Railway
Signaling &
Communications

SOLID STATE DEVICES

Description and Operations

Applications in Railroading

Affects on Signaling

P. N. Bossart,
Senior Consulting Engineer,
Research Department,
Union Switch & Signal

Dr. Bossart obtained a Bachelor of Science degree in ectrical Engineering from Carnegie Institute of Tech- logy in 1916. He attended classes at Columbia Uni- rsity where he received a degree in Electrical gineering in 1920 and he obtained his Doctorate De- ee in Physics from the University of Pittsburgh in 1933 A career engineer at Union Switch & Signal for more n 37 years, Dr. Bossart has been issued 60 patents. e has held various supervisory positions here. He has nt much time in the research and development of a riety of inductive communications and control systems imarily for railroad applications. In recent years, the sic principles of communication and control invented by r. Bossart have been applied to the steel, coal, and her industries.

olid state physics is the science of the physical properties of solids. It's usually restricted to solids where e atoms are arranged in a regular crystalline array. Many hysical properties are included, but for switching circuits, e important ones are electrical conductivity and mag- etism.

Another important term is semi-conductor. A semi-con- luctor is simply a material such as germanium or silicon rhose resistance is intermediate between a good con- luctor like copper, and a good insulator like quartz. If, as n Fig. 1, we measure the resistance between opposite aces of a 1 inch cube of copper, it would be about one millionth of an ohm, germanium 20 ohms, and quartz a billion, billion ohms.

We can't make an insulator from copper, nor can we make a good conductor from quartz, but science has discovered that from semi-conductor materials like germanium and silicon we can fabricate devices where the polarity of the applied voltage controls the resistivity and we can rapidly change it back and forth between a good conductor and a good insulator, say from 0.01 ohm to 60 megohms. This, of course, is what an ordinary switch does. You are familiar with the electronics of tuned circuits, and frequency selection, but the electronics of solid state switching involves only quick changes from open circuits to closed circuits and vice versa, without moving contacts.

Conductivity of Germanium In pure germanium at −460 deg F. every electron is locked in place in the regular crystalline array, and cannot move to conduct electricity, so it is an insulator. At room temperature, the heat or thermal agitation tears loose one electron, in every billion atoms, and this electron becomes free to carry negative electricity. The vacancy or "hole" where it was torn from also acts like a current carrier, but of positive electricity. Thus, in pure material we have a small and equal number of negative (n^-) carriers, electrons, and positive (p^+) carriers, holes, giving us the considerable resistance of about 20 ohms/inch cube resistance.

If very small amounts, say 1 part in a million of certain impurities are injected into germanium as by alloying or diffusing, we can easily provide 1000 times as many carriers, and by the choice of impurity, say arsenic, make these free carriers almost all, a million to one, electrons, or with indium as impurity make the carriers almost all holes. The resistance is greatly lowered to about 0.02 ohms /inch cube.

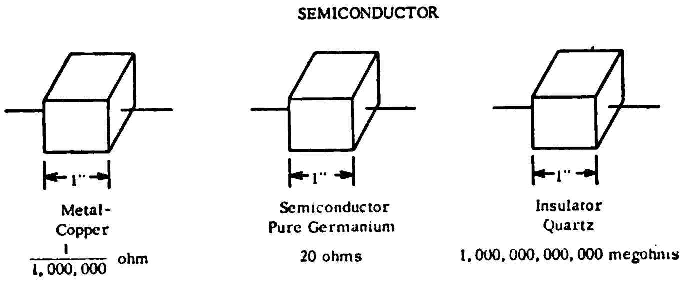


FIGURE 1

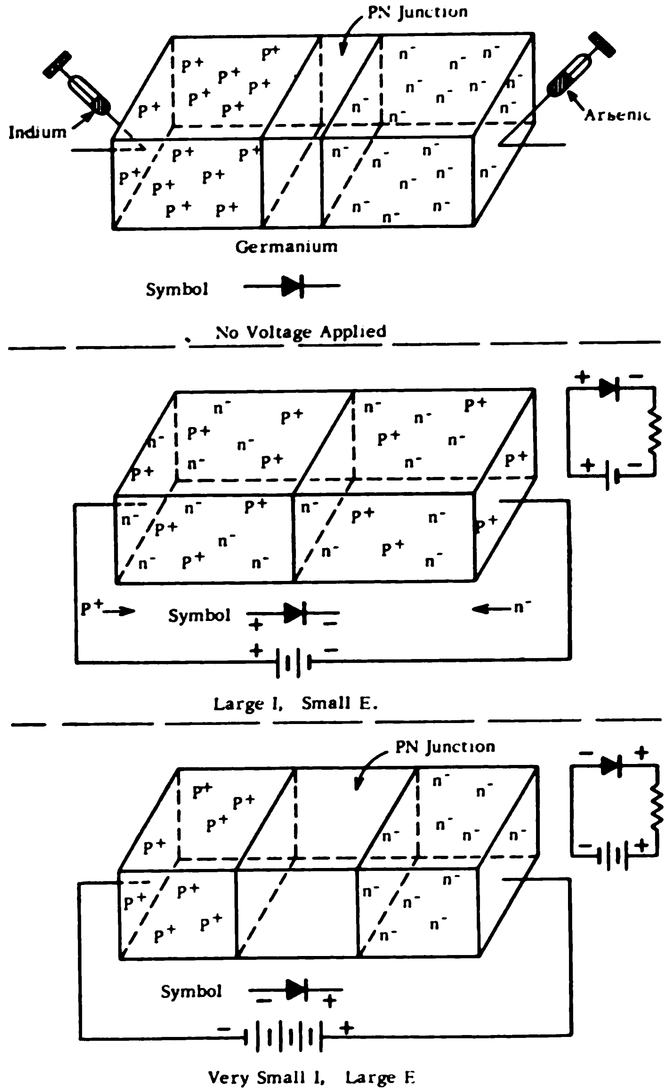


FIGURE 2

PN Junctions

Now, as in Fig. 2, take a single crystal, pure germanium, and put a little indium in one end and a little arsenic in the other. We get a lot of holes (p^+) as free positive carriers and very few electrons (n^-) at the indium end, and the opposite condition at the arsenic end. In the center where one type conductivity meets the other, a few of the two carrier types meet and recombine. This results in a space charge or small internal voltage which then keeps the two types separated. This is a *pn junction.* At 0 applied volts it is practically an insulator. If we add an electrical circuit with + at the positive end and —at the negative end, we overcome the small internal voltage of the space charge and we can readily move the carriers through the circuit, the holes or p^+ go from + to —, and the electrons or n^- go from — to + and both contribute to the forward current. This flows in la amounts with only a few tenths volt drop.

But if now the voltage is reversed, both carrier ty move to increase the width of the pn junction wh becomes a better and better insulator as the voltage raised. Up to the point of reverse breakdown, the v small leakage current is practically constant because t insulating junction gets thicker and thicker. PN junctio have been made to block 2,000 volts and up to 3,0 volts is expected. A PN junction is a semi-conductor dio or rectifier. It is represented in circuits with the famil arrow in direction of forward bias or easy flow. The dio is much used in solid state switching circuits for "an and "or" logic, for preventing sneak paths, and for la parallel arrays.

Single PN junctions are commercially available to co duct up to 250 amp in the forward direction with abo 1 volt drop, and to block voltages up to 1600 volts the reverse direction. The PN junction itself for this rati is a silicon wafer about the size of a dime and about as thick.

Transistors

Now suppose, as in Fig. 3, we take a sm piece of germanium, already doped n type. If we put little indium on two opposite faces, heat to about 600 d C to melt the indium, it will alloy and make both t and bottom p type. We now have two pn junctions wi the n type germanium common to both, all in a sing crystal. This center n region we call the base. This mak a pnp transistor. We could make an npn transistor if w started p type and injected arsenic at the two faces. We' talk only about pnp transistors in this paper, but if w reversed the polarities of applied voltages, our circui would fit npn's.

Electrically, this behaves somewhat like two diode face to face as it were. (See Fig. 4.) Either can act as a independent diode to the base. But if one conducts i the direction of easy flow or forward bias, it floods th central negative region with positive carriers, and th second diode can then conduct readily in the revers direction, which is the easy flow direction for the positiv carriers now in the base. We say the transistor turns o or is a closed switch. If we remove or reverse the voltag to the base, the transistor turns off or becomes an ope switch. The end region conducting in the forward direction we call the emitter because it emits or supplie positive carriers to the base and the other end the collector because it collects positive carriers from the bas to furnish current in the output circuit.

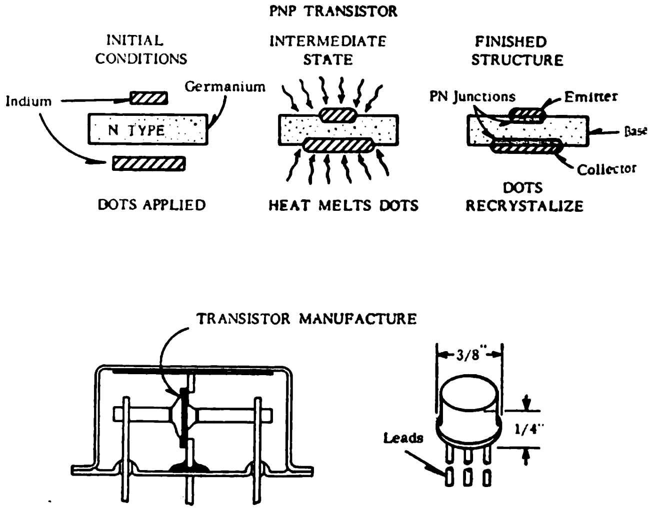
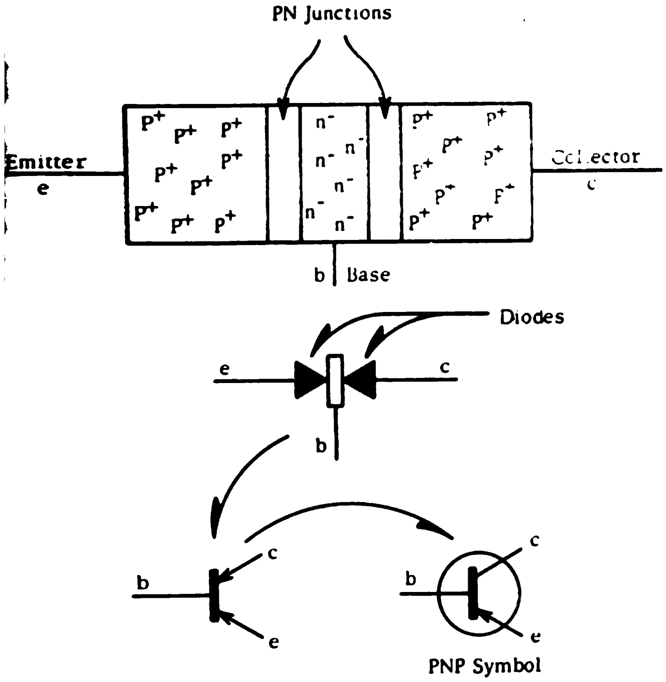
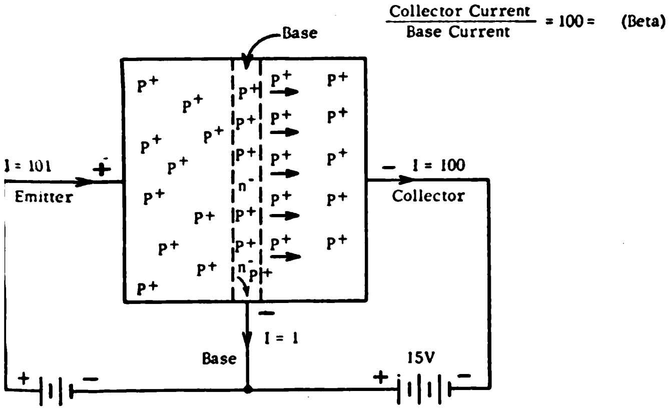


FIGURE 3



TRANSISTOR EQUIVALENTS

IGURE 4

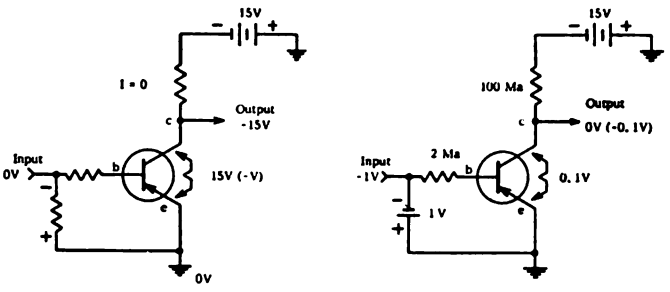


TRANSISTOR CURRENT AMPLIFICATION

FIGURE 5

By proper choice of base region geometry, shown in Fig. 5, that is by making the forward path emitter to base lead long and narrow, and the reverse biased path emitter junction to collector wide and short, the positive carriers flooding the base can drift (diffuse) to the collector pn junction much easier than to the base terminal, so that perhaps 100 times as many might go there and be swept into the collector, and we can get a collector current 100 times bigger than the base current. We call this factor, 100 in the example, the Beta of the transistor. This may vary from less than 5 to several hundred. Transistors are primarily current-operated devices in contrast to tubes which are voltage-operated. A new type transistor called Field Effect Transistor behaves much like tubes, but so far this has had little application.

If a transistor has no forward voltage on the input diode, no current flows; no input power, no output power. (See Fig. 6.) If turned on or conducting, a transistor might have 1 forward volt and 2 ma in the base input circuit or 2 mw. The output could be 100 ma at 15 volts or 1500 mw, so we have an amplifier multiplying input power by 750.



emitter diode - no bias
no current
Input 0V, Output -15V (-0V to -15V)

emitter diode - forward biased
Power in = 2 mw
Power out = 15V x 100 ma = 1500 mw
Power amplification = 750 times

POWER AMPLIFICATION

FIGURE 6

This amplification is a big factor in simplifying transistor switching circuits, for the switching provides at the same time amplification, and few auxiliary amplifiers are needed. If cascaded control switching is by diodes only, added amplifiers would be needed often.

Switching Logic—Relays Signal and control circuits need essentially four elements, "and" circuits, "or" circuits, "not" circuits, and "memory" circuits. You are familiar with these circuits in interlocking and control, although perhaps not by these names. In time sequenced circuits, we also need delay, which may be provided by capacitor-resistor circuits or by sequential pulses.

An "and" circuit, Fig. 7, is one where the output depends upon every input being present. A load fed through a string of relay front contacts in series would be an example, for load current can flow only if every relay is energized.

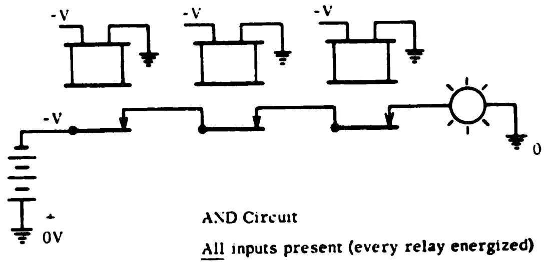
On the other hand, the output of an "or" circuit occurs when any one input is applied. A load fed through a number of relay front contacts in parallel is an "or" circuit, for if any one or more relays is energized load current flows.

The "not" circuit or inverter, Fig. 8, is one where an input produces no output, or no input produces an output. A load controlled on a relay back contact is a "not" circuit for if the relay is energized the load is open, but if the relay is not energized load current flows.

Memory circuits remember a momentary input, i.e., an output remains after the input is removed. A relay stuck over its own front contact as in Fig. 8, is a memory circuit, for it remembers an input pulse until the stick circuit is opened.

In relay circuits, inputs are relays, energized or not, and outputs are front or back contacts. Most transistor-diode switching for control circuits uses voltage level logic. A certain small range of voltage may be considered an input or output, and another range represents no input or no output. Thus we can call zero volts 0V (actually ±1V), one range or level and call −V (actually −6V to −15V) another. These values suit transistors and are representative in many switching systems. We can arbitrarily choose either range for an input or an output, and vary our choice throughout a system if we choose.

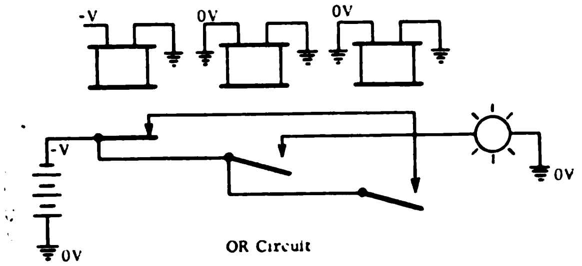
A useful characteristic of "and" and "or" circuits is that if we change our definition of which voltage range we consider an input, and change which range we consider an output then the "and" circuits become "or" circuits and vice versa. This is illustrated in Fig. 9. A series string of front contacts, or "and" circuit, (every relay energized) puts energy on output load and we have a normal "and" circuit. But if we call 0V or ground the input, the output



AND Circuit

All inputs present (every relay energized)

Output present (lamp lights)

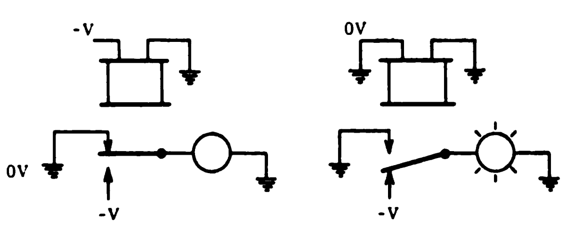


OR Circuit

Any input present (any relay energized)

Output present (lamp lights)

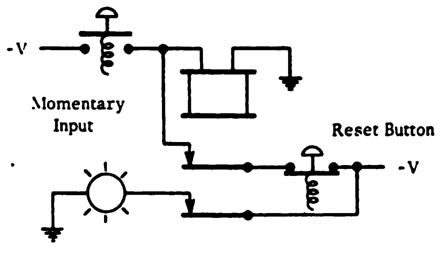
FIGURE 7



INVERTER OR NOT CIRCUIT

Input Present
No Output (Lamp Out)

No Input Present
Output (Lamp Lit)

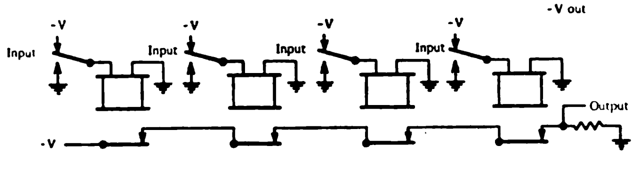


MEMORY CIRCUIT - Stick Relay

Output remembers momentary input

Can be reset by opening stick current

FIGURE 8



Direct Outputs
And Circuit
-V in (Every Input)
-V out

Or Circuit
-0V in (Any)
0V out

DUAL USE CIRCUIT

FIGURE 9

is 0V for any input 0V, and we have an ordinary “ circuit by this definition of input.

Or we can consider a parallel relay contact circ shown in Fig. 10, where any closed switch shorts the o put voltage to ground. This results in the output bei inverted or the opposite voltage range from the inp You'll note this can be either “or (nor)” with energiz relays or “and (nand)” with 0V as input. This is a dir analog of pnp transistor “nor” circuitry, where with —V the base, the switch is closed or the transistor turns and with 0V on the base, the switch is open as the transi tor turns off.

A purist calls this a “nor (not or)” or “nand (not and circuit because the output voltage range is inverted *Not* the input, but it may be used readily to suppl “and” and “or” functions in switching with proper regar to defining inputs and outputs. Usually any system co dition has available a choice of either voltage level a sociated with it as on the two output leads of flip flops and if only one is at hand and the other is wanted, transistor inverter can always supply it. This is sometime called DOUBLE RAIL LOGIC.

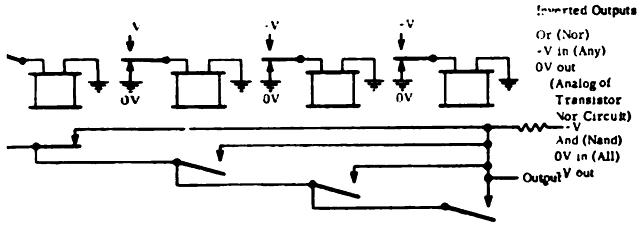
“Nor” circuitry, Fig. 11, is a very useful and economica way to do “and” and “or” transistor switching. It use parallel inputs to the base circuit, and defines the desire output as inverted, i.e., the opposite level from input Note that the same circuit with —V inputs may be use for “or” logic and with 0V inputs for “and” logic with pnp transistors as here. If a single input is used, the “nor” circui is an inverter or “*not*” circuit, for the output is the voltag range *not* the input.

The resistor to ±15V is for reverse bias, or to be sure the transistor is off with 0V (±1V) input especially at high temperatures. Bias is usually provided, althoug omitted for simplicity in many sketches shown here.

We should note that this transistor circuit, using only 1 transistor and six input resistors, fulfills the switching function of 6 contacts, each on a separate relay. If diodes were used instead of resistors in input circuits, there is practically no limit to the number of permissible inputs to a single transistor.

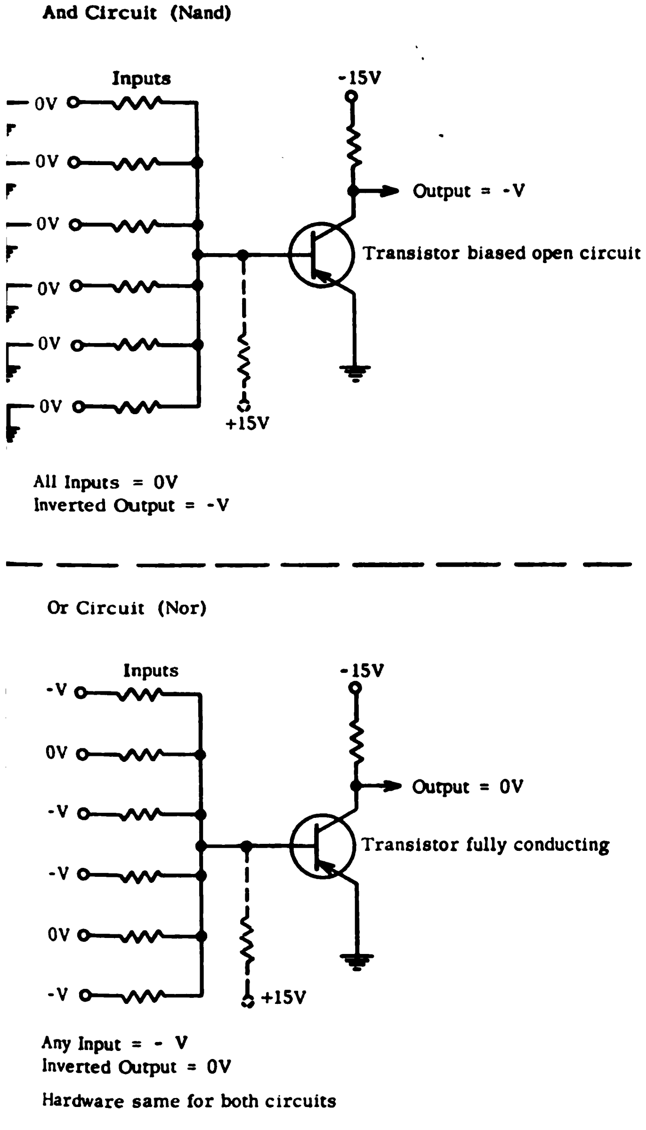
We can now see one of the very important differences between relays and transistors used for control switching. A relay is a device with only one or at most a very few energizing windings or inputs, but it can have as many isolated output circuits as contacts. A transistor can easily and economically have as many effectively isolated inputs as a designer could wish, but it has only one output. And the output has a common electrical connection with the input. Several circuits could be fed in parallel from the output, but there would be no electrical isolation between them. In usual transistor control circuits a common return connection exists throughout a large network. This is why it is not always satisfactory to substitute transistors as a quick fix for part of a relay system, say the high speed coding relays whose contacts wear out first. Circuit isolation, normal in relay circuits, can be achieved with transistors but at the expense of a great many additional and some relatively expensive circuit elements such as transformers, rectifiers, and AC-fed power supplies. It is much easier to make the sytem all transistorized up to the final outputs, which may then conveniently be relays, if desired. A word of caution here—if a solid state system feeds to or from a relay system, separate and carefully isolated power supplies should be used for each. Solid state circuits operate on pulses of a few volts, and inductive kicks and undesired transients from relays may be hundreds of volts.

Probably a single battery supply could be used if relays and solid state systems were initially designed to work together, with adequate power supply filters to each. But,



INVERTED DUAL USE CIRCUIT

URE 10



NOR CIRCUIT

FIGURE 11

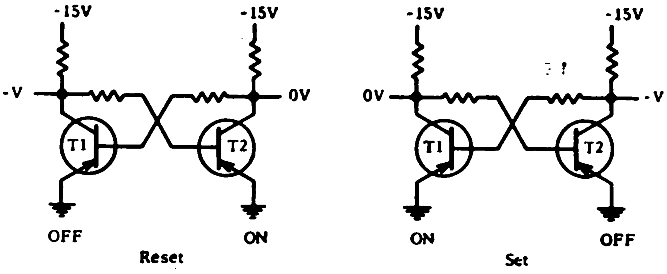
it is undesirable to attempt to use existing relay system batteries directly for power supply to solid state switching circuits. A DC-DC converter interposed provides satisfactory isolation.

Flip-Flops or Memory Consider our switching transistor used for "nor" logic. When we put a —V input to the base, the transistor conducted fully, or was on, and practically 0V appeared on the collector or output since the transistor was shorted to ground. If we put 0V on the base input, the transistor was non-conducting or off and the output or collector terminal was connected only to —15V supply and —V appeared on it. If, as in Fig. 12, we cross-connect two such transistors, collector to base through resistors, we can see conditions are such that one will be on and the other will be off. This is called a flip-flop. We arbitrarily say the flip-flop is set when the left-hand transistor, T1, is on, or reset when the right-hand transistor, T2, is on. It will remain in either state until it receives a momentary input to change it. The flip-flop is widely used for solid state memory.

If we wanted to change it so the conducting one turns off and the other one turns on, we can do it in several ways as shown in Fig. 13. If we connect the base of the nonconducting one to —V, it will conduct, and when its collector goes to 0V, it will turn off the other. Or we can put a positive pulse on the base of the conducting one, which will turn it off momentarily, and this will put a —V on the other's base which turns it on and holds the first one off. These operations can be repeated at will to set or reset the flip-flop depending on the input connected to the signal.

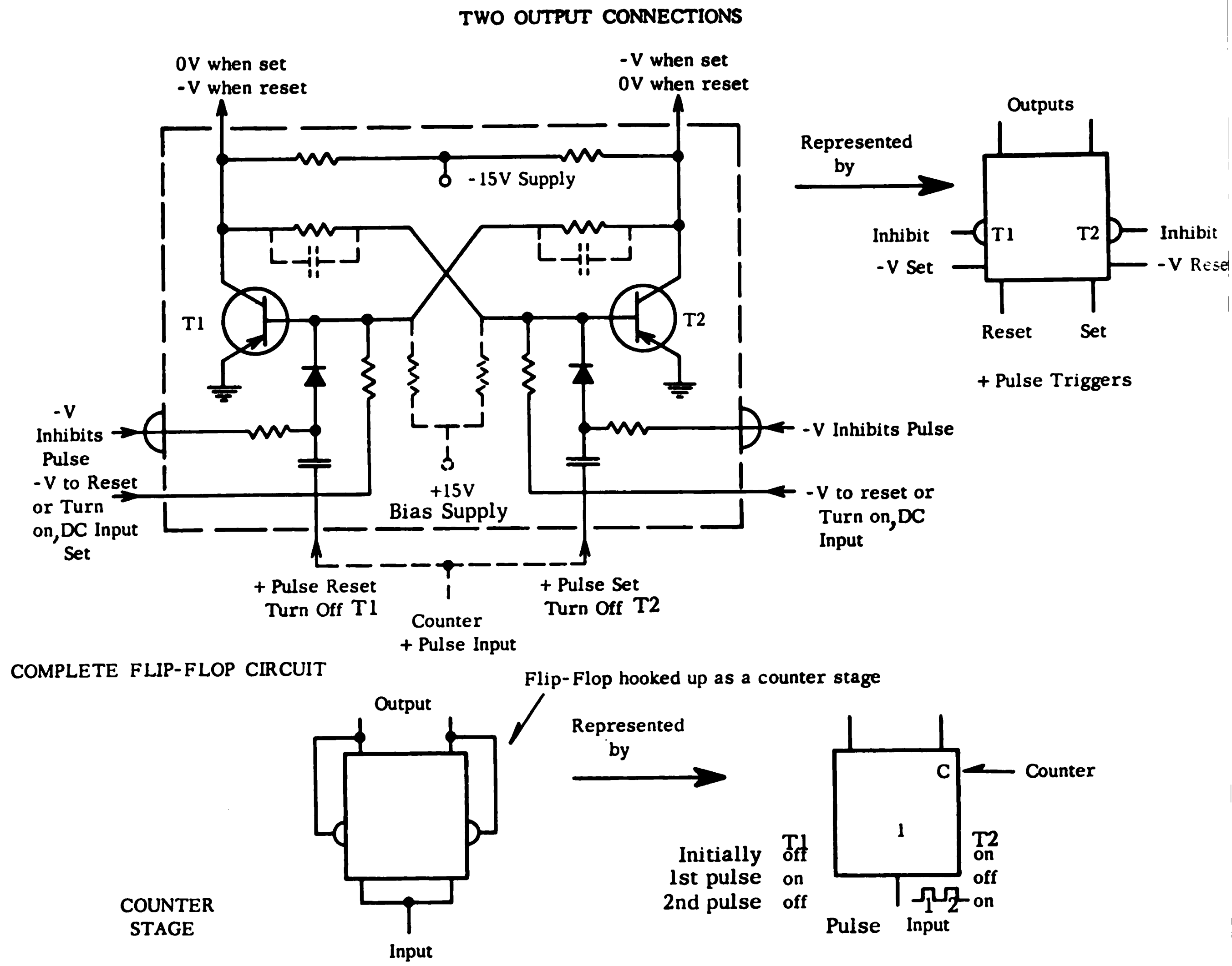
If we look at the positive pulse turn off, we see that the conducting base is close to 0V, only a few tenths of a volt, slightly negative. A positive pulse or change of only a fraction of a volt positive can turn it off, or back-bias the emitter-base rectifier. Now, if this positive pulse is fed through a condenser and a separate series diode, and we put the connection, diode to condenser terminal, at —V, then any positive-going pulse whose absolute peak amplitude was less than —V could not raise the condenser output to 0V, and no pulse gets past the reverse biased diode. The state of the flip-flop cannot be changed. This is an "inhibit" or prevent connection, and is crucial in making gates, counters, and shift registers from flip-flops. In the examples we are considering, a —V on the inhibit prevents the positive pulse from reaching the base. If —V is on the inhibit, the pulse can pass normally to turn off the transistor. The inhibit connection is shown by the small semi-circle to which a lead may be attached.

Counters If we connect a flip-flop with each transistor's output to its inhibit, as shown in Fig. 13, and tie together the set and reset pulse inputs, a pulse on the input can only pass to the side where inhibit input is 0V, and this is where that transistor is on, so the pulse turns off that transistor and that turns on the other and the flip-flop changes state. Now if we put another similar pulse on the same input lead, the inhibit conditions are reversed, and the pulse turns off the transistor just turned on and we're back to the original condition. Thus every two pulses the flip-flop goes through an on-off cycle back to its original state. When the transistor goes from off to on, its output lead goes —V to 0V, or a positive-going pulse, and if this is fed through a



FLIP-FLOP CIRCUIT

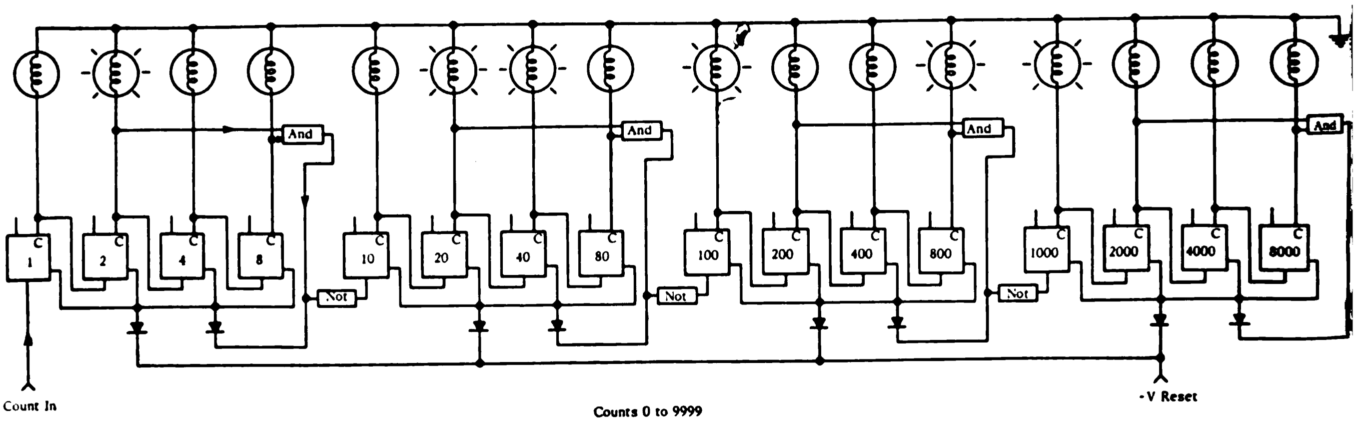
FIGURE 12



COMPLETE FLIP-FLOP CIRCUIT

COUNTER STAGE

FIGURE 13



Counts 0 to 9999

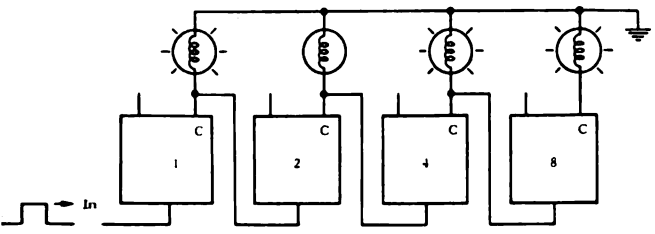
As shown reading from right to left - 1962.

BINARY CODED DECIMAL OR BCD COUNTER

FIGURE 15

condenser with output side initially at 0V we get a positive pulse. Connecting flip-flops as shown in Fig. 14 makes a *binary counter*. Any number of stages may be used, and the count doubles each stage. First pulse sets No. 1, second pulse resets it, but the output pulse from turn-on of right-hand transistor sets No. 2, third pulse sets No. 1, but does not change No. 2, the fourth pulse resets No. 1, this second positive-going pulse to No. 2 resets it and this sets the third flip-flop to count 4 and so on for as many stages as we wish.

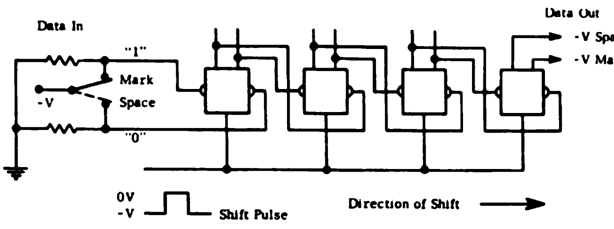
Four counter stages as shown in Fig. 15 could readily be connected so they would all reset at count of ten instead of 16, and then we could count in the decimal system or binary coded decimal, BCD, as it is called. Another four flip-flops could count by 10's from 10-90, using the first group's reset pulse, another group by 100's from



BINARY COUNTER

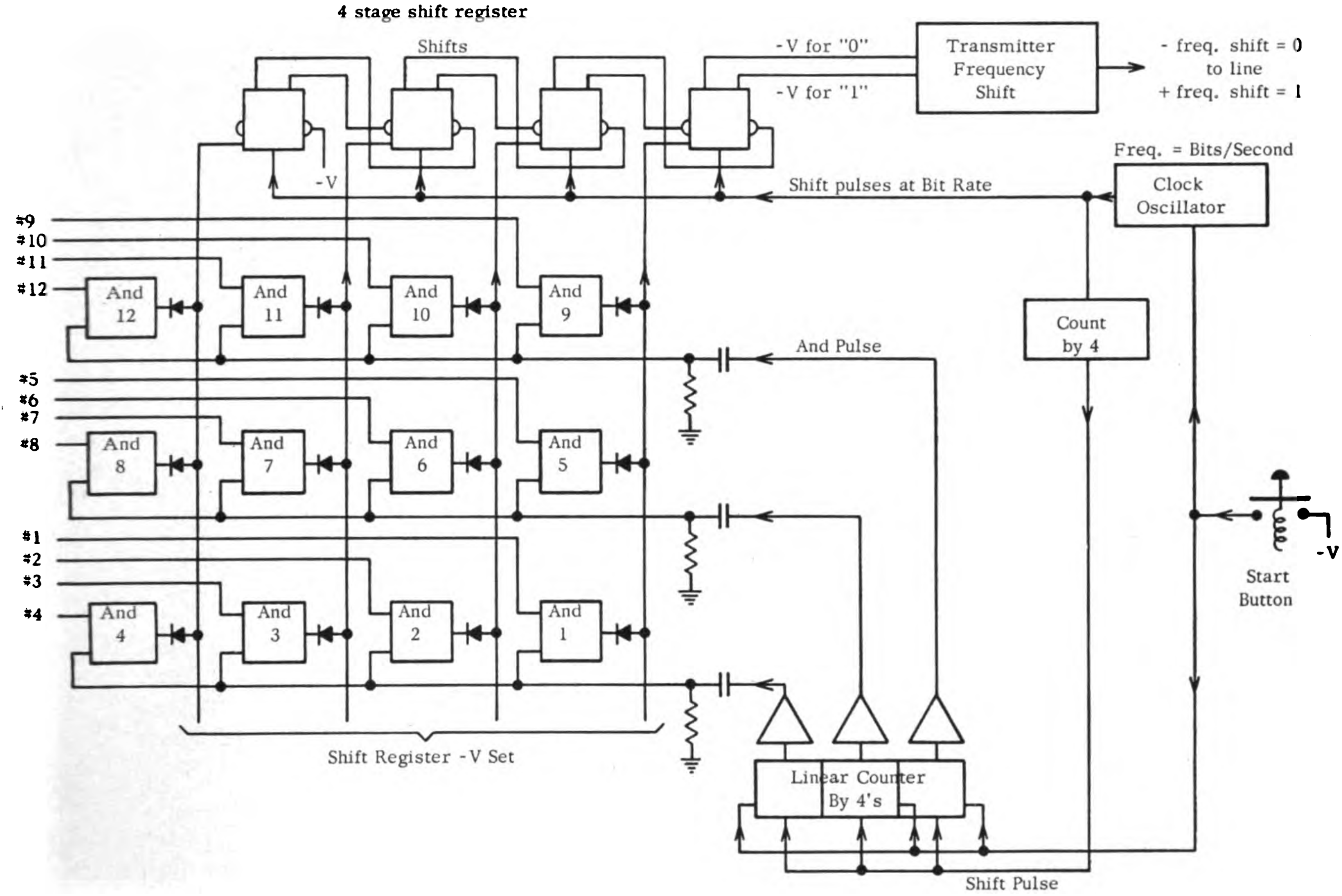
Count = Sum of values of lighted lamps = 13

GURE 14



SHIFT REGISTER

FIGURE 16



CODE SYSTEM - SENDING END

IGURE 17

100 to 900 from the second group's reset and so on. If you had indicating lights to show which flip-flops are set, you could readily read the number stored by adding the values marked on each lighted lamp. The counter shown reads 1962.

Information as Bits A single yes-no decision, relays up or down, flip-flop set or reset, is called a *binary digit* or *bit*. In logic, a bit is "1" if yes, "0" if no. Any amount or kind of information may be represented by bits with suitable coding. A flip-flop stores a single bit.

Shift Registers Another useful device is the Shift Register, Fig. 16. Here a number of flip-flops are connected as shown. A bit is stored in the first flip-flop. Then a positive-going pulse is applied to the shift input bus. The shift bus is connected in parallel to all of the same flip-flop inputs as used for the counter. Voltage levels from the first stage's output to the second stage's inhibit connections are connected so the pulse positions the second flip-flop in the same state as the first was before the pulse. At the same time the first stage can accept another bit from the data source. So now we have the first bit in the second stage and a second bit in the first stage. By continuing the same cycle, we can store in the register as many bits of information as there are flip-flops, and all have been fed serially into the first stage. When the register is full, the first bit will be in the last stage, and the last in the first. It receives and stores a serial bit message.

If we wish to put this information in other storage, we can switch all of it in parallel with a single pulse into a new set of storage flip-flops.

The shift register may just as easily all be filled in parallel at a single instant and the last stage connected to feed a serial transmission by subsequent shift pulses.

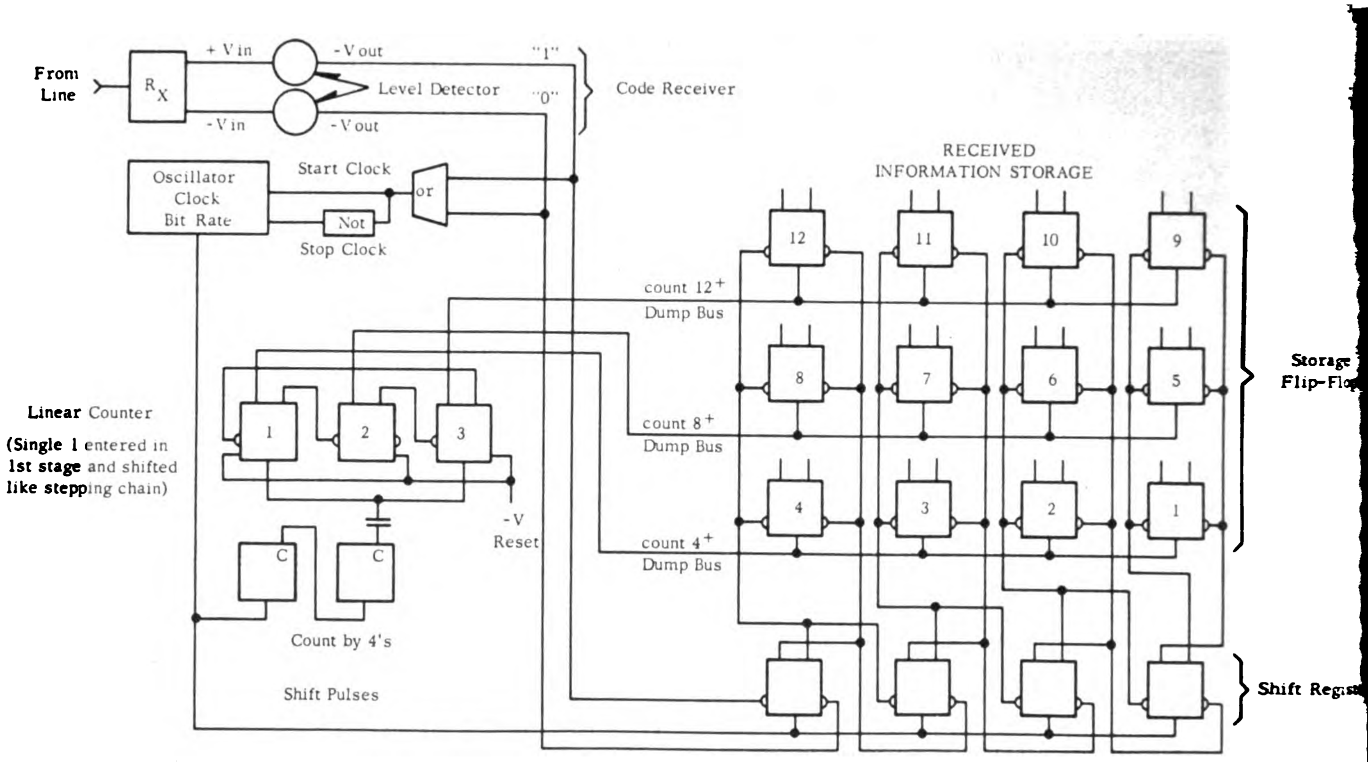
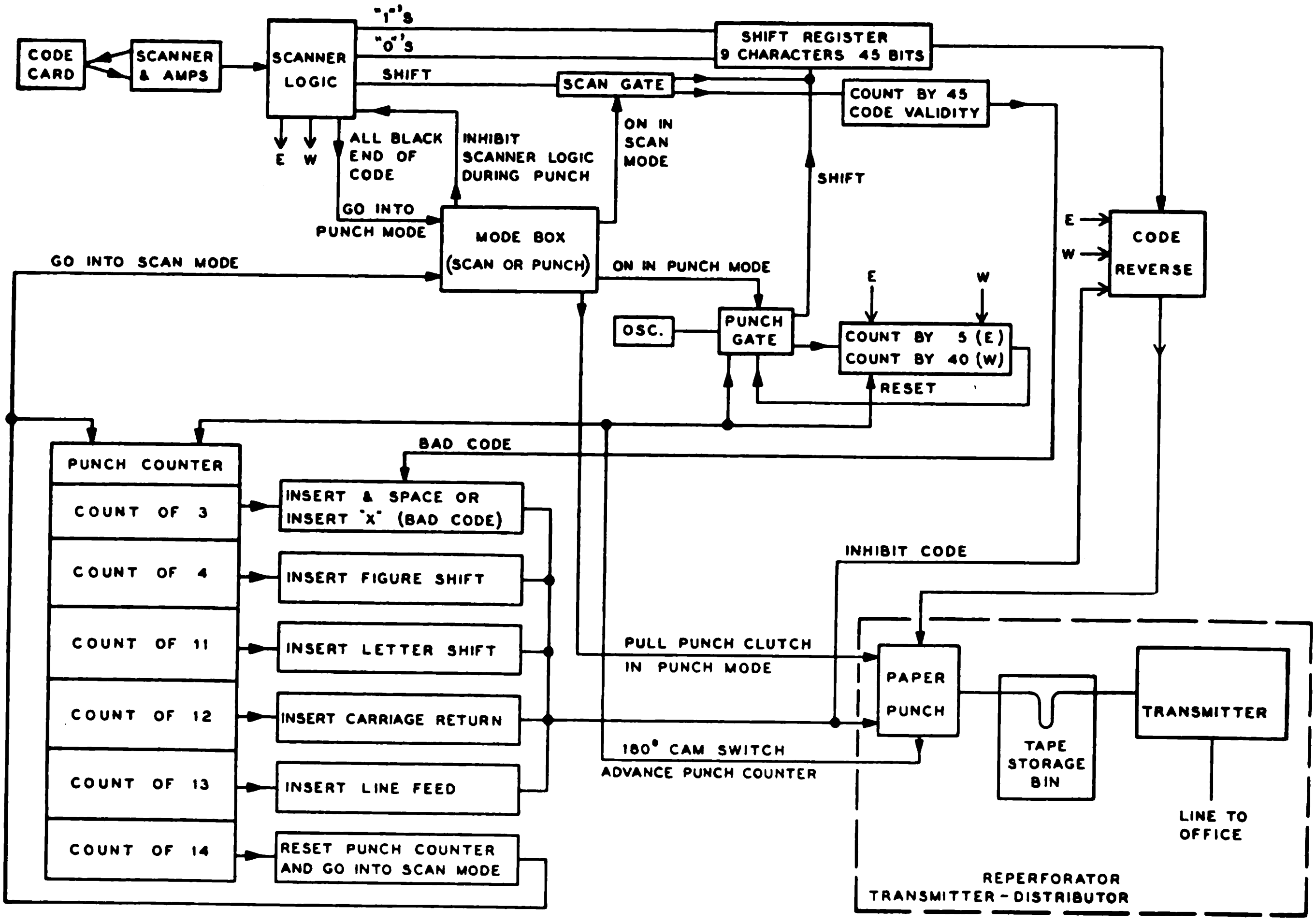


FIGURE 18

CODE SYSTEM - RECEIVING END



MAIN LOGIC DIAGRAM FOR CAR IDENTIFICATION SYSTEM

FIGURE 19

ode Systems A typical code system at the trans-
itting end could be as shown in Fig. 17. When the start
itton is pressed, pulse operated "and" circuits load the
ift register with the first 4 bits. The clock or timer puts
it a shift pulse for each bit at the desired bits/second
te. Teletype machines have synchronous start-stop timers
clocks to separate the 5 bits in a character. In the sys-
m shown the clock runs continuously throughout the
essage. Each pulse feeds an information bit from the
ght-hand end of the shift register to key the FST trans-
itter, either + or — shift. Every 4 pulses the shift register
filled in parallel with new data from the next group of
inputs. This fill pulse comes from the count-by-four input
the linear counter, solid state equivalent of a stepping
ain. In the linear counter, a single bit is shifted to the
xt stage by each pulse from the count-by-four counter,
d the pulse from this shift gates its respective group of 4
to the shift register at the proper time, intermediate to the
ift register's shift pulses. This may be obtained by using
e positive half cycle of clock AC to produce a shift pulse,
d using the negative half cycle to produce intermediate
ulses.

The receiving end, Fig. 18, is very similar. The crystal-
ntrolled clock or pulse timer starts when the first bit of
e message arrives and runs at the same rate as the trans-
itter clock. After four bits are shifted into the register,
e received data is stored in groups of 4 by pulsing
orage flip-flops with inhibits connected to the outputs
f the shift register. Of course, a complete system has a
reat deal more circuitry for additional capability, but
e same types of elements are used.

nion Car Identification In the block diagram,
ig. 19, of the Union car number identification system,
car-carried code plate is scanned by a solid state photo
etector whose output supplies proper voltage levels to
osition the input shift register to store a bit. It also
roduces shift pulses at the proper time to shift the in-
ormation one stage and register a new bit. If a letter or
ecimal digit is represented in a 5-bit code, 9 characters
ill the 45 stage shift register. A counter counts 45 to
heck that the identification has the correct number of
its.

When the read-in is complete and the car number is all
n the shift register, it is dumped to a tape punch, 5 bits
t a time, and each shift register stage with a "1" or mark
n it, has —V on the right which can operate the proper
unches to perforate the tape. Then 5 rapid shift pulses
rom the clock position the next character, and it can be
unched into the tape and so on until all 9 characters
re stored in a paper tape ready to put on the standard
ommunication facilities. If the detector senses the code
late is being read backward, the switching logic takes
he information from the other end of the shift register
o punch the tape, and shifts the register to suit. A counter
ounts and signals when the correct number of shift pulses
re applied. The scan and punch gates shown are "and"
gates.

Packaging We put this type of switching logic on
Printed circuit boards. One board has 16 transistors, each
with its associated "nor" or half flip-flop circuit in a separate
nylon encased module. It might be used for 16 "and" or "or"
circuits, or for 8 flip-flops, storage, or shift register.

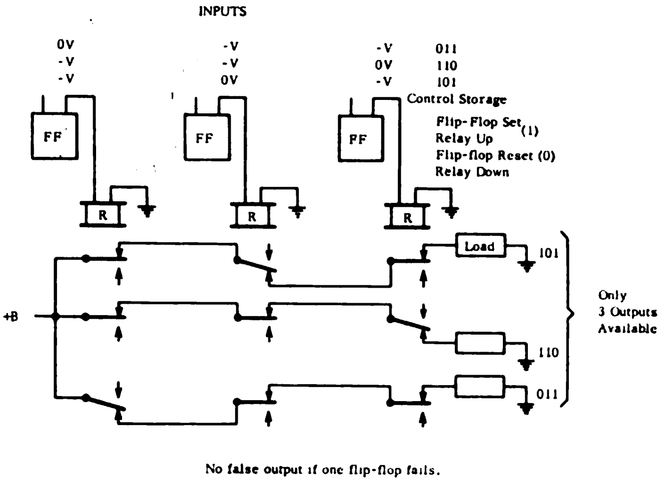
Silicon Controlled Rectifiers So far we have
talked about control and information circuits at relatively
low power. However, if the power supply is DC, such circuits could terminate in a power transistor capable of handling about 30 amp at voltages up to about 200 volts, and 6 kilowatts of power has been switched by such a single 250 watt transistor. This large switching capacity results because the transistor's losses are low if on or off. Only during the actual switching are the transistor's losses high, and this time is usually short compared to repetition time.

For switching relatively large amounts of power, a solid state switch called a silicon controlled rectifier, or an SCR, is available and coming into wide use. Some overlap in ranges exist between SCR's and transistors with about 15 amp as the center of the overlap region. These devices have four layers of alternating P&N type semi-conductor or 3 PN junctions, instead of the two in a transistor. They also have a gate or control terminal similar to a transistor base connection. If the power supply is AC and a DC load is attached, an SCR is now commercially available to rectify and switch up to about 150 amp DC at 600 volts blocking voltage for a single cell SCR. Experimental 500 amp, 800 volt units have been built. This 150 amp unit is only 1¼" dia. by 2¼" long. Four of these in a full wave bridge rectifier circuit could control about 200 kilowatts. For maximum ratings, heat fins or radiators and moving air or water are needed for cooling. Power converters for 750 kilowatts are being designed with SCR's.

For the 150 amp SCR, the low voltage DC gate or turn-on power averages about 1 watt SCR. However, these devices are like a gas tube thyratron. Once conducting, the small gate current loses control and cannot turn them off. The main current must be reversed or reduced to below a very small value to do this. Since a single cell rectifier on AC goes through a voltage reversal every cycle, this will turn them off if the gate current is turned off. Thus DC loads fed from AC power are easy to switch on and off. If you wish to switch large amounts of power from a DC source, special circuits capable of reversing the main current flow must be used. These usually store relatively large amounts of energy in an inductance or capacitor and discharge this energy through the conducting rectifier in the reverse direction to reverse or reduce the current to the turn off point.

These SCR's not only turn heavy power on and off, but when fed from AC and gated with rectified AC from the same supply, they can control the amount of current that flows by turning on the rectifier at different times or phases of the conducting half cycle. Only short DC gate pulses, less than 5 microseconds, are needed for turn on. Continuous variation full load to zero may be obtained.

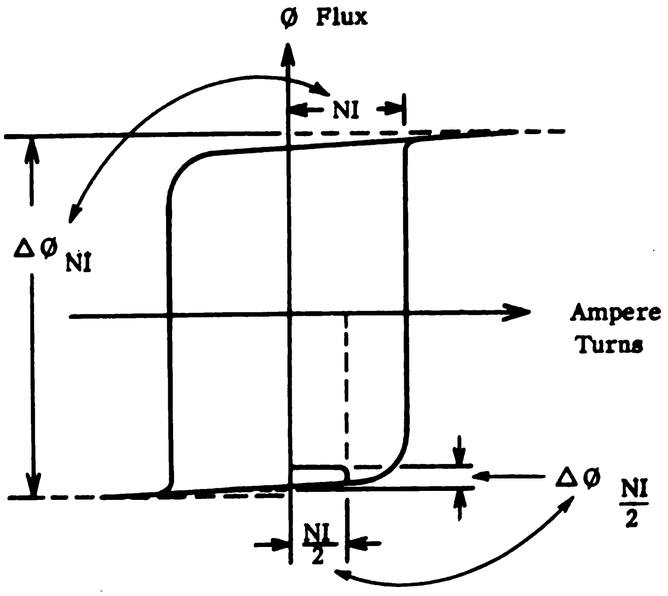
Fail-Safe Circuits To signal and communication men fail-safe circuits are especially important. In supervisory control circuits it is frequently specified that the failure of a single component shall not permit receipt of an erroneous control. Since information is usually stored on flip-flops, and a transistor might short circuit or open to keep a flip-flop in one position so that it will not respond to input information, some protection against a wrong order is needed. One way to provide such protection is to use redundancy such as three bits stored in three separate flip-flops for each control, so arranged that two are logical 1's or flip-flop set, and the other a logical 0 or flip-flop reset. Three bits can give three controls of this type 101, 110, 011. The flip-flops, when set, pick up an output relay. Each output relay has three transfer contacts, so three outputs can be obtained from three separate series strings of contacts as shown in Fig. 20. If you study this circuit you will find that a failure of any single flip-flop cannot falsely operate any of the three control circuits. Three bits can give a maximum of 2^3 or 8 choices. We use only three



No false output if one flip-flop fails.

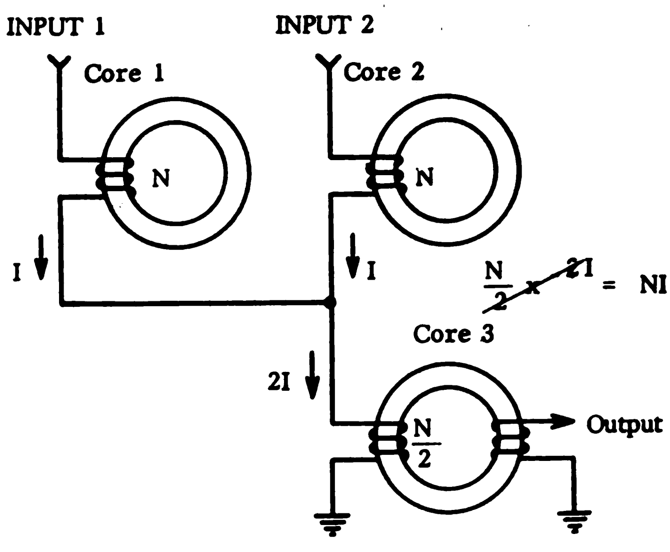
REDUNDANT CIRCUIT

FIGURE 20



SQUARE LOOP FLUX CURVE

FIGURE 21



FAIL-SAFE 2-INPUT "AND" CIRCUIT

FIGURE 22

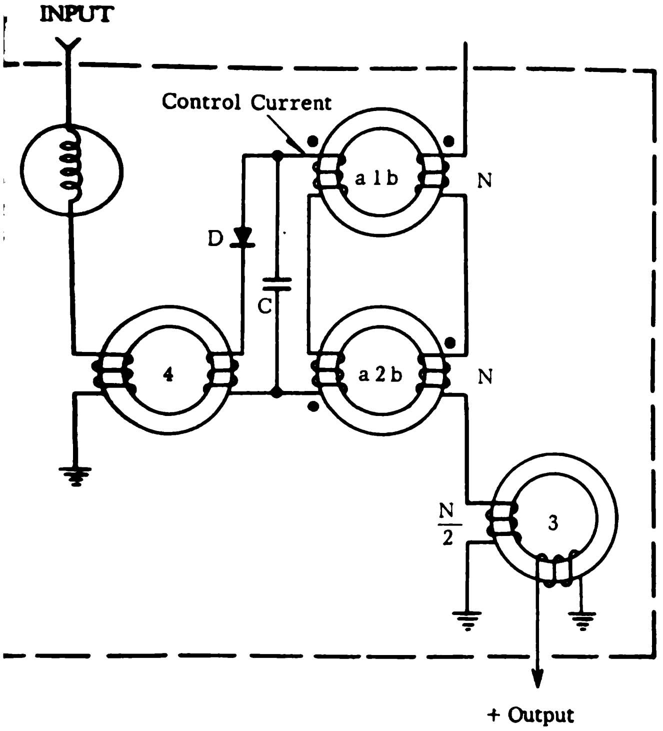
of these to obtain protection in this manner, so we this is redundant, or more than the minimum number bits needed for three choices.

Another fail-safe circuit could depend upon the co tinual high speed repetitive receipt of a control sto only for system cycle time. The control affected is peated back to the source, and checked for identity w the order before repetition. If check fails, repetition sto and the system goes to the most restrictive condition. So state systems can transmit at high speeds. An example the Union 540 code system which performed for mont on field test in the New York Subway at 2,000 bi second. This would permit over 500 bits or yes-no ord transmitted, checked back and repeated once ev second. You will see that this philosophy is the same the continuous coding required for a clear indication in t continuous cab signal systems widely installed where failure of the repetition changes the signal to the mo restrictive. But because of the relatively very high spe of solid state circuits, very much more information co be transmitted in an acceptably short time in a fail-sa manner. Relay systems handle up to about 100 bit second. Ferrite core logic switching may be good to 5,00 bits/second. Transistors can go to 5,000,000 bits/secon and high speed micro diodes switch at 100 million cycle second. With some solid state devices, switching ca be done in less than a billionth of a second.

A railroad installation using another approach to fai safe signaling was made about the first of last year. This i a solid state system for route logic control of Henley-on Thames 8-exit interlocking on the Western Region of th British Railways about 35 miles west of London. *(RSC Sept. 1962 page 13.)* This circuit philosophy was first developed by members of the electrical engineering de partment of the Imperial College of Science and Technology. The objective of the system is to provide fail-safe solid state logical components which provide the functions and safety of vital relays. Originally, it did not use transistors except in the power supply, and used diodes only where a loss of their rectifying property, either by short or open gives no output signal. A short or open of a condenser also gives no output signal. The two voltage states of the logic are for clear or logical "1" an AC voltage E originally 20 volts at 30 kc. The fail-safe or logical "0" is ground potential or zero volts (0V). The switching logic is performed principally with ferrite toroidal cores of the square loop type. A ferrite is a mixture of iron oxide and other metallic oxides which is highly magnetic and readily carries flux, but has very high resistivity, so it may be used with little eddy current loss at much higher frequencies than iron. This permits a winding of a few turns with little chance of shorts, on a small core to have relatively large induced voltages at the high frequencies used.

A characteristic of these square loop cores, Fig. 21, is that as you apply magnetizing force or ampere turns on a winding, practically no change in flux occurs until you reach a critical value of ampere turns. With a fixed voltage and frequency and a proper number of turns on the coil it will permit only a constant magnetizing current sufficient to switch the core between + and − magnetization. If a secondary winding is applied, a voltage will appear on it in the same way as any transformer. The loading effect is kept small compared to the magnetizing power. Now if this same current is passed through a winding an another similar core with only half as many turns, the magnetizing force is only half as much, very little change in flux occurs, so there is practically no output on a secondary winding on the latter core.

But, if we have two input cores, 1 and 2, and combine their currents, as in the ferrite "and" circuit shown in Fig. 22, twice the current times half the turns gives the



AMPLIFIER

IGURE 23

iagnetizing force that will completely switch core 3, and n output voltage appears on output winding. If any windng opens, no output can occur. The windings of only a ew turns can be made extremely unlikely to short. This nakes a 2-input "and" gate. By using this "and" output s one input to a second "and" gate, three inputs are btained and so on.

In such a system, power is dissipated through the logic, o amplifiers are needed to restore the signal. The amlifier, Fig. 23, for this purpose uses magnetic amplifier rinciples but in connection with square loop cores and fail-safe use of diodes and capacitors. A signal input s rectified by the diode, and the DC used to saturate ores 1 and 2. This reduces the impedance of their "b" vindings and bus power gets through to energize core , the output transformer. If the diode or capacitor open r shorts, the saturating DC is reduced so far it will not aturate cores 1 and 2 which become high impedance nd de-energize the output transformer. AC alone will not saturate the cores. Bus power at E supplies no current in the diode circuit because the "a" windings on cores 1 and 2 are poled equal and opposite.

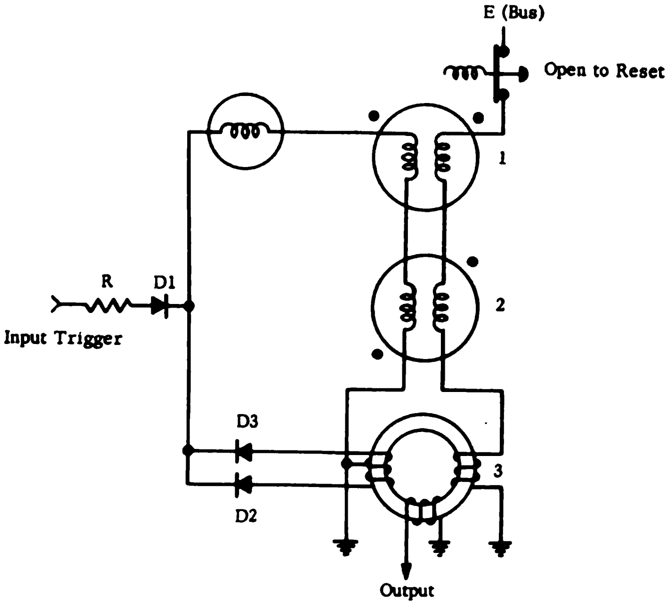
Another need is memory. This we can get as in Fig. 24, by letting a rectified input current pulse through D1 momentarily saturate the cores and so reduce the impedance of two saturable reactors, 1 and 2, because of the DC in their control windings permitting the energization of an output transformer 3 by bus power E. A center tapped output winding on core 3 in connection with two diodes D2 and D3 supplies full wave rectified DC to maintain core saturation of 1 and 2, and hence, an output voltage until power supply at E is opened. If E is reclosed, there will be no output until another set pulse is received at trigger input, because opening E restores the windings of cores 1 and 2 to the high impedance state.

The descriptions above fit the early work done at London University's Imperial College. Later developments by Mullard are incorporated at Henley. The AC power supply is 5 kc square wave. The 2 input "and" circuit is a single core with a midtapped input or primary winding with a separate input applied to each half through a separate transistor in series. Individual inputs to each half are necessary to fully switch the core for an output voltage to appear on the secondary. Since transistors are used only in the continuous AC switching, or half wave rectification mode, any open or short in them fails safe because of the loss of their rectifying and impedance changing properties.

By such square loop core circuits we can get about all the control elements we need for fail-safe circuitry. These circuits can be economical because the cores, transistors, diodes and condensers are inexpensive. The components can be made small. However, margins of operation and voltage regulation are closer and need tighter control than with the transistor digital circuits described, and because of the basic "and" gate limited to 2 inputs, many more gates are required than with multi-input "nor" gates.

We have now talked about solid state semi-conductors, pn junctions which form diodes, transistors, and SCR's and the application of these to logic or control switching. We've provided the needed basic "and", "or", "not", and "memory" functions. How these are applied to practical code control, indication, and information processing systems was shown. Heavy currents may be switched and controlled with silicon controlled rectifiers. Three techniques useful in fail-safe circuitry were described. Many other solid state switching circuits are available, but the ones discussed are among the most common.

Solid state devices have no moving parts, no filaments, no glass envelopes. They can stand lots of shock and vibration. They make small, rugged, and highly reliable devices leading to entirely new types of control and information systems. They are basically very fast switches, several thousand times faster than relays. This permits handling a great deal more information in short times, and thus permits high redundancy to give high freedom from error. And even where satisfactory competitive relay circuits exist in complex switching circuits, there is a likelihood that solid state circuits may become more economical. However, many cases arise where relays are the logical economic choice over solid state, and railroad signal and communication people should look to both for their switching needs. RSC



FAIL-SAFE MEMORY CIRCUIT

FIGURE 24