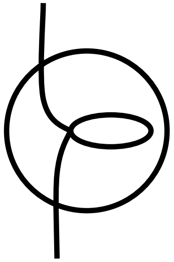
Mechatronics

Topic #8

Actuators: Principle of operation & BS2 interfacing

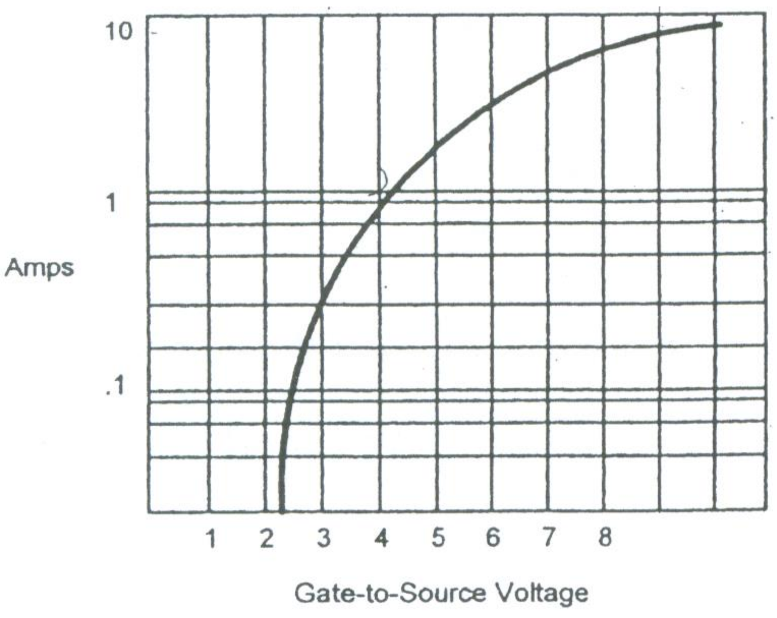
Controlling Outputs using BS2: Incandescent Lamp

- Incandescent lamps draw significantly more current than the safe current supply limit of BS2.
  - To control an incandescent lamp using BS2, some intermediate high current drive circuitry is needed.
  - Example: use an IRF511 MOSFET to deliver the current required by incandescent lamp.
- IRF511 MOSFET:
  - It can provide several amps of current to devices such as incandescent lamp/relay/solenoid.
  - It is an N-channel enchantment type MOSFET.
    - $\rightarrow$ High @ gate w.r.t. source turns ON the drain-source pair.



IRF511 Characteristics

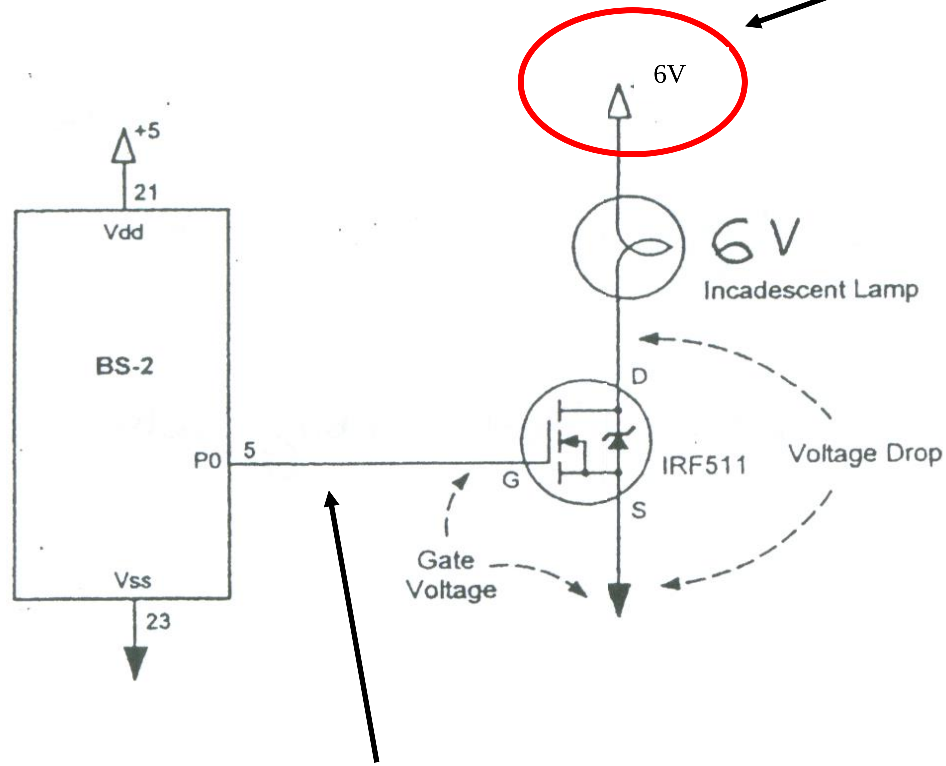
- By increasing V_{GS} applied on IRF511, larger current can be drawn from IRF511!
  - When V_{GS}=0, IRF511 is OFF.
  - When V_{GS} is say 5V, IRF511 can drive a device requiring up to 2Amp current.



IRF511's I/O characteristics

Controlling Incandescent Lamp using BS2

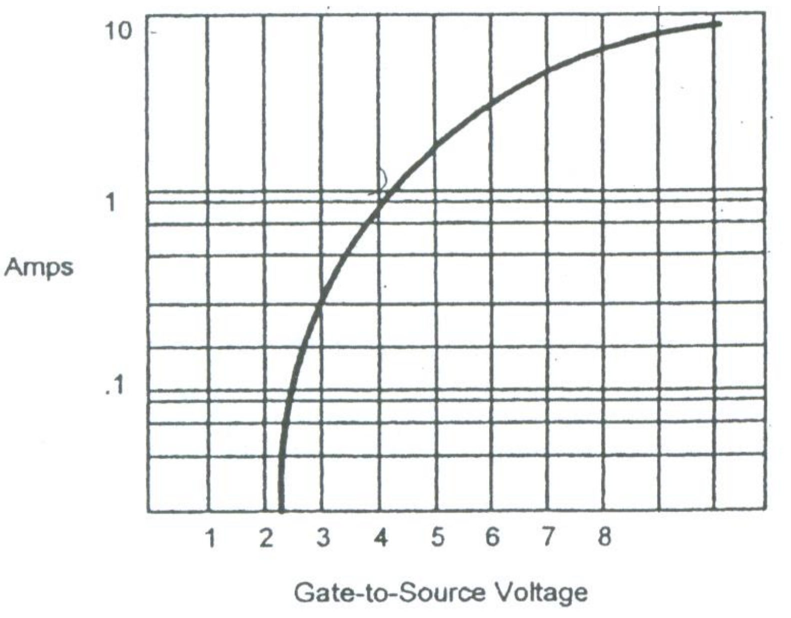
Use a voltage regulator with high current capability. “Do not” use +5V of BS2.



A high signal applied to the gate results in a very low “on-state” resistance, which results in a low voltage drop.

Exploiting IRF511 High Current Drive Capability

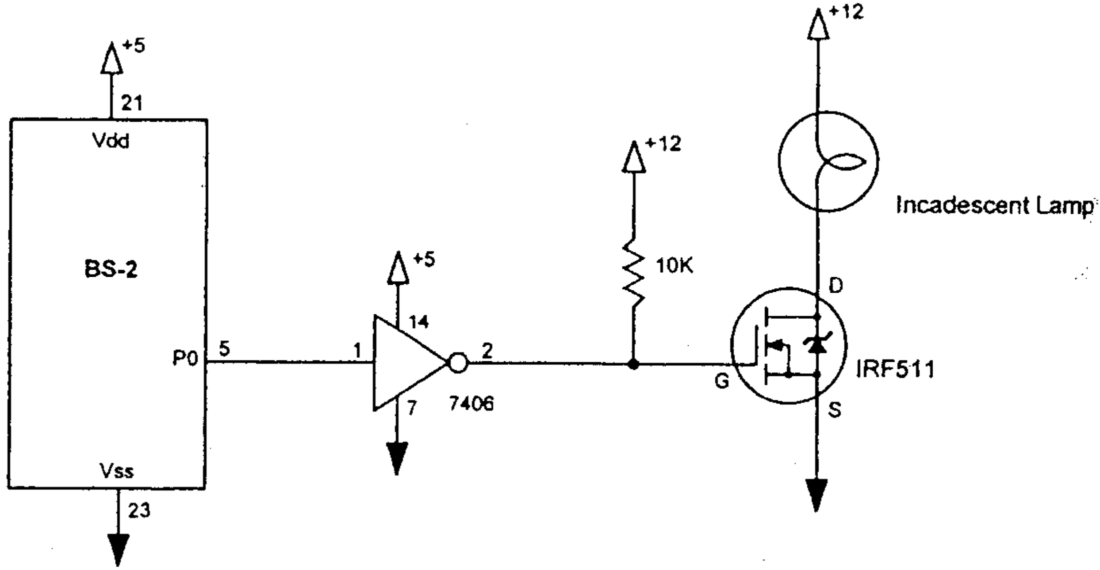
- To interface IRF511 MOSFET with BS2, we normally connect IRF511's source to ground and control its gate by BS2.
- Since BS2 can apply only low and high signals, when BS2 is driven high we have V_{GS}=5V.
  - Note that with V_{GS}=5V, IRF511 can yield ≈2Amp to drive loads.
  - Thus, when BS2 is used to control IRF511, we can achieve only limited current drive capability from IRF511.
- In order to drive loads requiring higher current, one must increase the gate voltage of IRF511 beyond the 5V limit imposed by BS2, i.e., V_{GS}>>5V.
- One solution to this problem is to use a 7406 IC.
  - 7406 IC is a high voltage, open-collector inverting buffer.
  - It requires 5 volts at its input to turn on.
  - It is a TTL type IC whose output can be connected to up to 30 V DC.



IRF511's I/O characteristics

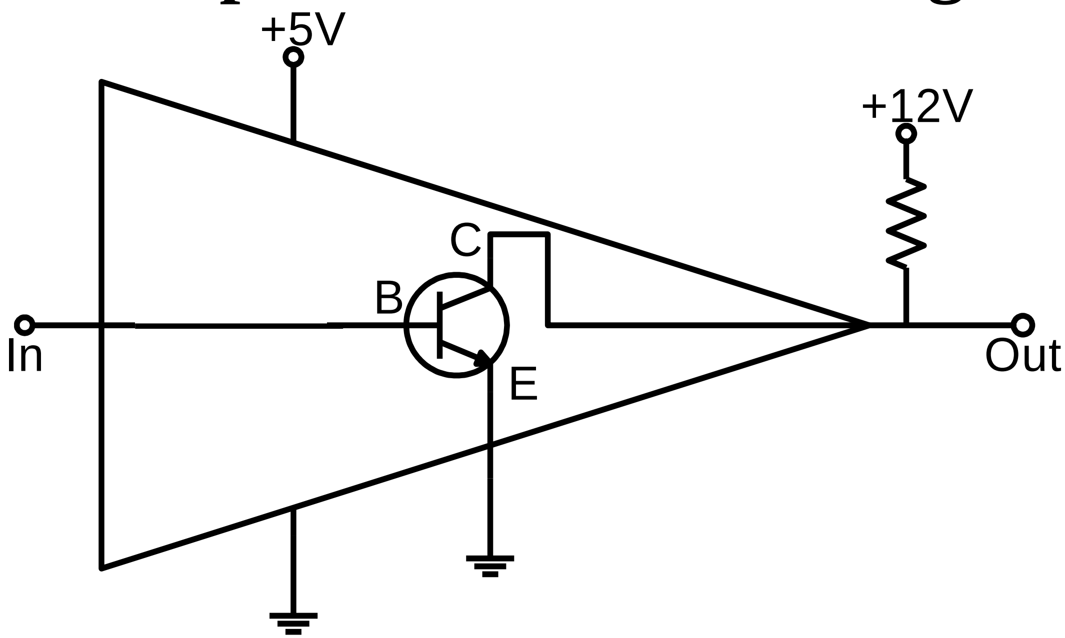
Controlling High Current Incandescent Lamp using IRF511 MOSFET and 7406 Buffer

- This figure illustrates the use of BS2, 7406 buffer, and IRF511 MOSFET to turn on a high voltage/high current incandescent lamp.
- Use of appropriate heat sink when driving high power loads is important.
- Since 7406IC is an inverting buffer
  - A low o/p at the BS2 pin P0 → 7406 output driven high (12V).
  - A high o/p at the BS2 pin P0 → 7406 output driven low (0V).
- A non-inverting high voltage buffer is also available: 7407IC.



A high-voltage applied to the gate of IRF511 using the 7406IC

7406IC: An Open Collector Inverting Buffer—I

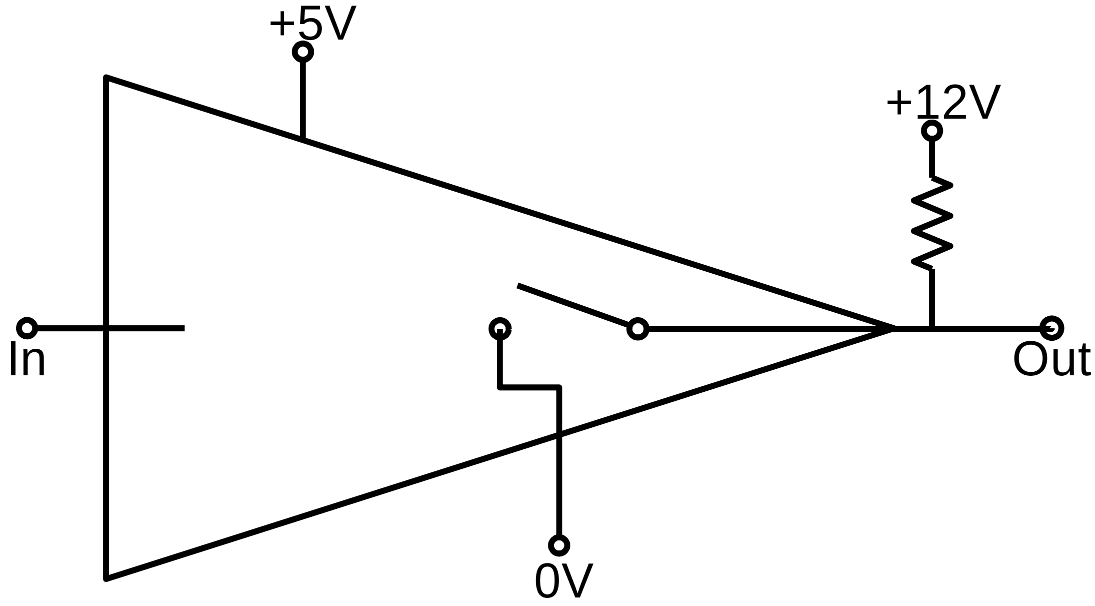


- Suppose In=High.
- $\rightarrow$ Base of the NPN transistor high compared to Emitter.
- Collector is connected to Emitter (or $V_C \approx V_E \approx 0V$)
- Output pin is driven low.

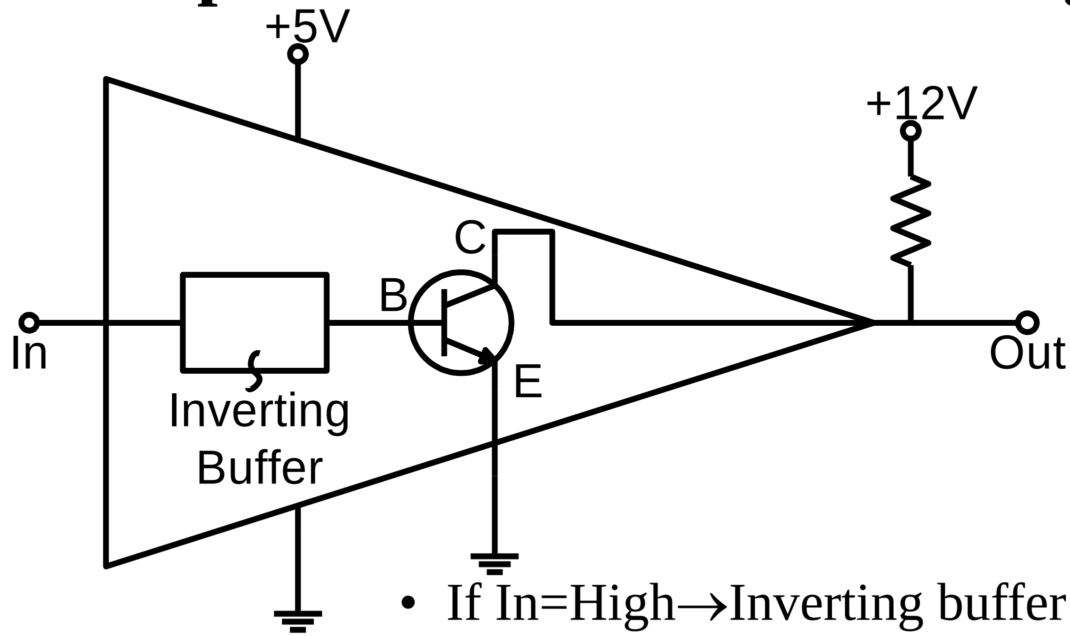
- Suppose In=Low.
- $\rightarrow$ Base of the NPN transistor is at the ground potential same as Emitter.
- Collector is not connected to Emitter.
- Collector is left open and floating.
- In order to give a fixed state to the output pin, we connect collector via a pull up resistor to an external voltage (+12V) so o/p is driven to +12V in this case!

7406IC: An Open Collector Inverting Buffer—II

- Alternatively, one can think of the 7406 inverting buffer as a switch driven in the following manner.
  - When the i/p In is Low, the switch is open and the o/p Out is pulled up to +12V.
  - When the i/p In is High, the switch is closed and the o/p Out is connected to Ground.



7407IC: An Open Collector Non-Inverting Buffer



- If In=High→Inverting buffer outputs Low.
- Base of the NPN transistor is at the ground potential same as Emitter.
- Collector is not connected to Emitter.
- Collector is left open and floating.
- In order to give a fixed state to the output pin, we connect collector via a pull up resistor to an external voltage (+12V) so o/p is driven to +12V in this case!
- Thus, High i/p → High o/p.

- If In=Low→Inverting buffer outputs High.
- Base of the NPN transistor high compared to Emitter.
- Collector is connected to Emitter (or $V_C \approx V_E \approx 0V$)
- Output pin is driven low.
- Thus, Low i/p → Low o/p.

Relays: Types

Mechanical relay

Miniature relay

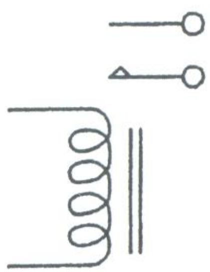
- Relays are electrically actuated switches.
- Basic kinds of relays:
  - Mechanical relays
  - Reed relays
  - Solid-state relays

Reed relay

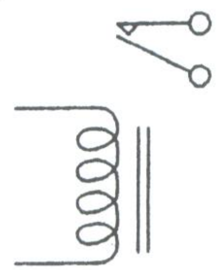
Solid-State relay

Common Symbols for Relays

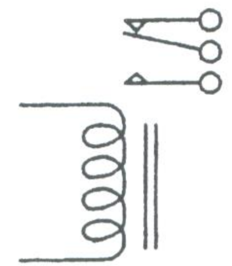
- Switch section for a mechanical relay can be obtained in many standard manual switch arrangements.
- Switch section for reed and solid-state relays are usually limited to SPST switching.



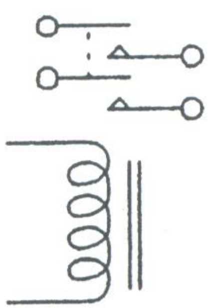
SPST (normally open)



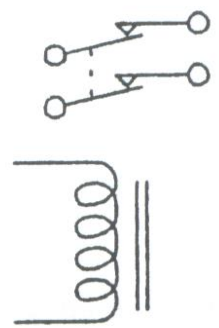
SPST (normally closed)



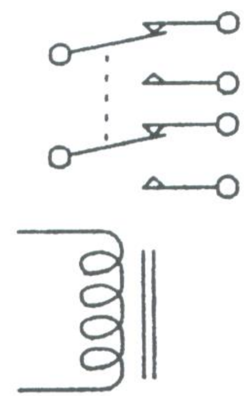
SPDT



DPST (normally open)



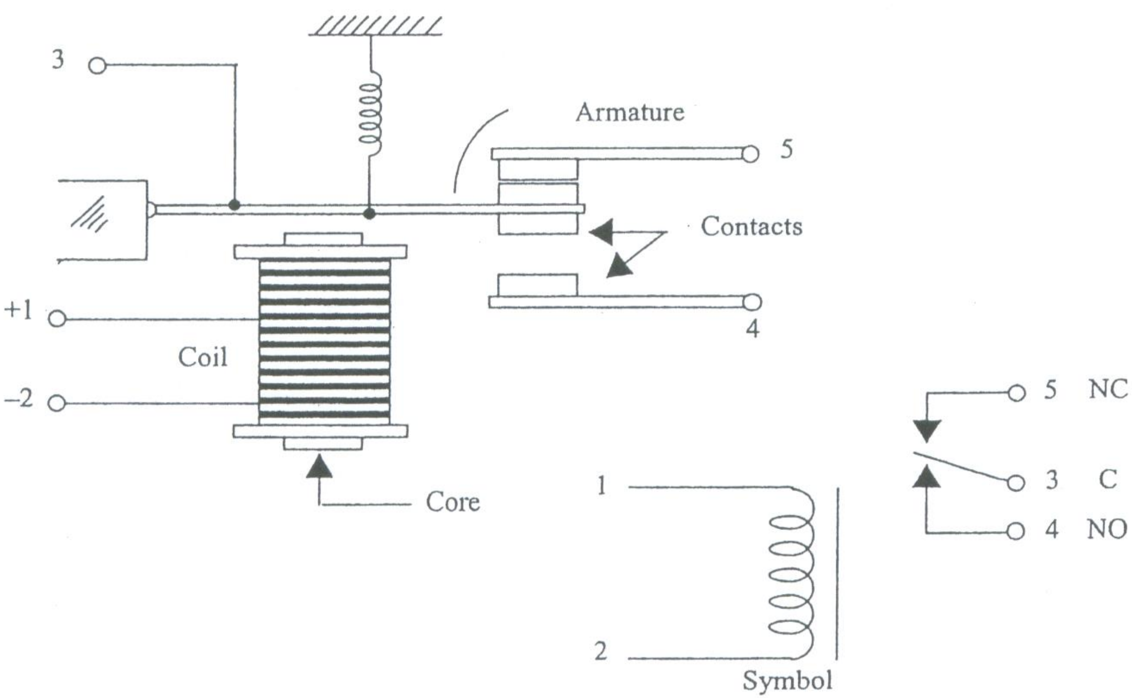
DPST (normally closed)

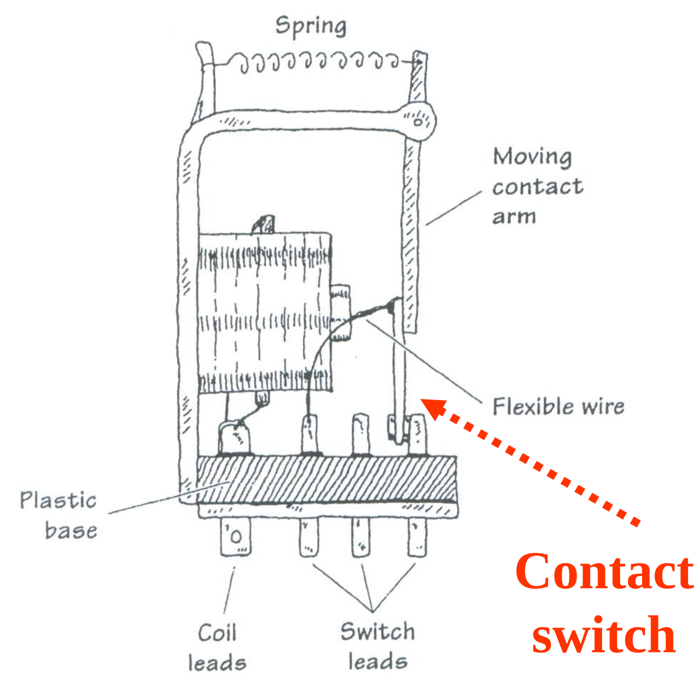


DPDT

Electro-Mechanical Relays—I

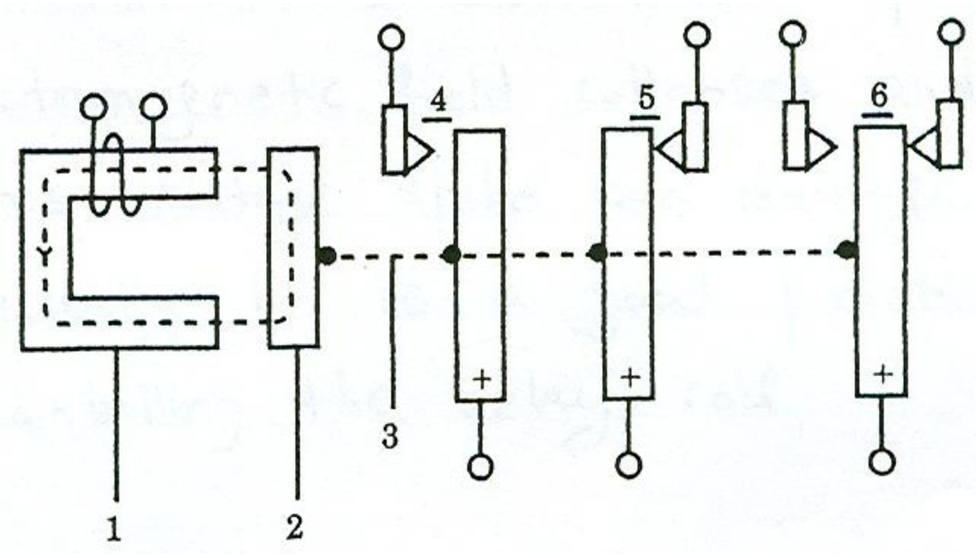
- A mechanical relay consists of an electromagnetic coil and one or more pairs of contacts.
- When a voltage is applied to the relay coil, the current flow energizes the coil thus creating a magnetic filed.
- The magnetic filed attracts a movable contact and closes the switch.
- When the current flow through the coil is cut, the magnetic filed disappears and the movable contact is released.
- By spring loading the movable contact, it is ensured that upon release it returns to its nominal open position.
- External circuitry can be appropriately interfaced to the relay contacts such that when the movable contact is triggered, the circuit turns on/off.





Relay and Contactors

- Relay and contactors are driven by AC or DC electro-magnets, and they open and close contacts. For example, the figure below shows a relay.
  - Electro-magnet 1 pulls armature 2.
  - Mechanical linkage 3 transmits armature motion to one or more contacts.
  - Contacts driven by mechanical linkage may include:
    - normally open contact 4
    - normally closed contact 5
    - transfer contact 6
- Relay and contactors differ only in size.
  - Contactors are large relays and thought of as connecting power loads.
  - Relays are usually thought of as performing logic.

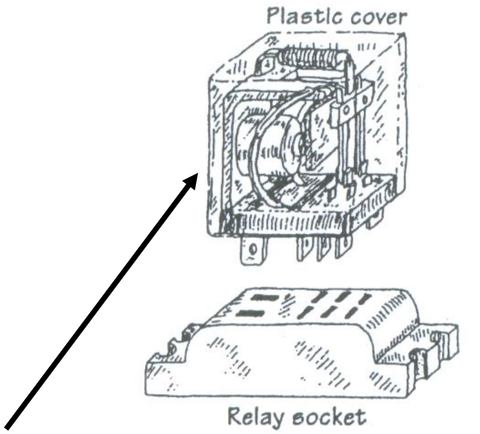


Latch Relay

- A special type of relay is called a “latch relay”. It is turned on when current is allowed to flow in one direction
- It remains on even when this current is cut.
- To turn off the relay, it is necessary to apply a current in the opposite direction.
- Some latch relay may use two coils, one to turn on the relay and one to turn off the relay.

Subminiature Mechanical Relays

- Very useful in industrial automation, remote switching, controlling high current load.
- Control i/p (e.g., given by BS2) is isolated from the circuit connected @ the relay o/p.
- Low voltage and low current control i/p allows control of high voltage and high current load connected @ the relay o/p.
- Mechanical relays are designed for high contact currents 1 to 15A.
- Low coil current (20mA-100mA)
- Available with dc or ac coils.
- DC-actuated relays:
  - Excitation voltage ratings: 6, 12, and 24V.
  - Coil resistance rating: 40, 160, and 650Ω.
- AC-actuated relays:
  - Excitation voltage ratings: 110 and 240V ac.
  - Coil resistance rating: 3400Ω and 13600Ω.
- Mechanical relays have relatively slow switching (10ms to 100ms).

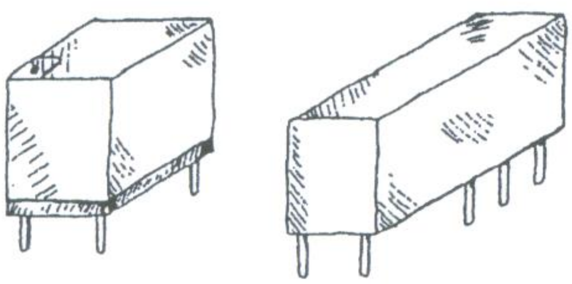


Subminiature relay

Subminiature relay

Miniature Mechanical Relays

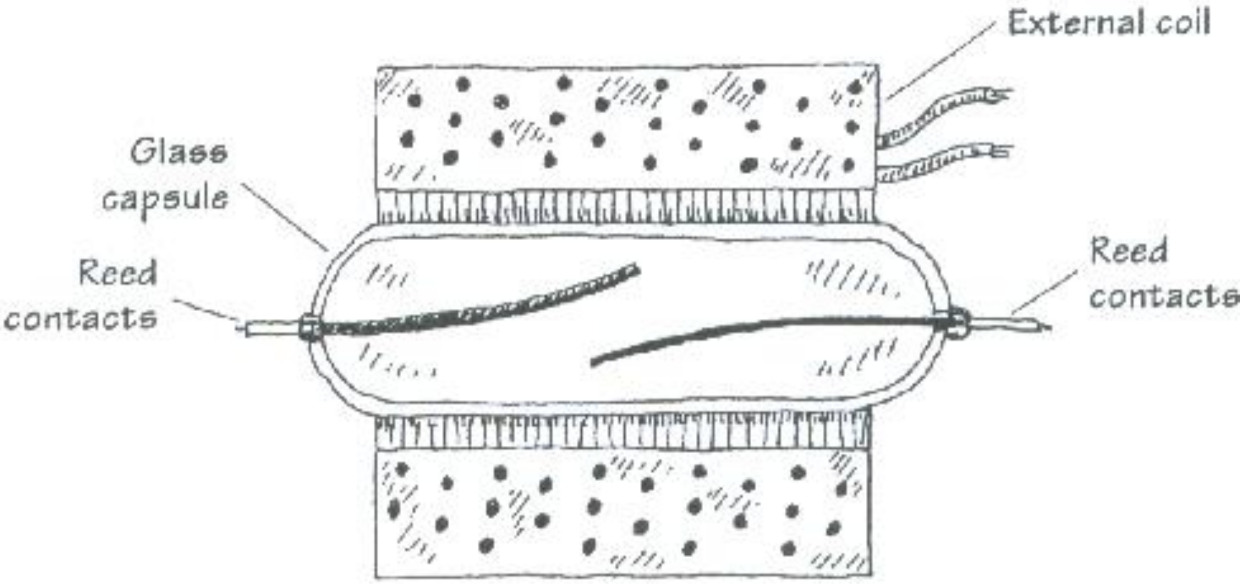
- Similar to subminiature relay, however, designed for greater sensitivity and lower level currents.
- Almost exclusively actuated by dc voltages, but may be designed to switch ac currents.
- Excitation voltages of 5,6,12, and 24V dc, with coil resistance from 50 to 3000Ω.

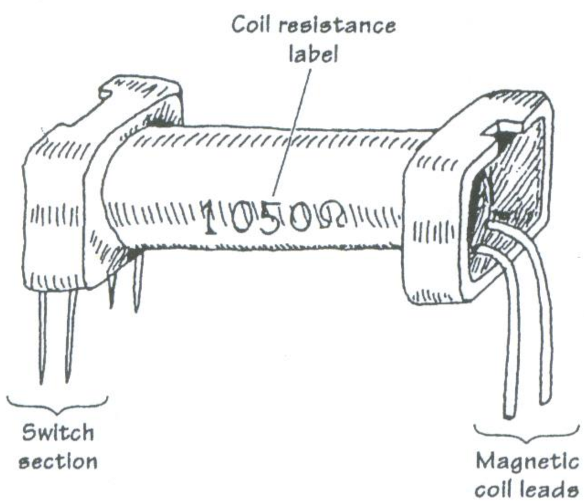


Miniature relay

Reed Relays

- A reed relay consists of a pair of thin flexible metal strips called “reeds.”
- The reeds are placed in a glass-encapsulated container that is surrounded by a coil magnet.
- When the current is sent through the encapsulating wire coil, the reeds collapse thus closing the switch.
- Reed relays are designed for moderate currents from 500mA to 1A.
- Low mass of reeds allows for moderately fast switching 0.2ms to 2ms.



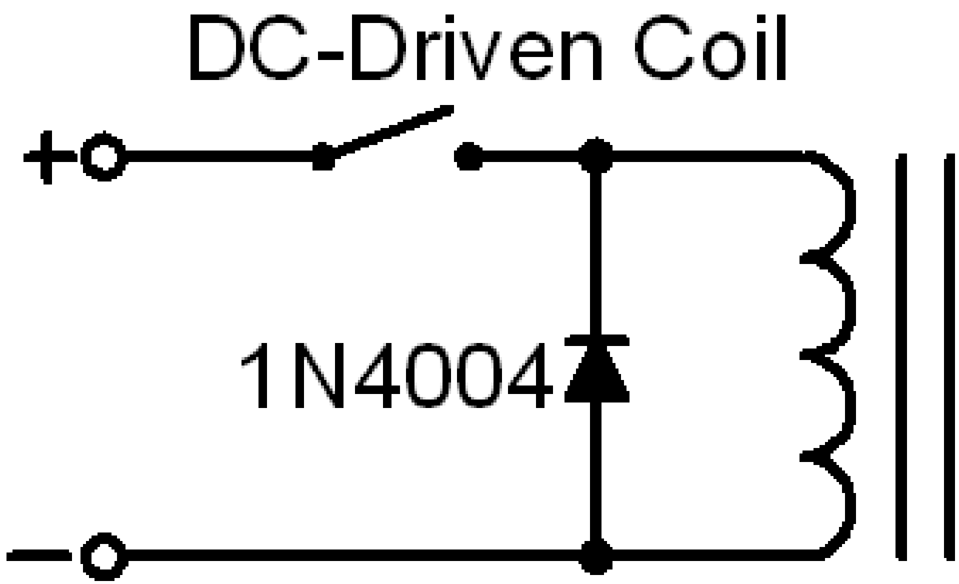


Relay Kickback and Transient Suppressors

- To make a relay change states, the voltage across of its magnetic coil should be at least within ±25% of the relay's specified control voltage rating.
- Some electromagnetic relays draw low current and can be connected directly to BS2. Caution!
- The coil of the relay acts as an inductor.
  - Inductors do not like sudden changes in current.
- When BS2 attempts to switch off the relay, the electromagnetic field collapses and a voltage spike is generated. Essentially, any attempt to suddenly change the current creates a voltage spike.
  - This voltage spike can damage sensitive MOS type circuits.
- To avoid voltage spikes, transient suppressors are generally used.
- Transient suppressors are available in prepackaged form, or you can make them yourself.
- Usually it is a good practice to buffer BS2's digital output controlling the relay coil.

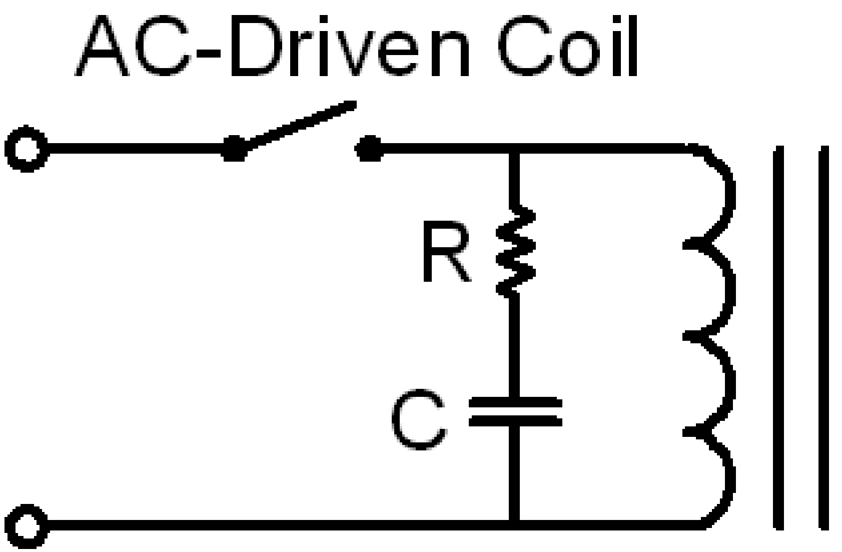
Transient Suppressors for DC-Driven Coil

- Placing a diode in reverse bias across a relay's coil eliminates voltage spikes.
  - Essentially, the diode goes into conduction before a large voltage can form across the coil.
  - The diode must be rated to handle currents equivalent to the maximum current that would have been flowing through the coil before the current supply was interrupted.
  - A good general-purpose diode that works well in such applications is the 1N4004diode.



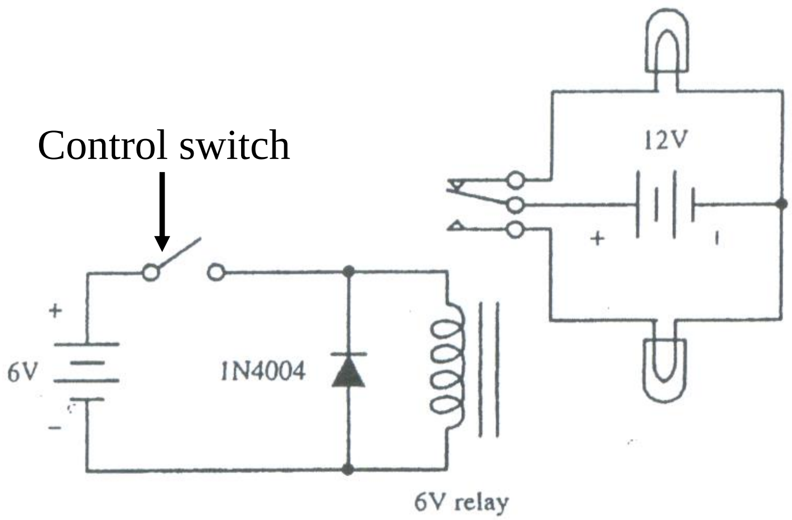
Transient Suppressors for AC-Driven Coil

- When dealing with ac-actuated relays, using a diode to eliminate voltage spikes will not work—the diode will conduct on alternate half-cycles.
- Using two diodes in reverse parallel will not work either—the current will never make it to the coil.
- Remedy:
  - Use an RC series network placed across the coil. The capacitor absorbs excessive charge, and the resistor helps control the discharge.
  - For small loads driven from the power line, use $R = 100\Omega$ and $C = 0.05\mu F$.



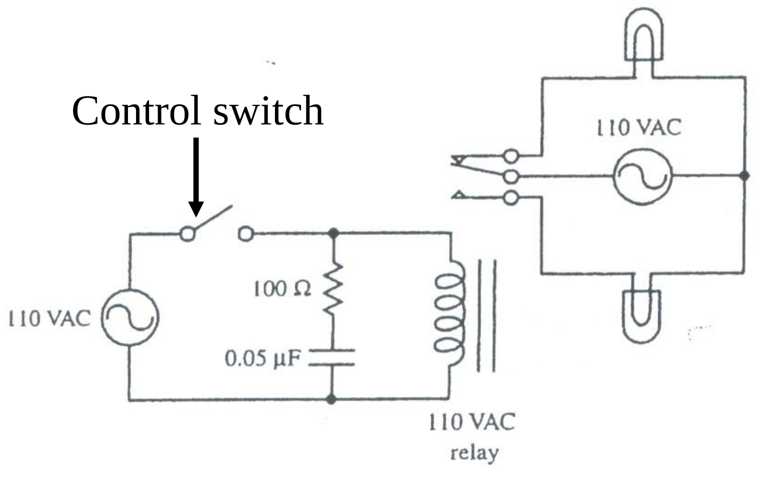
Relay Circuits: DC Actuated Switch

- DC-powered SPDT relay is used to supply current to one of the two dc-light bulbs.
- When the switch in the control circuit is opened, the relay is relaxed, and the current is supplied to the upper bulb.
- When the switch in the control circuit is closed, the relay coil receives current and pulls the flexible-metal conductive plate downward, thus supplying current to the lower bulb.
- The diode acts as a transient suppressor.



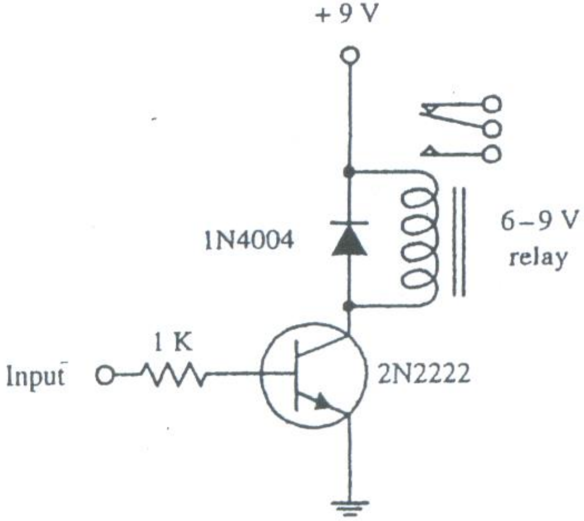
Relay Circuits: AC Actuated Switch

- AC- powered SPDT relay is used to switch ac current to one of the two ac-light bulbs.
- The behavior in this circuit is essentially the same as in preceding DC-powered relay switching circuit.
- However, in this circuit, currents and voltages are all AC.
  - Here, an RC network is used as a transient suppressor.
- The resistor and capacitor used for transient suppressor must be rated for a potential transient current that is as large as the typical coil current.



Relay Circuits: BJT-based Relay Driver

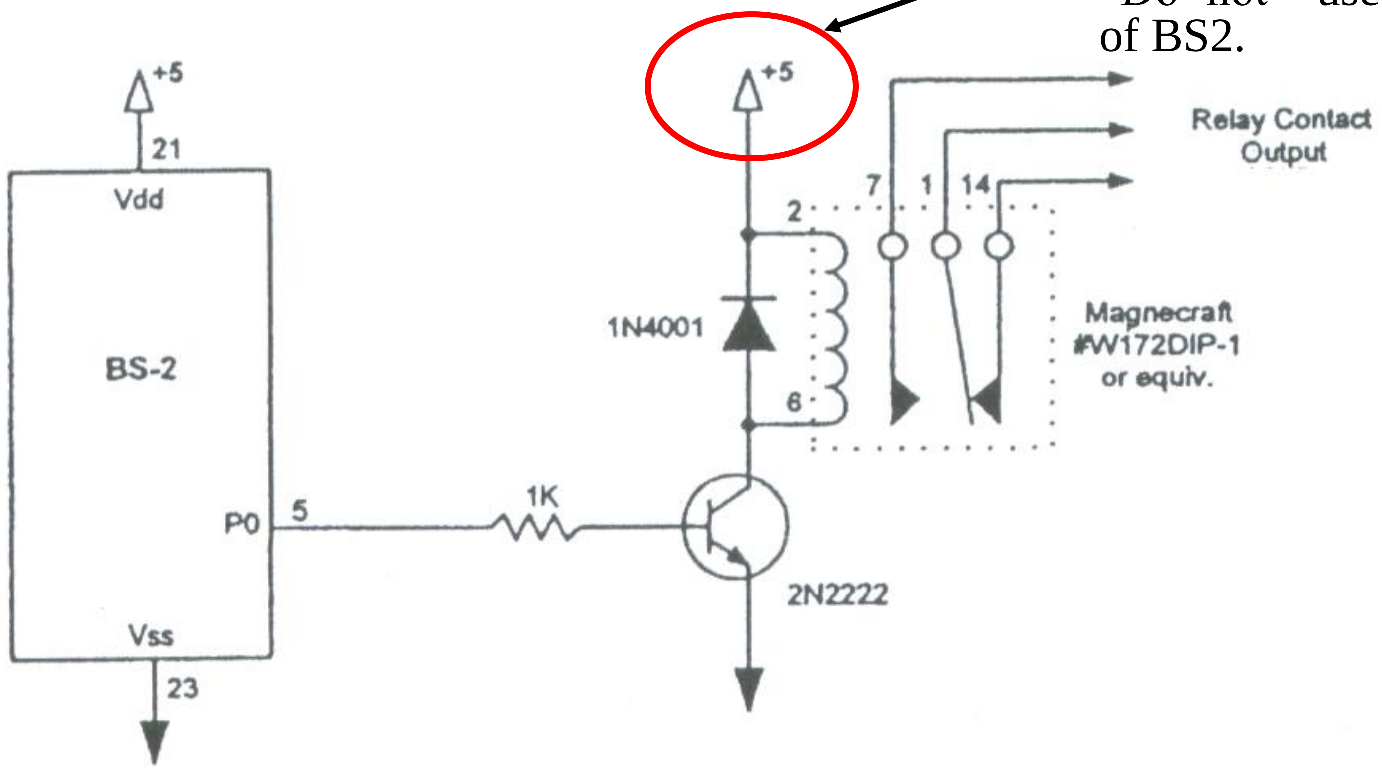
- If a relay is to be driven by an arbitrary control voltage (≠ 5V), then the circuit shown here can be used.
- The NPN BJT acts as a current-flow control valve.
- With no i/p voltage and i/p current applied to the base lead of the BJT, the collect-to-emitter channel of the transistor is closed/blocked, hence blocking current flow through the relay's coil.
- If a sufficiently large i/p voltage and i/p current are applied to the base lead of the BJT, the collect-to-emitter channel of the transistor opens/unblocks, allowing current to flow through the relay's coil.



Relays with BS2 — I

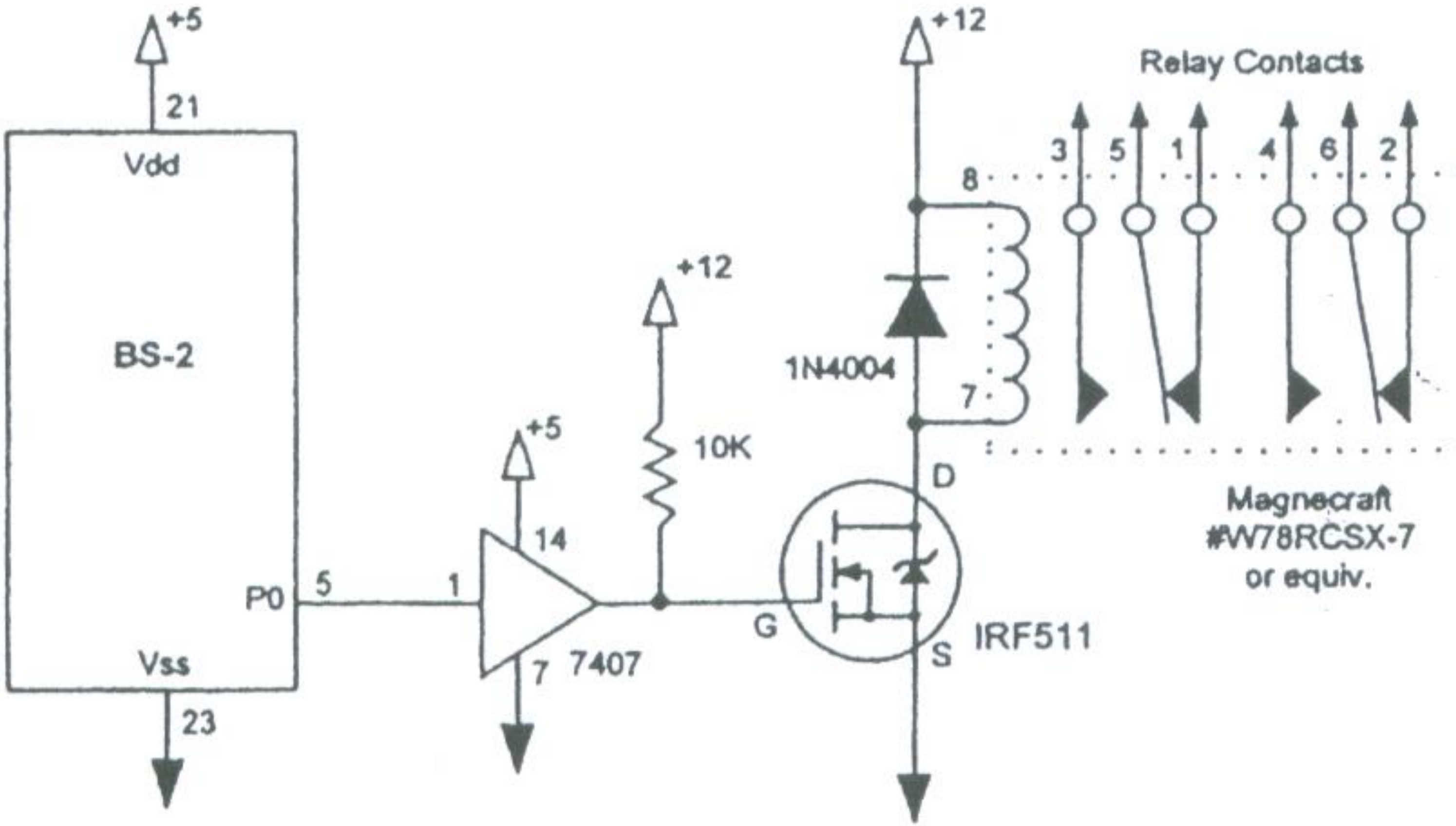
- A BJT is used to provide sufficient drive current for the relay.
- When P0 is driven high, the collector-emitter pair of the BJT conducts, allowing activation of relay.
- When P0 is driven low, the electromagnetic coil is deactivated and it generates a reverse voltage spike.
- The reverse voltage spike is shorted by the IN4001 diode

Use a voltage regulator with high current capability. “Do not” use +5V of BS2.



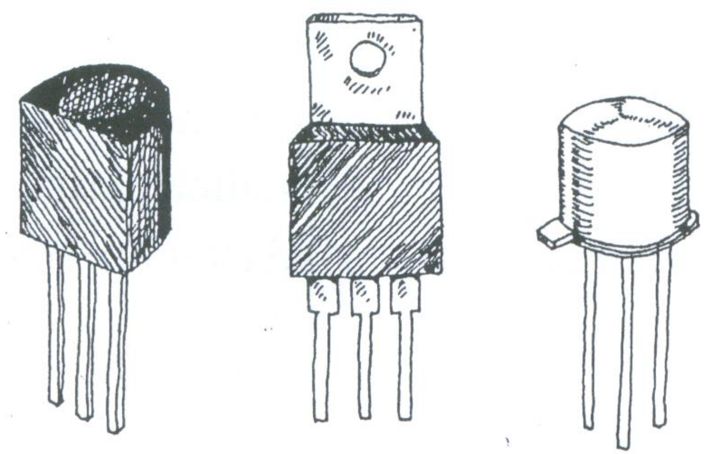
Relays with BS2—II

- Some relays require significantly higher current/voltage for their switching action.
- The following circuit uses a 7407 non-inverting buffer IC and an IRF511 MOSFET to activate a high current mechanical relay.
- When BS2 pin P0 is driven high, the relay is turned ON.



Solid-State Relays—I

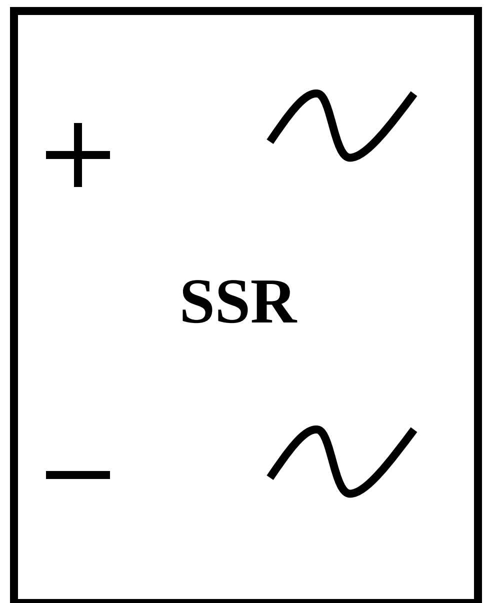
- SSRs are made from semiconductor materials.
- SSRs include transistors (FET, BJTs) and thyristors (SCRs, triacs, diacs, etc.).
- SSRs do not have suffer from any contact wear.
- SSRs provide rapid switching speeds (1 to 100 ns).
- SSRs have usually high “on” resistance
- SSRs requires a bit of fine tuning.
- SSRs are less resistant to overloads compared with electromechanical relays.



Solid-State relay

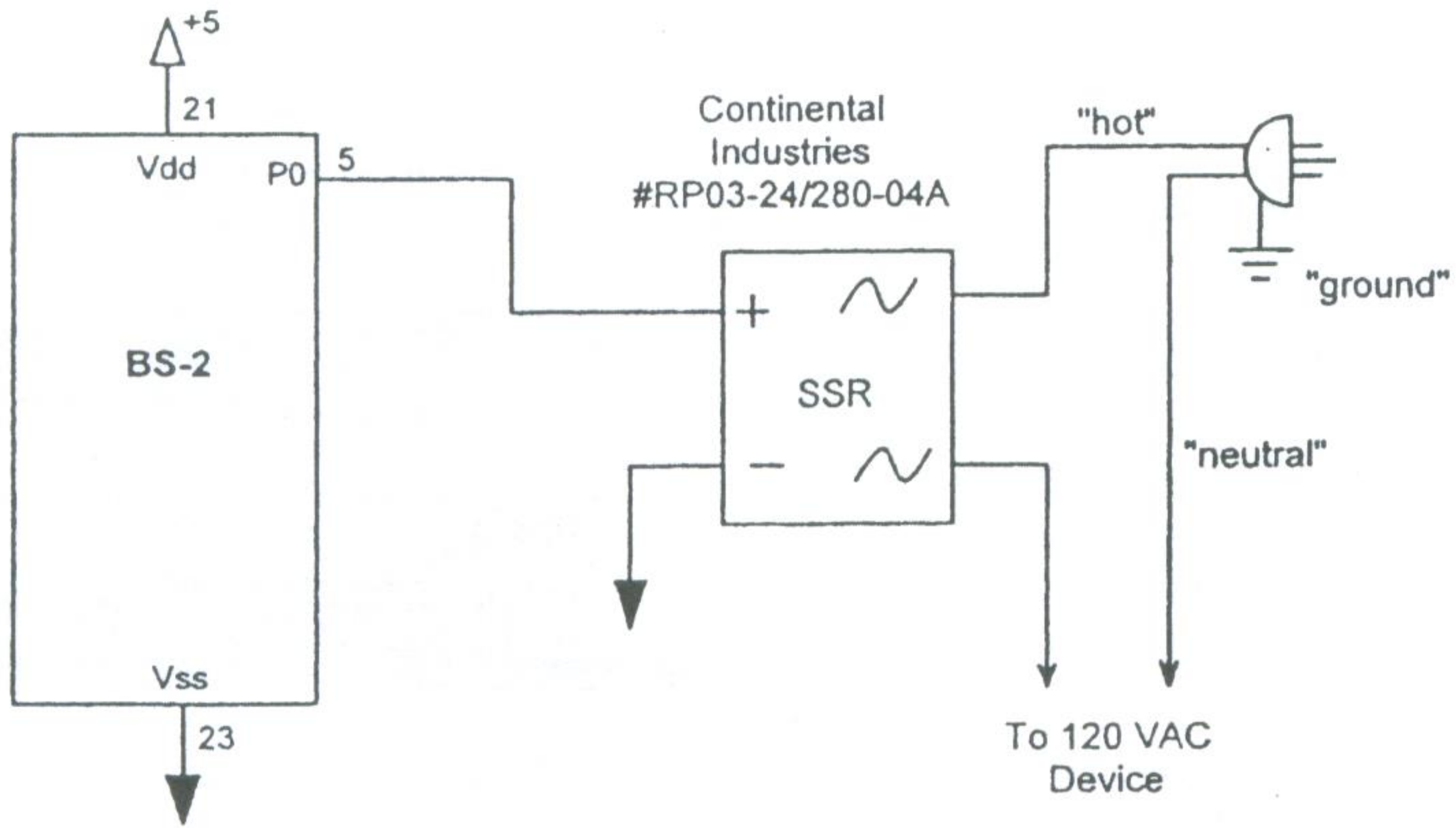
Solid State Relays—II

- SSRs are simple and safe to connect to BS2 for controlling high voltage device.
- SSRs are available in a wide range of current ratings from a few μA to 100mA.
- Most SSRs use built-in opto-isolator circuitry!
- Advantages:
  - BS2 and associated drive circuiting connected to the input of SSR and the high voltage load connected at the output of SSR are electrically isolated
  - Opto-isolation circuit of SSR requires very low current so it can be easily interfaced to BS2.



Solid State Relay with BS2—I

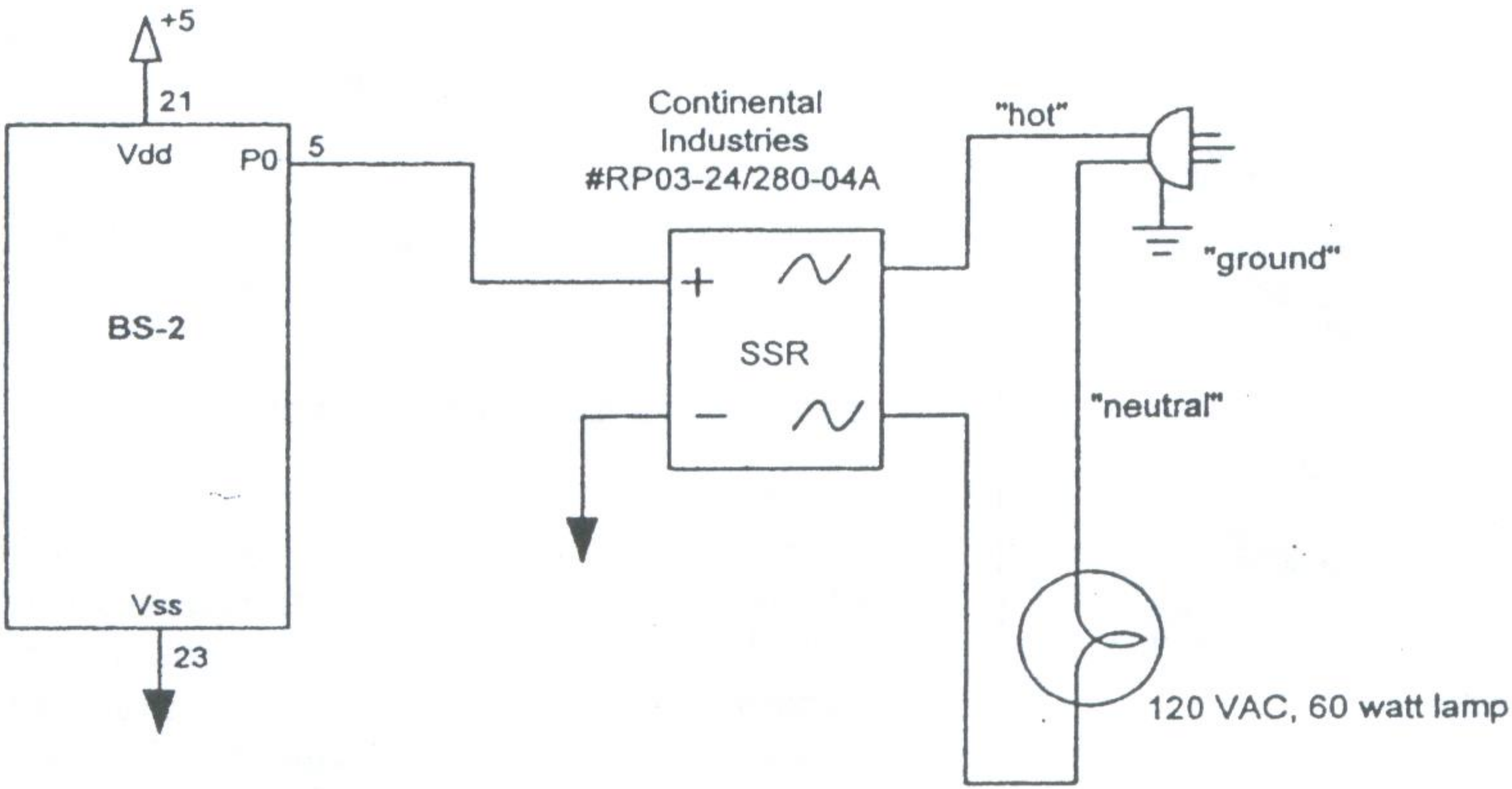
- A generic circuit for controlling an SSR using BS2 is given below.



Be extremely cautious with 120V AC !!

Solid State Relay with BS2—II

- Use of a BS2 controlled SSR that switches a 120AC, 60 watt lamp is given below.
- A high o/p at pin P0 of BS2 turns the lamp on.



Be extremely cautious with 120V AC !!

Solenoid: What is it?

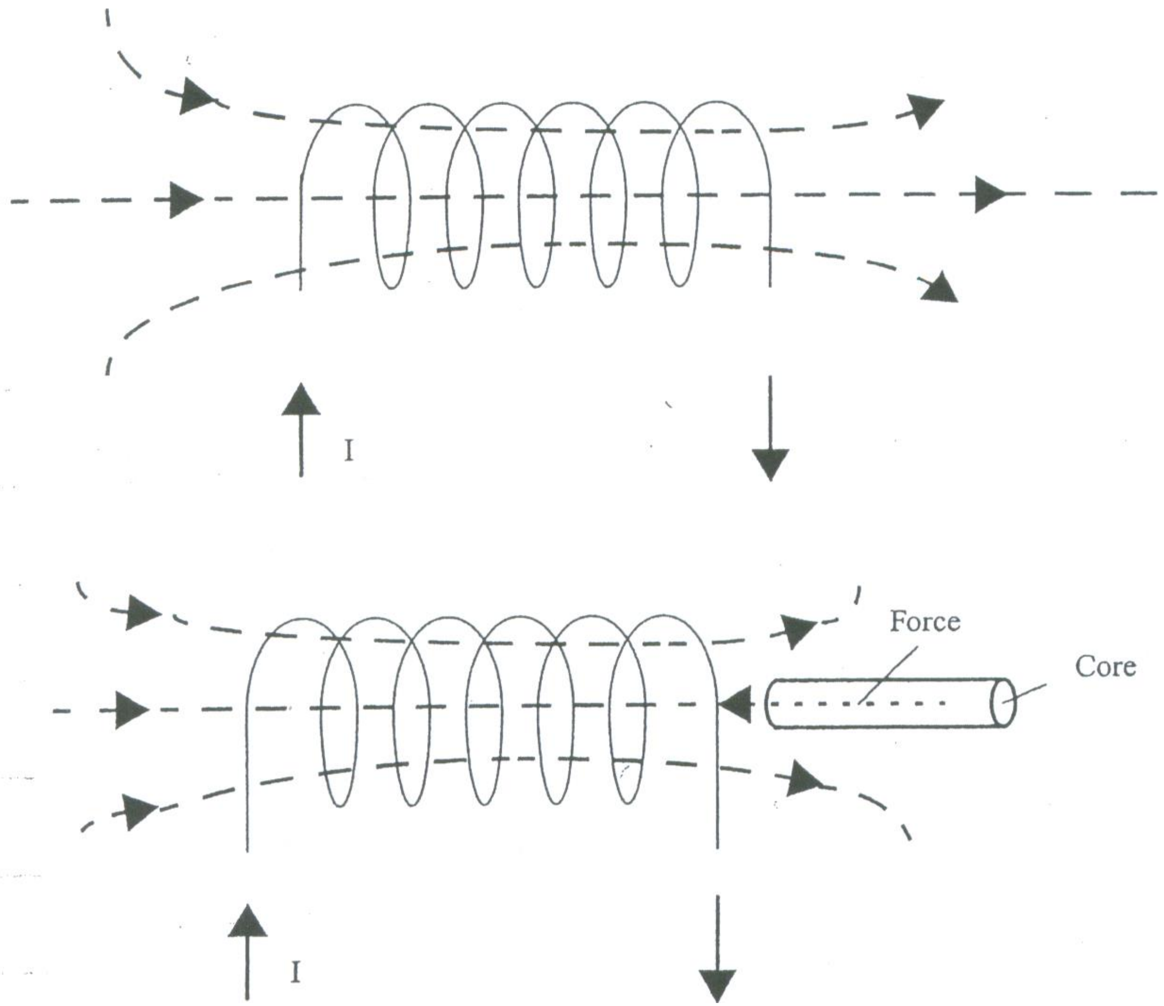
- Solenoid: An electromechanical device that converts electrical energy into linear or rotary motion.

- All solenoids include a coil for conducting current and generating a magnetic field, an iron or steel shell or case to complete the magnetic circuit, and a plunger or armature for translating motion.

- Solenoids can be actuated by either AC or DC.

Solenoid: Principle of Operation —I

- By introducing a current flow through a long straight coil of copper wire, a uniform magnetic field can be produced around the wire.
- When a ferrous object (e.g., a nail) is placed near the coil, it is pulled by magnetic forces generated by the coil.
- The pull exerted on the ferrous object produces a mechanical force.

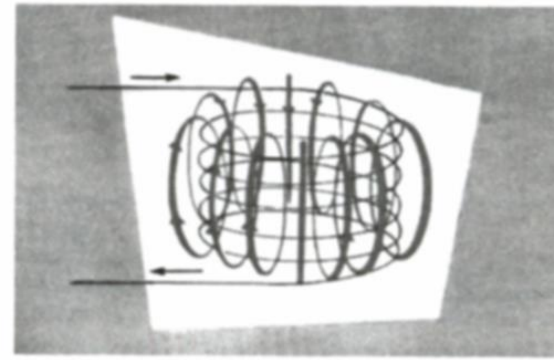


Principle of operation

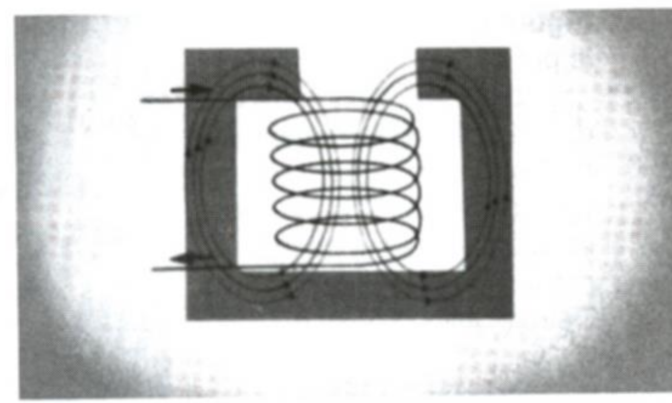
Solenoid: Principle of Operation —II

- The magnetic field produced by a current carrying coil flows around the coil and through its center.
- Increasing the # of turns of wire coil increases the strength of magnetic field
- Although the magnetic field can flow in air, by providing a path through a ferro-magnetic material, e.g., iron, the magnetic field can be shaped and concentrated in a certain space to take advantage of its strength.

If we make a coil of many turns of wire, this magnetic field becomes many times stronger, flowing around the coil and through its center in a doughnut shape.



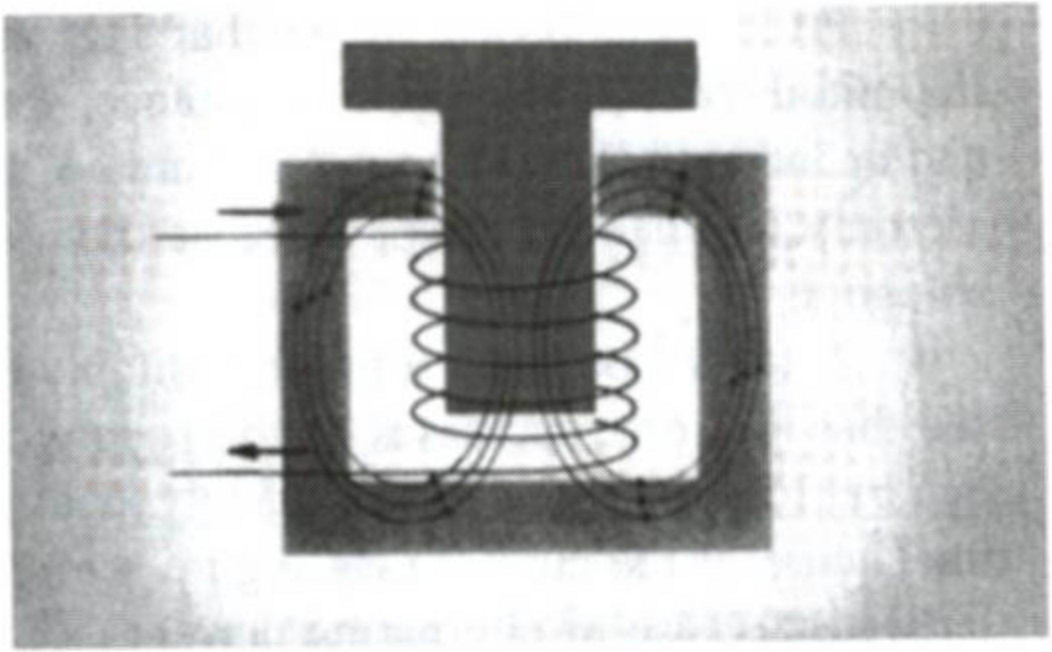
Although this magnetic field will flow in air, it flows much more easily through iron or steel—so we add an iron path, or *C stack*, around the coil that concentrates the magnetism where we want it.



Principle of operation

Solenoid: Principle of Operation —III

- Having produced and generated the magnetic field, we now turn to exploit it to produce useful action by inserting a movable “ferrous” piece, called plunger, into the hollow center of the current carrying wire coil.
- Application of control input energizes the coil producing the concentrated magnetic field which draws the plunger into the coil.
- Force experienced by the plunger is governed by:
  - Current passing through the coil, # of turns in the coil, the material of plunger/core, the distance that the plunger moves (i.e., the solenoid stroke).
- Common specs: 3 to 48VDC control voltage for coil and 50mA to 2A coil current.



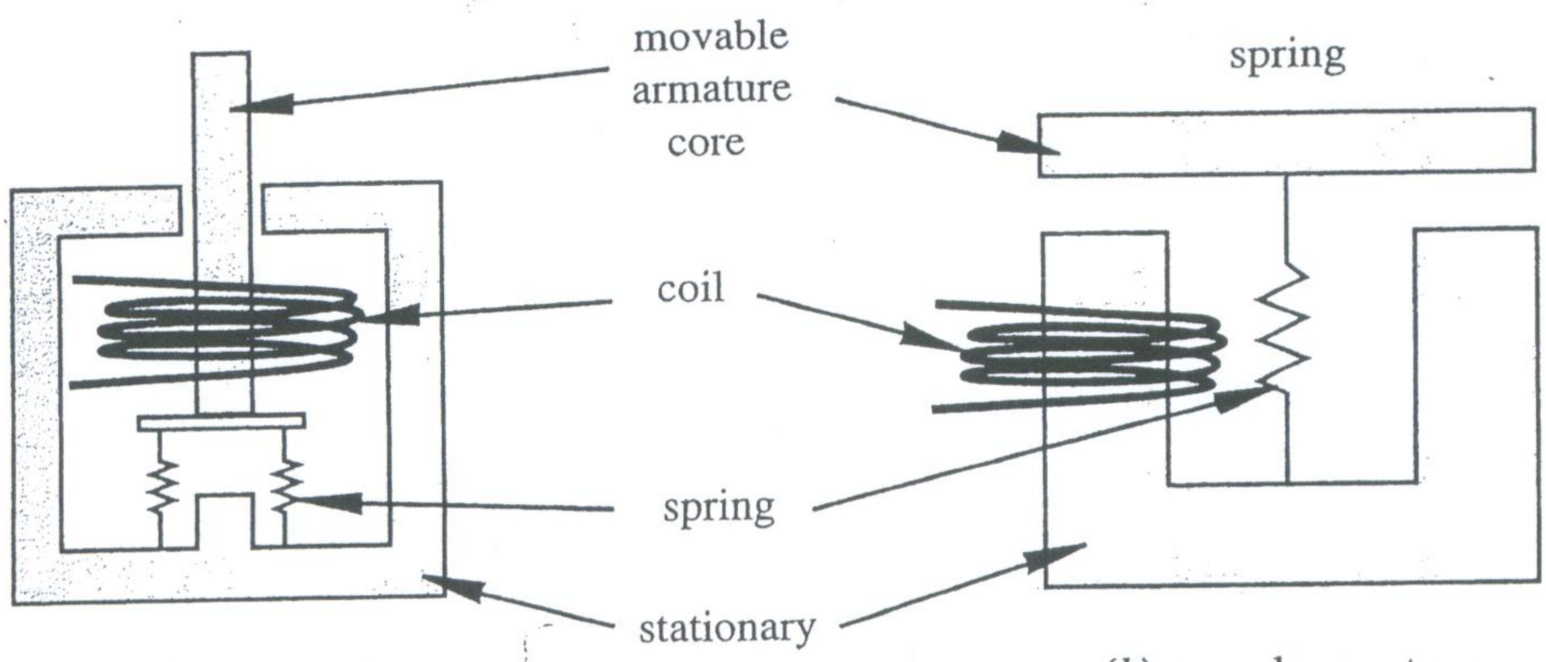
Solenoid Force

- Force produced by solenoid is governed by the following equation.

$$F = \frac{1}{2}(NI_0)^2 \frac{\mu_0 A}{X^2}$$

  - F: initial solenoid force (N)
  - N: # of turns of wire in coil
  - I_0: initial current (A)
  - μ_0: permeability ($4\pi \cdot 10^{-7}$ H/m in air)
  - A: plunger cross-sectional area (cm^2)
  - X: air gap (cm)
- To increase initial force
  - Increase # of turns in coil
  - Increase cross-sectional area
  - Increase initial current

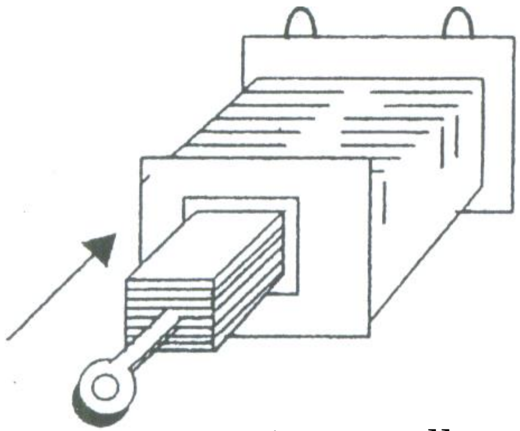
Types of Solenoids—I



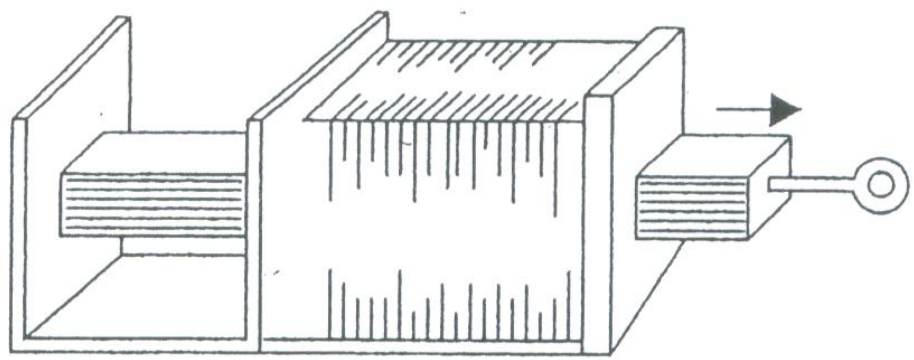
(a) plunger type

(b) nonplunger type

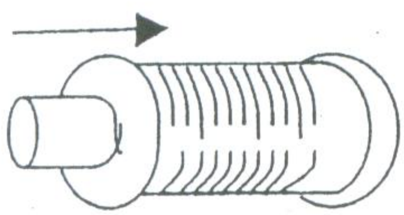
Types of Solenoids—II



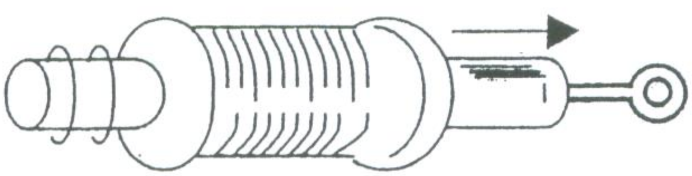
Linear Pull



Linear Push

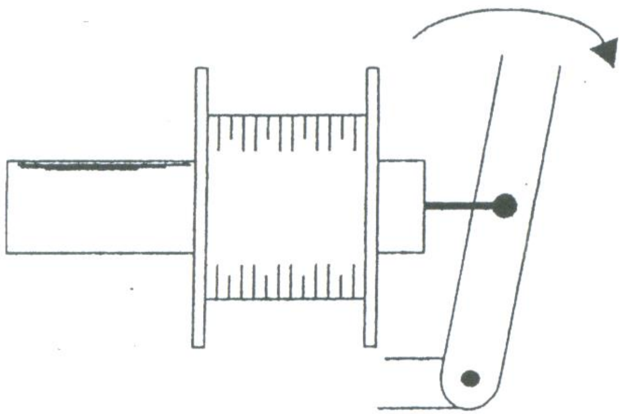


Linear Tubular Pull

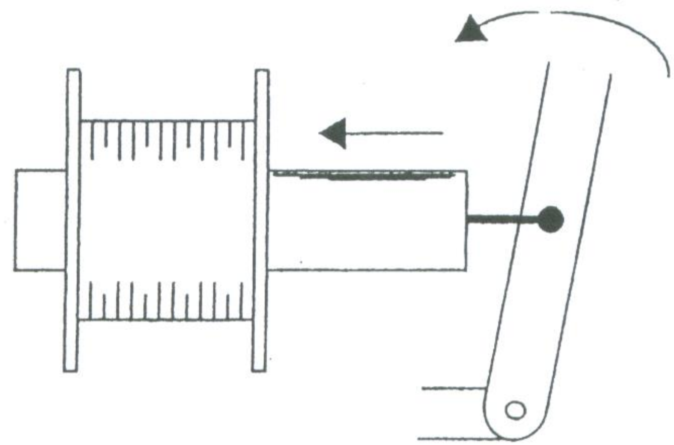


Linear Tubular Push

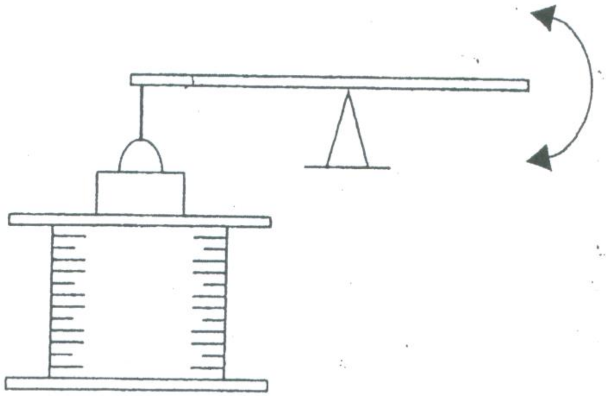
Types of Solenoids—III



Push solenoid to turn an arm



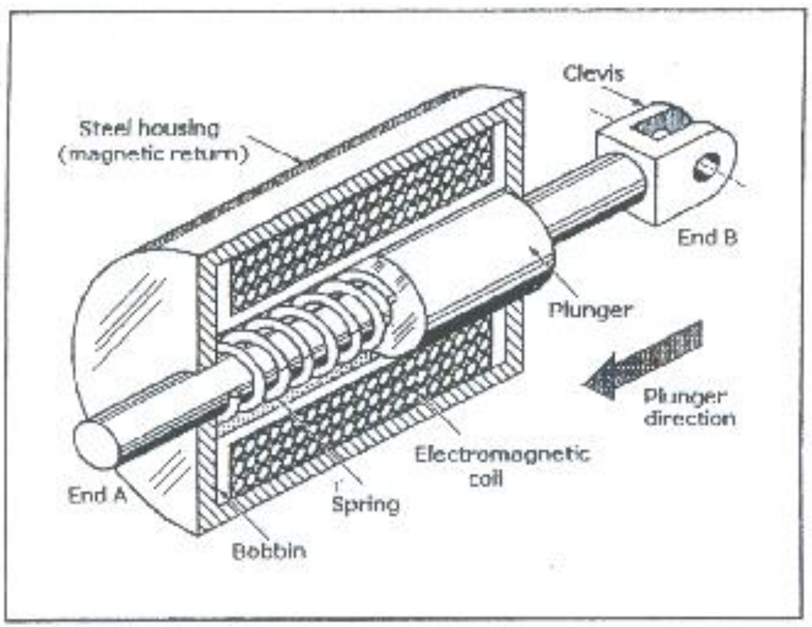
Pull solenoid to turn an arm



Solenoid actuates a level

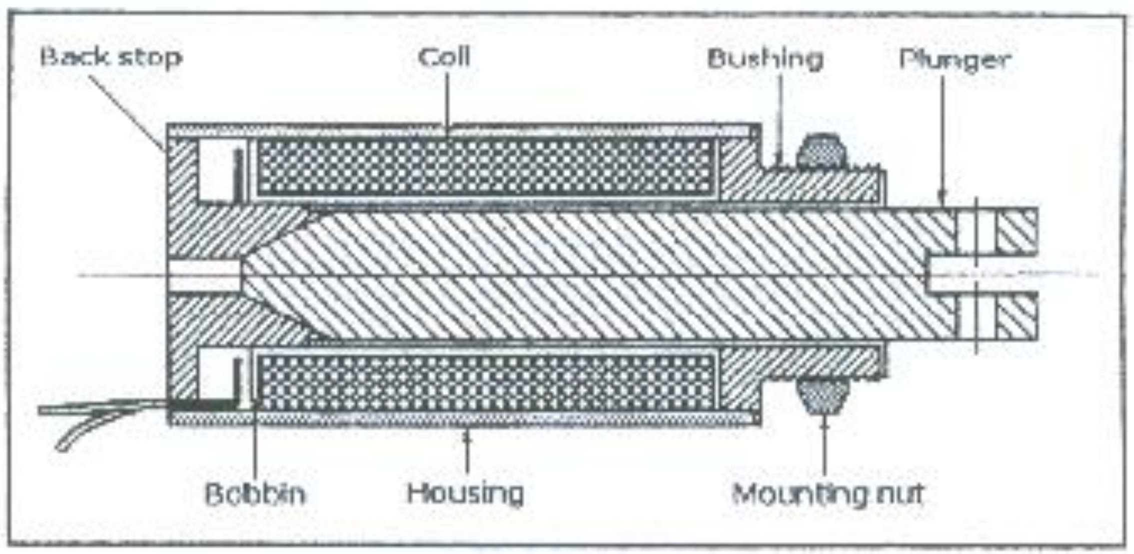
Types of Solenoids: Linear Solenoids

- Pull-in and push-out functions of a solenoid.
  - The plunger pushes out when the solenoid is energized while the clevis-end B pulls in.



Types of Solenoids: Linear Solenoids

- Cross-section view of a commercial linear pull-type solenoid with a clevis.
- The conical end of the plunger increases its efficiency.
- The solenoid is mounted with its threaded brushing and nut.



Types of Solenoids: Open-frame Solenoids

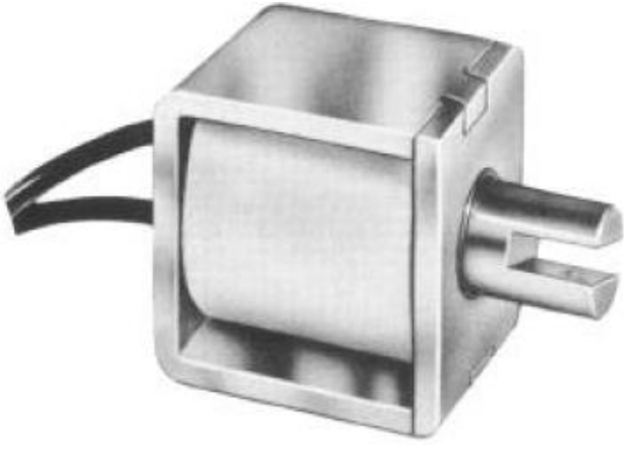
- Open-frame solenoids are the simplest and least expensive models.
- Open-frame solenoids have open steel frames, exposed coils, and movable plungers centered in their coils.
- Simple design permits them to be made inexpensively in high-volume production runs so that they can be sold at low cost.
- The two forms of open-frame solenoid are the C-Frame solenoids and the box-frame solenoids.
- They are usually specified for applications where very long life and precise positioning are not critical requirements.

Types of Solenoids: C-Frame solenoids

- C-Frame solenoids are low-cost commercial solenoids intended for light-duty applications.
- The frames are typically laminated steel formed in the shape of the letter C to complete the magnetic circuit through the core, but they leave the coil windings without a complete protective cover.
- The plungers are typically made as laminated steel bars. However, the coils are usually potted to resist airborne and liquid contaminants.
- These solenoids can be found in appliances, printers, coin dispensers, security door locks, cameras, and vending machines.
- They can be powered with either AC or DC current.
- C-frame solenoids can have operational lives of millions of cycles, and some standard catalog models are capable of strokes up to 0.5in.

Types of Solenoids: Box-Frame solenoids

- Box-frame solenoids have steel frames that enclose their coils on two sides, improving their mechanical strength.
- The coils are wound up on phenolic bobbins, and their plungers are typically made from solid bar stock.
- The frame of some box-type solenoids are made from stacks of thin insulated sheets of steel to control eddy current as well as keep stray circulating currents confined in solenoids powered by AC.
- Box-frame solenoids are specified for higher-end applications such as tape decks, industrial controls, tape recorders, and business machines because they offer mechanical and electrical performance that is superior to those of C-Frame solenoids.



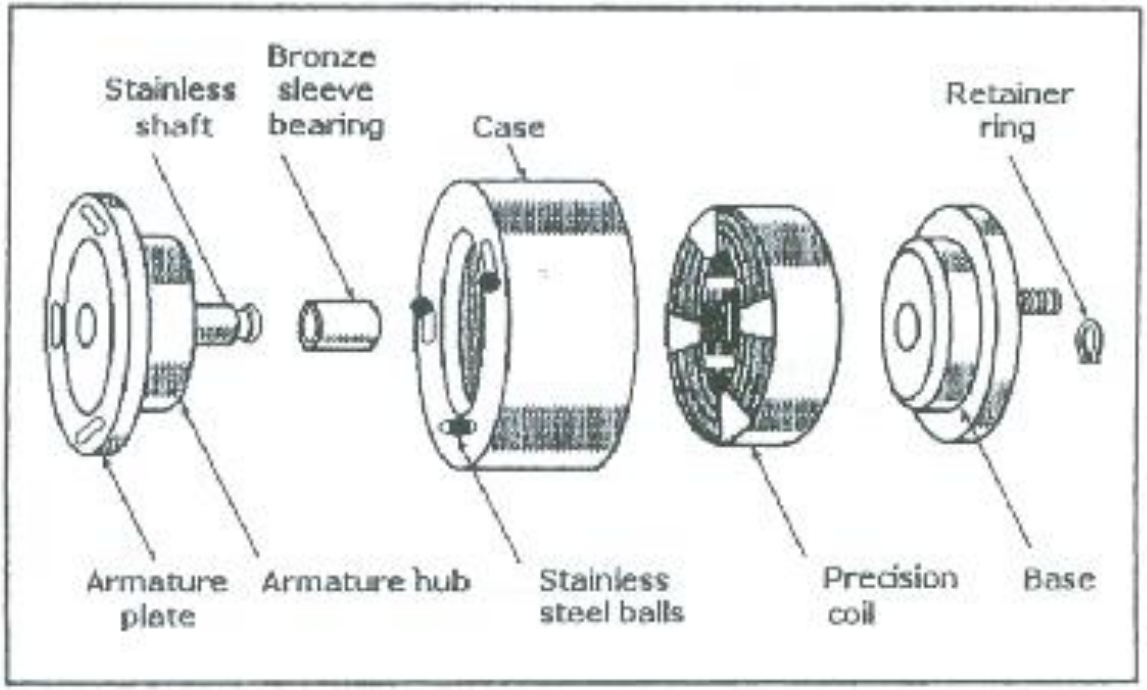
Types of Solenoids: Tubular Solenoids

- The coils of tubular solenoids have coils that are completely enclosed in cylindrical metal cases that provide improved magnetic circuit return and better protection against accidental damage or liquid spillage.
- These DC solenoids offer the highest volumetric efficiency of any commercial solenoids, and they are specified for industrial and military/aerospace equipment where the space permitted for their installation is restricted.
- These solenoids are specified for printers, computer disk-and tape drives, and military weapon systems; both pull-in and push-out styles are available.

Types of Solenoids: Rotary Solenoids—I

- Rotary solenoid operation is based on the same electromagnetic principles as linear solenoids except that their input electrical energy is converted to rotary or twisting rather than linear motion.

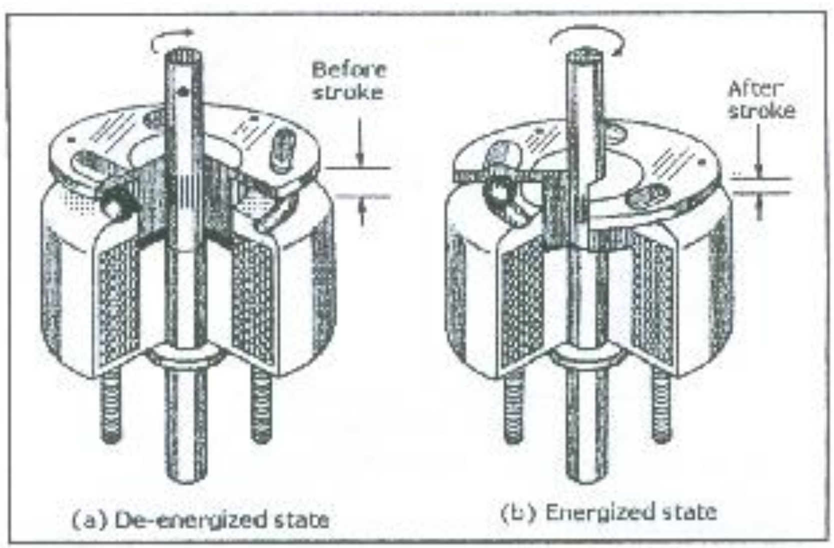
Types of Solenoids: Rotary Solenoids—II



Exploded view of a rotary solenoid

Types of Solenoids: Rotary Solenoids—III

- When the solenoid is energized, the armature pulls in, causing the three ball bearings to roll into the deeper ends of the lateral slots on the faceplate.
- This converts linear motion to rotary motion.

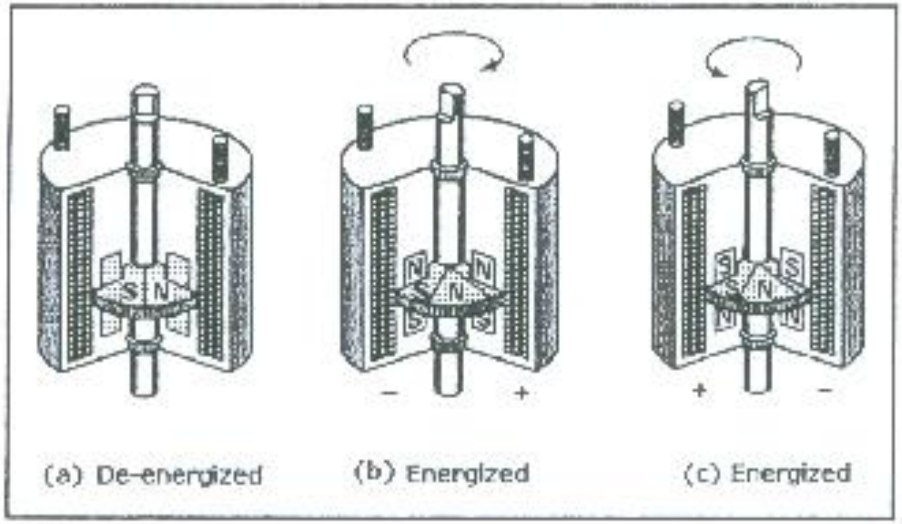


Cutaway views of rotary solenoid

Types of Solenoids: Rotary Actuator

- The rotary actuator operates on the principle of attraction and repulsion of opposite and like magnetic poles as a motor.
- In this case the electromagnetic flux from the actuator's solenoid interacts with the permanent magnetic field of a neodymium-iron disk magnet attached to the armature but free to rotate.

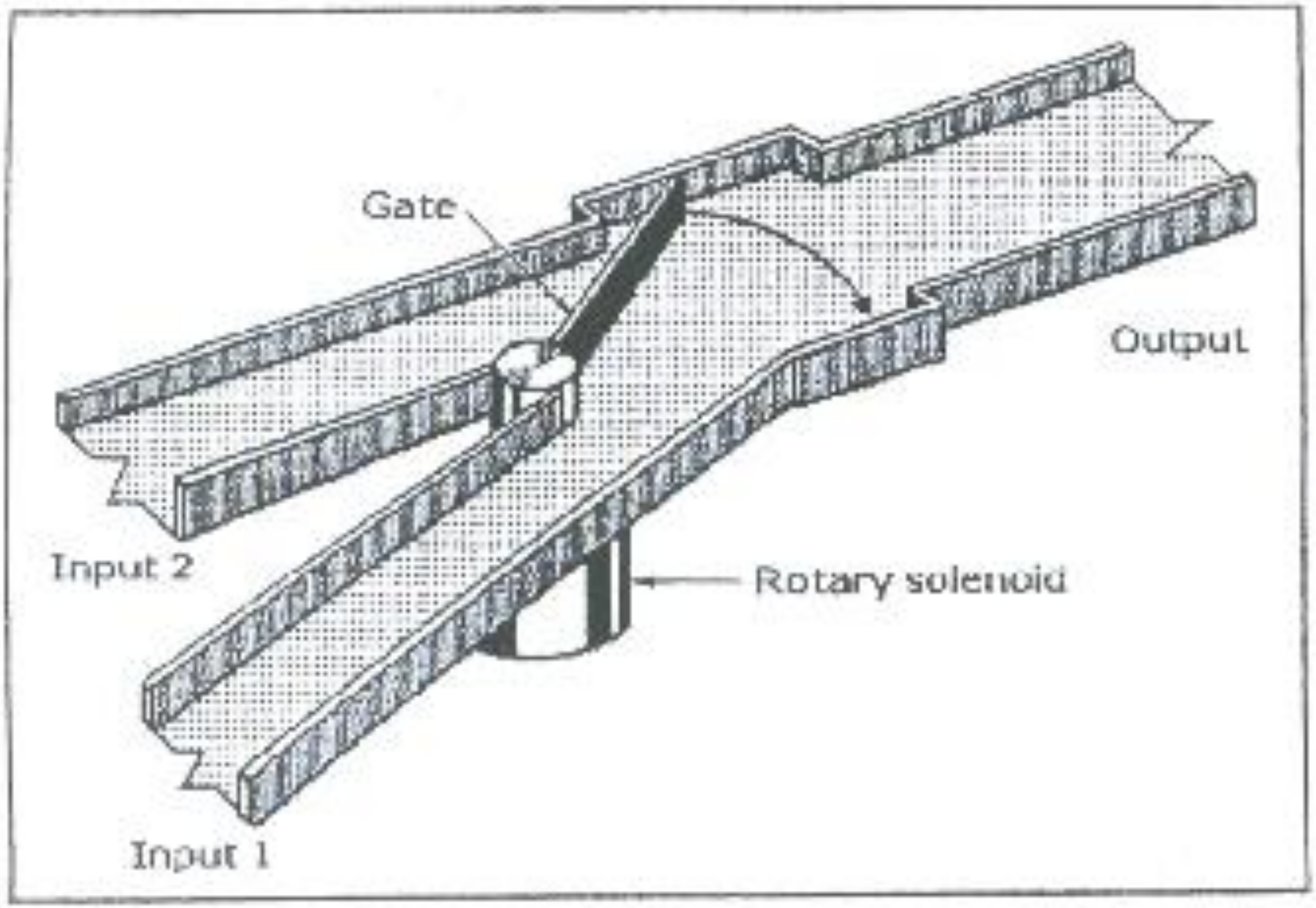
- A permanent magnet disk is mounted on the armature.
- This magnet interacts with the solenoid poles.
- When the solenoid is de-energized, the armature seeks and holds a neutral position (a).
- When the solenoid is energized, the armature rotates as shown in (b).
- When the solenoid i/p is reversed, the armature rotation is reversed (c).



Bi-directional rotary actuator

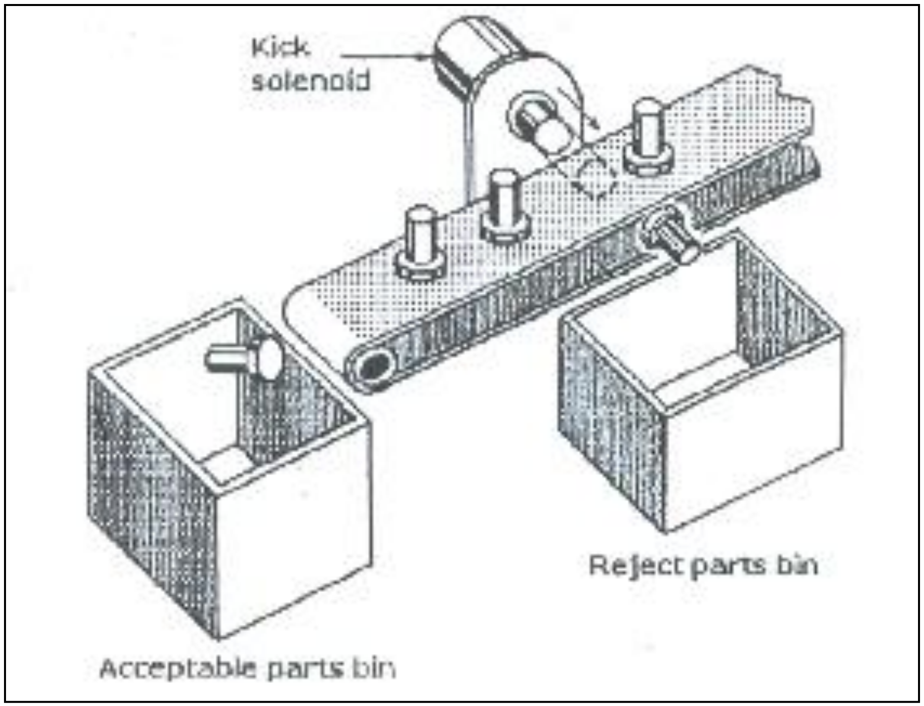
Solenoid Application: Parts or Material Diversion

- This arrangement consist of a rotary solenoid with a gate attached to solenoid's armature.
- The gate can swing to either of the two alternate positions under pushbutton or automatic control to regulate the flow of parts or materials moving on the belts or gravity feed.



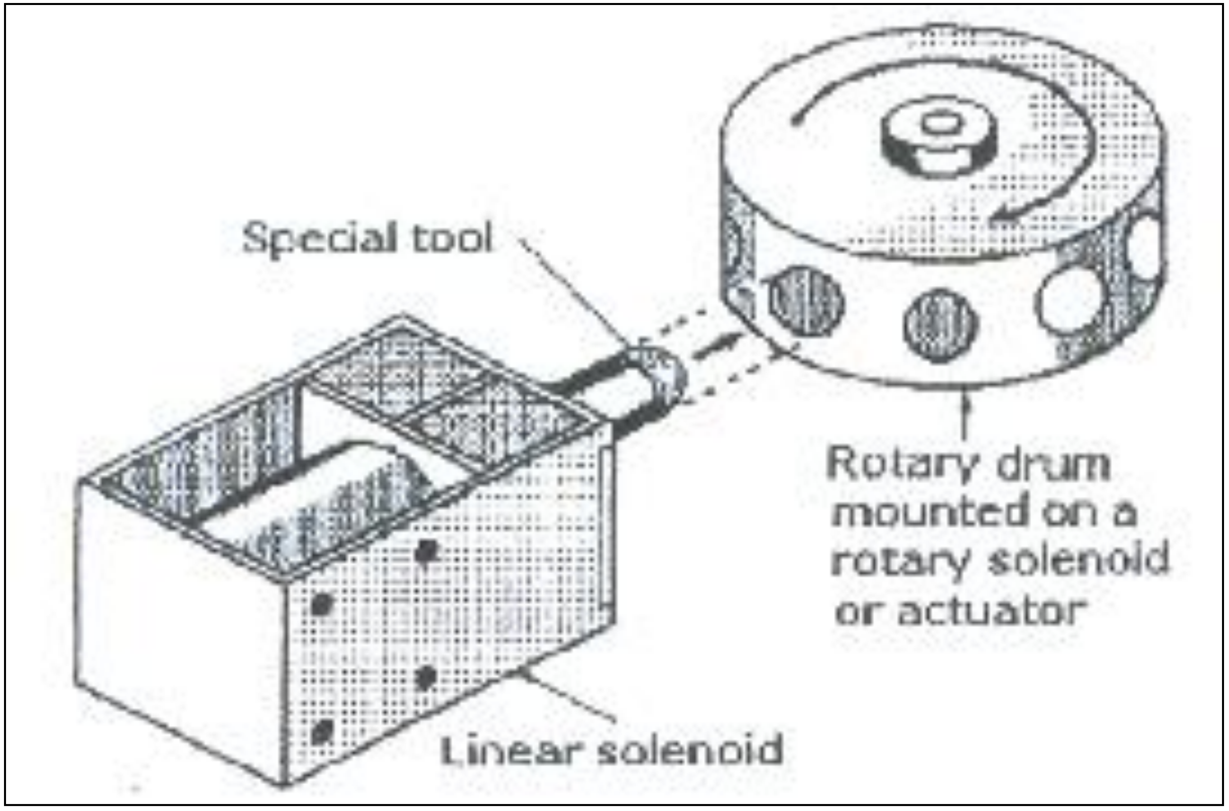
Solenoid Application: Parts Rejection

- A push-out linear solenoid can rapidly expel or reject parts that are moving past it into a bin when triggered.
- An electronic video or proximity sensing system is required to energize the solenoid at the right time.



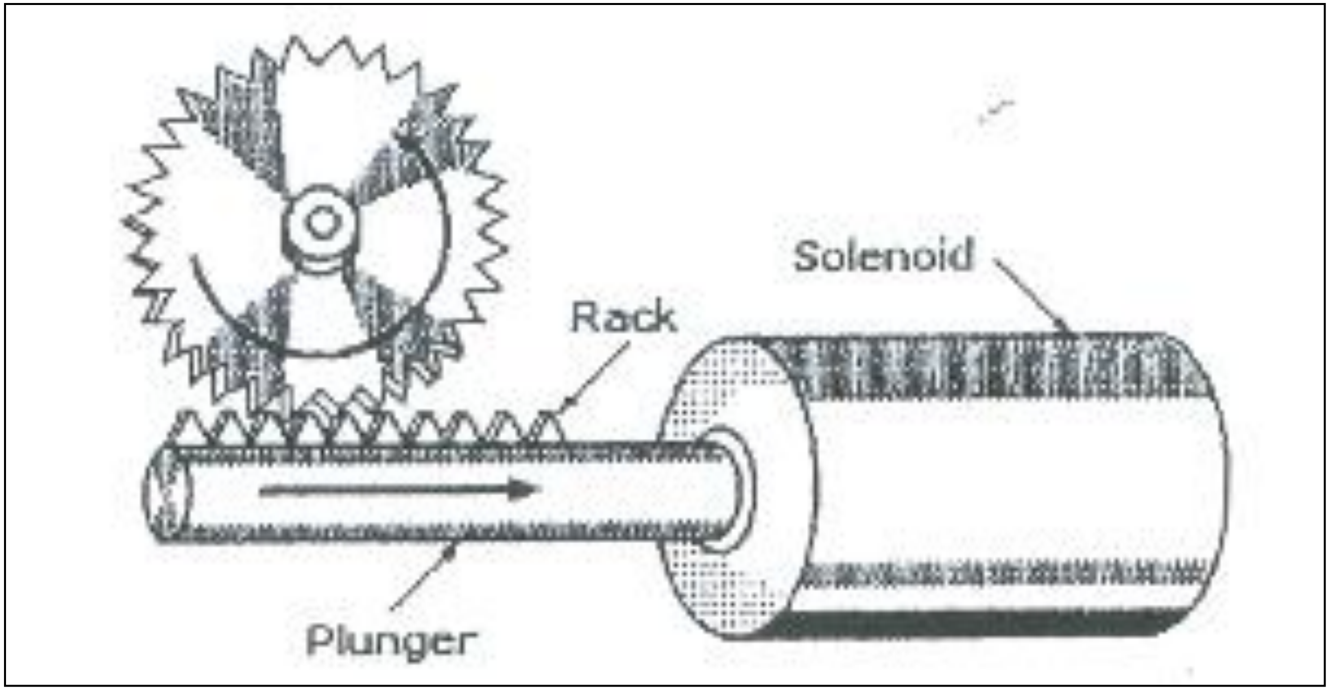
Solenoid Application: Rotary Positioning

- A linear push-out solenoid is paired with a multi-station drum containing objects that are indexed by a linear solenoid or actuator.
- This arrangement would permit automatic assembly of parts to the objects on rotary drum or the application of adhesives to the objects on the rotary drum as the drum is indexed.

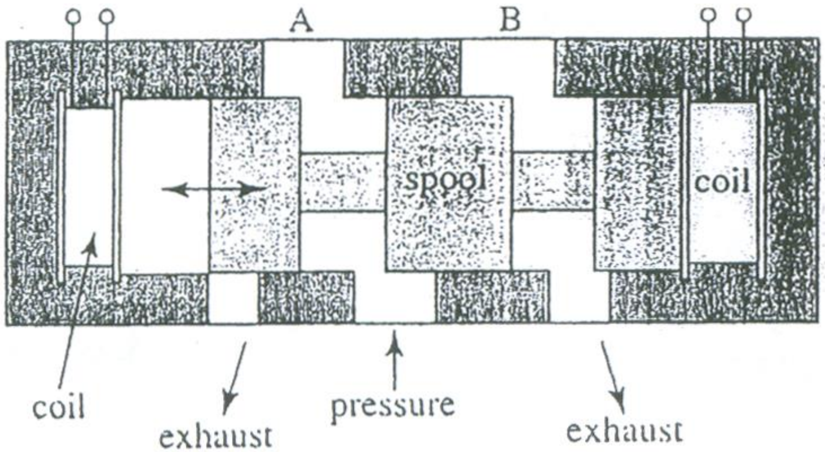


Solenoid Application: A Ratcheting Mechanism

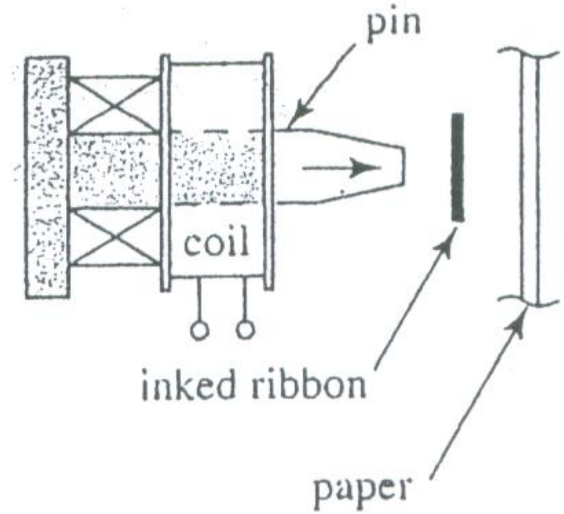
- A pull-in solenoid with a rack mounted on its plunger becomes a ratcheting mechanism capable of turning a gear for the precise positioning of objects under operator or automated control.



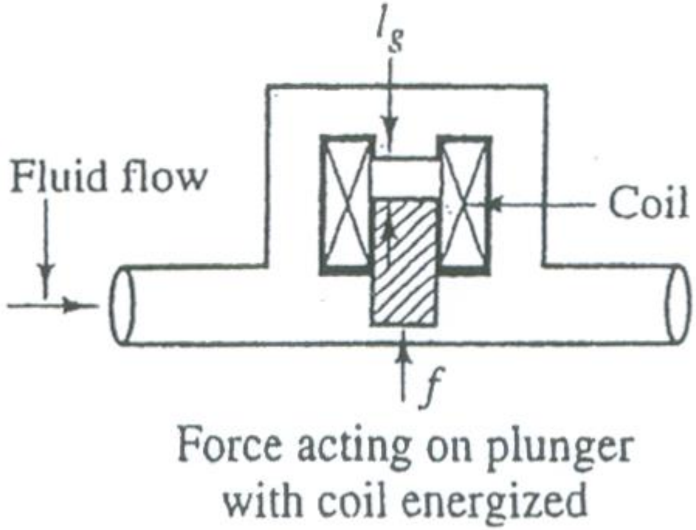
Solenoid Application: Valve



Solenoid operated valve



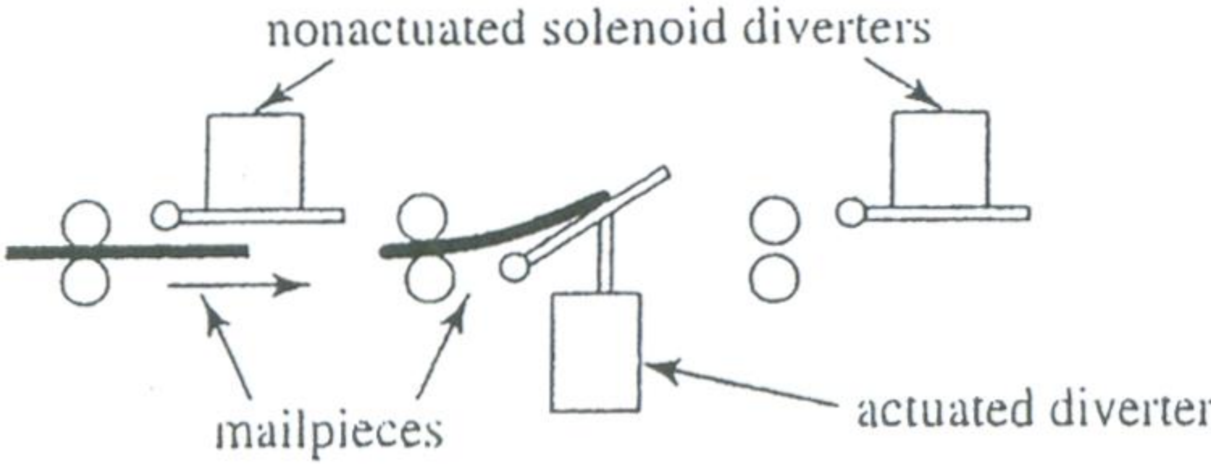
Printer pin solenoid



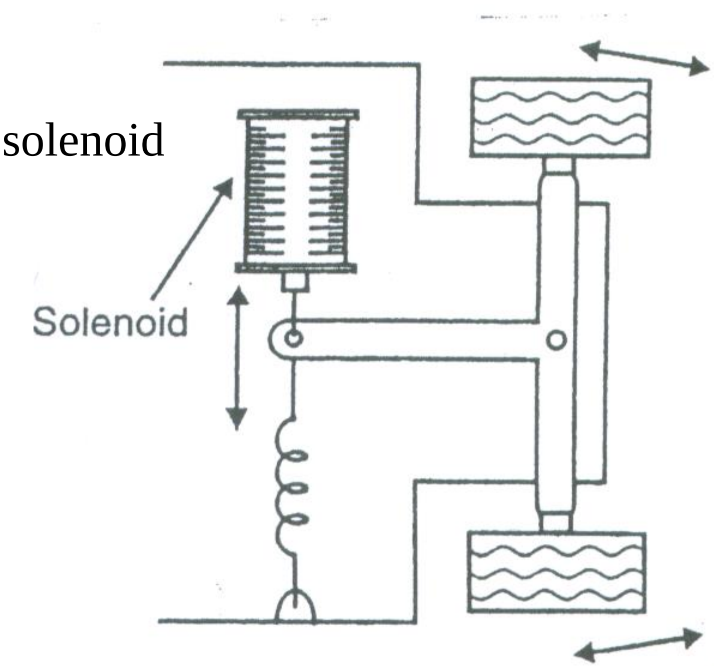
Solenoid valve

Solenoid Application: Mail Diverter and Robot Steering

Mail diverter

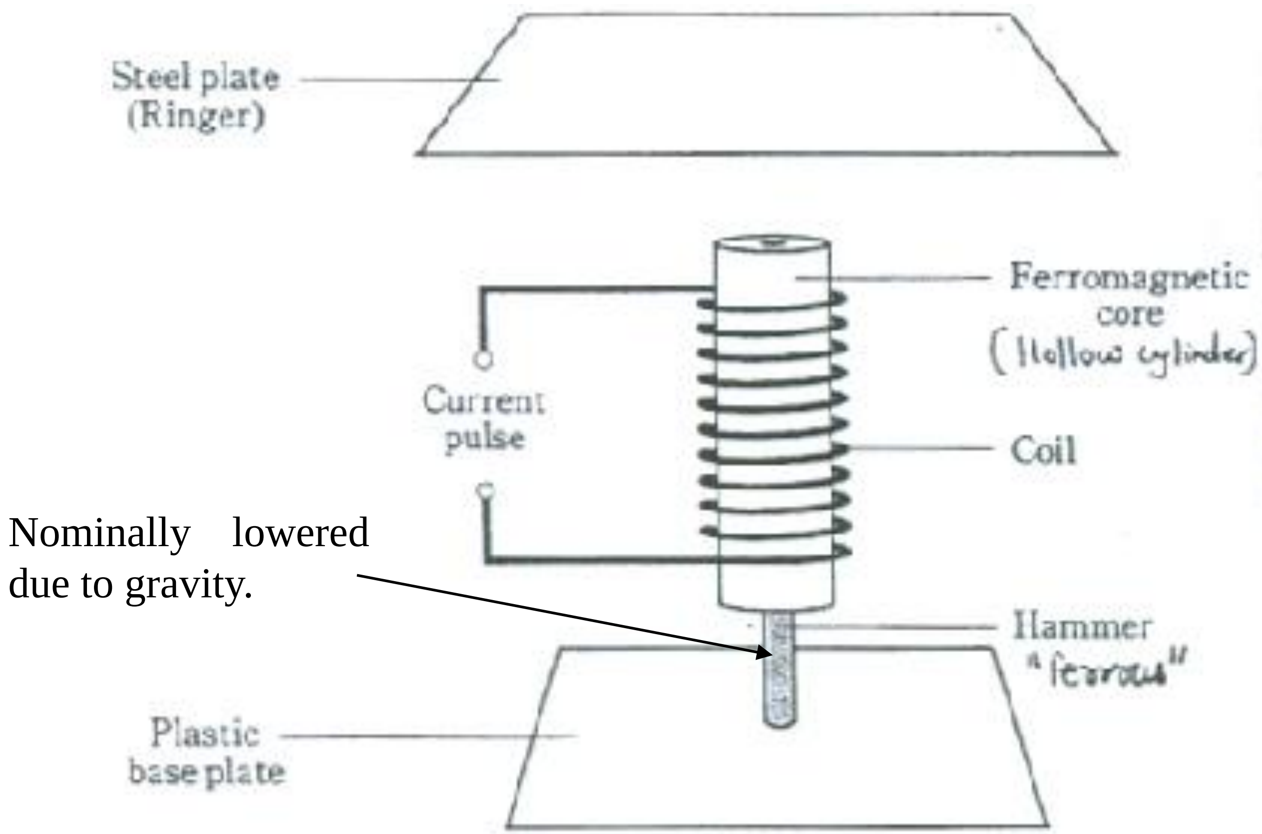


Robot steering control using solenoid



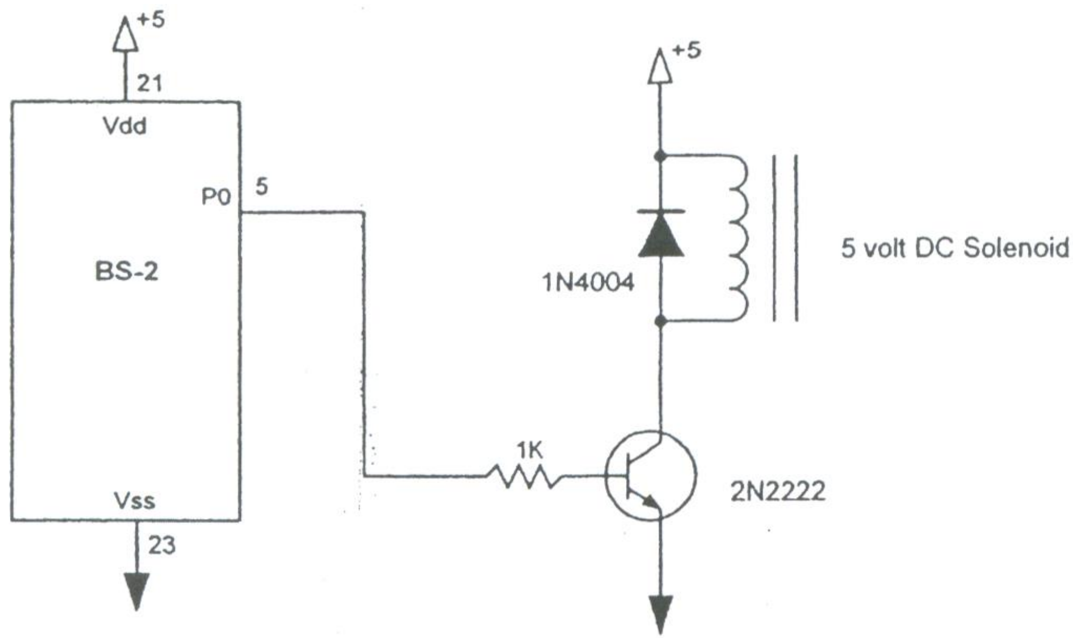
Solenoid Application: Door Bell

- Ferrous hammer is pulled into the core when current is applied to the coil.
- As the hammer is pulled up, it exits from the upper portion of the core and strikes the steel plate.



Interfacing Solenoids with BS2—I

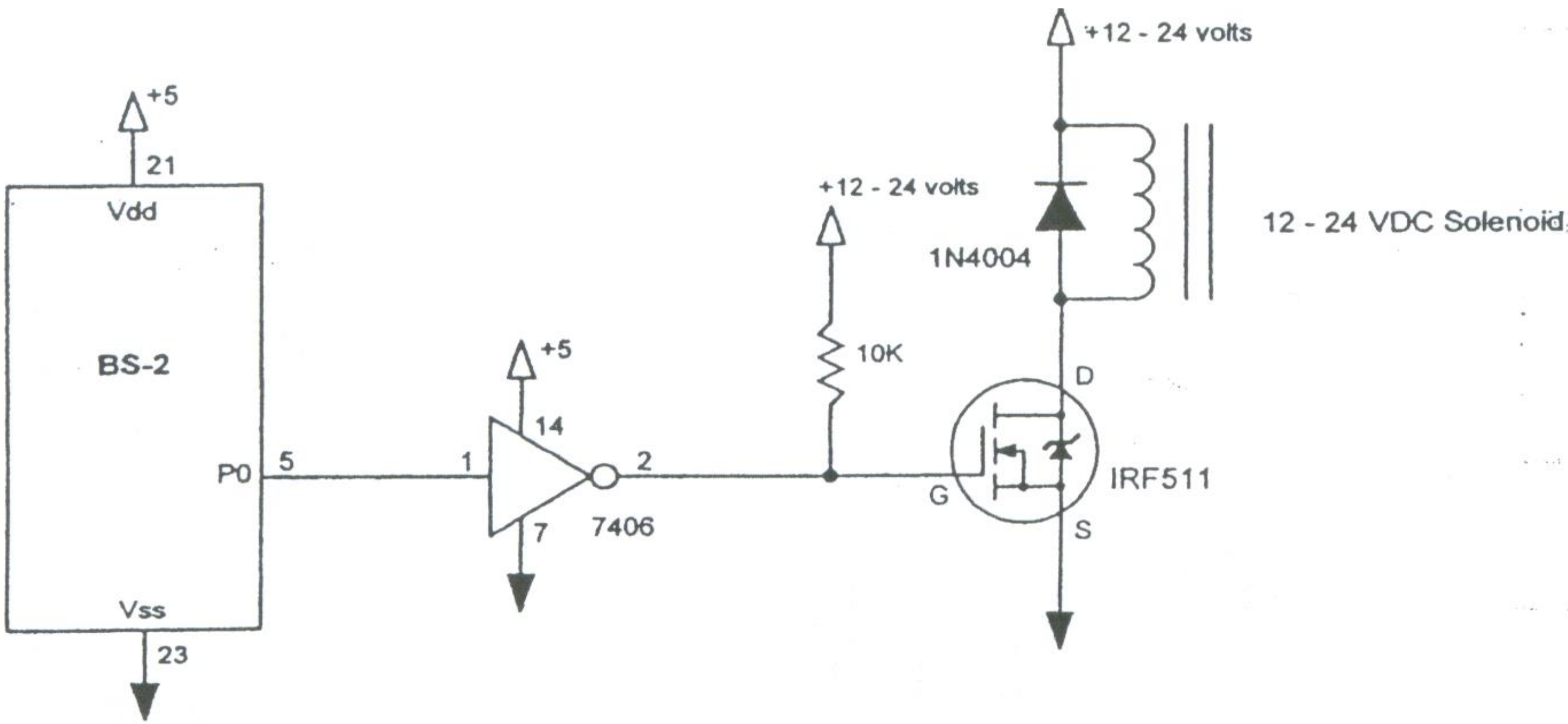
- An NPN BJT is used to switch a low voltage solenoid.
- The diode protects the sensitive circuitry from the voltage spike created by collapsing magnetic field.



A simple NPN transistor solenoid driver circuit

Interfacing Solenoids with BS2—II

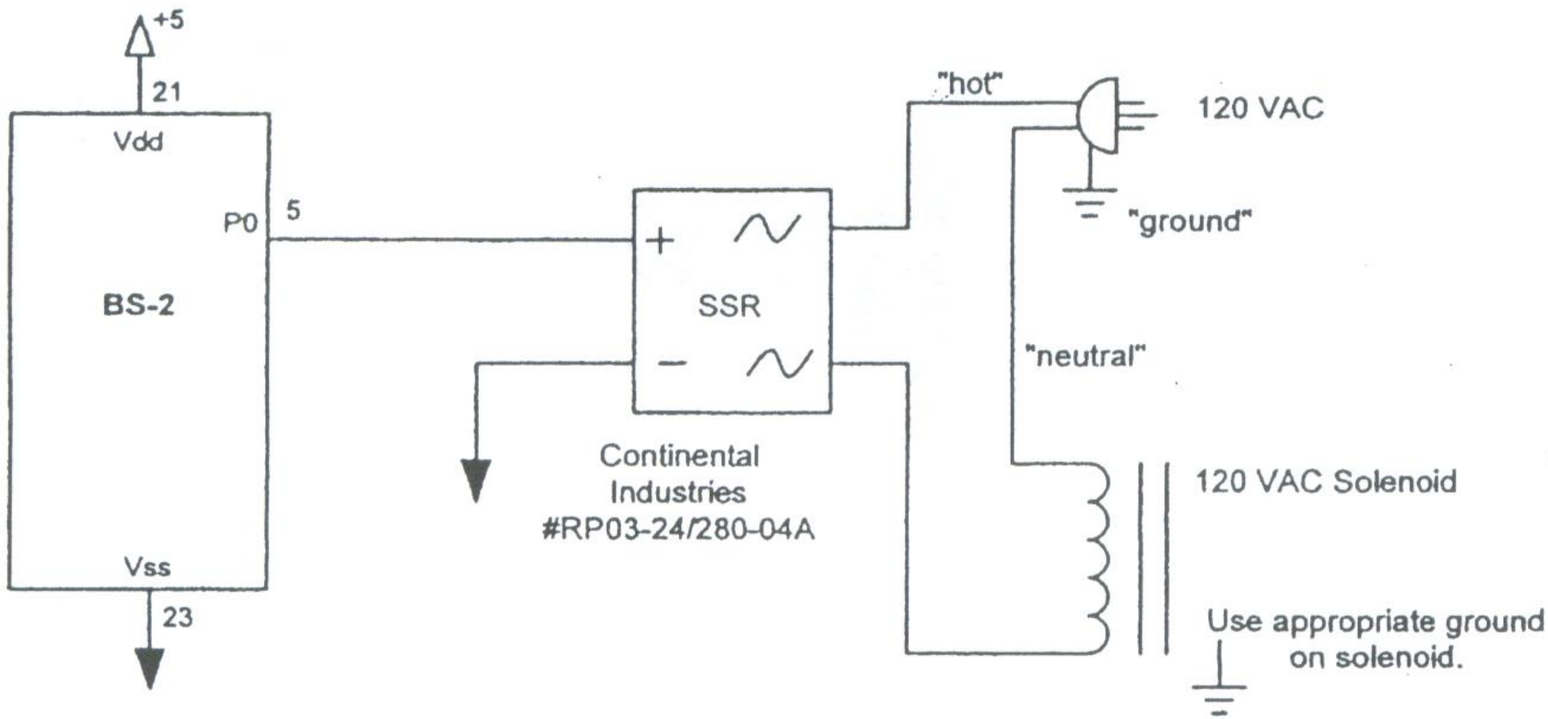
- Use of 7406 inverting buffer and IRF511 MOSFET allows operation of a high voltage DC solenoid using BS2.



Driving a high current solenoid

Interfacing Solenoids with BS2—III

- A SSR and an 120VAC solenoid is used when one needs significantly amount of “pull power”



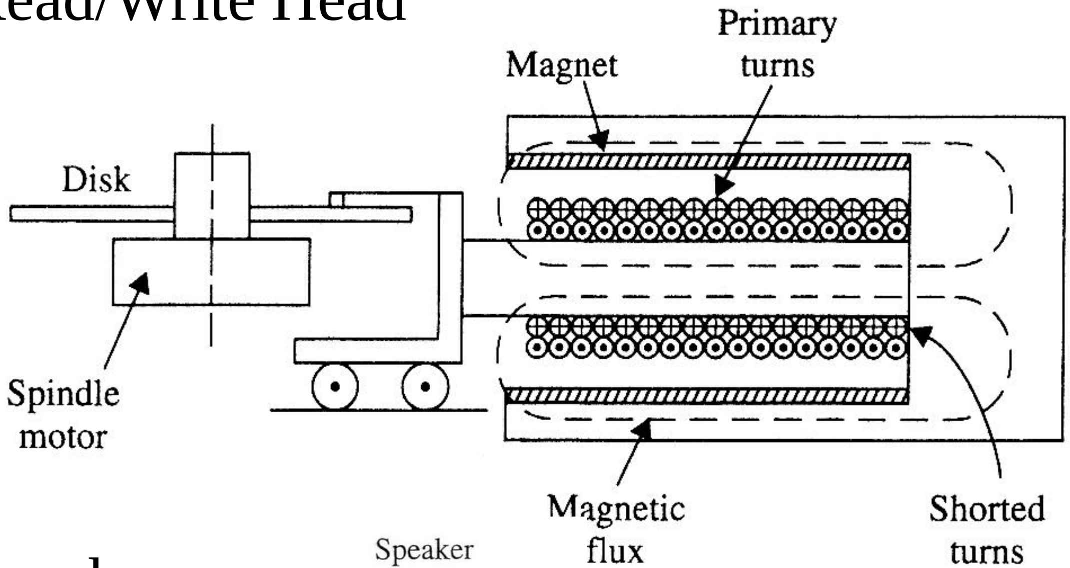
Driving a 120VAC solenoid

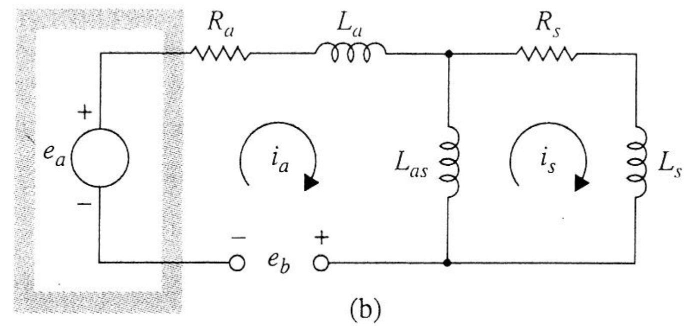
Practical Facts About Solenoids

- Solenoids can be used to produce linear or rotary motion, either in the push or pull mode. The most common solenoid types are:
  - Single-action linear (push or pull). Linear stroke motion, with a restoring force (from a spring, for example) to return the solenoid to the neutral position.
  - Double-action linear. Two solenoids back to back can act in either direction. Restoring force is provided by another mechanism (e.g., a spring)
  - Mechanical latching solenoid (bistable). An internal latching mechanism holds the solenoid in place against the load.
  - Keep solenoid. Fitted with a permanent magnet so that no power is needed to hold the load in the pulled-in position. Plunger is released by applying a current pulse of opposite polarity to that required to pull in the plunger.
  - Rotary solenoid. Constructed to permit rotary travel. Typical range is 25 to 95°. Return action via mechanical means (e.g., a spring).
  - Reversing rotary solenoid. Rotary motion is from one end to the other; when the solenoid is energized again it reverses direction.

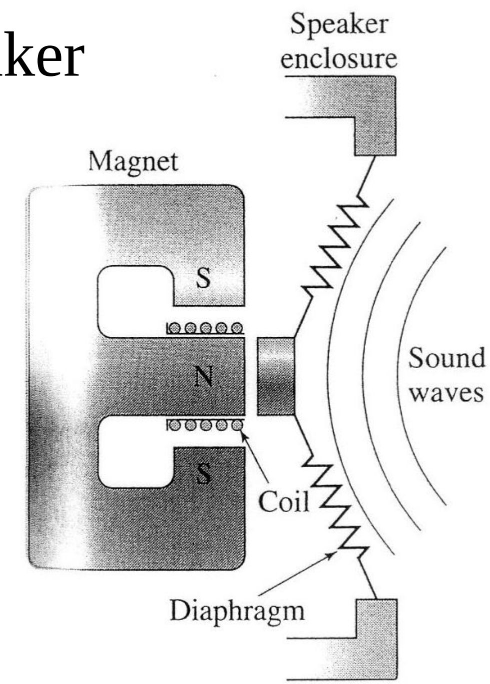
Beyond On/Off Solenoids

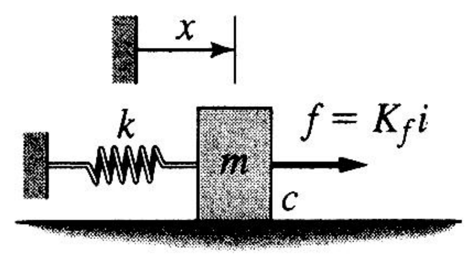
Read/Write Head

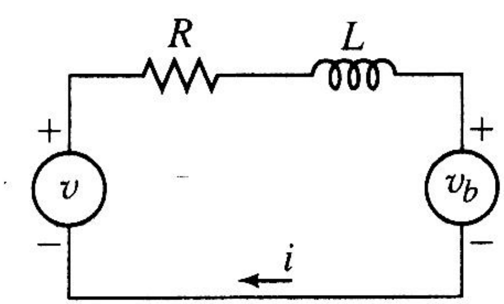




Speaker

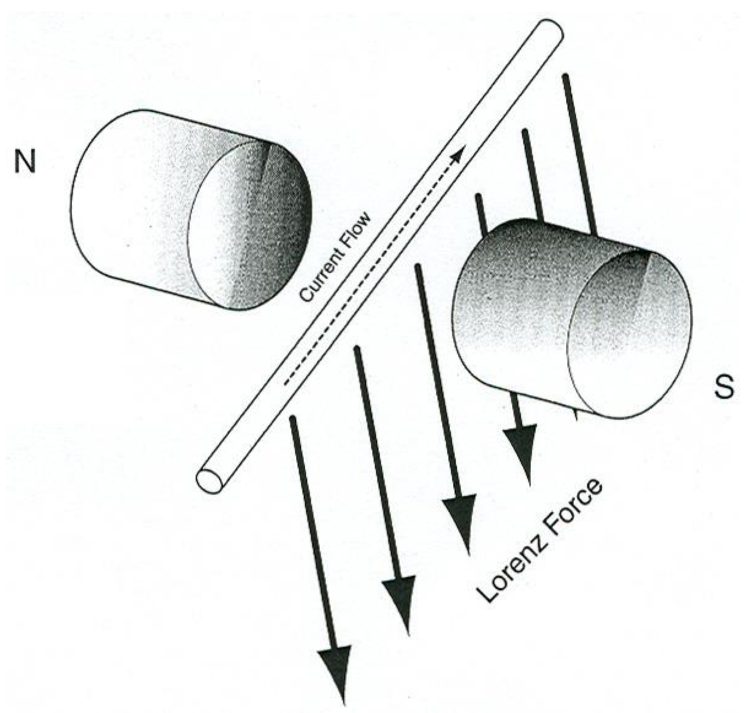


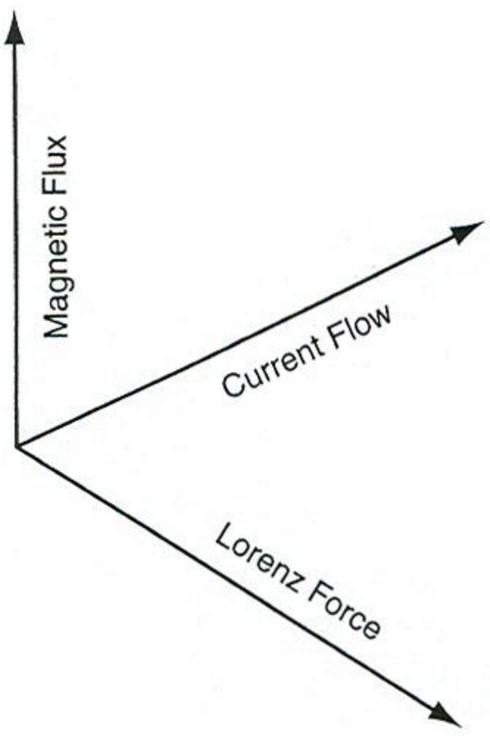




DC Motor Principle of Operation: Lorenz Force

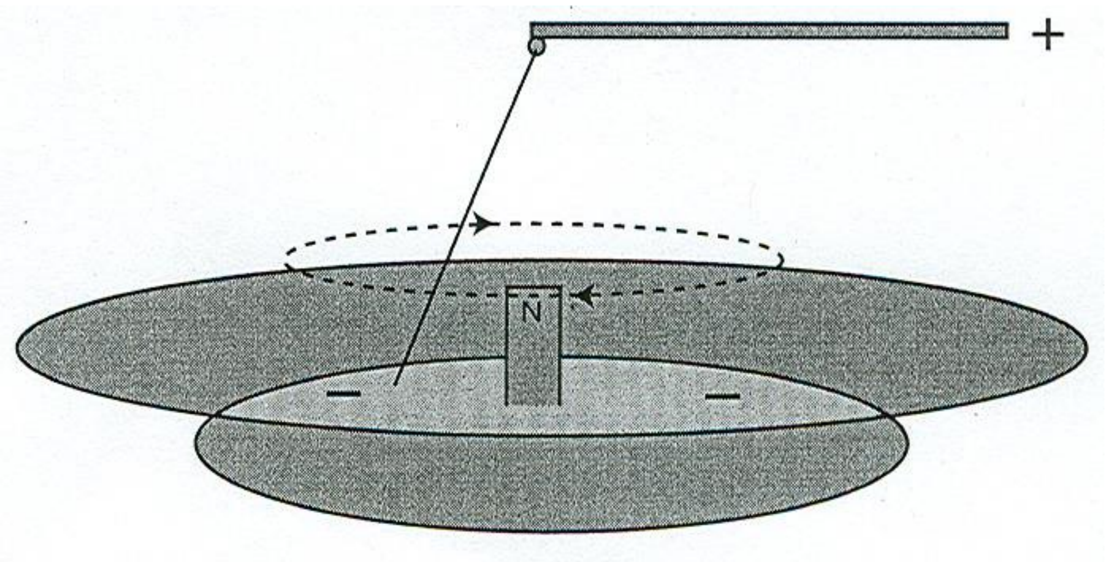
- When a current carrying conductor is placed in a magnetic field, a force is produced orthogonal to both the magnetic field flux and current flow direction.
- Left hand rule:
  - With your left hand, point your fingers forward and your thumb up.
  - If your fingers point in the direction of current flow and your thumb points in the direction of magnetic flux (North to South), your palm faces in the direction of the Lorenz force.





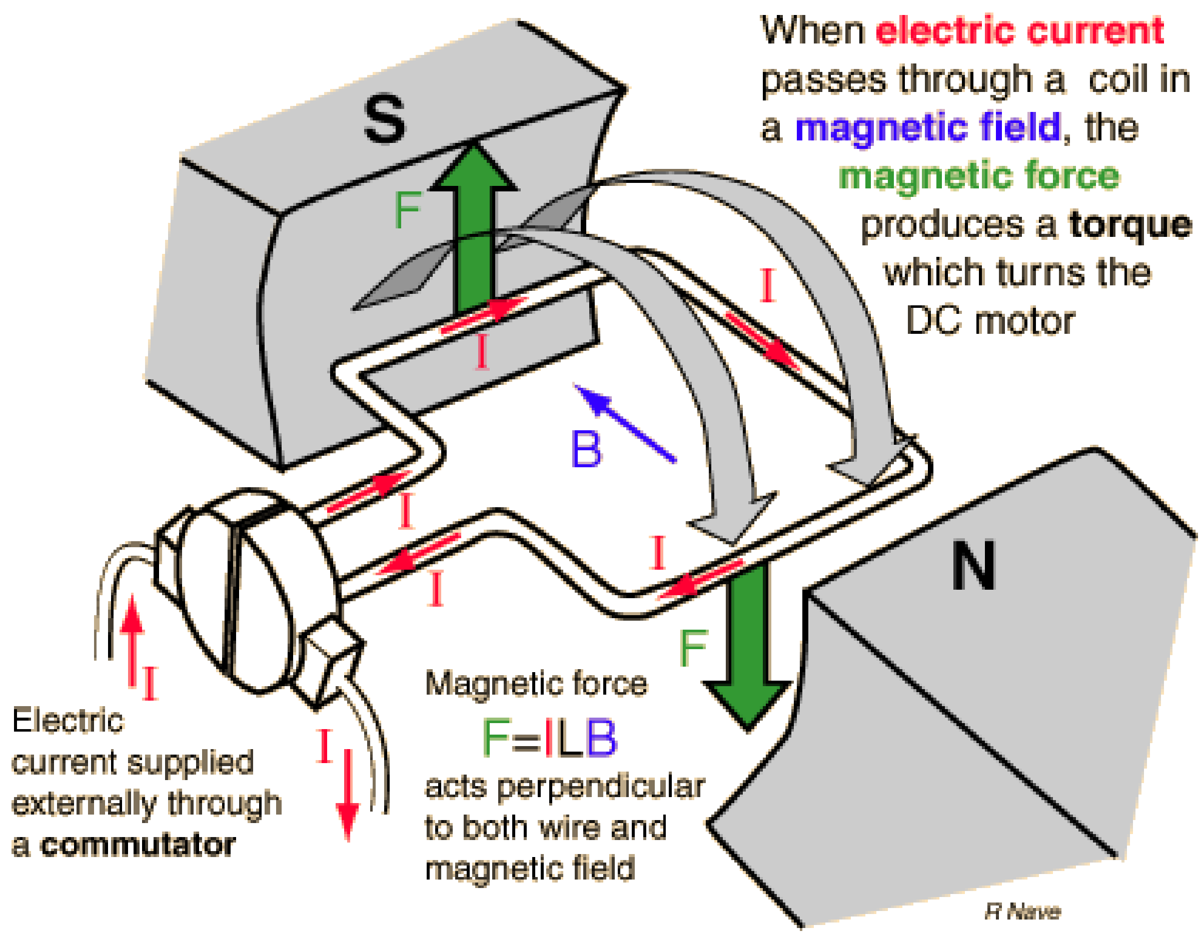
DC Motors: Faraday's Motor (1821)

- Place a magnet in a shallow dish of mercury and above it suspend a wire.
- Connect one end of the wire to one pole of a battery and allow the other end of the wire to dangle in the dish of mercury.
- The dish of mercury is connected to the other pole of the battery.
- Since mercury is conductive, it acts as a liquid commutator brush and current flow through the wire.
- The current flow in the wire creates a magnetic field which interacts with the permanent magnet → the wire is pushed out and around the permanent magnet!
- Result: a single-pole motor producing steady circular motion.



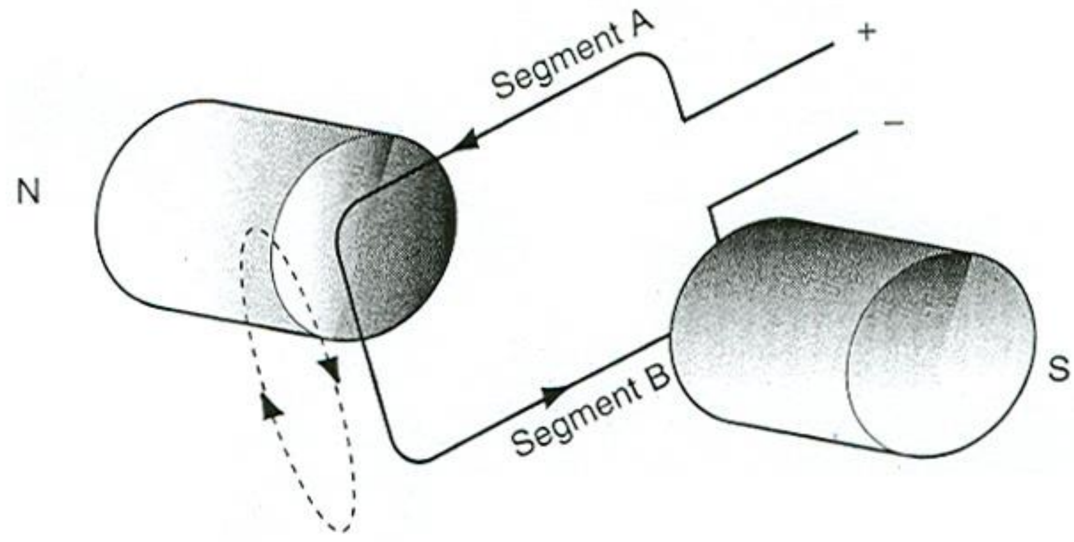
DC Motors: How it Works—I

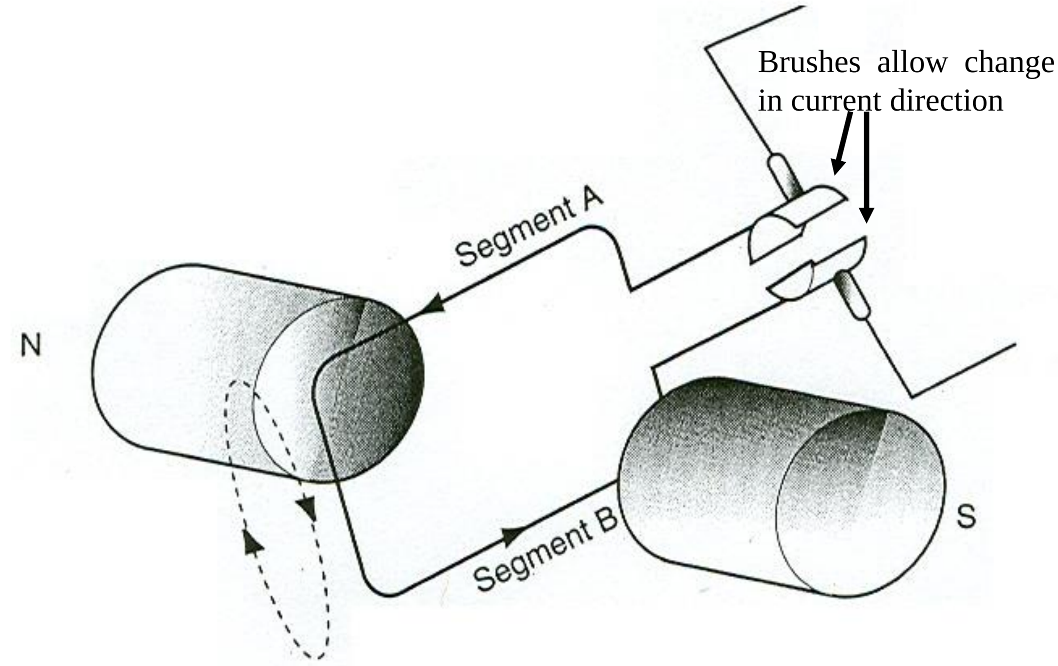
- A DC motor operates when a current is allowed to flow through the motor coil.
- Flow of current in motor coil interacts with the magnetic field → rotary motion.
- Like relays and solenoids, DC motors can also produce reverse voltage spikes when voltage applied across motor coil is removed.
- Since the inductive kick can damage sensitive motor drive circuitry (specially BS2-based driver), it is important to use a separate power source to drive motor and use diodes to prevent damage due to reverse spike.



DC Motors: How it Works—II

- Consider the coil is connected to a power source as shown so that initially segment A is forced up and segment B is forced down.
- When the coil lies in the vertical plane, as shown, segment A is at its highest point (it can not be pushed up any more) and segment B is at lowest point (it can be pushed down any more).
- If the current flow directions in the segments A and B remain as shown in the figure, the coil will not turn any more.
- In order to allow the coil to continue to turn, at this point the current flow directions in the segments A and B must be reversed.





DC Motors 101—I

- Simple two-lead, electrically controlled devices.
- Comes with a rotary shaft on which gears, wheels, propellers, etc. can be mounted.
- Produce significant rpm for their size.
- Direction:
  - Direction of rotation of a motor depends on the direction of current flow through it.
  - By reversing the motor connections, its direction of rotation is reversed.
- Yield little torque and allow minimum position control at low speeds.
- Available in many different shapes and sizes.
- Rotational speed rage 5000-8000rpm.
- Voltage:
  - Operating voltage range of small DC motors: 1.5-48V.
  - Cease to function below 50% of the operating voltage.
  - Overheats if the voltage applied exceeds 30% of the operating voltage. The maximum voltage limit of DC motor should not be exceeded.

DC Motors 101—II

- Speed:
  - Motor speed depends on the applied voltage and applied load.
  - For a no load or constant load condition, the motor speed increases with increasing voltage.
  - For a constant voltage input, the motor speed decreases with increasing load.
  - Most efficiently controlled by means of pulse-width modulation.
- Torque rating: amount of force a motor can exert on a load.
  - Usually given in lb/ft, g/cm, or oz/in.

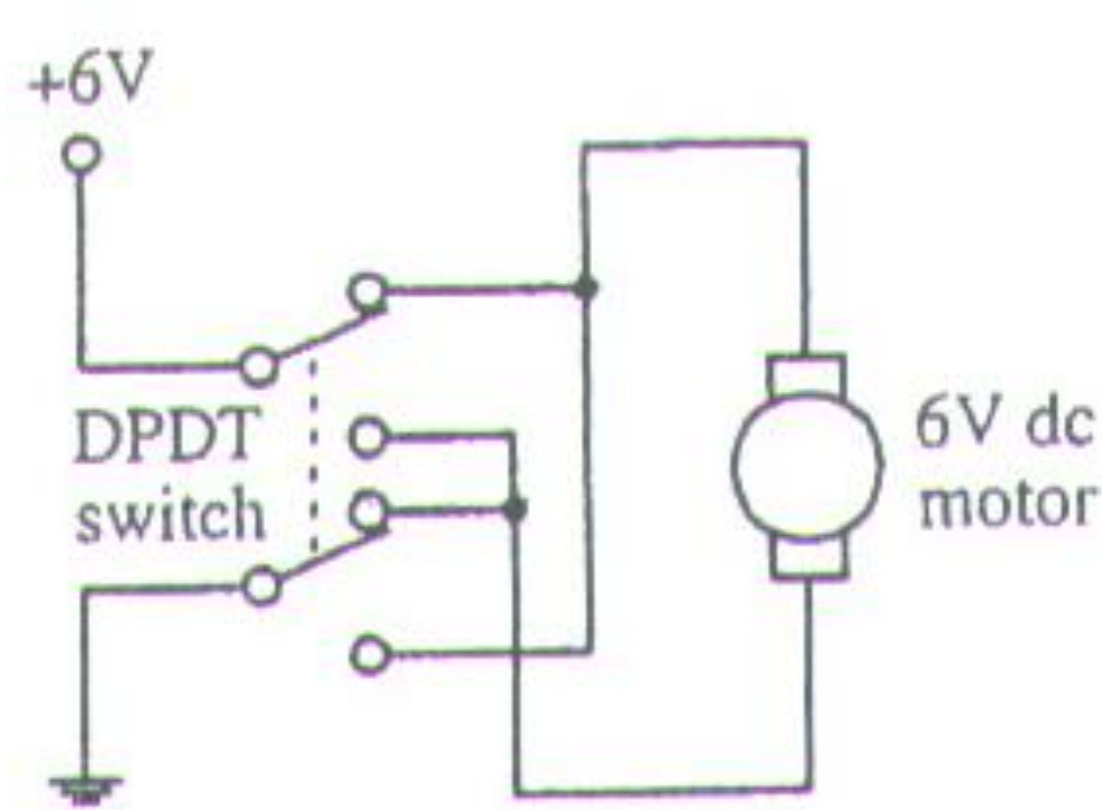
- Current:
  - At no load, a motor draws little current, and as load increases, the current drawn by motor increases.
  - Stall current: current drawn at the moment the motor stalls.
  - Should not use excessive load that can stall the motor.
  - Stalled motor acts as a short circuit that generates excessive heat, which can damage the motor.

DC Motors: Directional Control—I

- Can be changed by using double pole double throw (DPDT) switch.
  - Manual DPDT switch does not give automatic control.
- Can use relays to control a DPDT switch.
  - Relays tend to be bulky and expensive.
- Can use a transistor as switch.
  - Transistors are SPST (single pole single throw) switches.

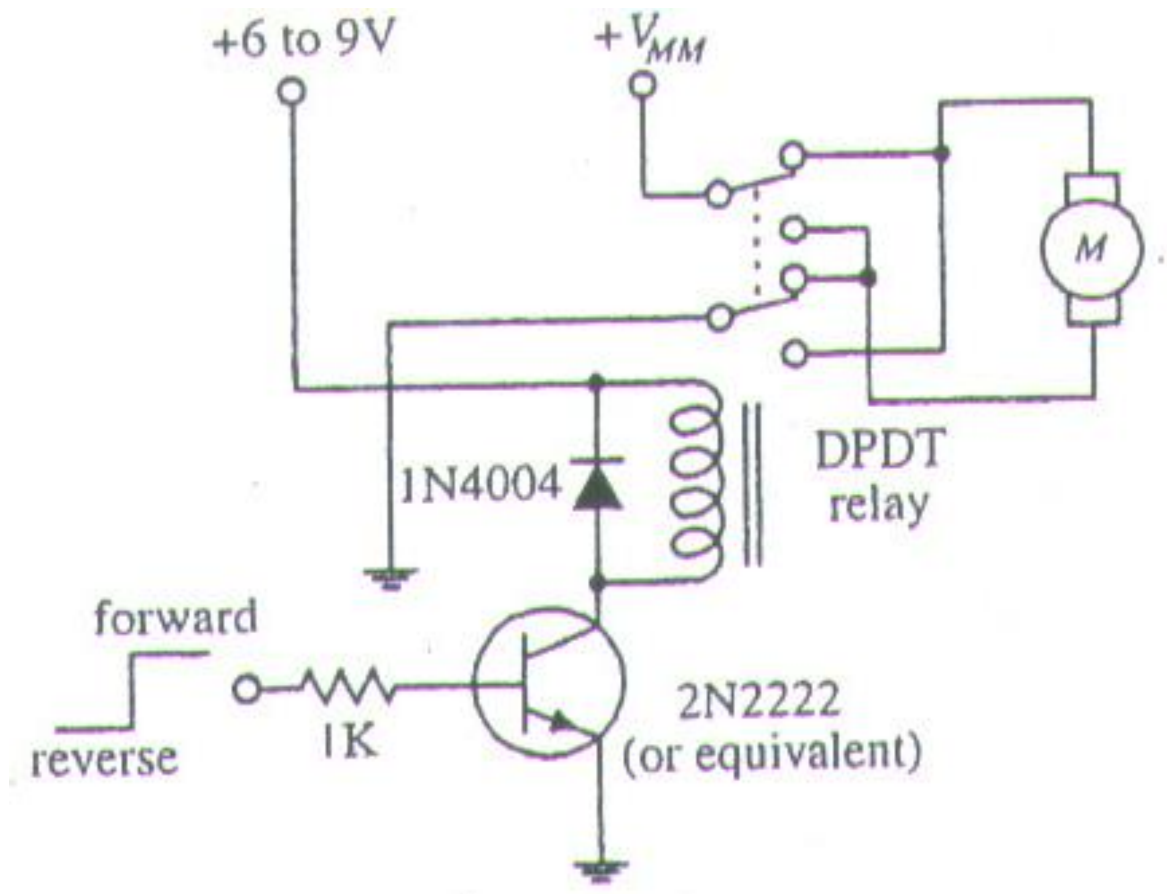
Directional Control—II

- To change a motor's direction of rotation from say clockwise to counterclockwise, polarity applied to the motor's lead must be reversed.
- Manual control of a motor's direction of rotation can be accomplished by using a simple manual DPDT switch.



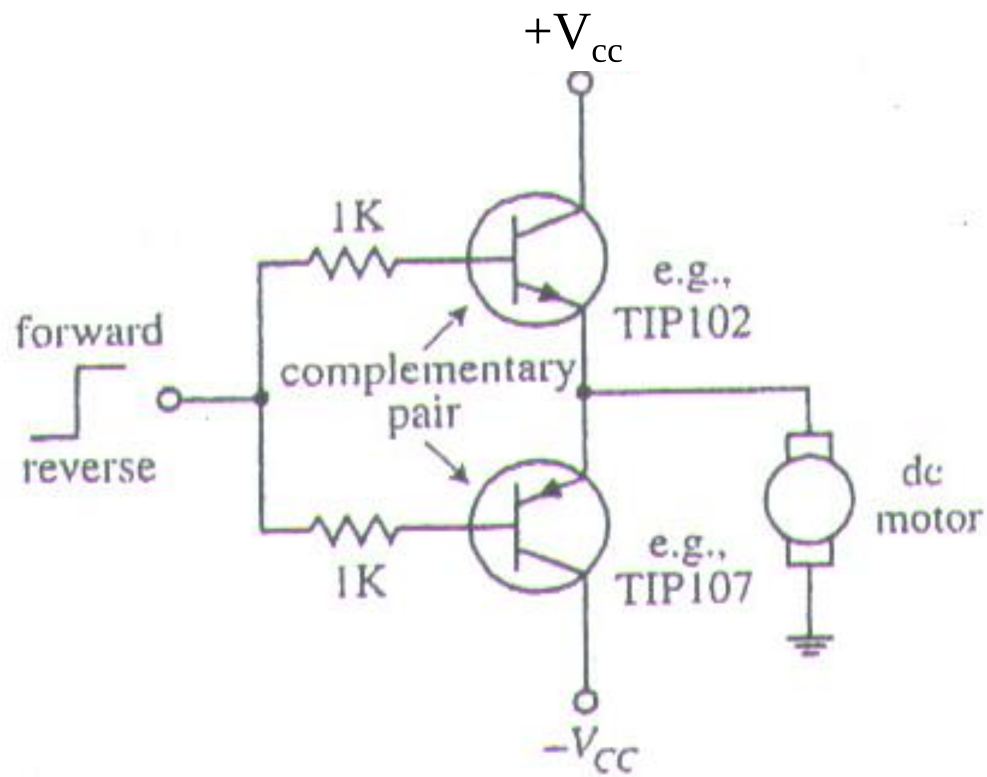
Directional Control—III

- For logic-based control of a motor’s direction of rotation, a transistor-driven DPDT relay can be used.



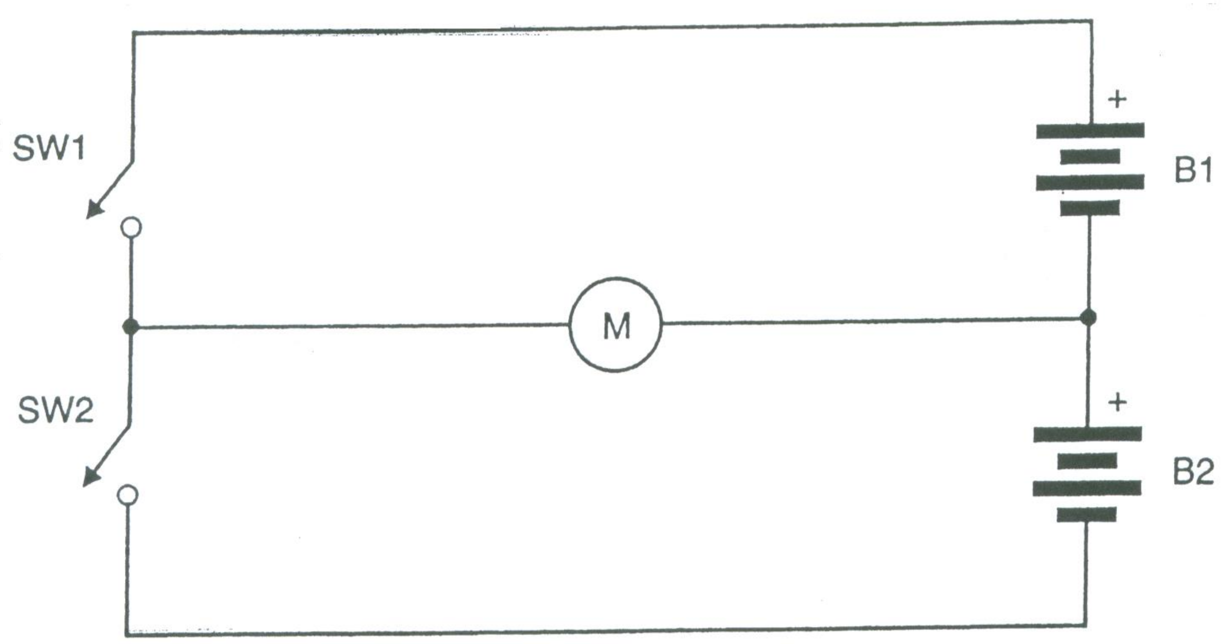
Directional Control—IV

- Logic-based control of a motor's direction of rotation can also be done using a push-pull transistor circuit built using a complementary pair of transistors.
- In the following circuit, the upper transistor is an npn power Darlington and the lower one is a pnp power Darlington.
- When i/p logic is high, the upper transistor conducts, allowing current to pass from positive supply to ground via the motor.
- When i/p logic is low, the lower transistor conducts, allowing current to pass from ground into negative supply via the motor.

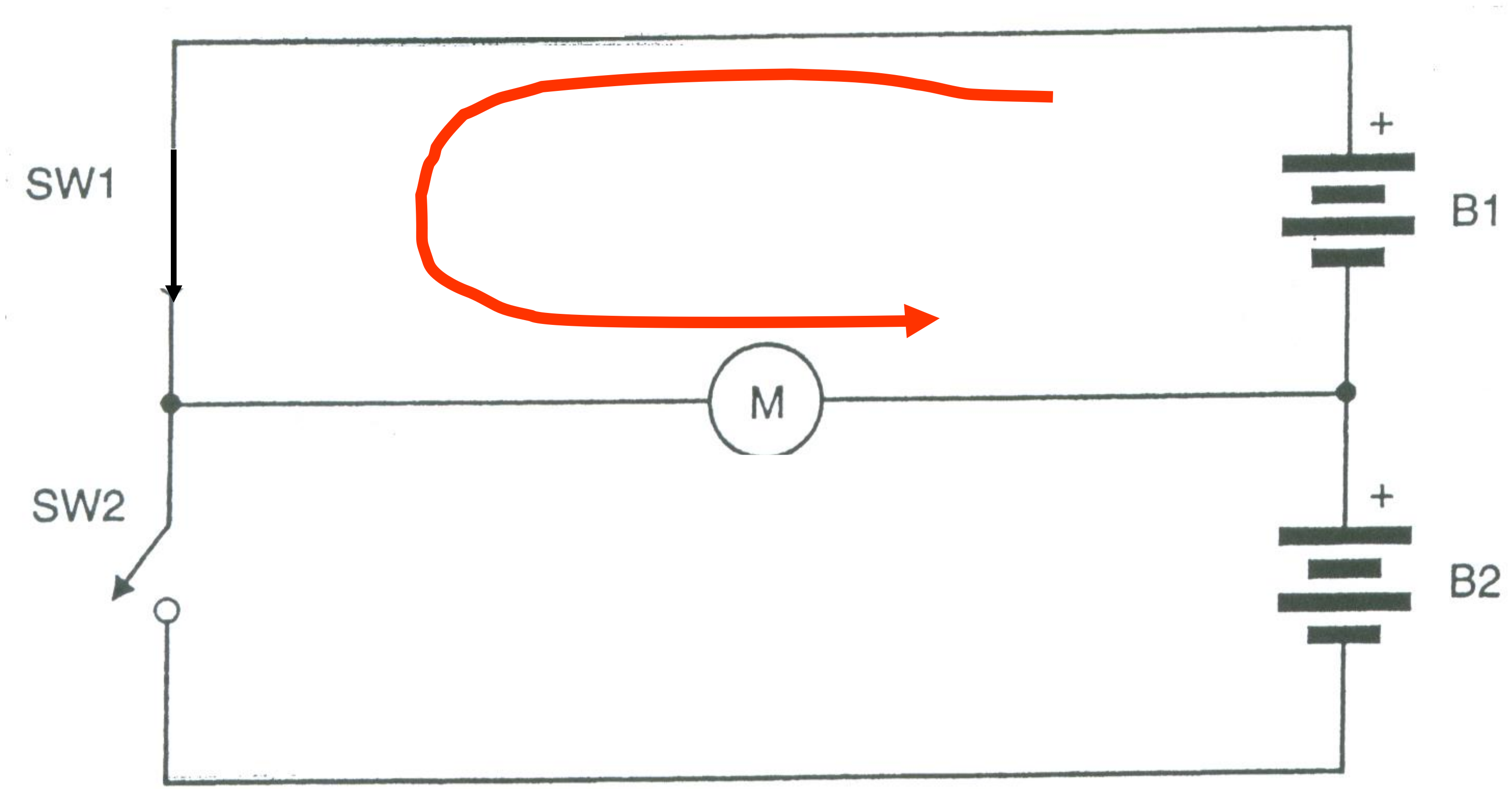


Directional Control Using Bridge Circuits: Half Bridge Circuit #1—I

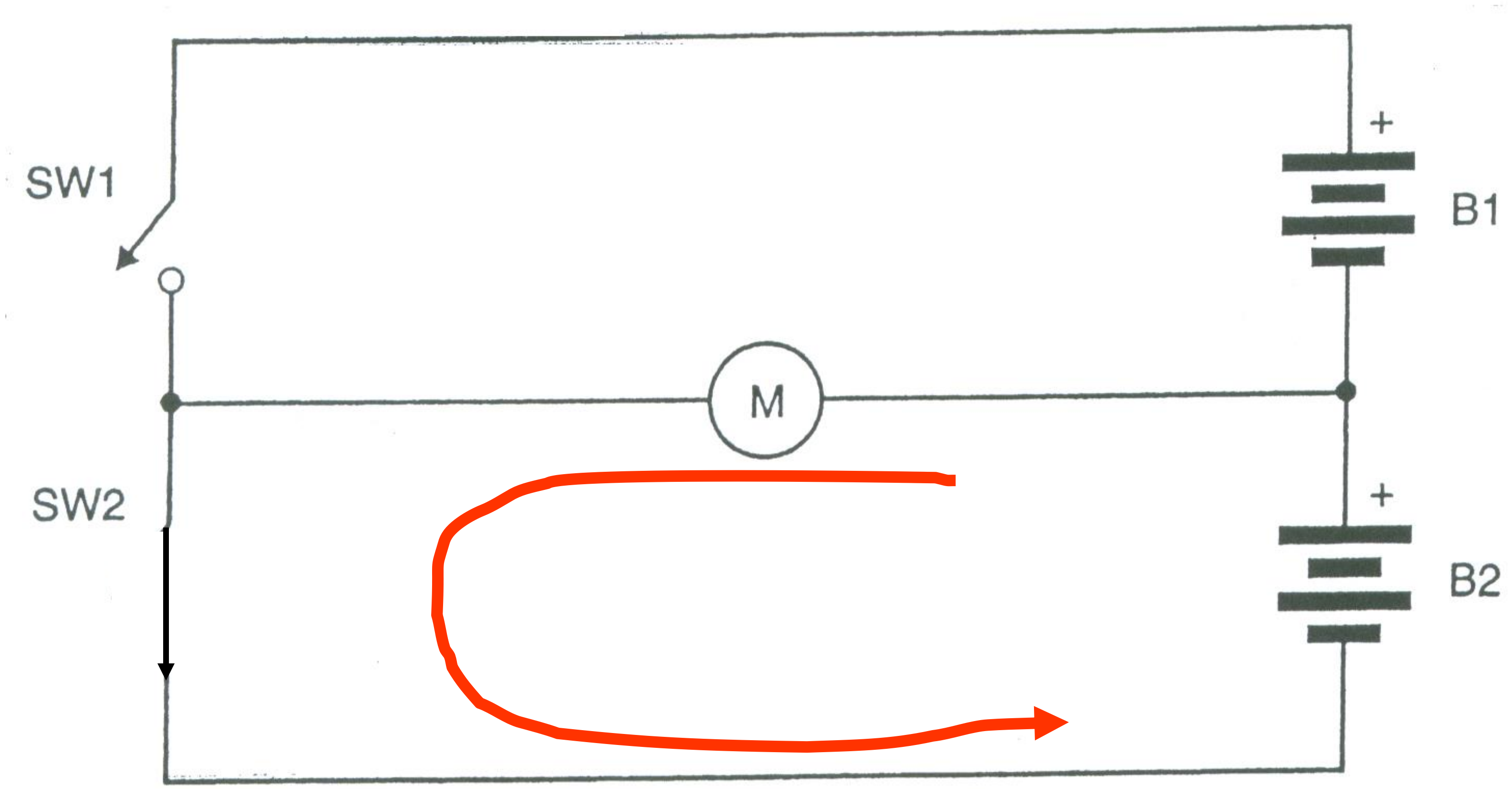
- Consider the following circuit consisting of 2 voltage sources, 2 switches, and a DC motor connected in a special manner.
- When SW1 is closed, B1 is connected to the motor, current flows from left to right, motor turns in one direction.
- When SW2 is closed, B2 is connected to the motor, current flows from right to left, motor turns in the opposite direction.
- SW1 and SW2 cannot be closed simultaneously, as this leads to B1 and B2 being in short-circuit.



Half Bridge Circuit #1—II



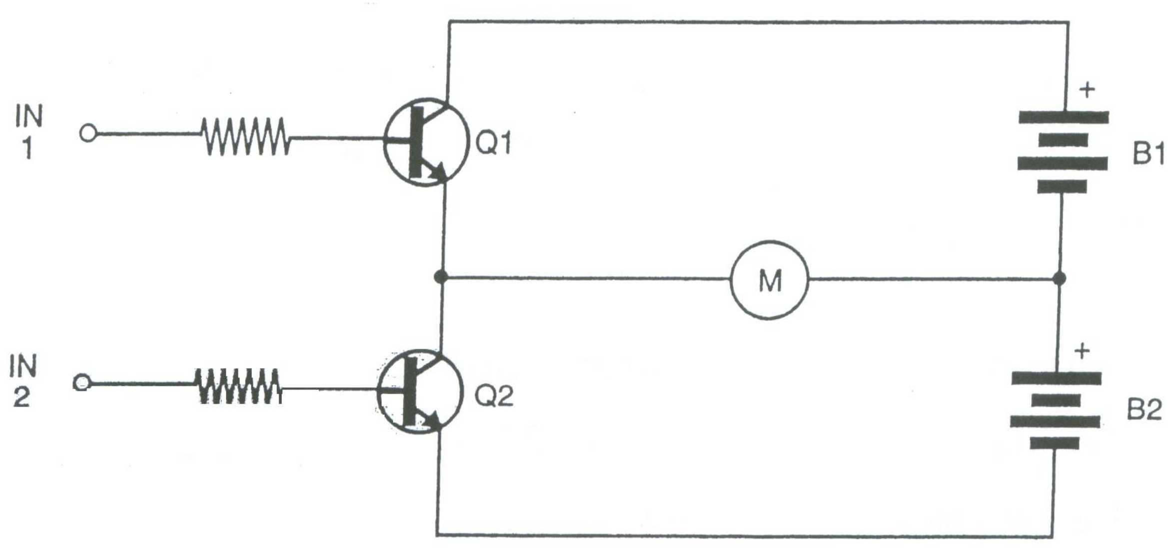
Half Bridge Circuit #1—III



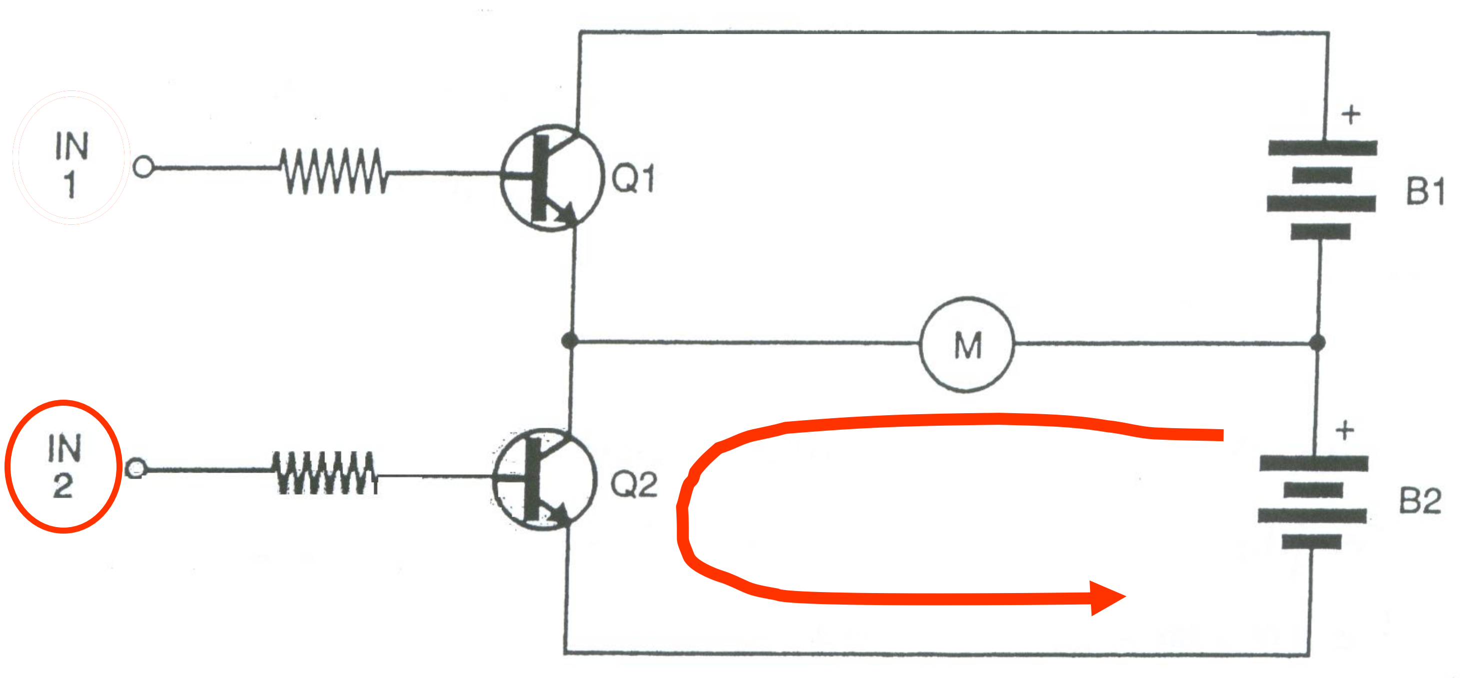
Switch

Half Bridge: Circuit #2—I

- Consider the following circuit consisting of 2 NPN BJT's, 2 voltage sources, and a DC motor. Manual switches have been replaced by 2 BJT's for electrical switching.
- When IN1 is high, Q1 conducts $\rightarrow$ motor is driven in the forward direction by B1.
- When IN2 is high, Q2 conducts $\rightarrow$ motor is driven in the backward direction by B2.
- IN1 and IN2 cannot be driven high simultaneously, as this would cause B1 and B2 to be short circuited.
- The main disadvantage of a half bridge DC motor drive circuit is that it requires a dual power supply.

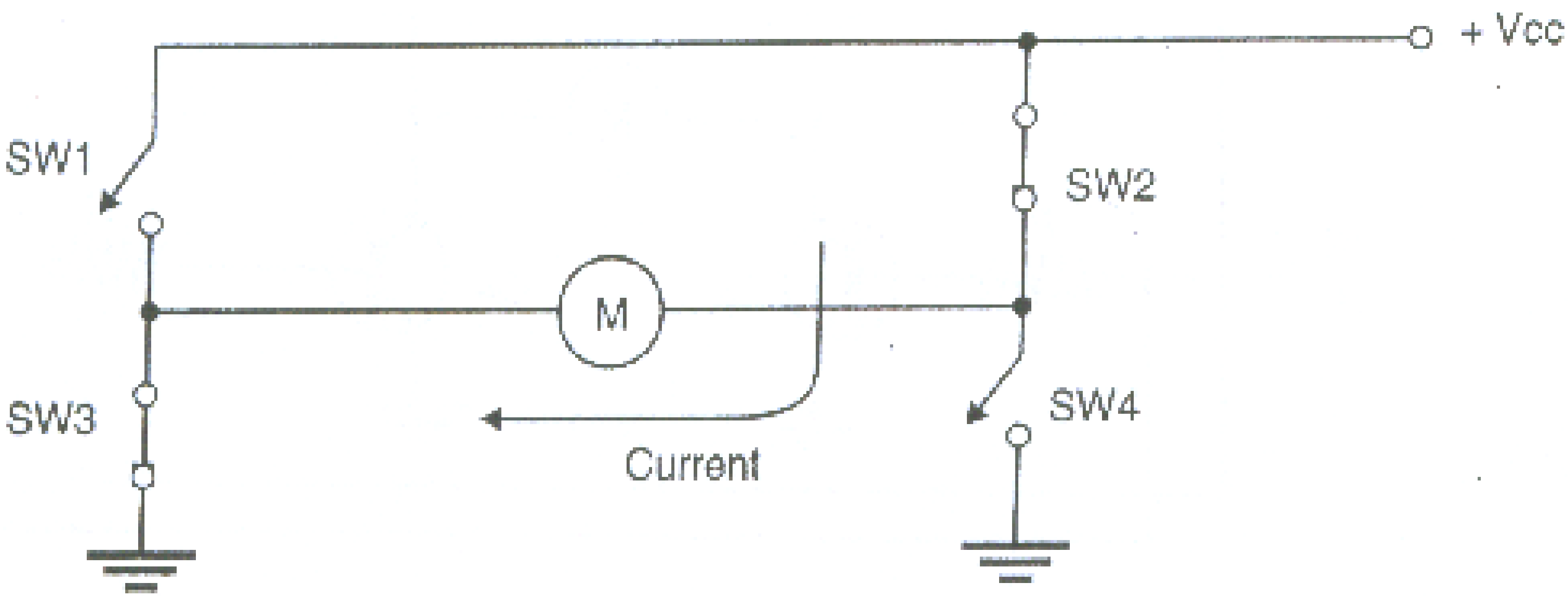


Half Bridge: Circuit #2—II



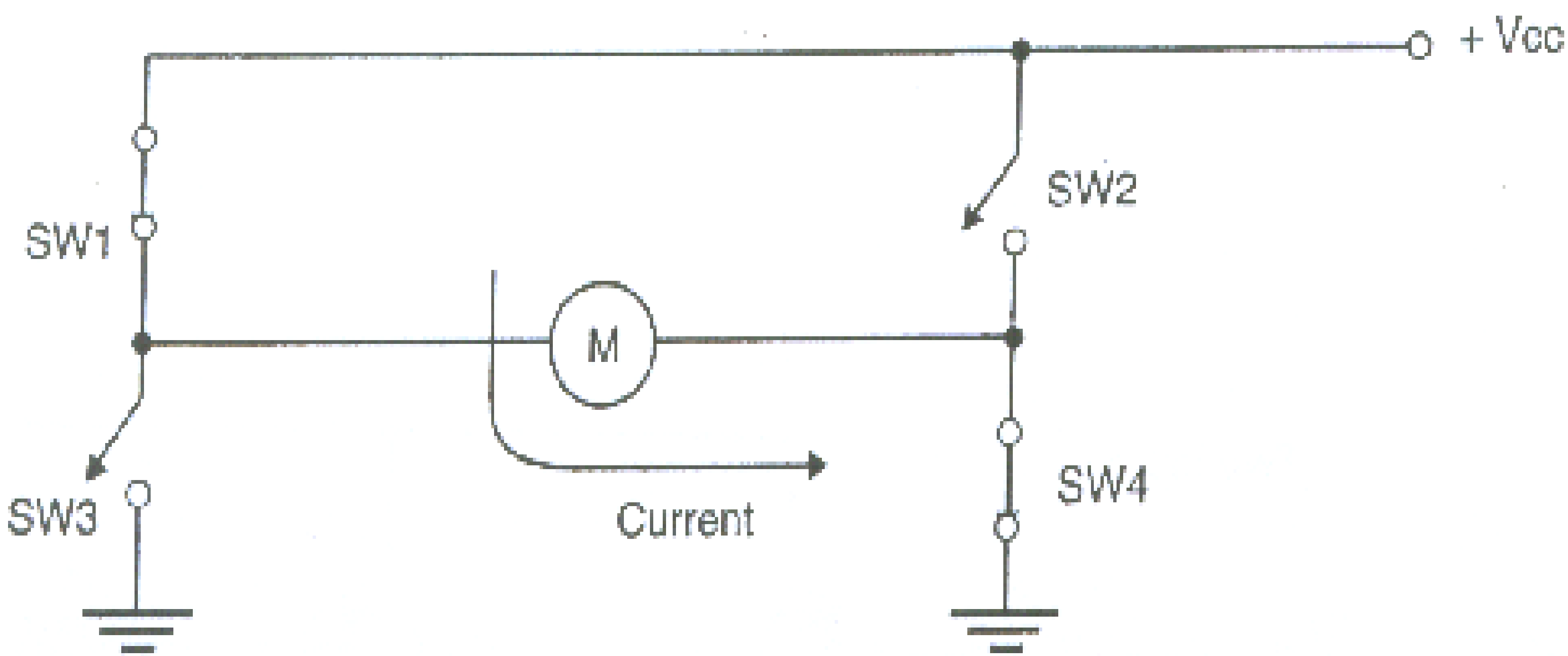
Full Bridge "H-Bridge": Circuit #1—I

- A very popular circuit used to control the direction of a motor is the so called Full-Bridge "H-Bridge" circuit.
- In what follows, we develop the concept of an H-Bridge circuit.
- Consider the following circuit consisting of 4 switches, 1 voltage source, and a DC motor.
  - When SW1 and SW4 are closed (with SW2, SW3 open),the voltage source drives the motor in forward direction.

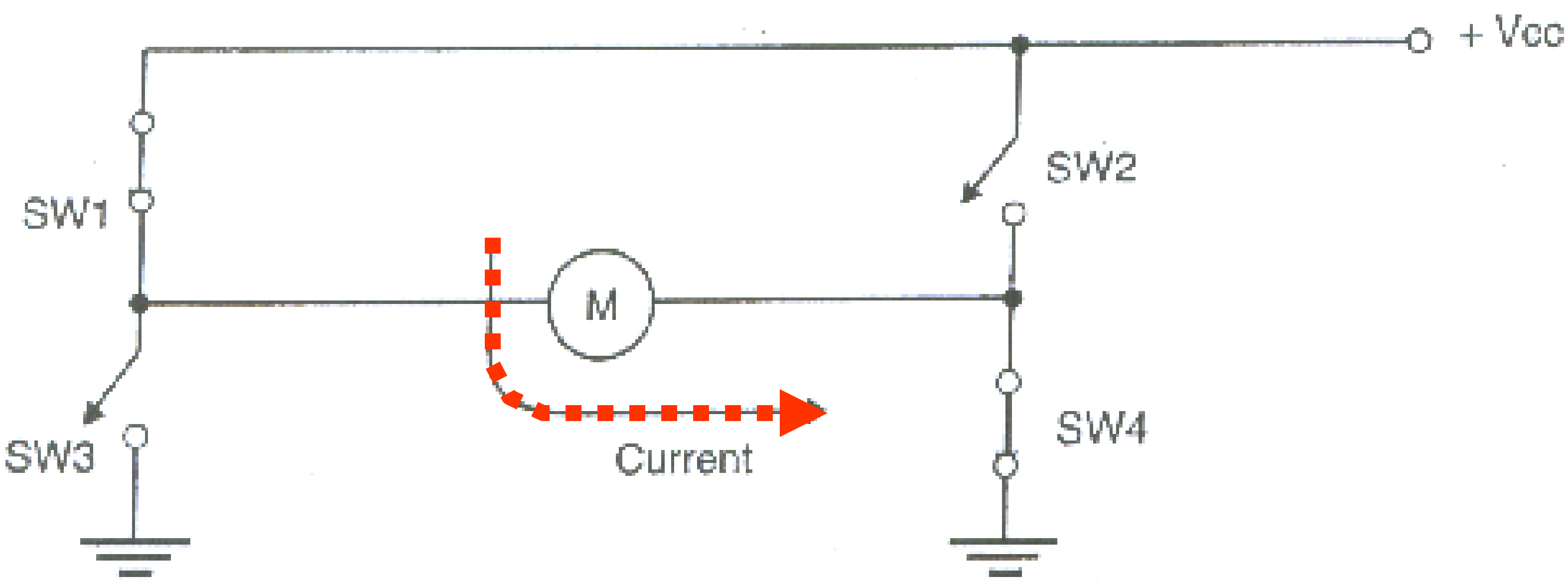


Full Bridge: Circuit #1—II

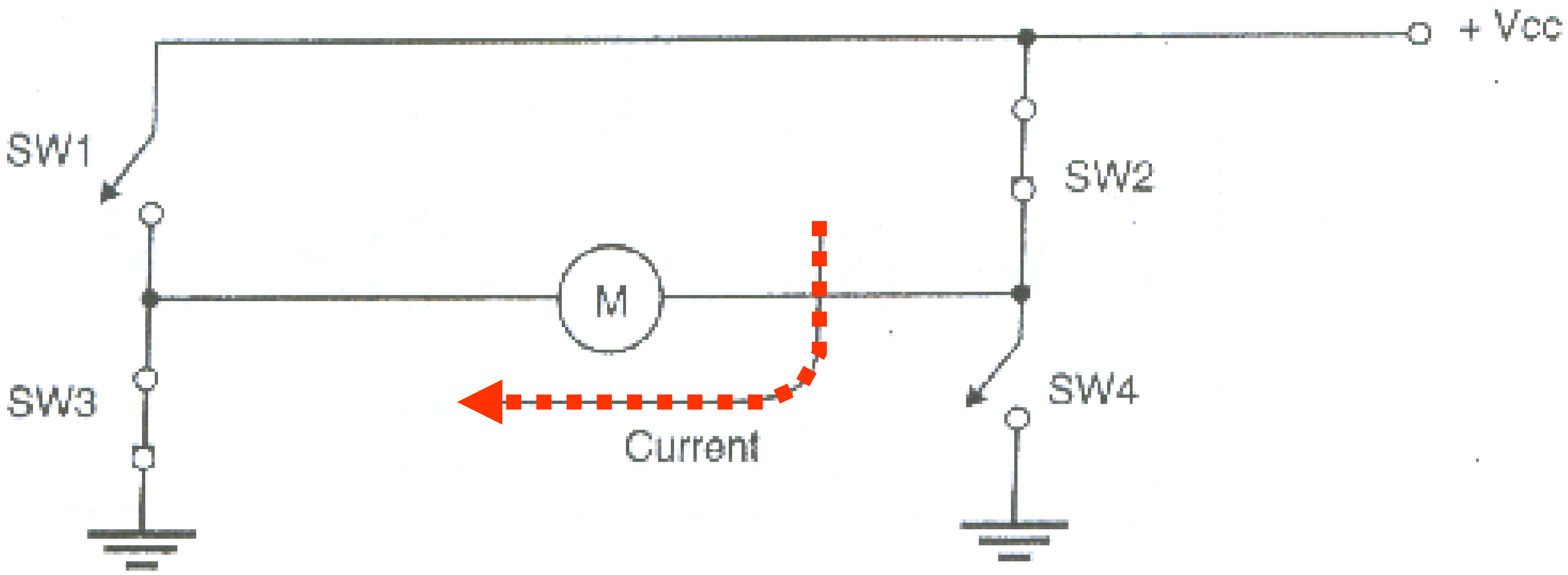
- When SW2 and SW3 are closed (with SW1 and SW4 open), the voltage source drives the motor in reverse direction.
- Note that simultaneous closure of SW1 and SW3 is not permitted. Similarly, simultaneous closure of SW2 and SW4 is not permitted.



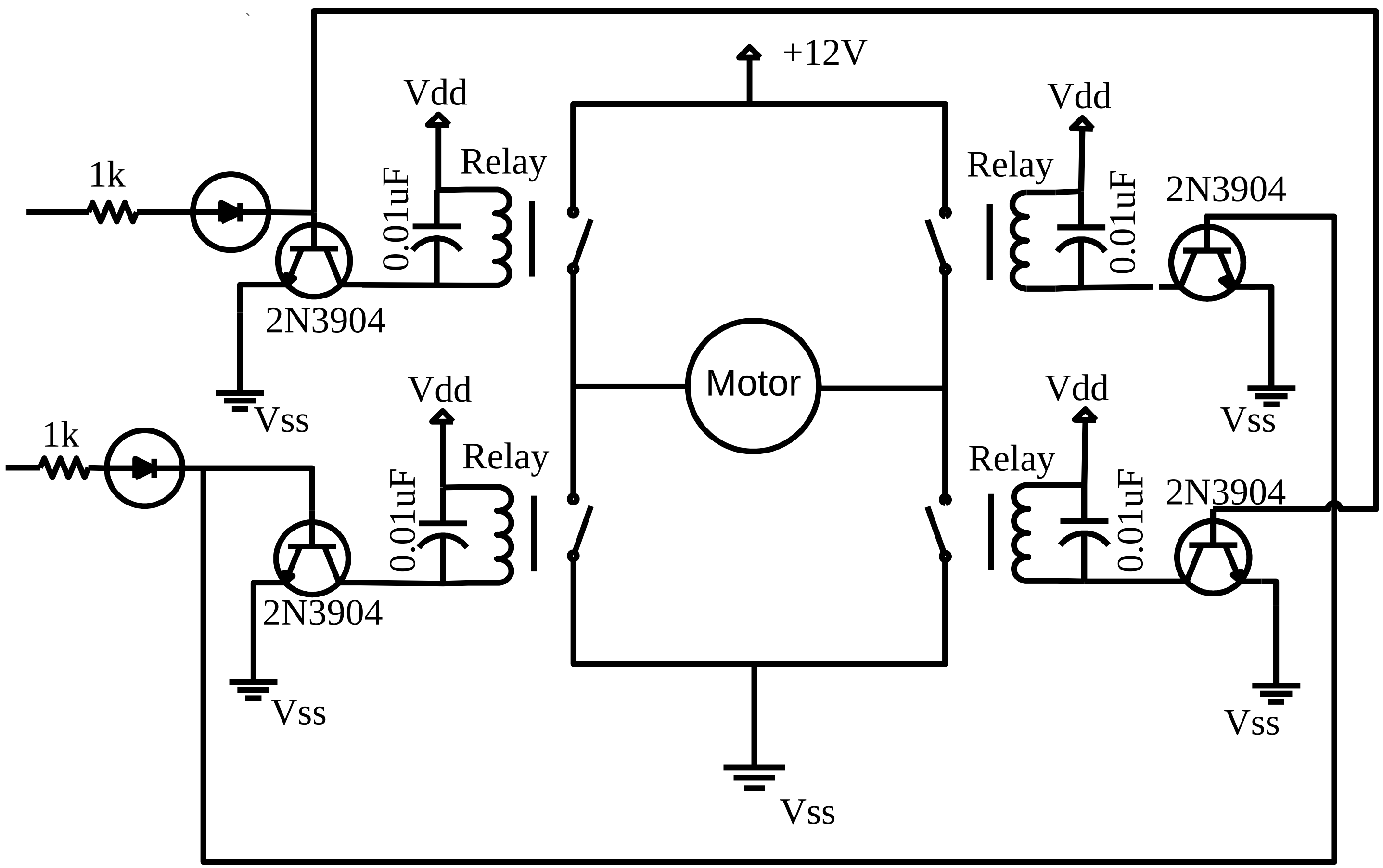
Full Bridge: Circuit #1—III



Full Bridge: Circuit #1—IV



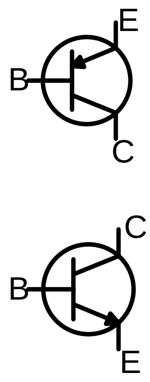
Full Bridge: Circuit #2

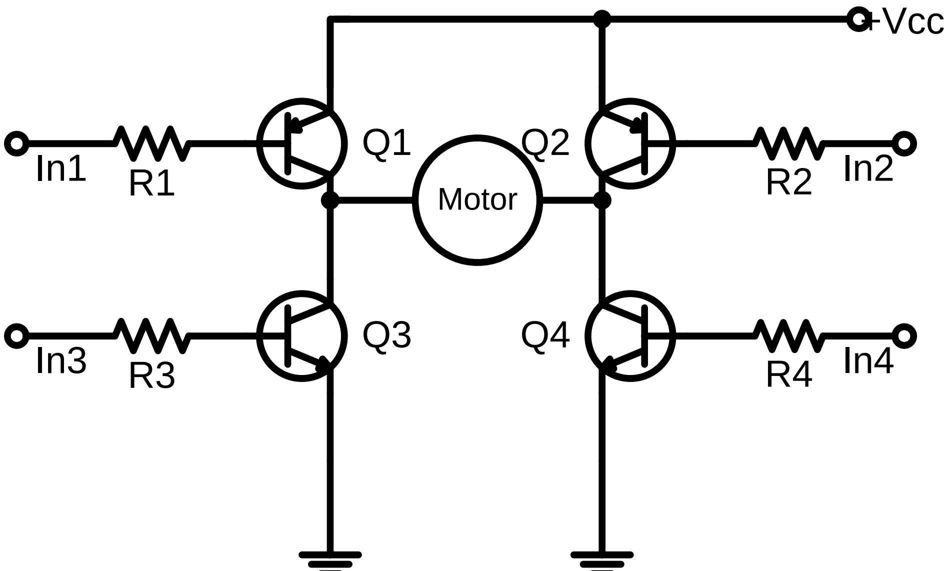


H-Bridge using Relays

Full Bridge: Circuit #3—I

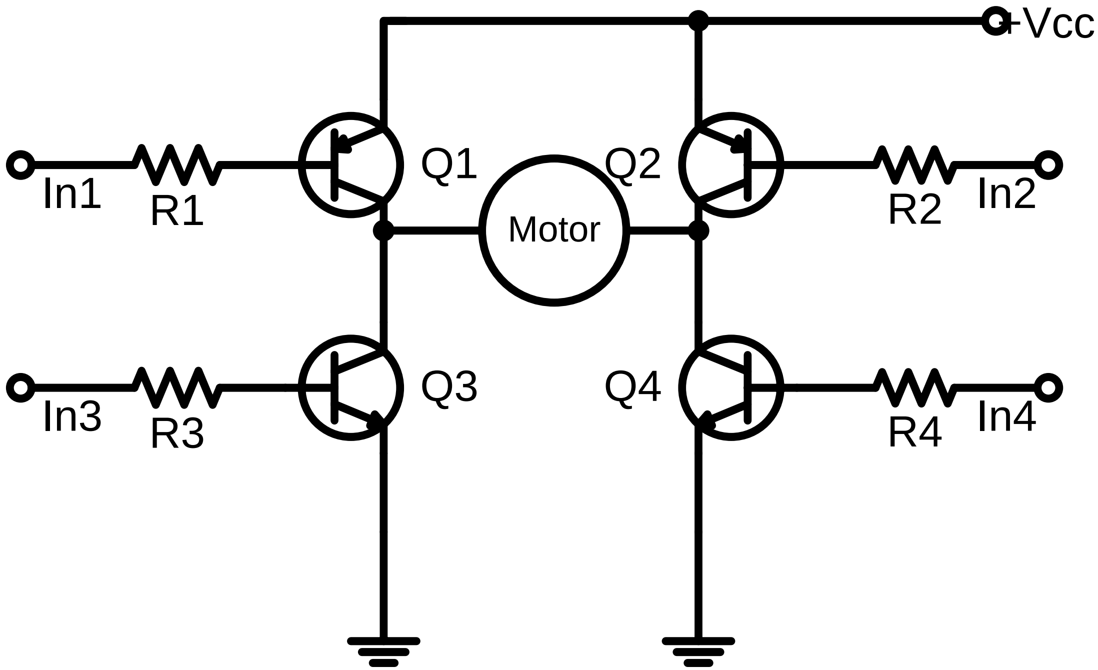
- Consider the following circuit consisting of 4 BJTs, 1 voltage source, and a DC motor.
  - Note that the four manual switches have been replaced with transistors Q1-Q4.
- Recall how the PNP and NPN transistors conduct.
  - NPN transistor. Normally off. When base potential higher than emitter potential, collector-emitter pair conducts. $V_c > V_e$.
  - PNP transistor. Normally off. When base potential is lower than emitter potential, emitter-collector pair conducts. $V_e > V_c$.



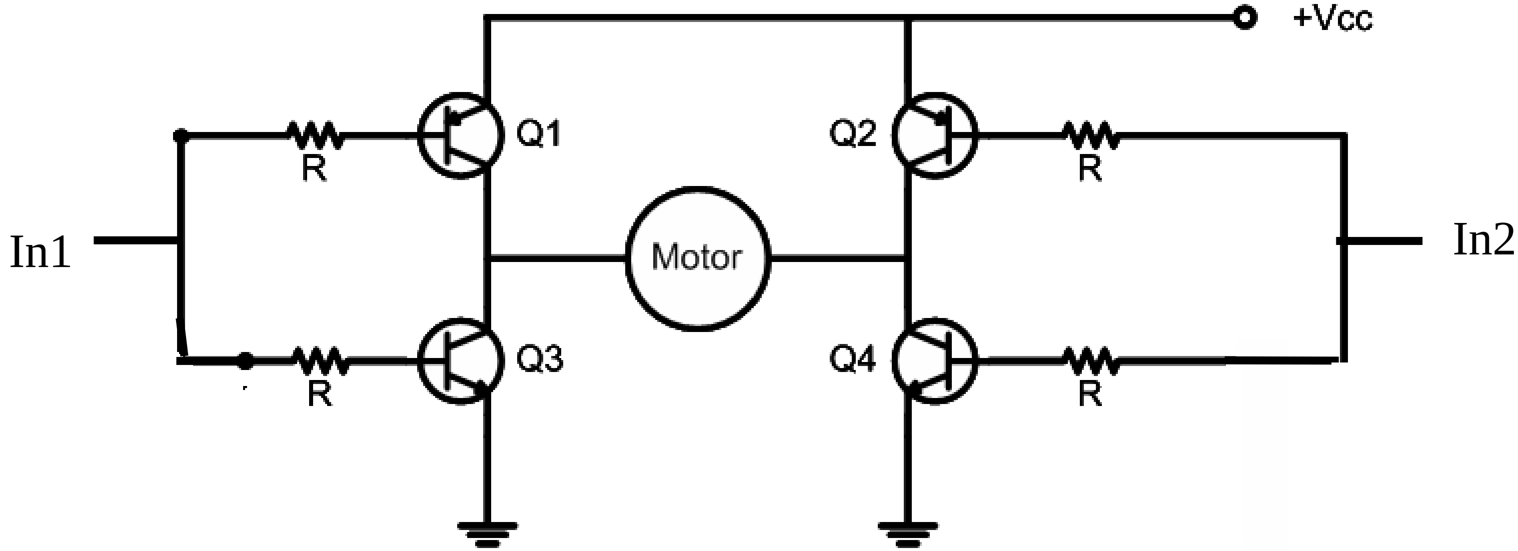


Full Bridge: Circuit #3—II

- With $V_{in1} \leq V_{cc}$-0.6V and $V_{in4} \geq 0.6$V, the circuit completes from V_{cc}-Q1-Motor-Q4-Ground. Thus, the motor turns forward.
- With $V_{in2} \leq V_{cc}$-0.6V, $V_{in3} \geq 0.6$V, the circuit completes from V_{cc}-Q2-Motor-Q3-Ground. Thus, the motor turns forward.
- Here, 4 inputs are being used to appropriately switch the transistors.



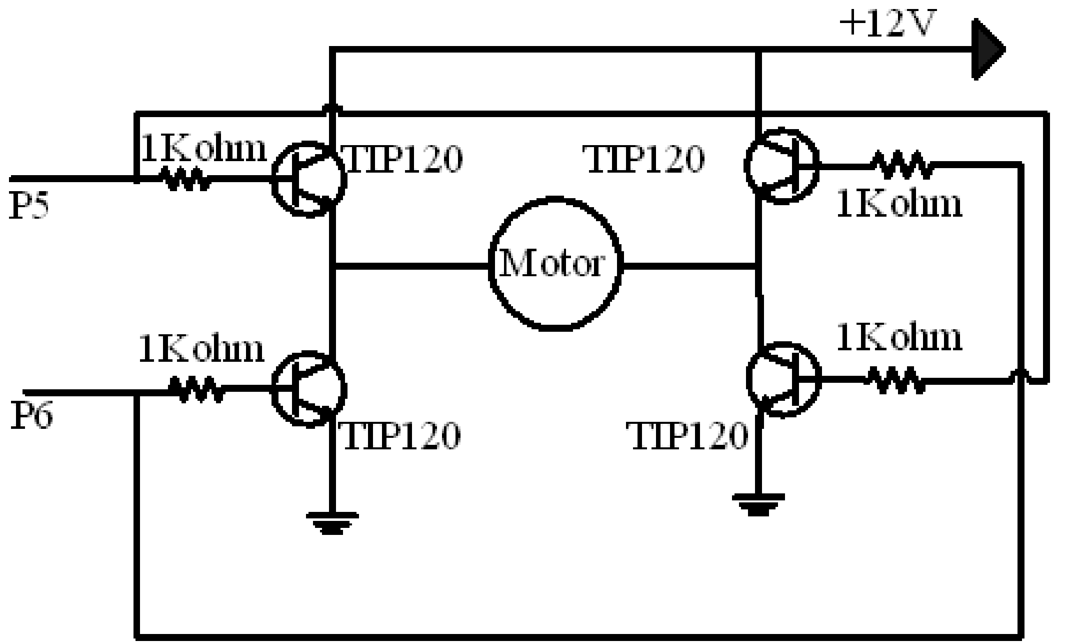
Full Bridge: Circuit #4



- In this full bridge circuit, we use only two inputs to control the base leads of a pair of transistors. Now we have four possibilities of motor operation as indicated in the table.

IN1	IN2	Motor	Notes
High	Low	forward	
Low	High	backward	
Low	Low	No motion	
High*	High*	*	Forbidden

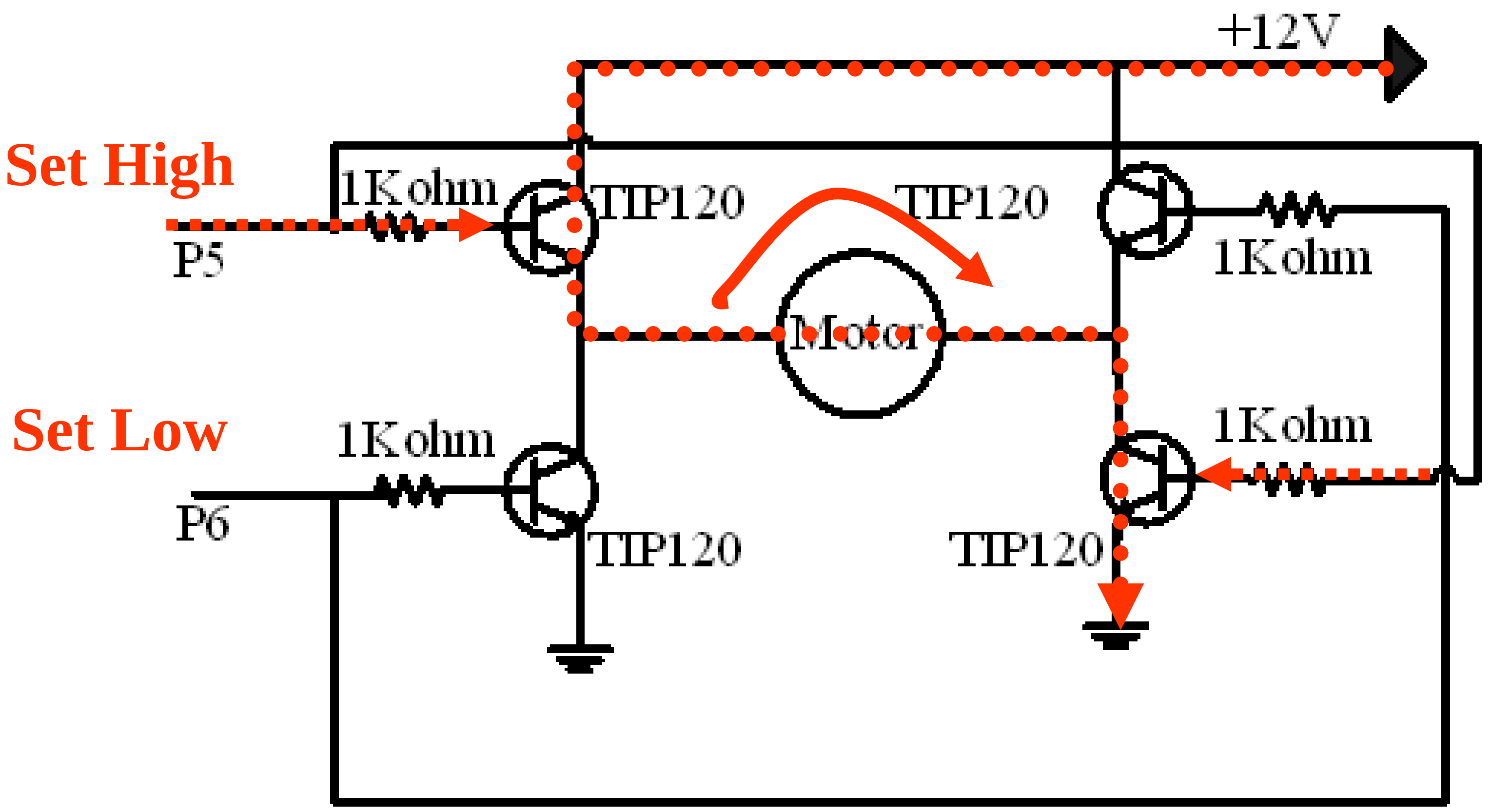
Full Bridge: Circuit #5—I



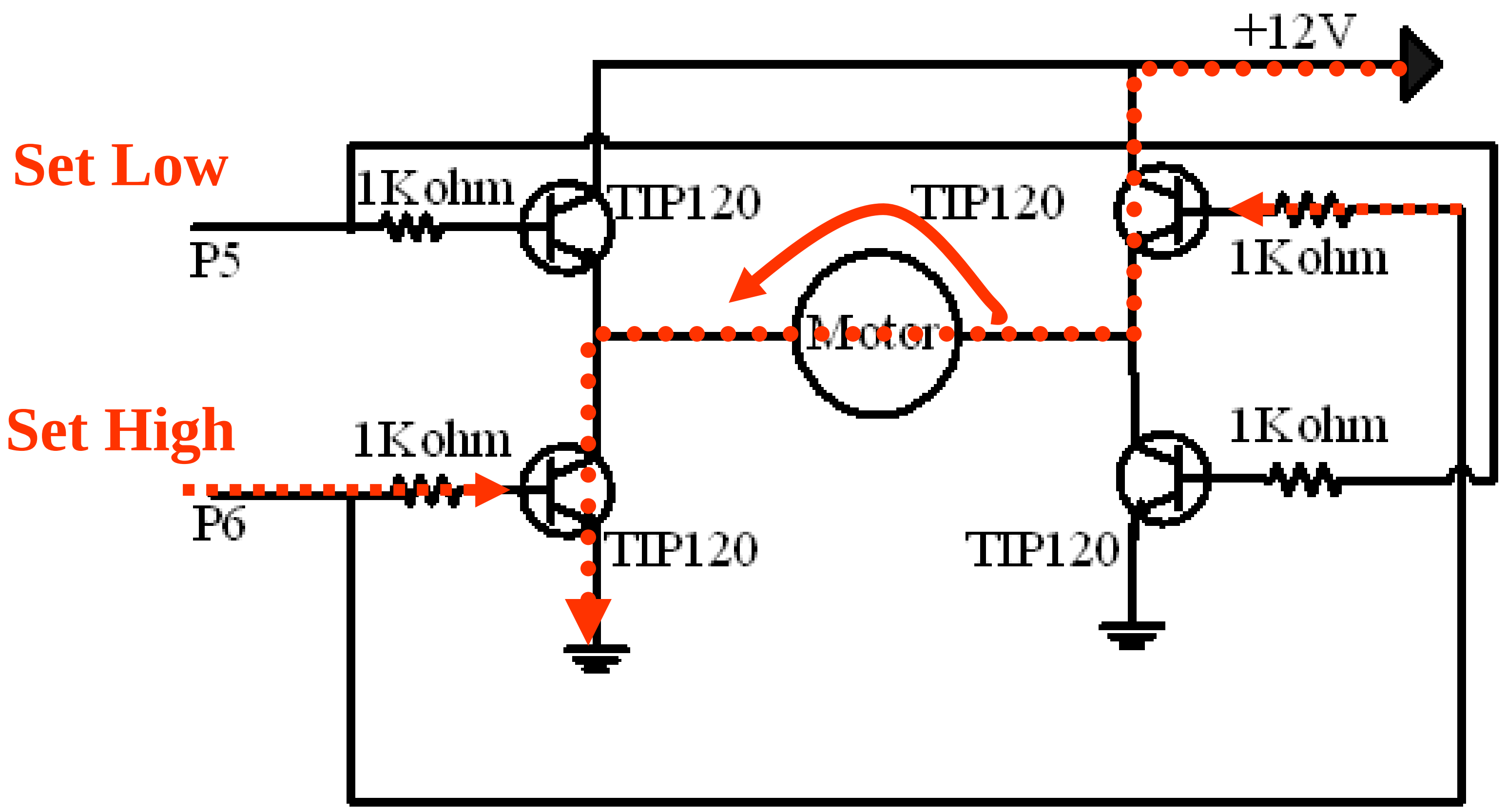
- In this full bridge circuit, we only use NPN transistors to control the direction of rotation of a DC motor.

P5	P6	Motor	Notes
Positive	Ground	forward	
Ground	Positive	backward	
Ground	Ground	No motion	
Positive	Positive	*	Forbidden

Full Bridge: Circuit #5—II



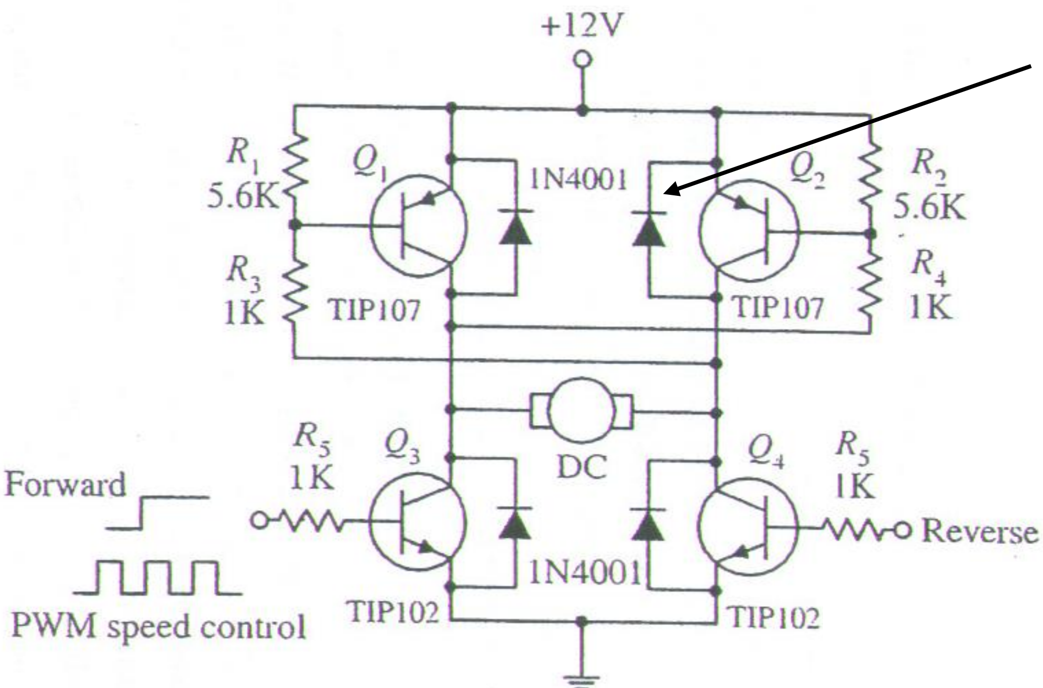
Full Bridge: Circuit #5—III



A Full Fledged H-Bridge using BJTs

- +5V is applied to the forward input, while no power is applied to the reverse input.
- Speed can be controlled via PWM
- How this circuit works:
  - High signal enters Q3's base, Q3 conducts, which allows Q2 to conduct.
  - Current flows from positive supply terminal through the motor from right to left (forward).
  - To reverse the direction, remove High signal from Q3, and apply to Q4 instead.

Bipolar transistors H-bridge



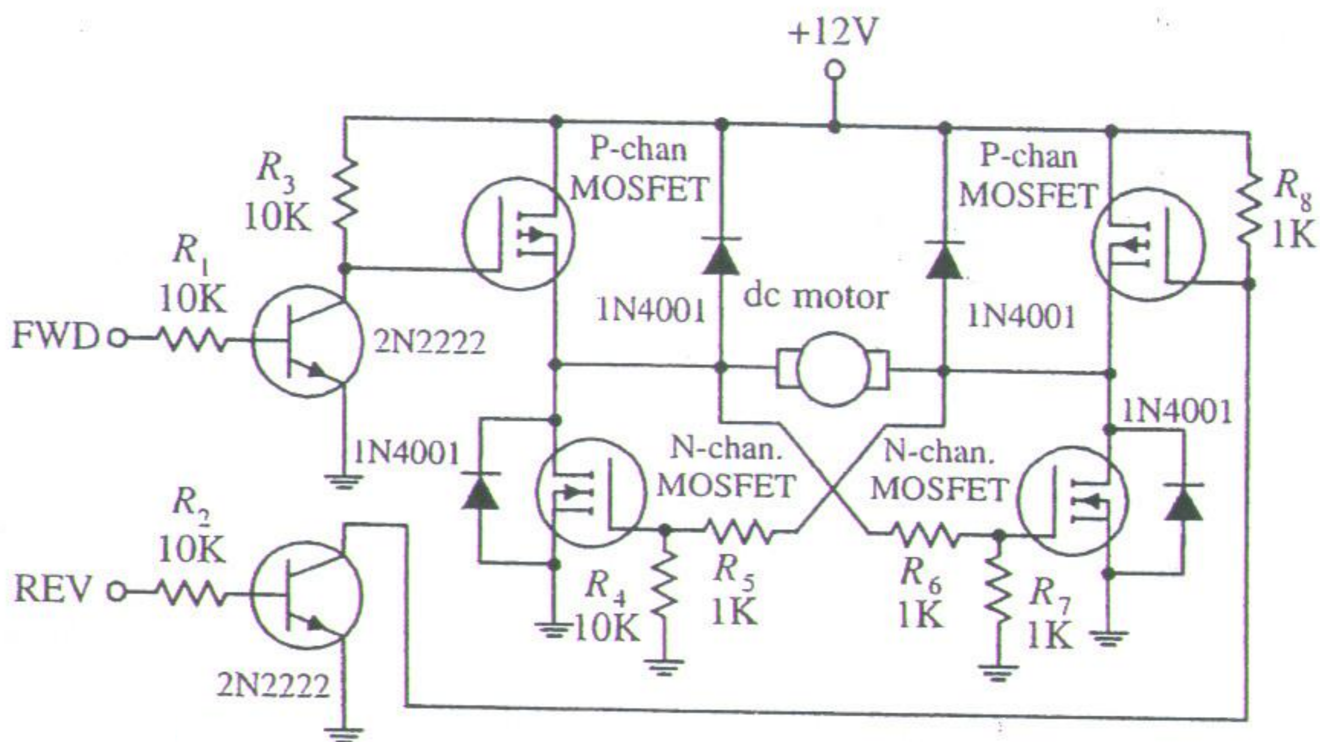
Diodes are being used to prevent BJTs being damaged by inductive kickback.

A signal must not be applied here when a signal is being applied to the forward lead.

A Full Fledged H-Bridge using MOSFETs

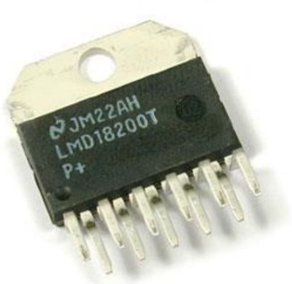
- Works in a similar manner as the full fledged BJT-based H-bridge.
- Diodes are used to overcome transient spikes generated by the motor's coils, so that other components within the circuit are not damaged.

MOSFET H-Bridge

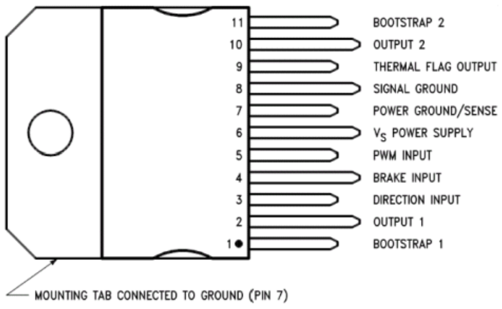


H-Bridge Motor Driver ICs—II

- Common H-Bridge solutions include:
  - National Semiconductor's LMD18200, LMD18201, LM15200
- LMD18200
  - High-current, easy-to-use H-bridge chip (3A, 12-55V).
  - TTL and CMOS compatible.
  - Comes with clamping diodes, shorted load protection, and a thermal warning interrupt output lead.
- L293D (Unitrode)
  - Very easy to use, cheaper than LMD18200
  - Can't handle as much current
  - Not many functions available.



LMD18200



LMD18201

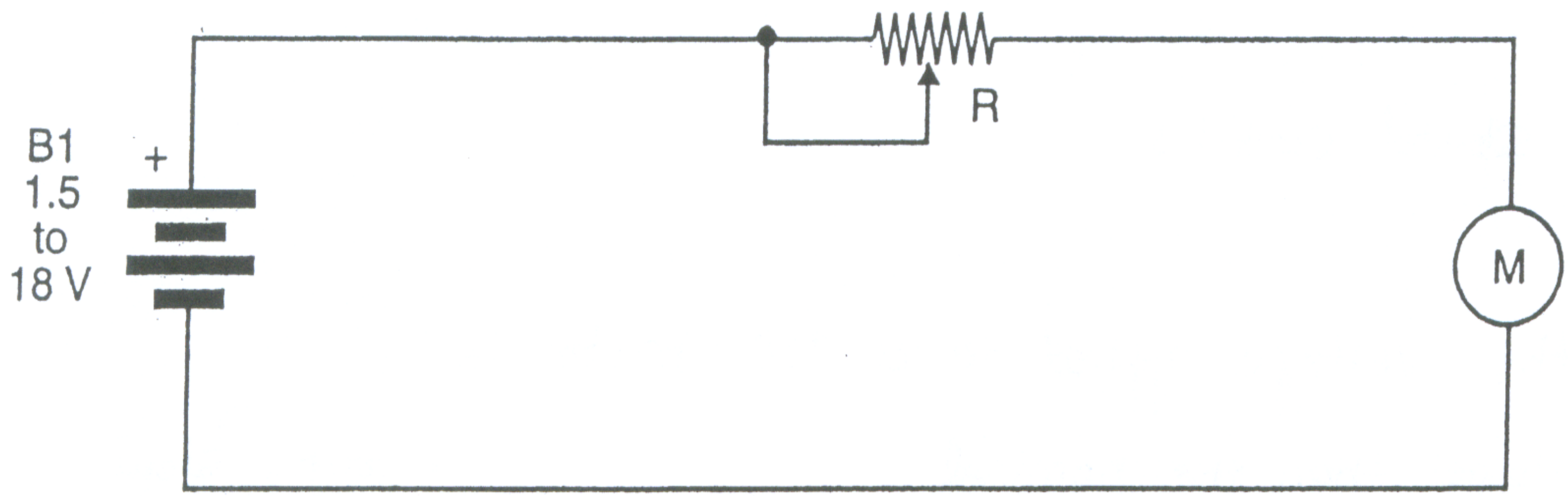
L293D

DC Motors: Speed Control—I

- When the voltage i/p applied to a motor is
  - Lower than the nominal voltage $\rightarrow$ motor runs slower.
  - Larger than nominal voltage $\rightarrow$ motor runs faster.
- Linear control:
  - Connect a potentiometer in series with the motor.
  - Change the potentiometer resistance to vary the voltage applied to the motor.
  - The current flow is also influenced by this approach.
  - Problems:
    - Current drawn by the motor also flows through the pot, leading to energy wastage. Necessitates use of heat dissipation methods.
    - Very inefficient, creates more heat as the resistance increases (according to Ohm's Laws), and that can cause a potentiometer meltdown.
    - Usually DC motor acts as a variable load (current flow through the motor depends on the load and motor speed). Use of pot as described does not allow soft start of the motor while keeping the torque constant. It leads to a hard start which may induce jerk behavior.

Speed Control—II

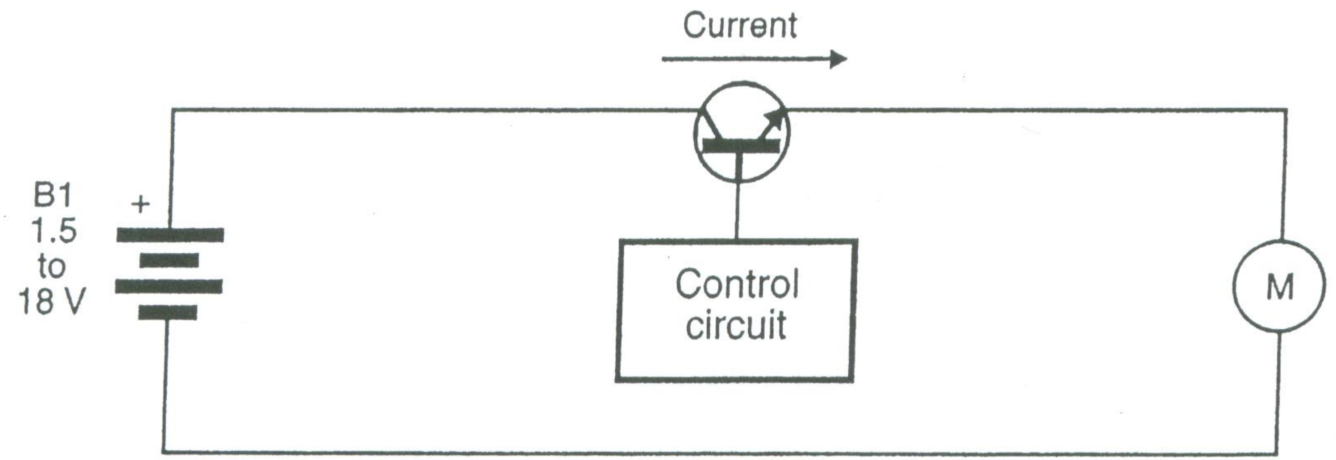
- Potentiometer in series with motor, change the potentiometer resistance to vary the voltage applied to motor.



Not recommended

Speed Control—III

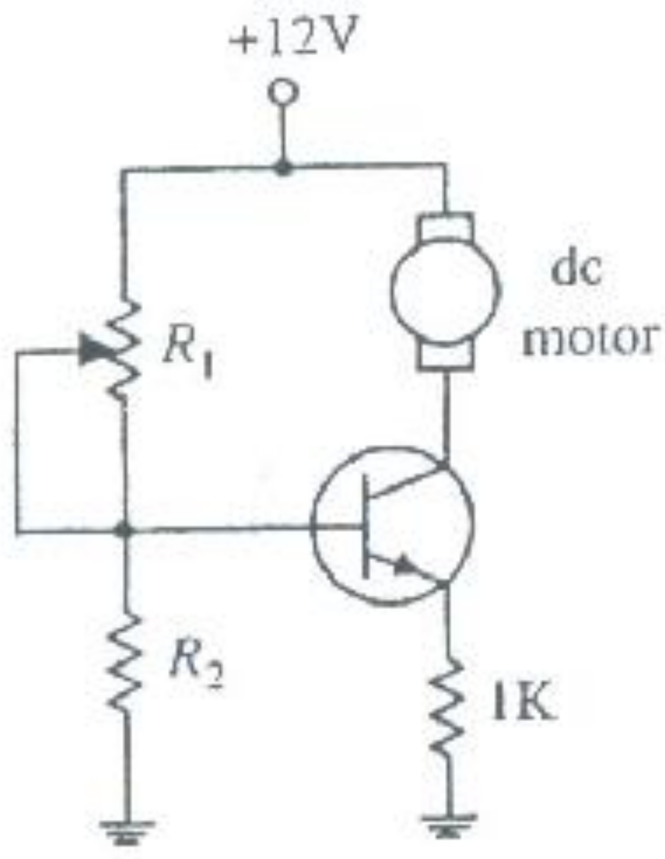
- One can also use a BJT as a variable resistor.
- The base voltage/current changes the resistance across collector-emitter pair thus varying the current flow through the circuit connected through collector-emitter pair.
- Now the BJT must dissipate heat.
  - Power dissipated by transistor = (voltage drop across transistor) × (current flow through the transistor)



Not recommended

Speed Control—IV

- Use a series connection of a potentiometer and a fixed resistor to control the base voltage/current in the BJT base.



Not recommended

DC Motor Speed Control Using PWM

- In order to conserve energy and prevent component meltdown, we can perform speed control of a motor by using an approach that sends to the motor short pulses of current.
- The speed of the motor can be controlled by varying the width and frequency of the applied pulses.
- Controlling a motor’s speed in this manner prevents any components from experiencing continuous current stress.

Pulse-Width-Modulation 101

- Pulse-Width-Modulation (PWM)
  - It is an effective method to deliver controlled amount of power to loads such as motors.
  - Basic idea: use square voltage pulses to power a load. The amount of power delivered to load depends on the duration of each pulse (duty cycle).
  - Let the on duration for each pulse be t_{on}.
  - Let the off duration t_{off}.
  - Let T denote the the period of square wave, then $T=t_{on}+t_{off}$.
  - The duty cycle is given by:

$$100\left(\frac{t_{on}}{T}\right)\%$$

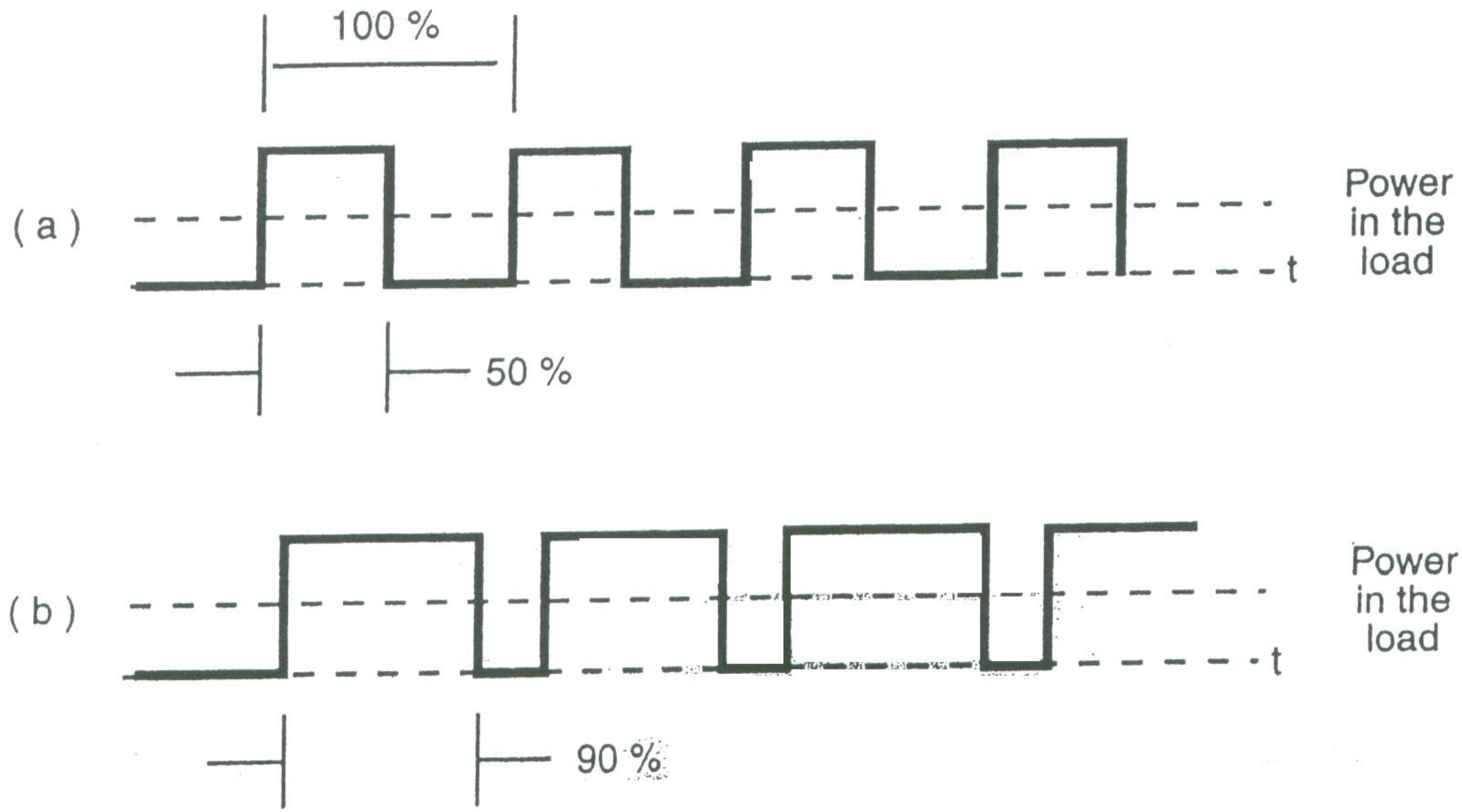
- If $t_{on}=t_{off}$, duty cycle will be:

$$100\left(\frac{t_{on}}{t_{on}+t_{off}}\right)=50\%$$

- If t_{on} = 0.9T, t_{off} = 0.1T, duty cycle= 90%, etc.
- Controlling the width of pulses allows us to control the power applied to the motor.
- The process of controlling the duty cycle of square wave is called modulation and the circuit used to accomplish this task is called pulse-width-modulator.

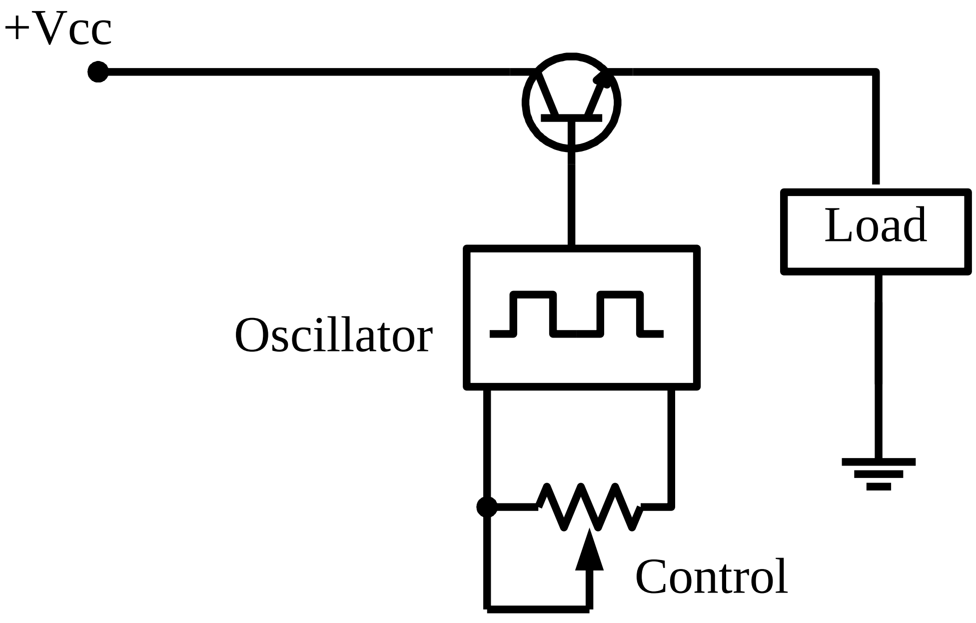
Pulse-Width-Modulation: Graphic Illustration

- The power delivered to the motor depends on the pulse width.



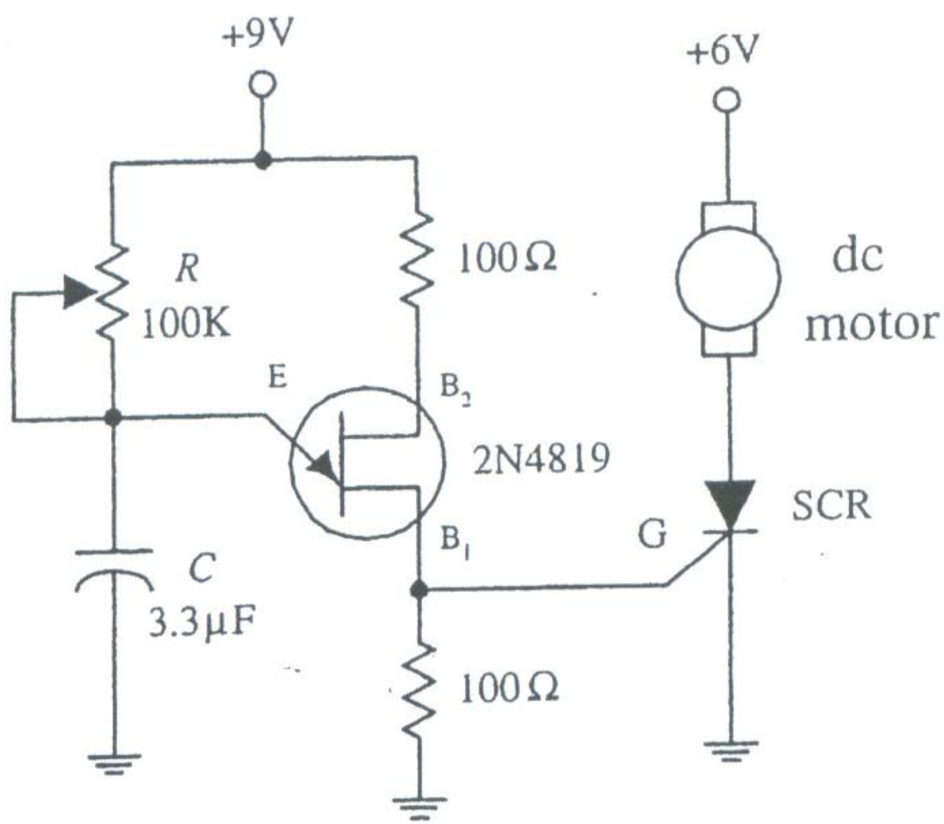
Pulse Width Modulator

- The output of a variable duty oscillator is fed to the control lead “base” of a power transistor.
- When the oscillator is running, the transistor turns on/off at the same frequency as the oscillator, applying a square wave voltage to the load.
- The average voltage on the load depends on the duty cycle of the square wave.



DC Motor Speed Control using PWM—I

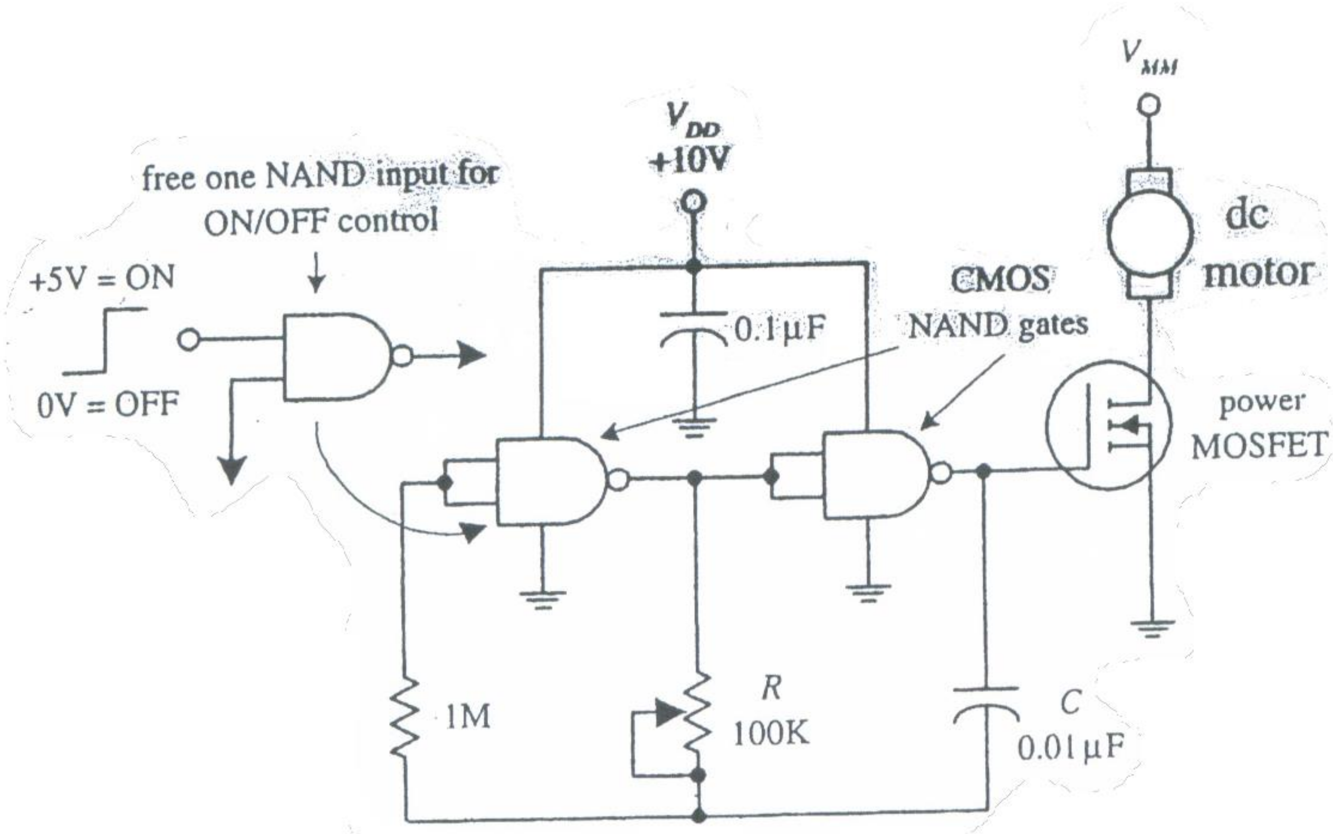
- Here a UJT relaxation oscillator is used to generate a series of pulses that drive an SCR on and off.
- To vary the speed of the motor, the UJT oscillator's frequency is adjusted by changing the RC time constant.



UJT/SCR Control Circuit

Speed Control using PWM—II

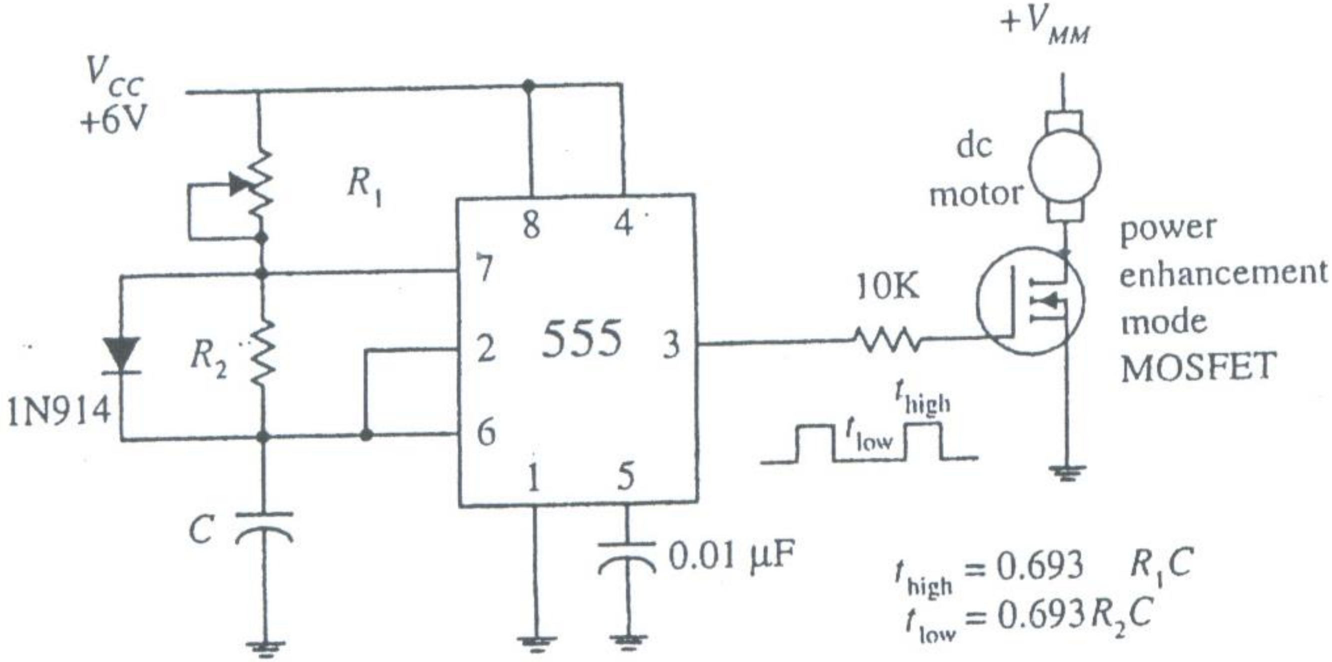
- A pair of NAND gates make up the relaxation oscillator section, while an enchantment-type power MOSFET is used to drive the motor.
- Like the preceding circuit, the speed of the motor is controlled by the oscillator's RC time constant.



CMOS/MOSFET Control Circuit

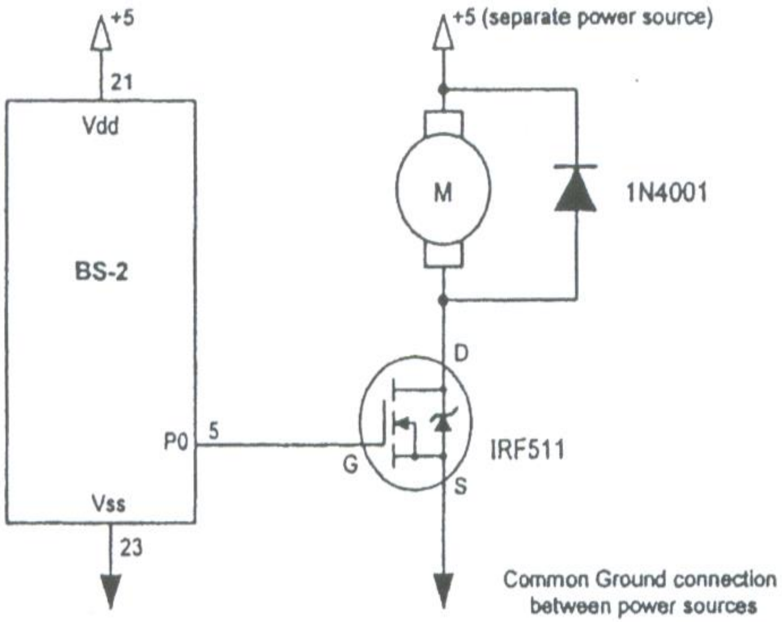
Speed Control using PWM—III

- This circuit USES a 555 timer to generate pulses that drive a power MOSFET.
- By inserting a diode between pins 7 and 6, as shown, the 555 timer is placed into low-duty cycle operation.
- R_1, R_2, and C set the frequency and on/off duration of the output pulses



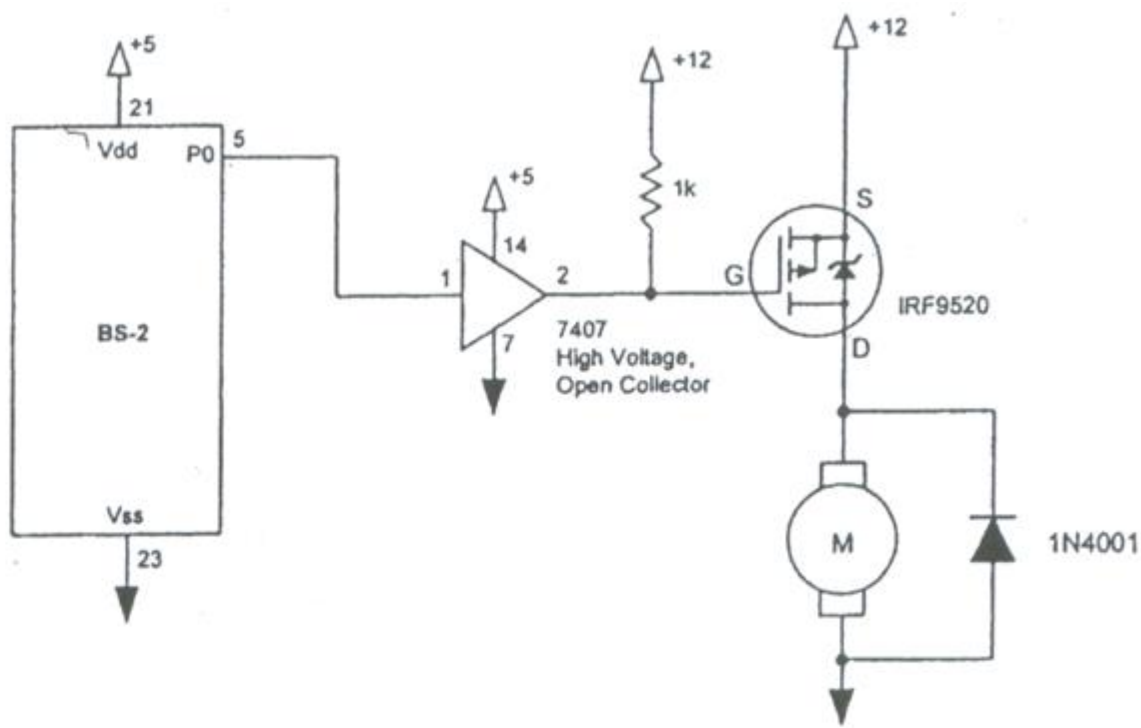
Interfacing DC Motor with BS2: On/Off Control Circuit #1

- Interface an N-channel MOSFET IRF511 to BS2 as shown.
- Interface the motor between the +5V of power supply and the drain of MOSFET, with MOSFET source connected to ground.
- Place a 1N4001 diode in reverse biased mode parallel to motor.
- With BS2 o/p high on P0 → MOSFET gate is driven positive relative to source of MOSFET.
  - The drain source pair of the MOSFET conducts and motor turns on.
- With BS2 o/p low on P0 → MOSFET stops conducting, a reverse voltage spike is generated in the motor which conducts through a diode.
- A low voltage (5VDC) motor is being used in this circuit.



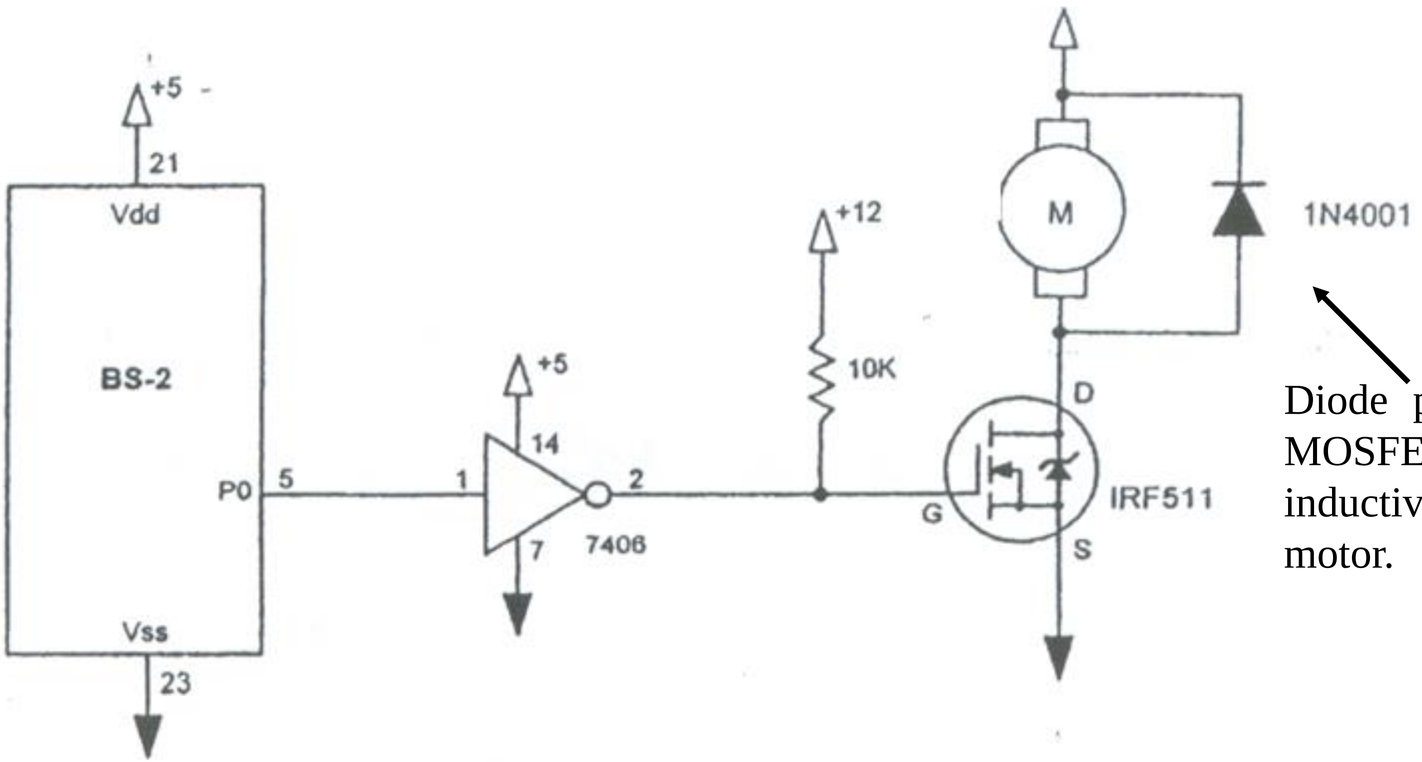
On/Off Control Circuit #2

- The following circuit allows on/off control of a high voltage (12VDC) motor.
- BS2 drives the open collector, non-inverting buffer whose output is tied to 12VDC.
- When BS2 is low, 7407 buffer outputs 0V DC which drives a P-channel MOSFET.
- The 12VDC potential difference between source-gate yields higher drive capability.
- P0 low → motor turns on, P0 high → motor turns off.



On/Off Control Circuit #3

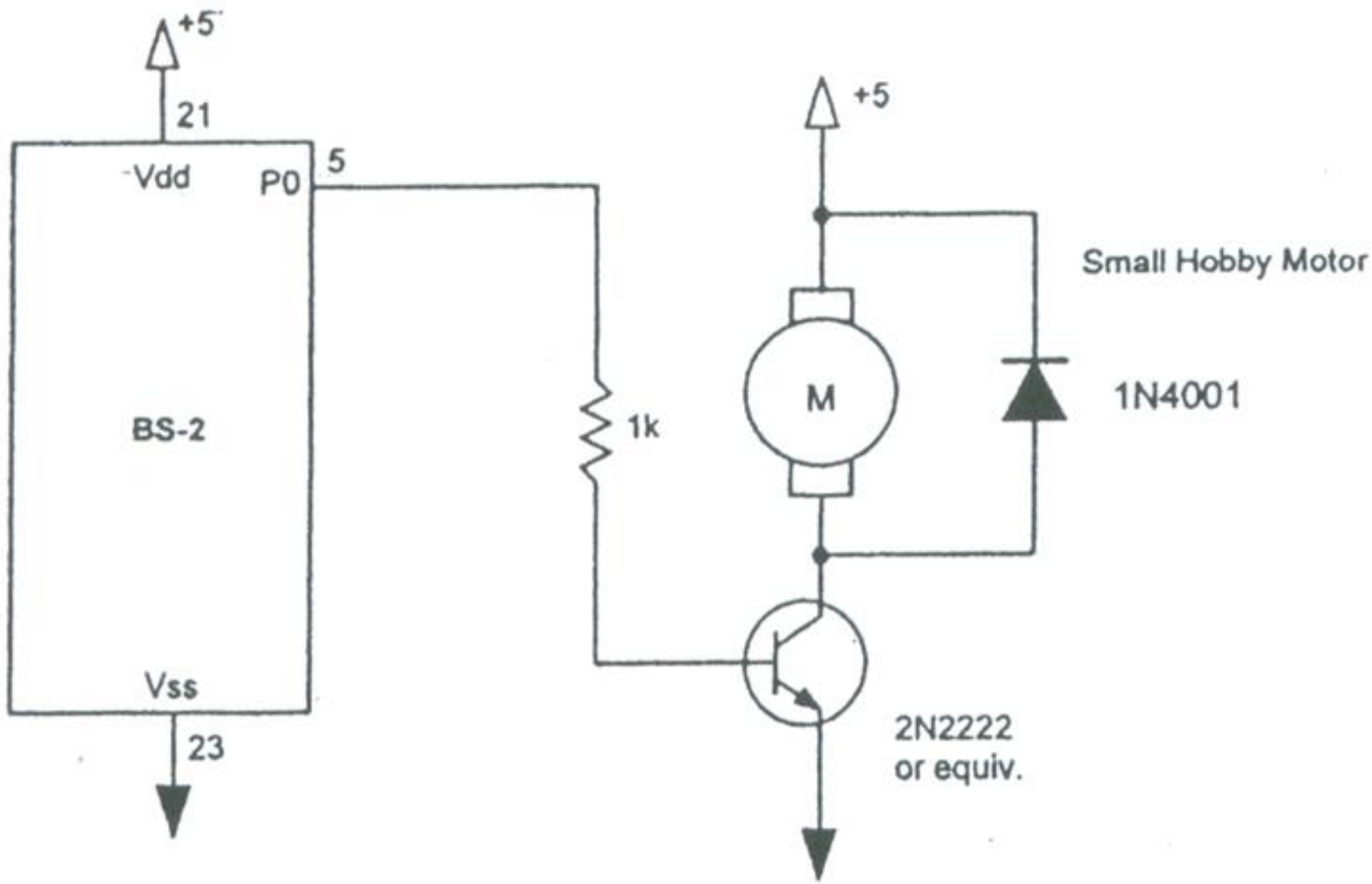
- The following circuit is also used for on/off control of a DC motor.
- In this circuit: P0 low → inverting buffer is turned on → 7406 outputs 12V which appears at the gate of an N-channel MOSFET IRF511.
  - The motor is turned on.
  - With Vg – Vs = 12V, the MOSFET provides high drive capability.
- With P0 high → inverting buffer is turned off → 7406 outputs 0V so motor turns off.



Diode prevents damage to MOSFET by overcoming inductive kick from the motor.

On/Off Control Circuit #4

- In this circuit, an NPN BJT is used to turn on/off a low voltage, low current hobby motor.
- The current rating of BJT must be appropriately selected to provide the drive current required by the motor.



DC Motor: On-Time Control Circuit #1

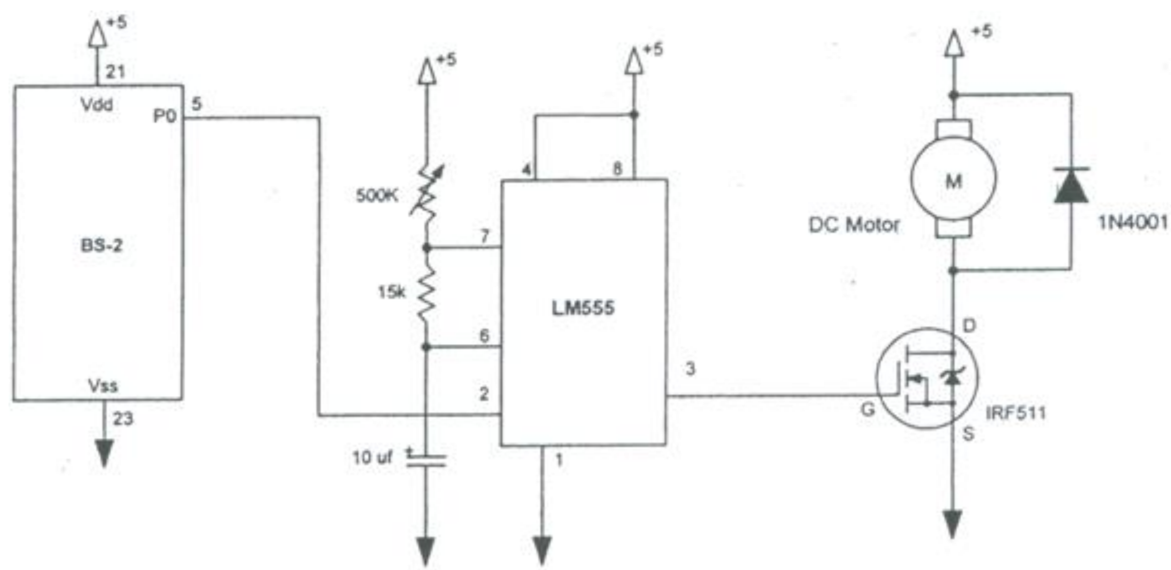
- In this circuit, the DC motor is turned on for a period of time, determined by the 500k pot and 10μF capacitor.
- When a low going pulse appears at PIN2 of the LM555 timer, the IRF511 MOSFET is turned on which turns the motor on.
- PIN2 of LM555 timer should be turned high immediately after being turned low.
- This circuit allows us to off-load the task of running the motor for a certain period and then stopping it.
- BS2 simply turns the motor on, it does not have to monitor time to turn the motor off, since LM555 takes care of the timing issue (monostable operation mode).

- Sample code:

  low 0

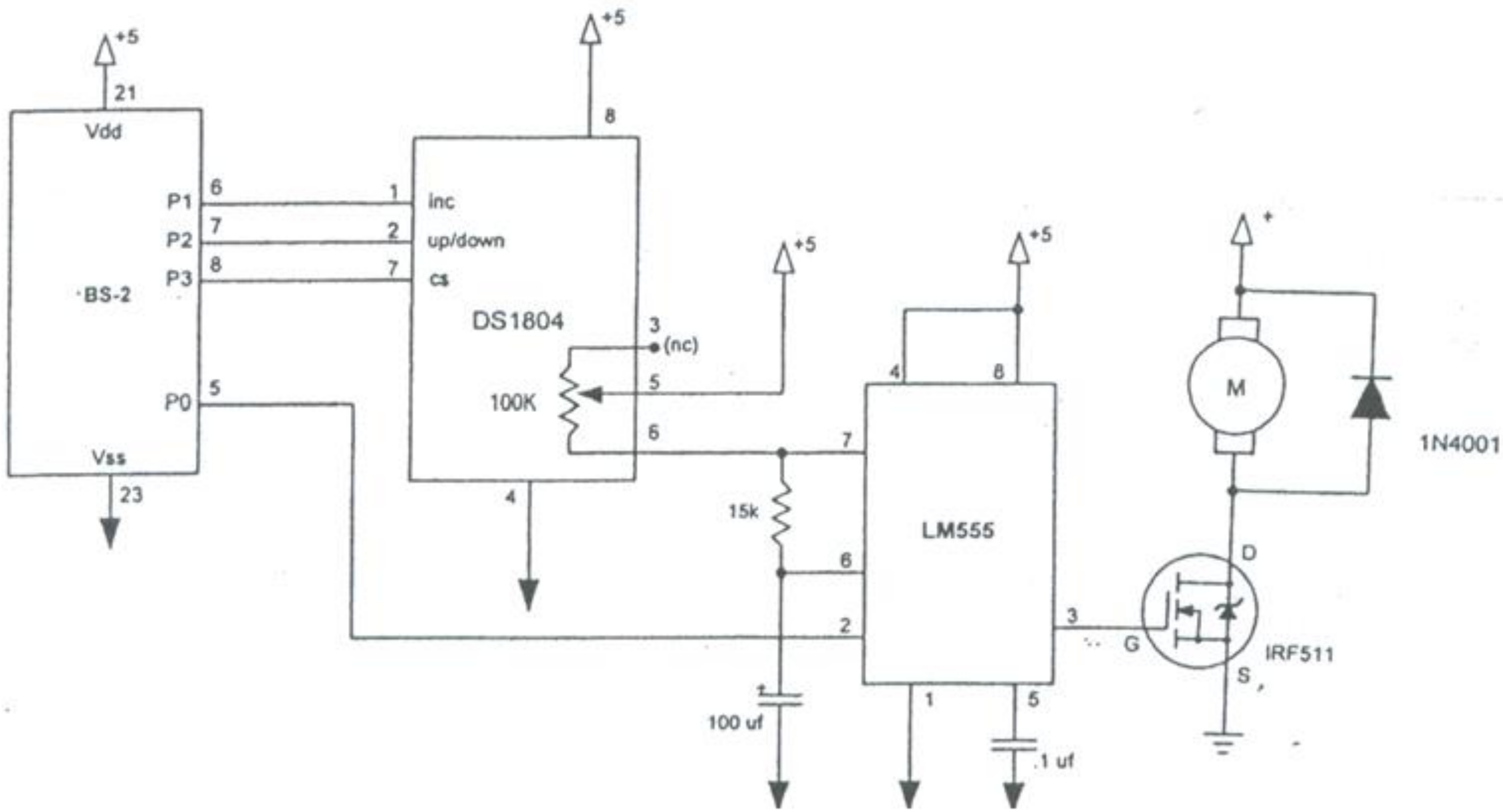
  high 0

  '(rest of the code here)



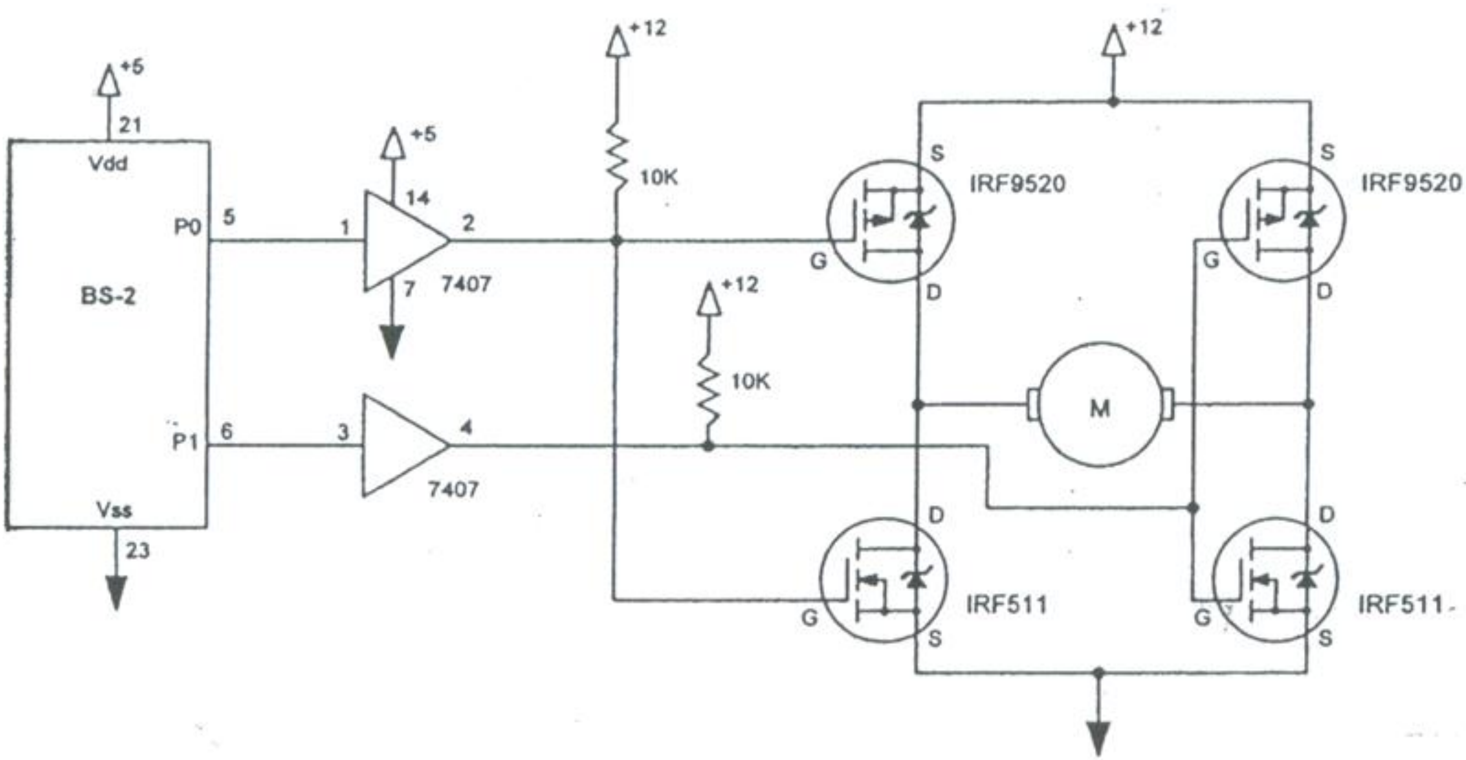
On-Time Control Circuit #2

- Very similar to circuit shown on the previous viewgraph.
  - Recall, we used a 500k pot to control the ON-time of the motor. “Manual control.”
- To allow automatic control of ON-time duration of motor, here a digital pot is used.
- By selecting a proper setting for solid state pot, the motor ON-time duration is controlled.



Interfacing DC Motor with BS2: H-Bridge Circuit—I

- This circuit uses a MOSFET-based H-bridge for the direction control of a DC motor.
- The outputs from P0 and P1 of BS2 are processed by the 7407 non-inverting buffers. The buffer outputs control two pairs of two MOSFET's each to perform direction control.

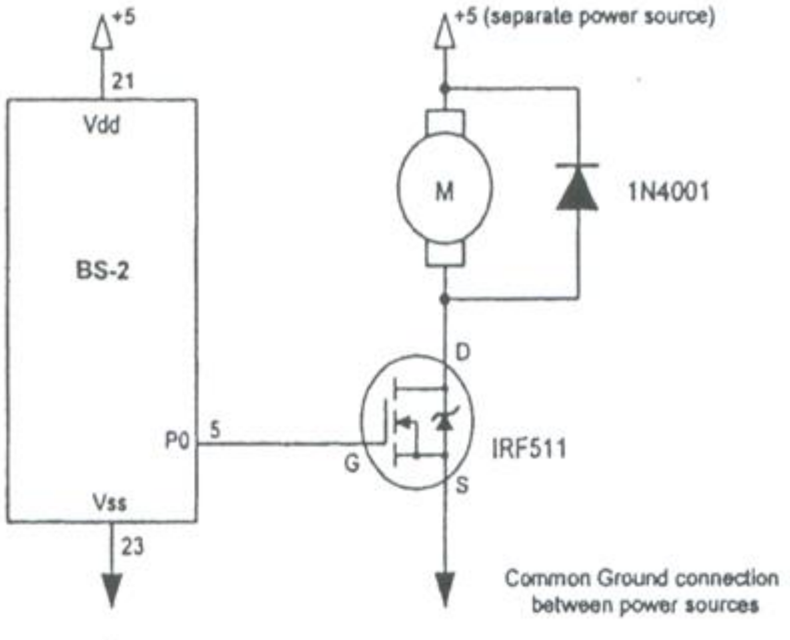


Sample Code:

```
loopstart:
high 0
low 1
pause 2000
low 0
high 1
pause 2000
goto loopstart
```

DC Motor Speed Control using PWM

- Consider DC Motor on/off control circuit #1 (reproduced below).
- We can use the PWM technique to control the speed of motor.
- Sample code shown below can be used to get:
  - Motor on at full speed (on all the time).
  - Motor on only 50% of time (slower speed compared to 100%).
  - Motor on only 25% of time (slower speed compared to 50%).
  - Motor accelerating

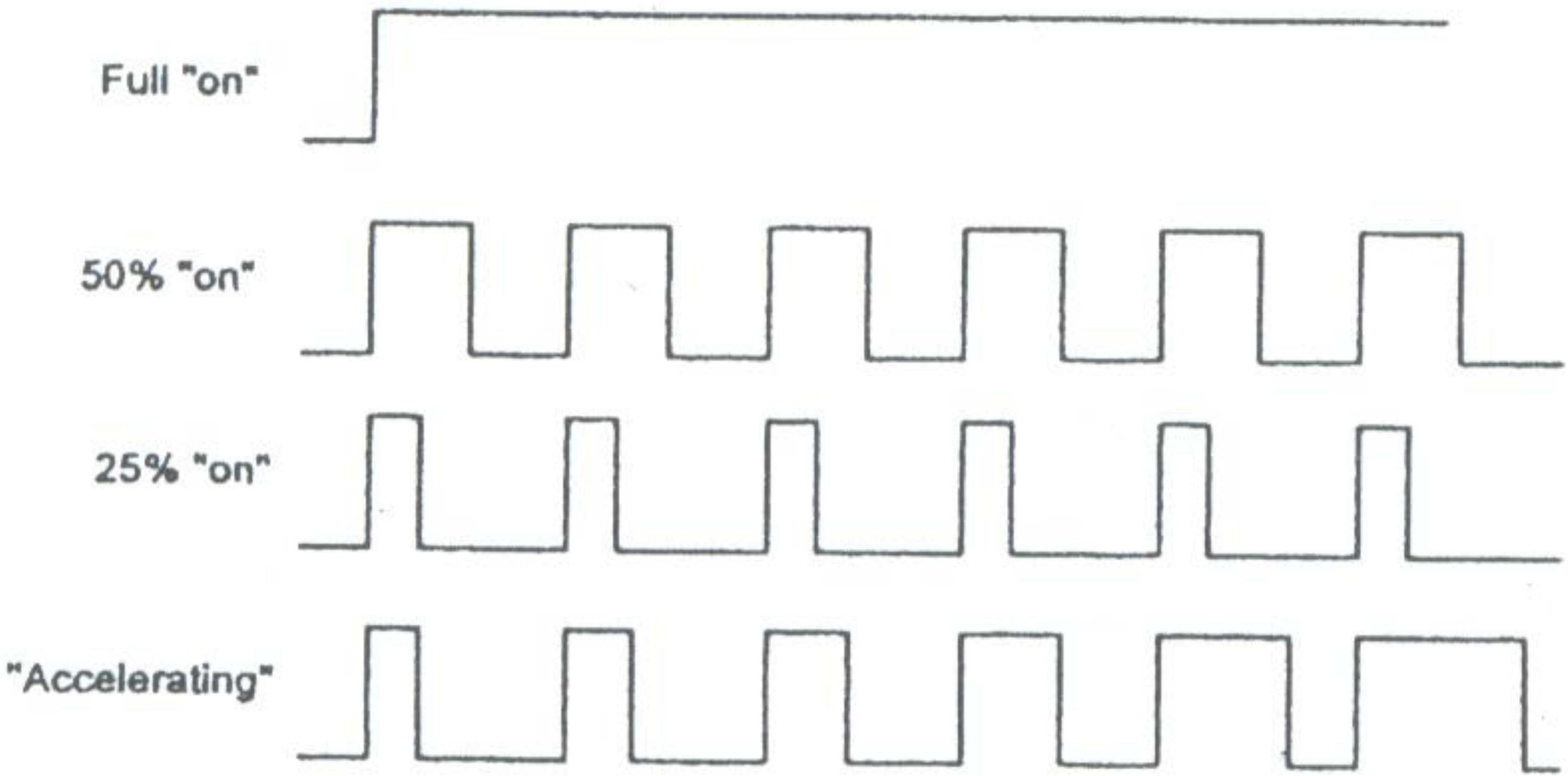


Sample PWM Code

```
x var word
y var word
here:
debug “This is full-on”
debug cr
high 0      ’On all the time.
pause 2000
debug “This is 50% on”
debug cr
for x = 1 to 200
high 0
pause 5                ’ON for 5 milliseconds
low 0
pause 5                ’OFF for 5 milliseconds
next
```

```
debug “This is 25% on”
debug cr
for x = 1 to 100
high 0
pause 5     ’ON for 5 milliseconds
low 0
pause 15  ’OFF for 15 milliseconds
next
pause 2000
debug “This is accelerating”
debuc cr
for y = 100 to 1
high 0
pause 15
low 0
pause y
next
goto here
```

PWM Signal Produced by the Sample Code



DC Motor Challenges

- At least on robotics projects one has to deal with moving power supplies giving rise to such issues as: rechargeability, energy density, capacity, voltage, internal resistance, etc.
- Power supply noise:
  - Current demand varies as motor starts or changes direction.
  - Commutator brush noise introduced due to breaking/making of contact that leads to inductive kickback.
  - PWM noise which also causes motor to turn on/off leading to inductive kickback.
    - It is usually advisable to use separate power supplies or motor and microcontroller.
- Electromagnetic interference may be produced as PWM pulses current in motor coil or as motor brushes make/break contact with the power supply.
- Audible noise:
  - When PWM frequency matches up with one of the resonant frequencies of motor structure (in the audible range).
  - Gearbox and other mechanical components.

Guidelines for Parallax Standard Servo Motor

Servo Motor—I

- DC motors with feedback position control
- As long as the coded signal exists on the input line, the servo will maintain the angular position of the shaft
- As the coded signal changes, the angular position of the shaft changes

Servo Motor—II

Technical Specifications

> Power 6vdc max

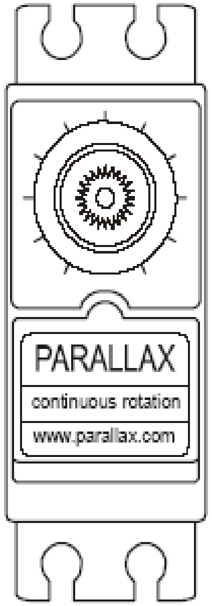
> Speed 0 deg to 180 deg in 1.5 seconds on average

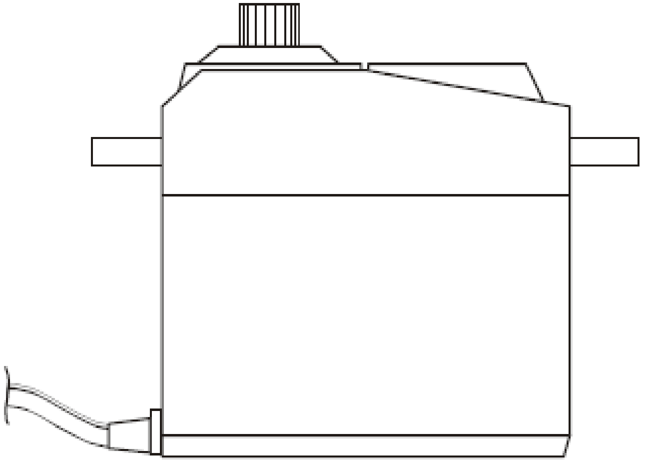
> Weight 45.0 grams/1.59oz

> Torque 3.40 kg-cm/47oz-in

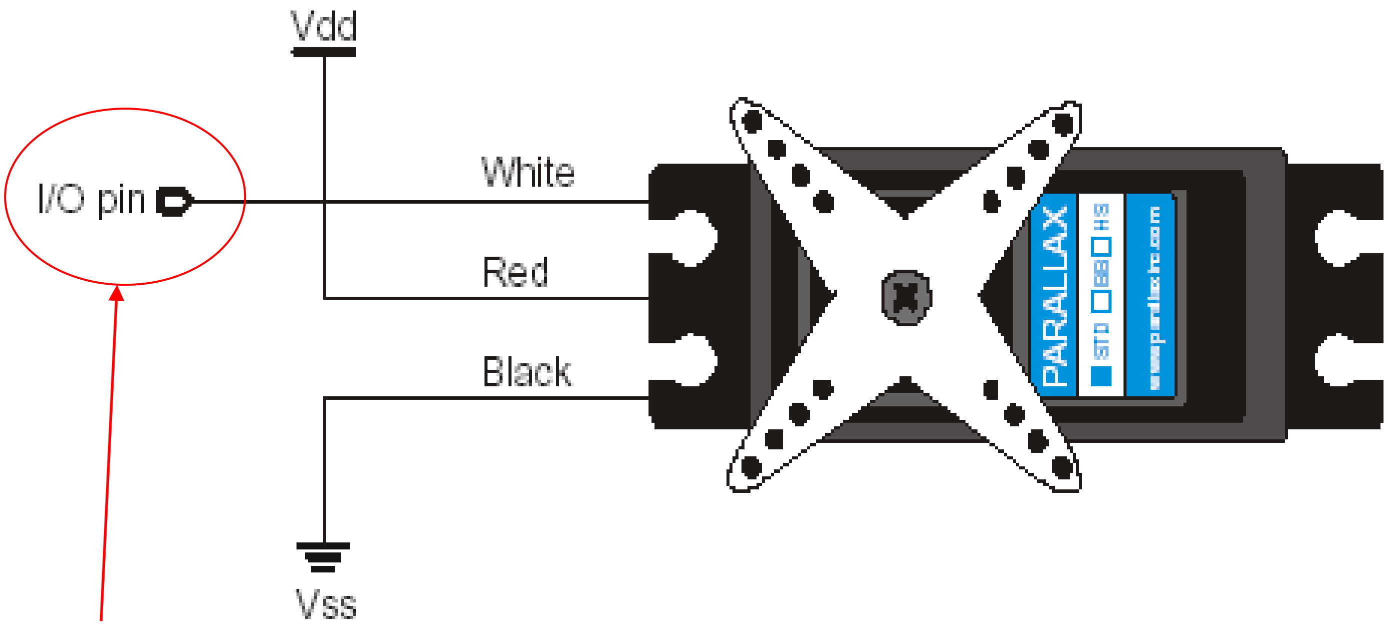
> Size mm (L x W x H) 40.5x20.0x38.0

> Size in (L x W x H) 1.60x.79x1.50





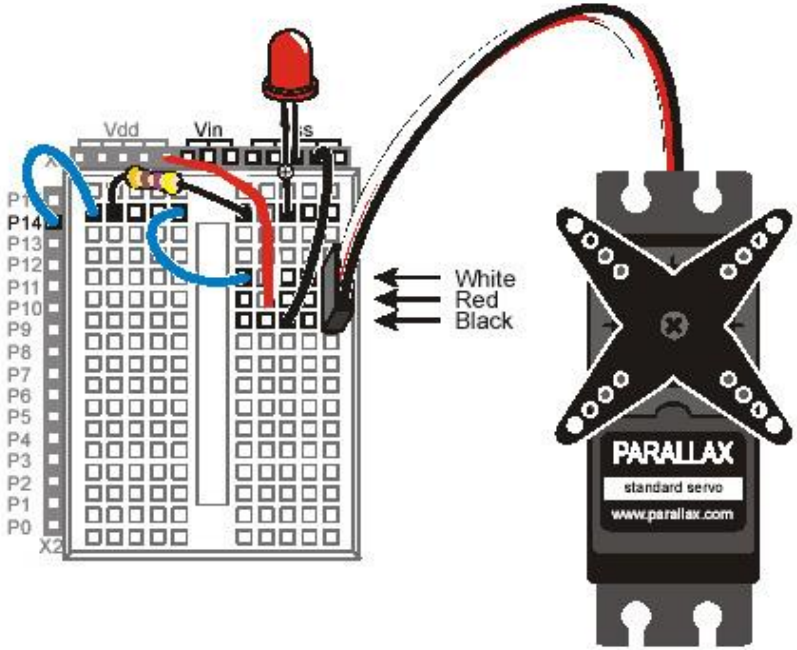
Servo Motor Wiring



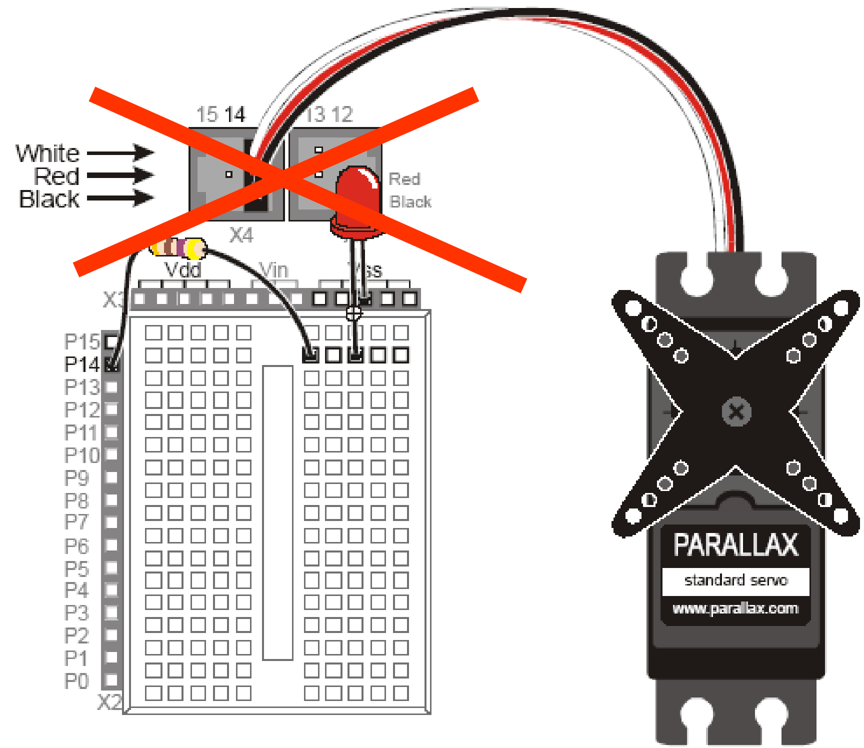
This pin can be any I/O pin

Servo Motor with BS2—II

Board of Education Rev B



Caution: Do not connect servo here when using wall transformer or 9V battery. Servo is to be connected here only when using AA battery pack with ≤ 6V.



When more than 2 servos are to be connected, need to use additional capacitors across V_{dd} and V_{ss}.

Servo Motor: How It Works?—I

X var byte
Output 12

Here:
For X = 1 to 100
Pulsout 12, 500
Pause 10
Next
Pause 500

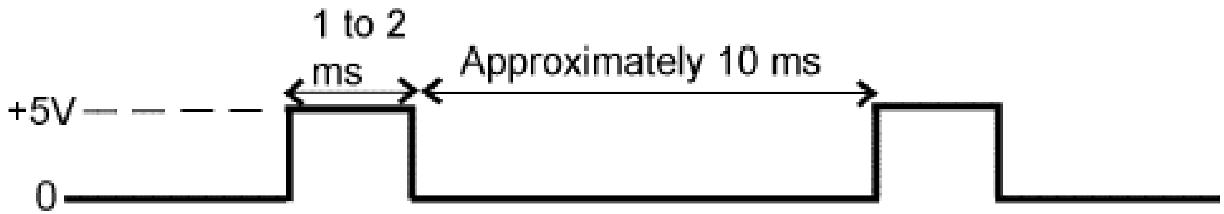
For X = 1 to 100
Pulsout 12, 1000
Pause 10
Next
Pause 500

Goto Here

Pulsout Pin #, Duration

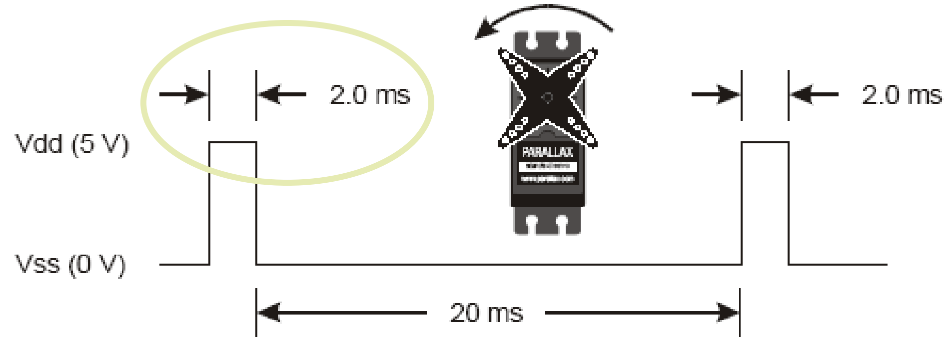
!! Caution
Fix the Duration between 500 to 1000

12 is pin number of BS2
500 means 1milisecond

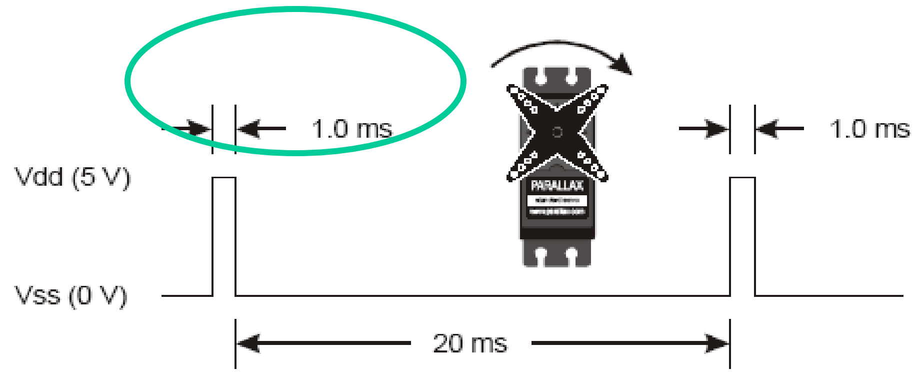


Servo Motor: How It Works?—II

```
FOR counter = 1 to 150
    pulsout 14, 1000
    pause 20
NEXT
```




```
FOR counter = 1 to 150
    pulsout 14, 500
    pause 20
NEXT
```




```
FOR counter = 1 to 150
    pulsout 14, 750
    pause 20
NEXT
```