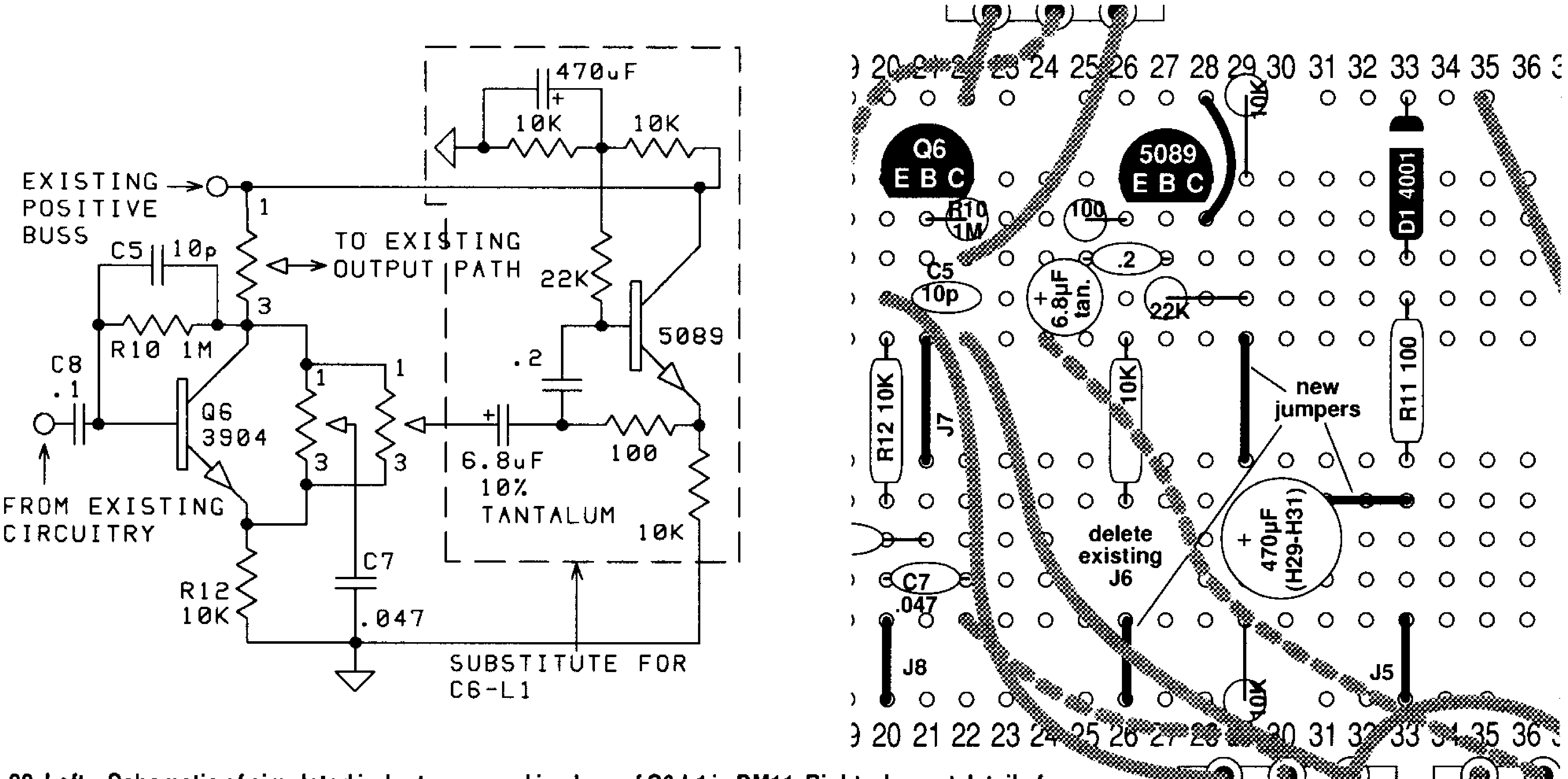


Fig. 22. Left—Schematic of simulated inductance used in place of C6-L1 in DM11. Right—Layout detail of same.

formed by L1-C6, which falls near 80 Hz. Both tone pots apply boost/cut in excess of 30 dB.

Q. Let's say I don't want to remove the inductor from a wah pedal. Is there another way to realize the bass tone function?

A. Modify the 80-Hz simulated resonance from TOM11 and plug it into DOM11. The response isn't identical, but close. Fig. 22 shows a schematic and a layout fragment.

Tremolo-Matic XVIII

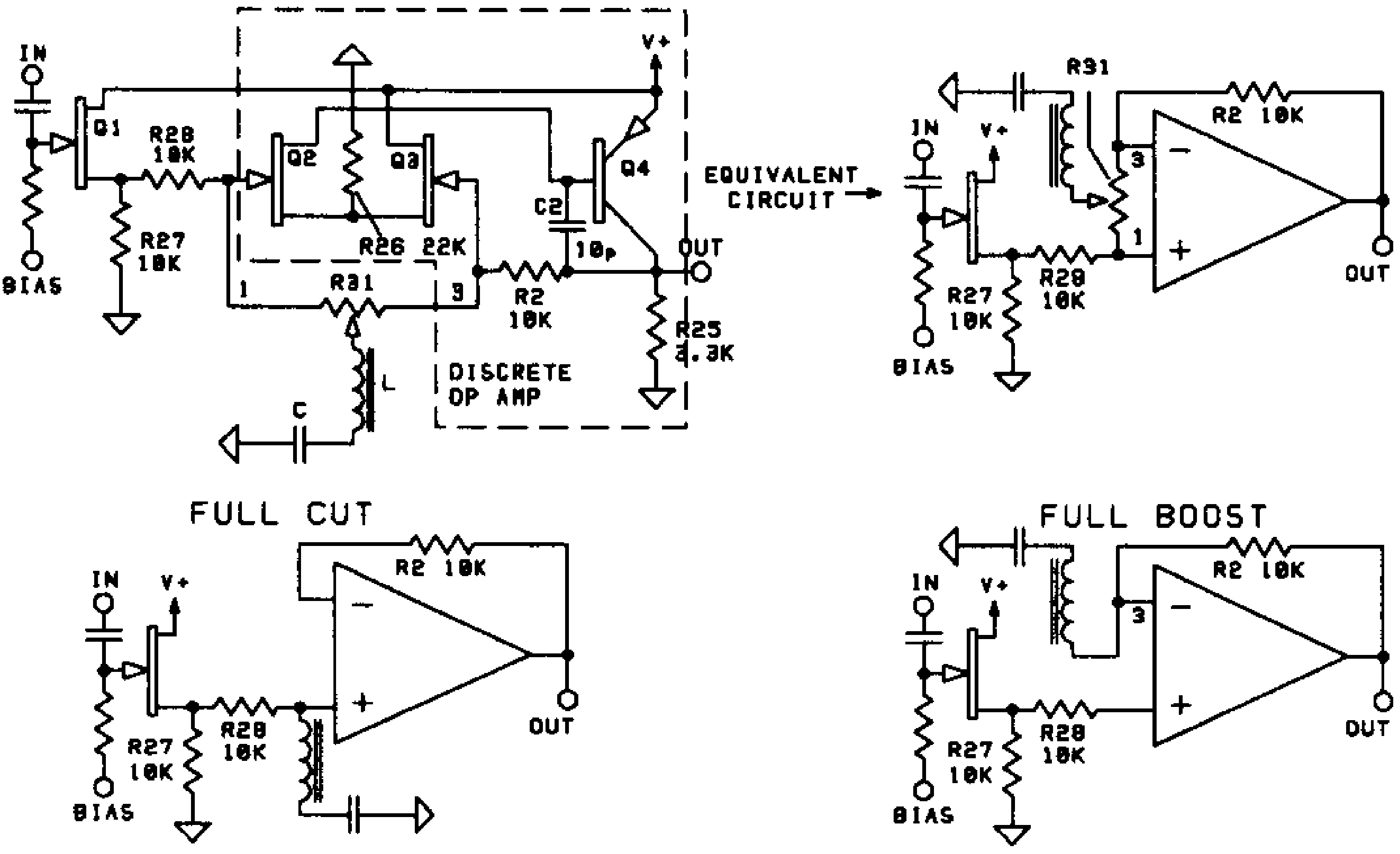
A. TOM18 uses a standard op-amp-based soft triangle oscillator; nothing new here.

The modulation core consists of two FETs configured as a differential amplifier. Modulation is achieved by varying both FETs' gate bias simultaneously. To accomplish this and couple the signal as well, we used a center-tapped transformer. A single-ended output could have been taken at either drain; but use of differential output and a transformer results in automatic feedthrough cancellation.

Q. What's the point of this box?

A. It has several points. (1) Novelty. (2) A different sound. (3) Automatic feedthrough cancellation. (4) Didactic value; specifically, the illustration of non-resistor bias paths (T1) and non-resistor collector loads (T2).

Fig. 23. Equalizer uses discrete op amp. With R31 fully CCW, L-C forms passive notch filter with R28. With R31 fully CW, boost equals [1 + (R2÷LC impedance)].



Boost-O-Matic IV

A. BOM4 is a treble booster than uses a couple of high-transconductance FETs. Each FET is wired as an inverting amp with variable treble gain; the two are wired in series. C4 and C7 aid stability by lowering ultrasonic gain.

Both FETs get their bias through a single trimpot and separate 1M resistors. Variable bias lets the player alter the squashing threshold as desired.

Q. This box appears to use not one, but two supplemental decoupling networks: R5-C1 and R3-C9.

A. You called it. Oscillation becomes a risk when gain exceeds 40 dB and the output is in phase with the input. Keep input and output leads widely separated.

Split-O-Matic VI

A. SOM6 was conceived as a one-in/four-out line driver for studio use. Low current drain demanded complementary outputs. After testing a number of bias networks under load, the one that held up best used transistors instead of diodes. (This approach was found in the internal schematic of a high-speed, high-current buffer op amp. We recreated it using discrete transistors. See Ref. 1)

Q. I notice that the input coupling cap, C1, is huge relative to the 0.01–0.033µF input caps of FET-based stages.

A. Yes, and the reason pertains to noise. BPTs generate something called noise current that drops a noise voltage across an impedance connected to the input. A 0.01µF cap has high impedance at low frequencies. Use of a 0.01µF input coupling cap in a BPT stage might result in excessive noise. FETs generate insignificant noise current, so we can use small caps without creating excessive noise. A 10µF cap has low reactance at low frequencies, so the BPT's noise current drops no audible noise voltage across it. The drawback of a large cap is that it lets in more bass than some players want.

Tremolo-Matic XXII

A. TM22 uses a variable-waveform oscillator [*see Vol. 10, No. 1—Ed.*] that generates ramp, triangle, & negative ramp; plus a soft squarewave with variable duty cycle.

The axe feed negotiates Q1, a feedback-biased inverting amp with nominal gain of 1, but with over 20 dB of treble boost produced by R25-C12. Preamp output couples through C10-R22 to the inverting input of a discrete-transistor VCA made up of Q2–Q6.

Q. In the VCA model circuit, you showed a 10K input resistor and 100-ohm base bias resistors. Here you've got 1K base bias resistors and a 47K series input resistor.

A. These differences are intentional. Q1's output impedance is about 4.7K ohms, so we need to show it a load of at least 47K to avoid loading losses. We scaled up the resistors to raise the VCA's input impedance. Also note that the ratio 47K:1K is only half that of 10K:100. This effectively boosts the VCA's gain from one (0 dB) for the stock circuit, to two (6 dB) for this tremolo circuit. The increased input level moves closer to a gentle form of distortion that proved agreeable in listening tests. Also, combined with the treble boost in the preamp, we can tack a de-emphasis network (R14-15-16-C9) onto the output to reduce modulation noise to very low levels.

Feedthrough trim is straightforward and resistant to changes in supply voltage.

Tone-O-Matic XI

Q. Looking at TOM11's schematic, I don't see how the basic circuit achieves boost and cut.

A. Check out the schematic juxtaposed with op-amp equivalent schematics (Fig. 23).

Q. What's going on with Q5-Q8?

A. Q5-Q8 and their associated components each simulate an inductor in series with a capacitor, with one end tied to ground. These circuits are discussed at length in the Weird Tone issue [*Vol. 8, No. 4—Ed.*]

Q. What's the purpose of R14-16-18-24?

A. Stability. These resistors reduce the maximum boost/cut somewhat. Without them, the equalizer exhibits instability in the form of noise bursts at the extremes of pot rotation.

References

1. *Linear Applications Handbook*, National Semiconductor Corp., 1986 [*p. 533, internal schematic of LH0002 buffer op amp; chips' internal schematics are worth studying because they contain countless examples of transistor biasing methods*]

2. *Linear Databook, Vol. 1*, National Semiconductor Corp., 1988

3. *Discrete Semiconductor Products Databook*, National Semiconductor Corp., 1989

4. Hayward, Wes; and Doug DeMaw: *Solid State Design for the Radio Amateur*, American Radio Relay League, 1986

5. *Heath/Zenith Basic Electronics Course*, Heath Company, 1982

6. Jung, Walter: *Audio IC Op-Amp Applications*, 3rd Ed., Howard W. Sams, 1987, ISBN 0-672-22452-6