Mechatronics (ROB-GY 5103 Section A)

- **Today's lecture:**
  - Relays
  - Solenoid
  - DC motor
- (See Topic #8 from Main Text for details)

Relay

- Electrically actuated switches

Relay

- Electrically actuated switches
    - Imagine if a transistor had an actual mechanical switch inside

Relay

- Electrically actuated switches
  - Imagine if a transistor had an actual mechanical switch inside
  - **Transistors:**
    - Faster and require less power to switch
    - No bounce
  - **Relays:**
    - Cheaper to handle large currents
    - Electrically isolated from load

Relay

- Three main types:

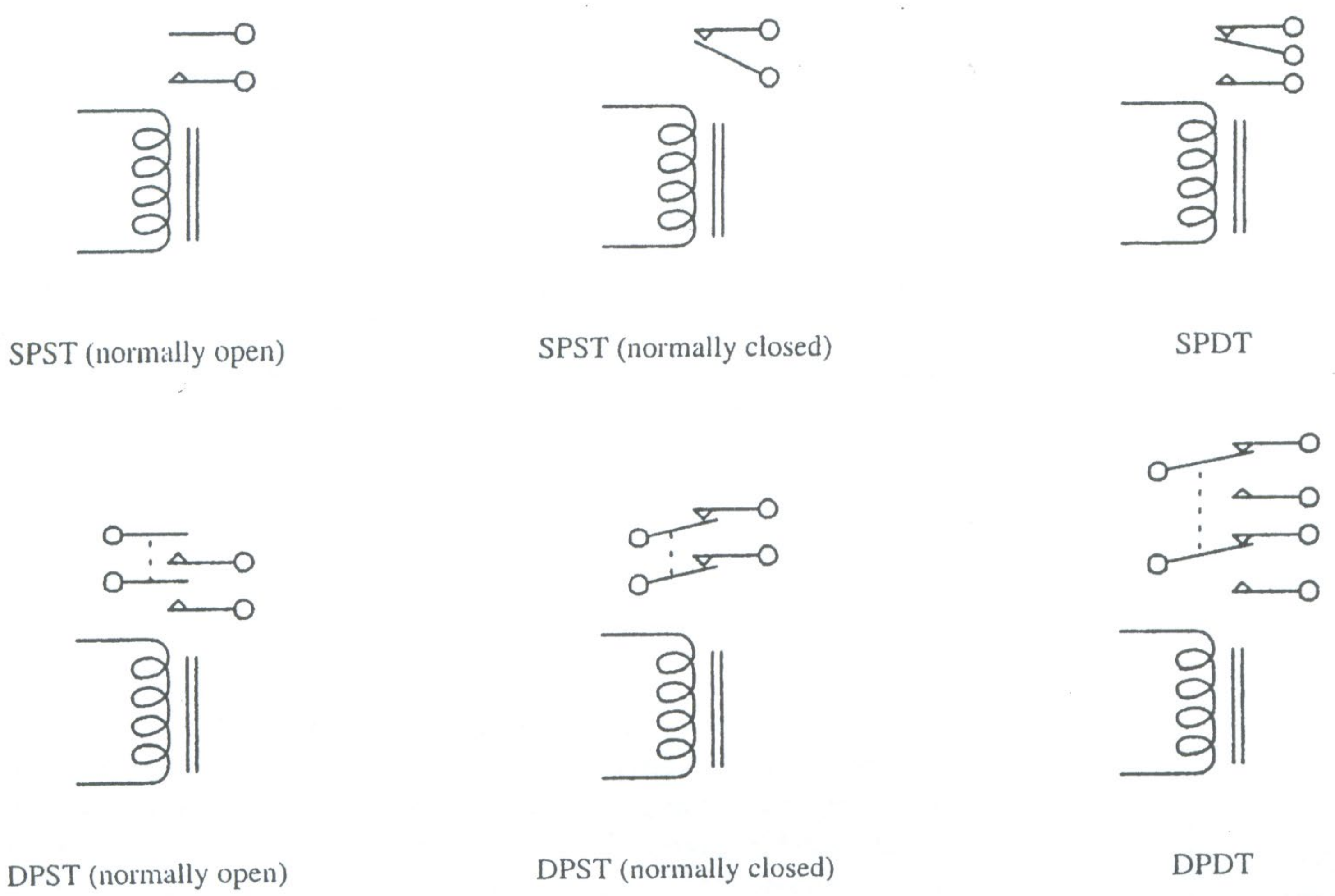
Electromechanical relay

Reed relay

Solid-State

Relay Symbols

- Same switch types as mechanical switches



Relay Symbols

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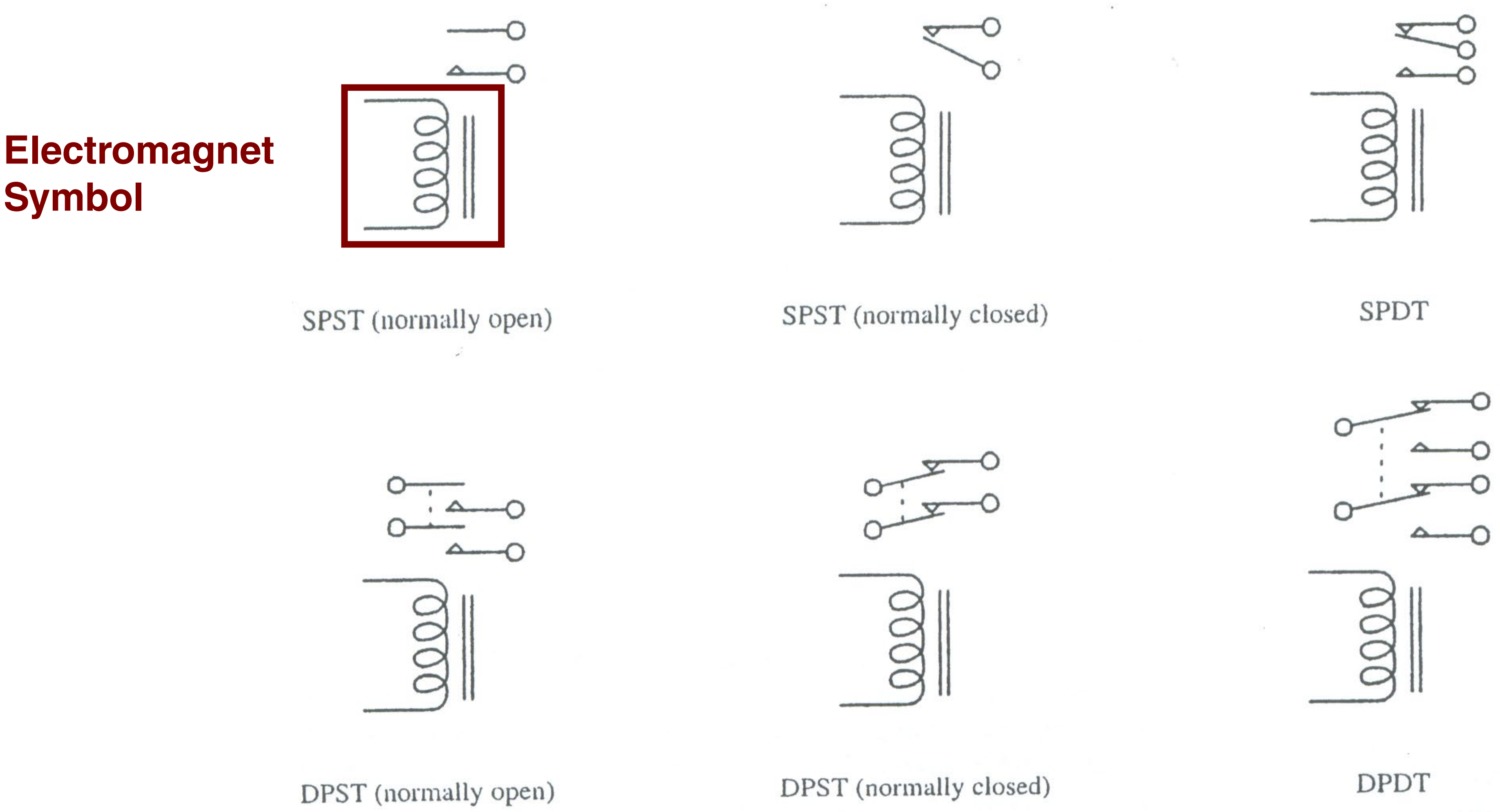

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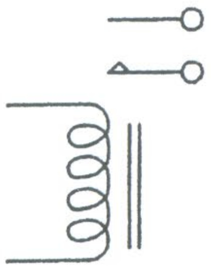
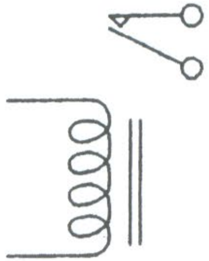
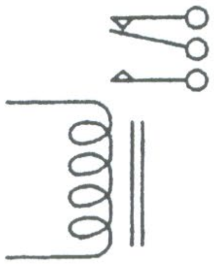


SPST (normally open)

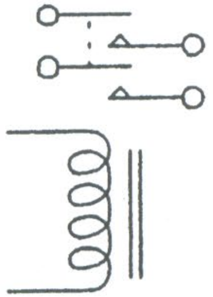


SPST (normally closed)

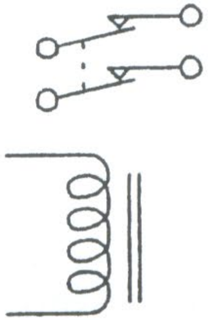


SPDT

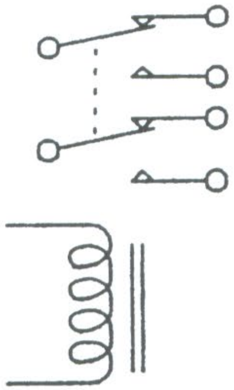
Reed and solid-state relays are usually SPST



DPST (normally open)



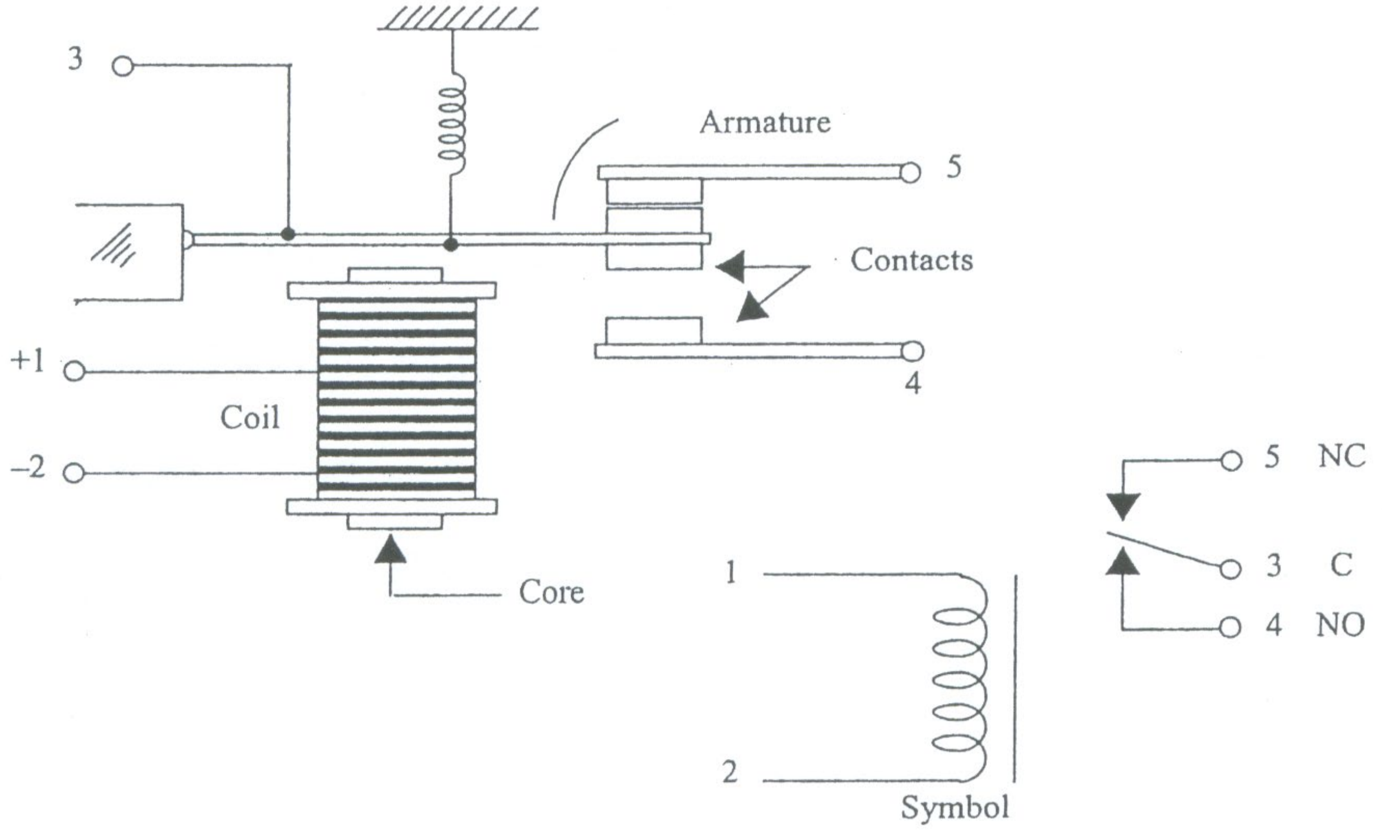
DPST (normally closed)

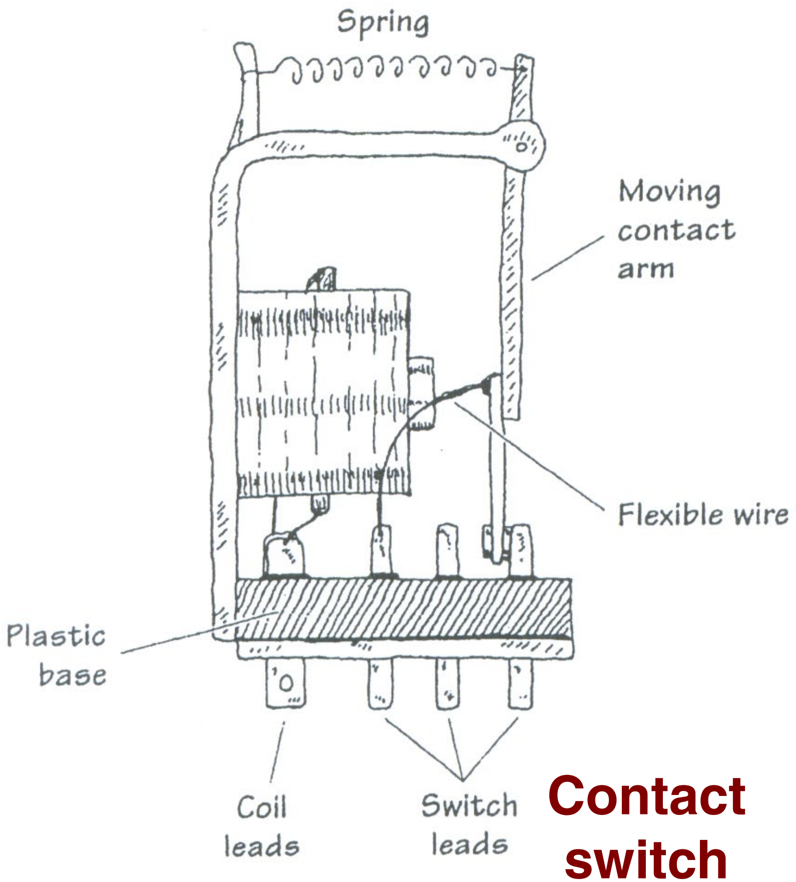


DPDT

Electromechanical Relays

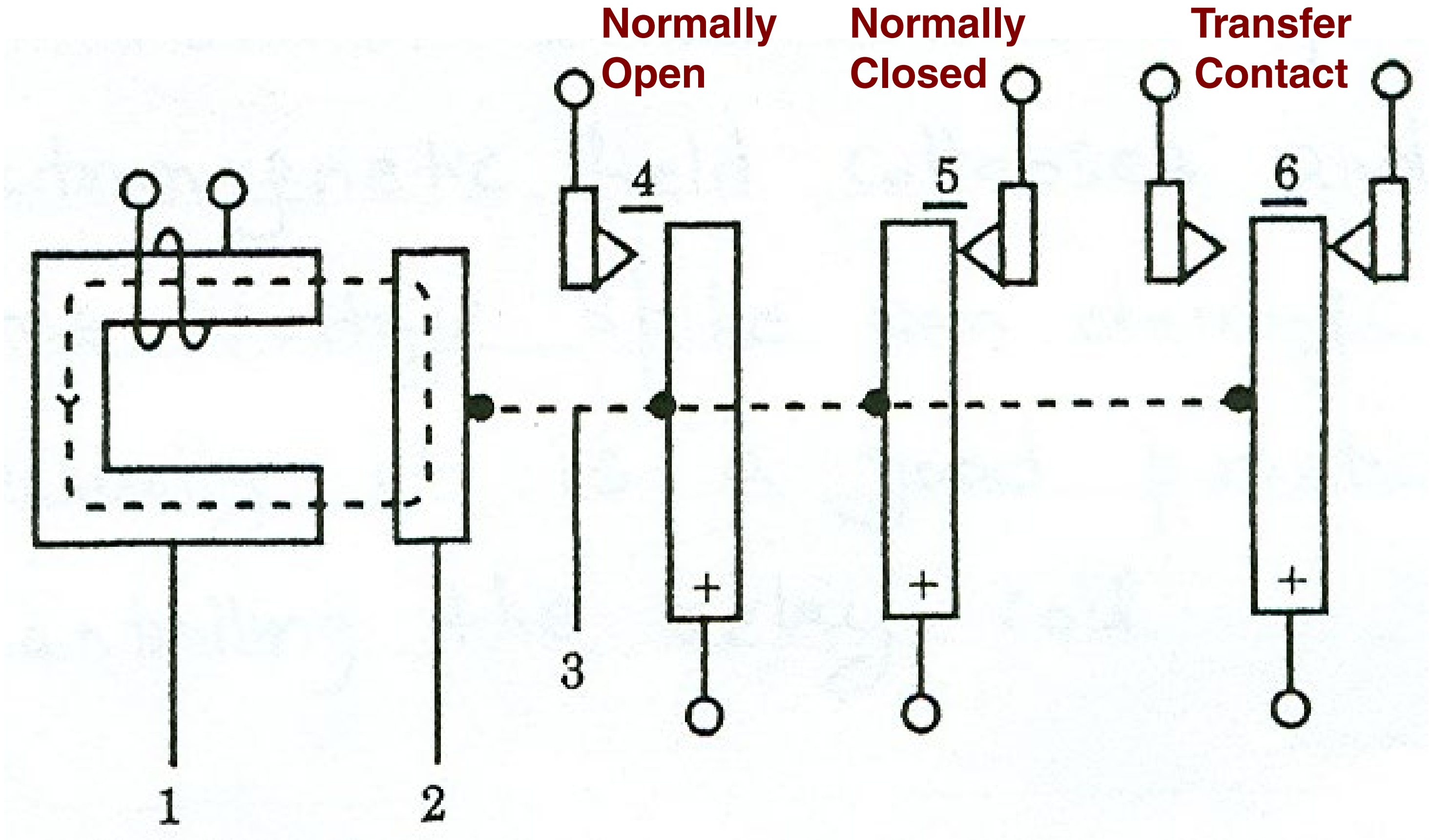
- Consists of (AC or DC) electromagnet and one or more pairs of contacts.





Contact switch

Electromechanical Relays



Armature (2) and **contacts** (4, 5, 6) are connected by **linkage** (3)

Electromechanical Relays: Contactors

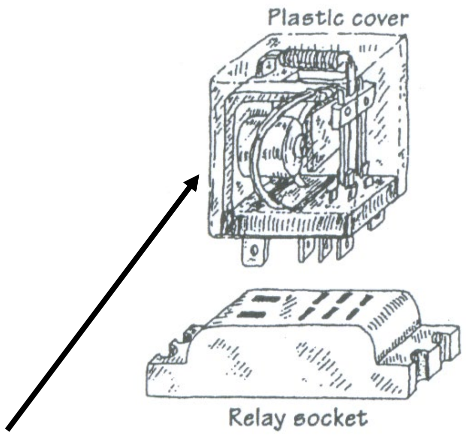
- “Big” relay is referred to as a **contactor**
  - Handles large currents
- Contactors are large relays and thought of as connecting power loads.
- Relays are usually thought of as performing logic.

Electromechanical Relays: Latch Relay

- A **latch relay** turns **on** when the current flows in one direction
  - Remains **on** even when this current is cut
  - Turns **off** when the current flows in the opposite direction
- Some latch relays may use two coils
  - One coil to turn on the relay
  - One coil to turn off the relay

Electromechanical Relays: Subminiature Mechanical Relays

- Smallest
- Very useful in industrial automation: remote switching, controlling high current load



Subminiature relay

Subminiature relay

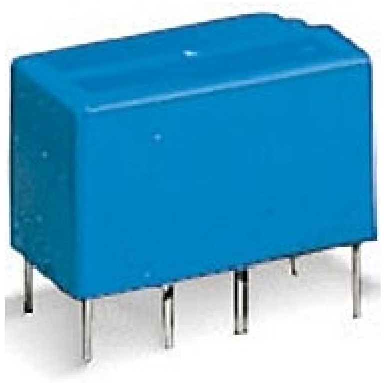
Electromechanical Relays: Subminiature Mechanical Relays

- **High contact current** (1–15 A)
- **Low coil current** (20–100 mA)
- **Slow switching** (10–100 ms)

- **AC** or **DC** electromagnetic 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 240VAC.
    - Coil resistance rating: 3400Ω and 13600Ω

Electromechanical Relays: Miniature Mechanical Relays

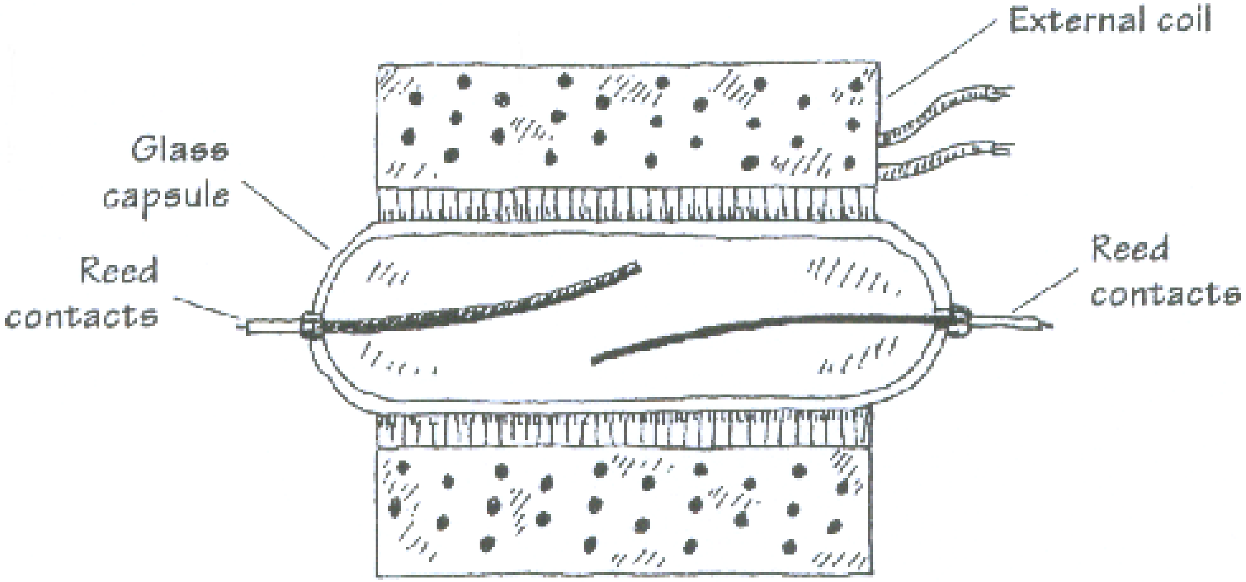
- Designed for greater sensitivity and lower level currents in comparison to subminiature relay
- Almost exclusively actuated by DC voltages, but may be designed to switch AC currents.
- Excitation voltages: 5,6,12, and 24V
- Coil resistance: 50 to 3000 Ω.

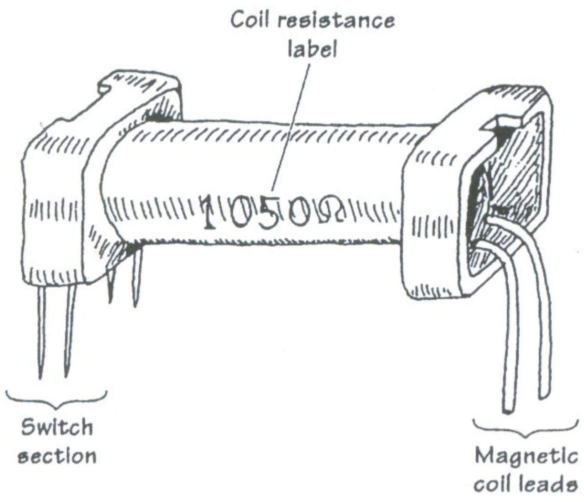


Miniature relay

Reed Relays

- A **reed relay** consists of a pair of thin flexible metal strips **(reeds)**
- Reeds are inside a glass capsule surrounded by a electromagnetic coil
- Reeds contact when current passes through wire coil





Reed Relays

- Most are normally open
- Moderate currents (500 mA to 1A)
- Low mass of reeds allows for moderately fast switching (0.2 ms to 2 ms)

Notes of Caution

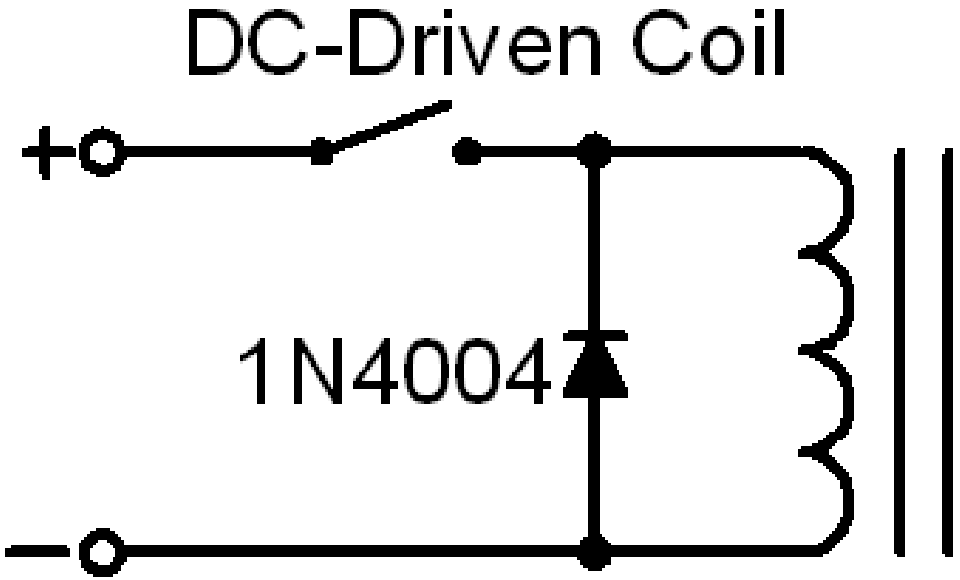
- To switch a relay on/off:
  - Voltage across magnetic coil must be within ±25% of the voltage rating
- **Relay coil acts as an inductor and inductors do not like sudden changes in current.**
  - Some electromagnetic relays draw low current and can be connected directly to BS2
  - When BS2 attempts to switch off the relay, the electromagnetic field collapses and a **voltage spike** is generated.
    - Any attempt to suddenly change the current will creates a voltage spike.
- This voltage spike can damage sensitive MOS-type circuits.

Relay Kickback and Transient Suppressors

- To avoid voltage spikes, **transient suppressors** are generally used
  - Transient suppressors are available in prepackaged form
  - Can make them yourself
- Usually it is a good practice to buffer BS2's digital output controlling the relay coil

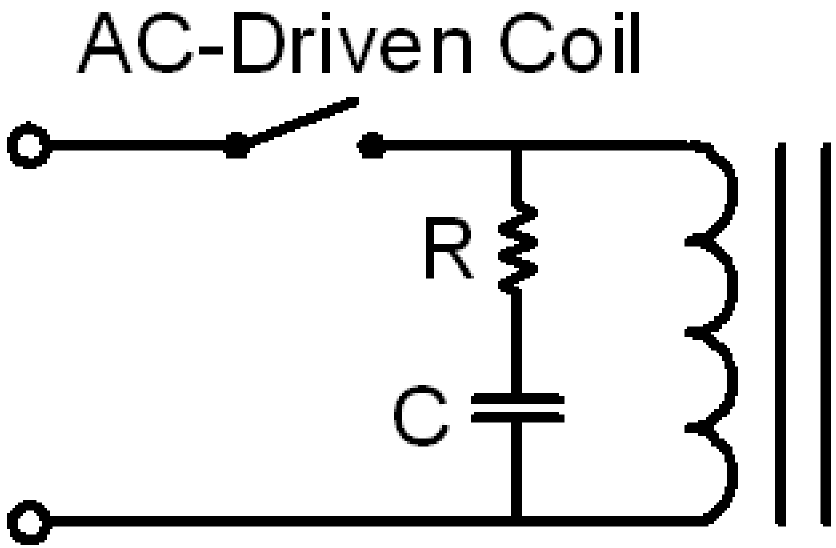
Transient Suppressors for DC-Driven Coil

- Diode in **reverse bias** across relay coil
  - Diode conducts before a large voltage can form across the coil
- Diode must be rated for the maximum current that would have been flowing through the coil before the current supply was interrupted
- 1N4004 diode is a good general-purpose diode for such applications

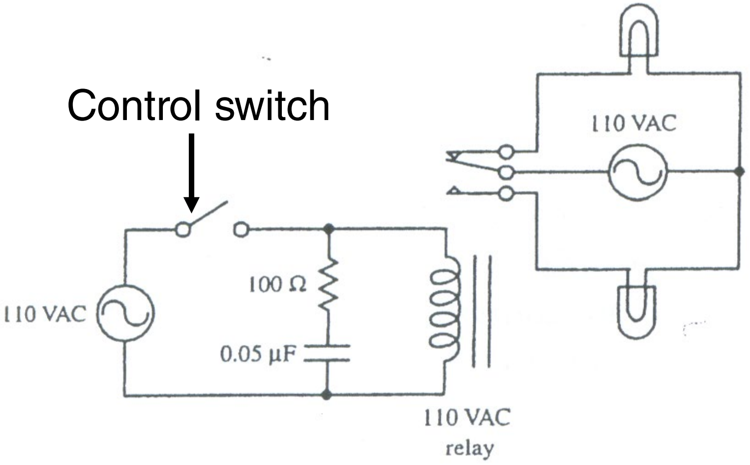


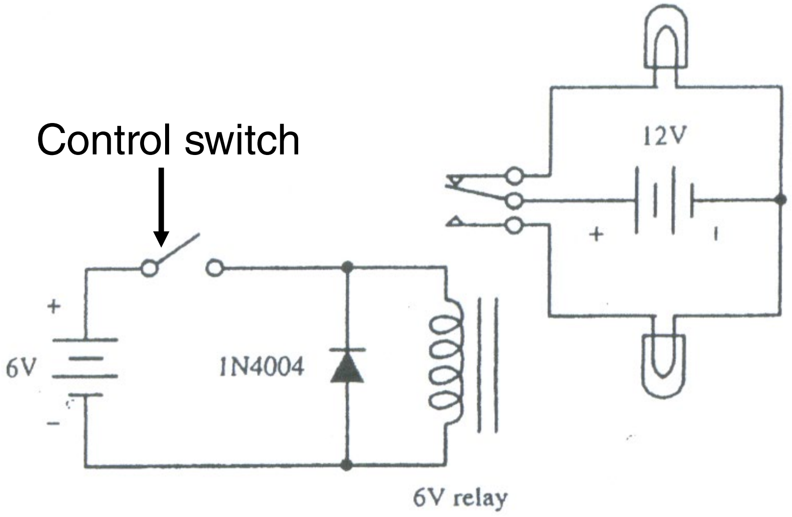
Transient Suppressors for AC-Driven Coil

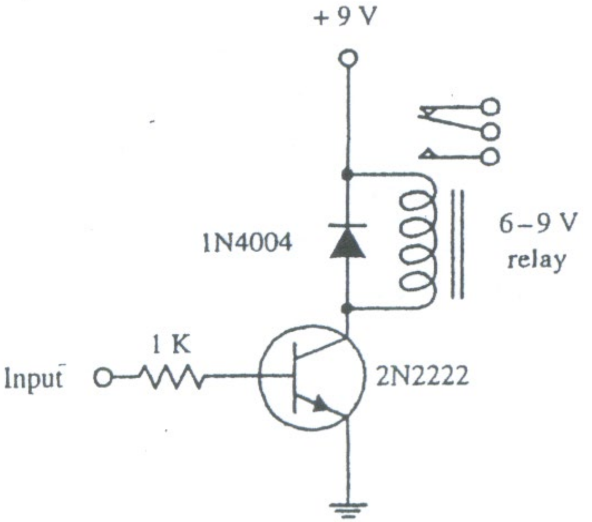
- Diodes do not work
  - 1 diode: always conducts on alternate half-cycles
  - 2 diodes in reverse parallel: current will never pass through coil
- **Solution: RC circuit**
  - Capacitor absorbs excessive charge
  - Resistor controls the discharge.
- For small loads driven from the power line
  - use R = 100 Ω and C = 0.05 μF.



Relay: Examples



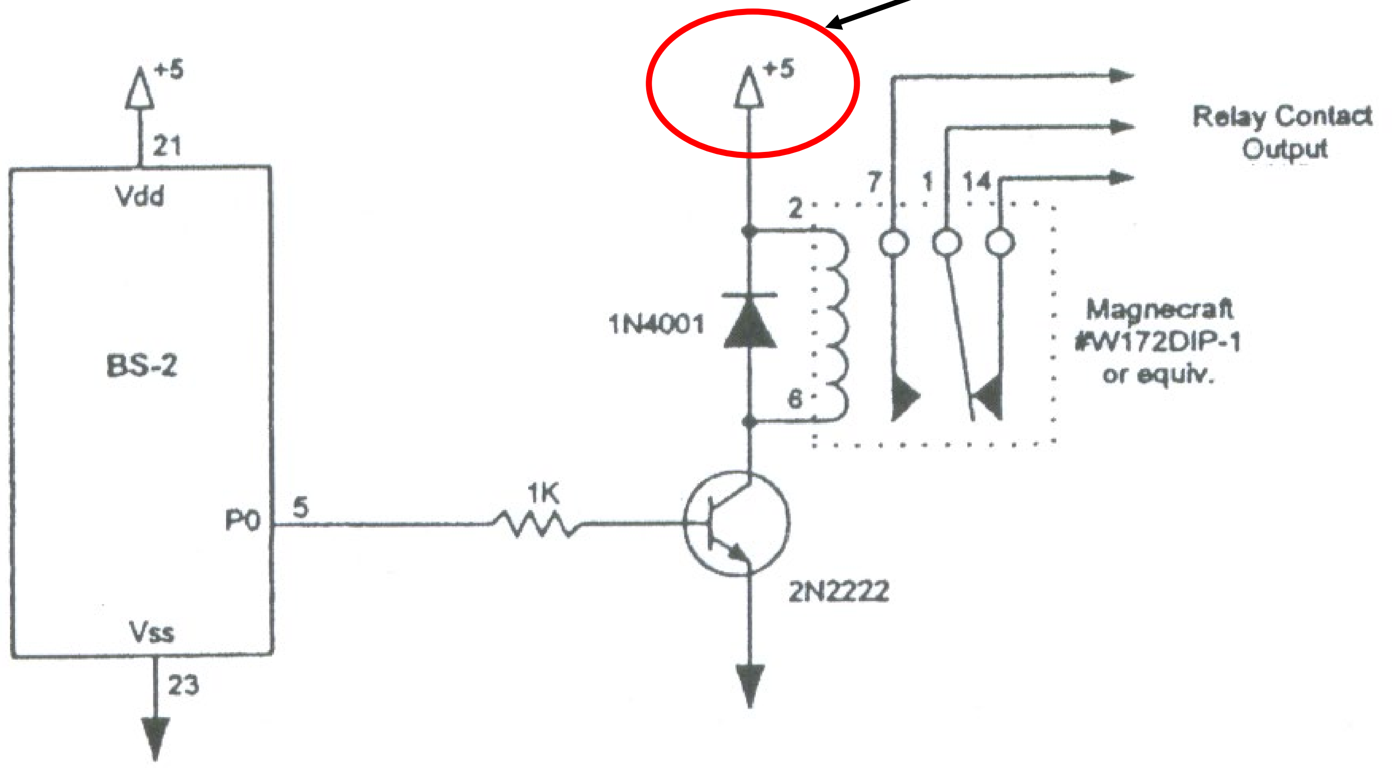




Relays with BS2

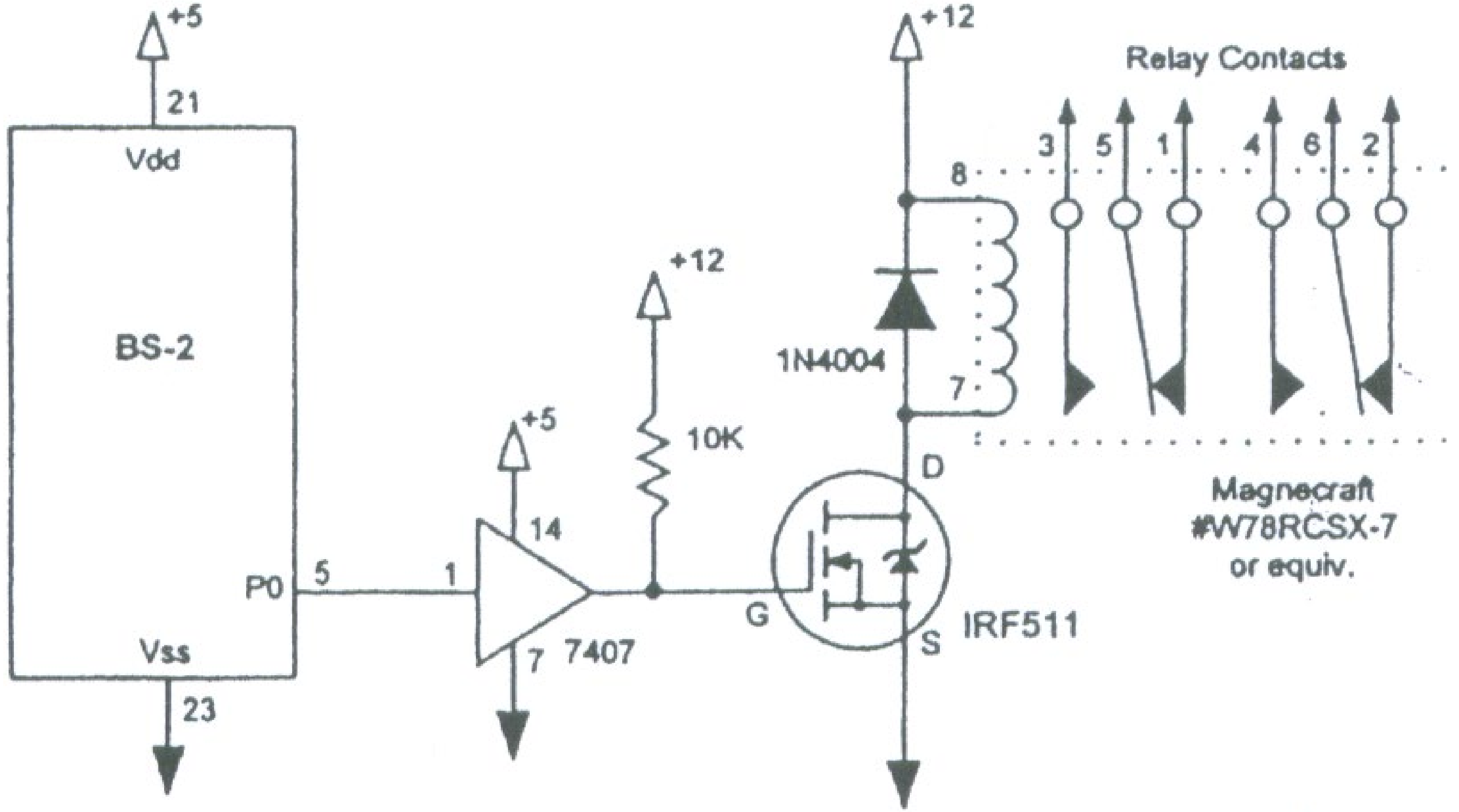
- BJT provides sufficient drive current for the relay.
- Reverse voltage spike is shorted by the IN4001 diode

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



Relays with BS2

- For relays that require significantly higher current/voltage:
  - 7407 non-inverting buffer IC and an IRF511 MOSFET



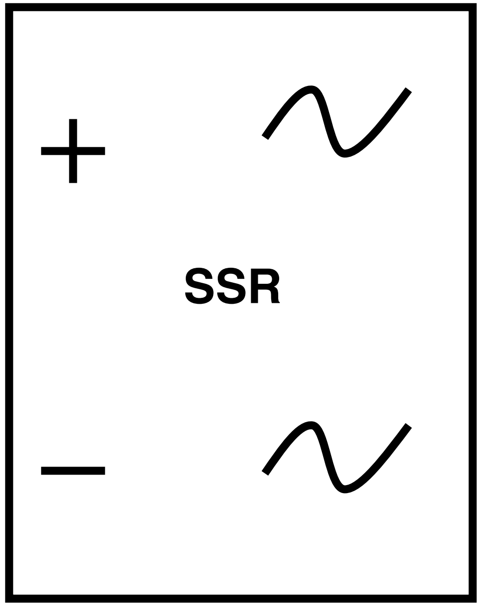
Solid-State Relays

- Semiconductor-based
  - Include transistors (FET, BJTs) and thyristors (SCRs, triacs, diacs, etc.).
  - Rapid switching speeds (1 to 100 ns)
  - No contact wear
- **Downsides:**
  - usually high “on” resistance
  - require fine tuning.
  - less resistant to overloads compared with electromechanical relays

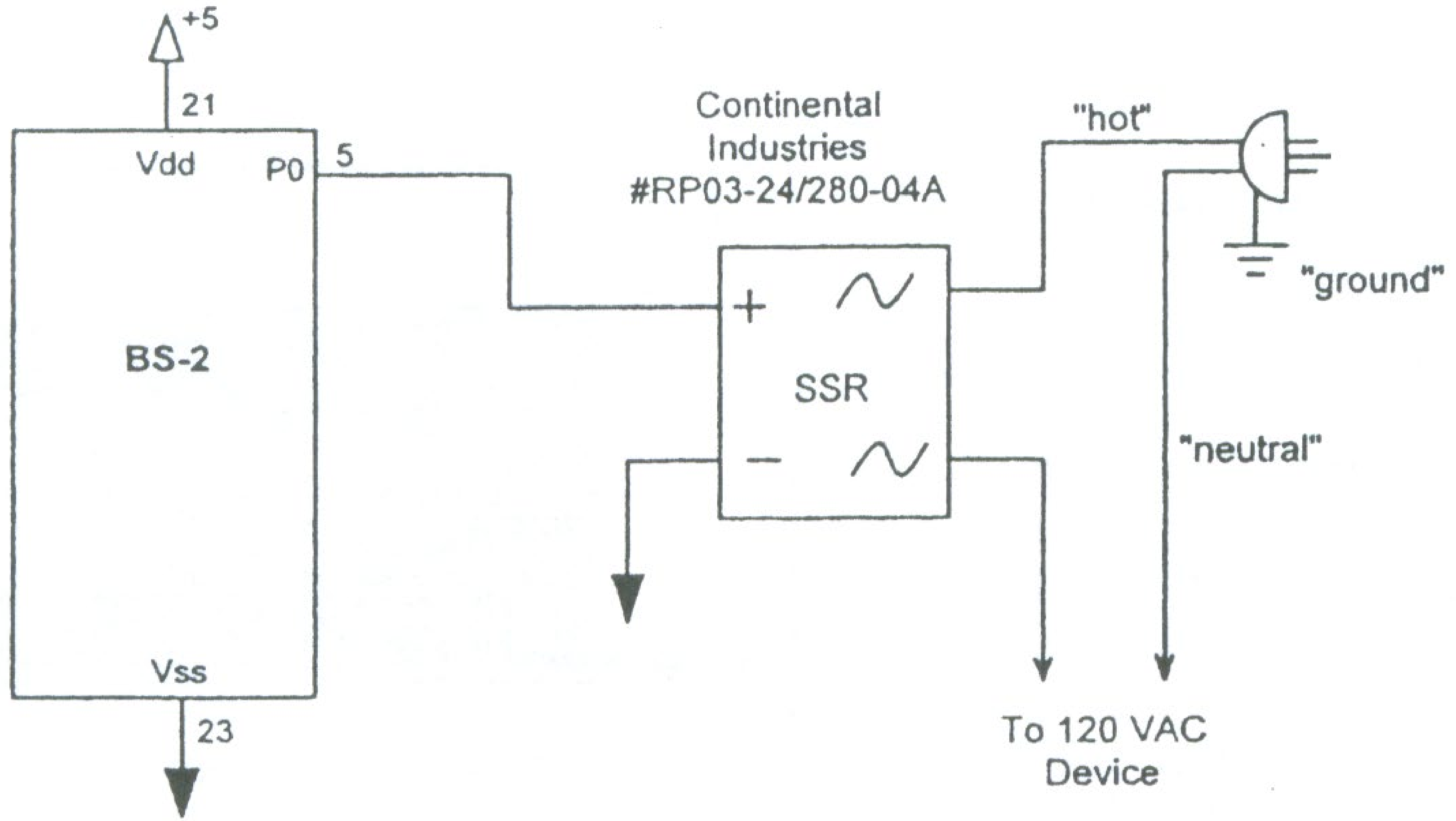
Solid-State relay

Solid-State Relays

- Available in a wide range of current ratings from a few µA to 100mA.
- Most solid-state relays use built-in opto-isolators
- **Advantages:**
  - Simple and safe to connect to BS2 for controlling high voltage device
    - SSR input and the high voltage load connected at the output of SSR are electrically isolated
    - Opto-isolation circuit of SSR requires very low current

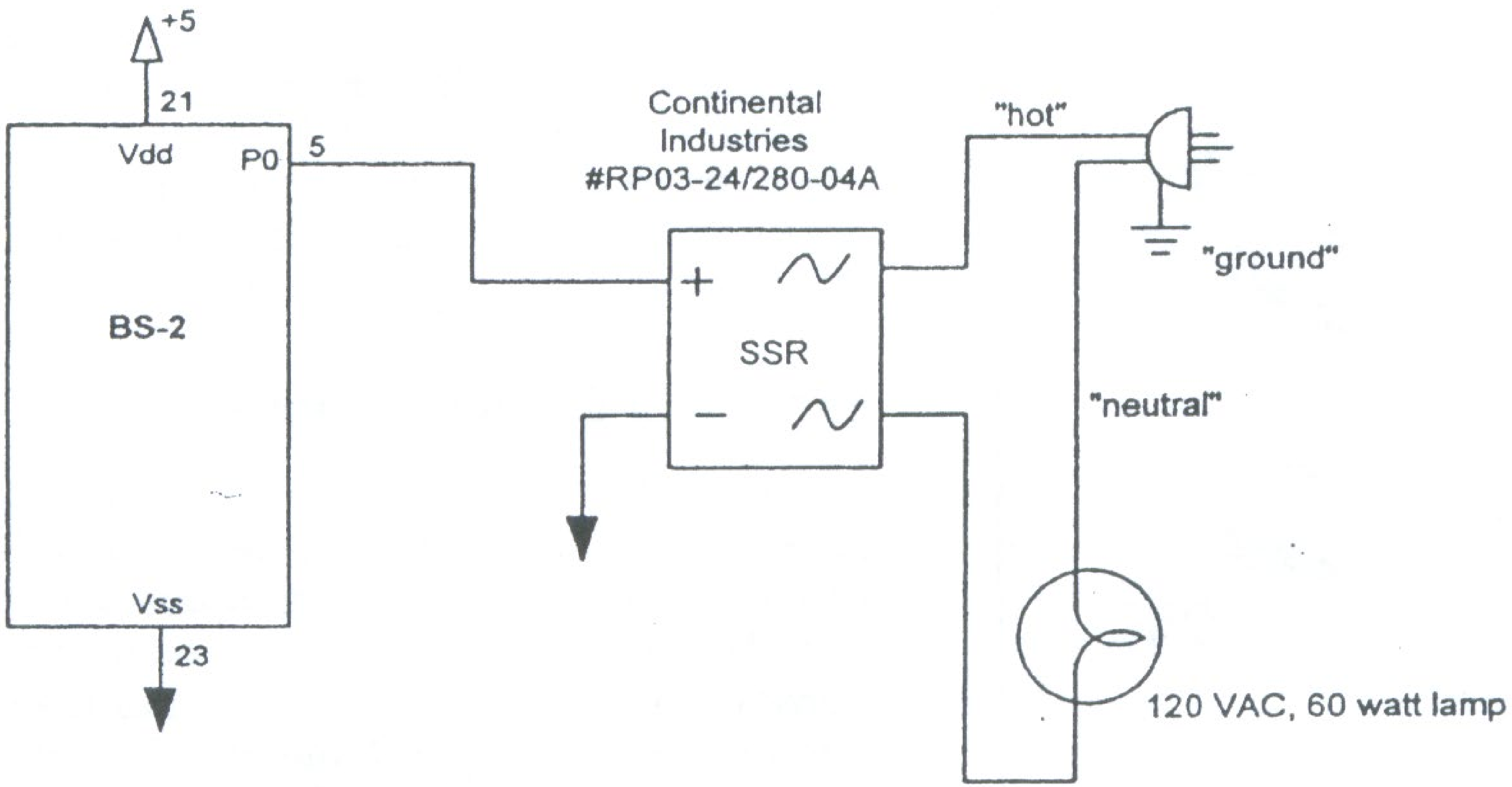


Solid State Relay with BS2



Be extremely cautious with 120V AC !!

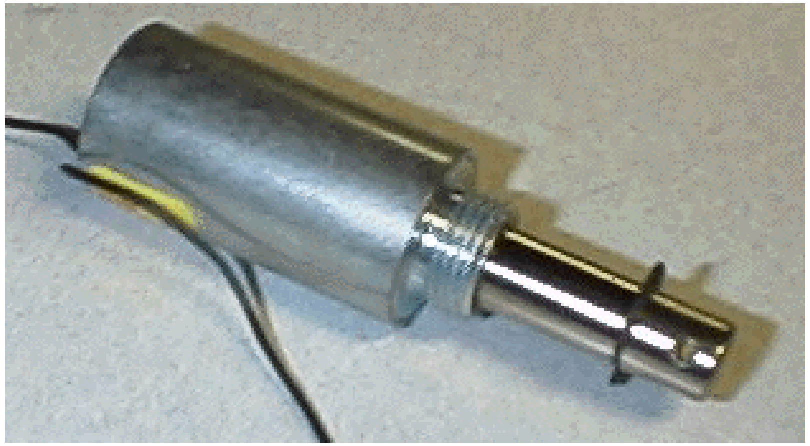
Solid State Relay with BS2



Be extremely cautious with 120V AC !!

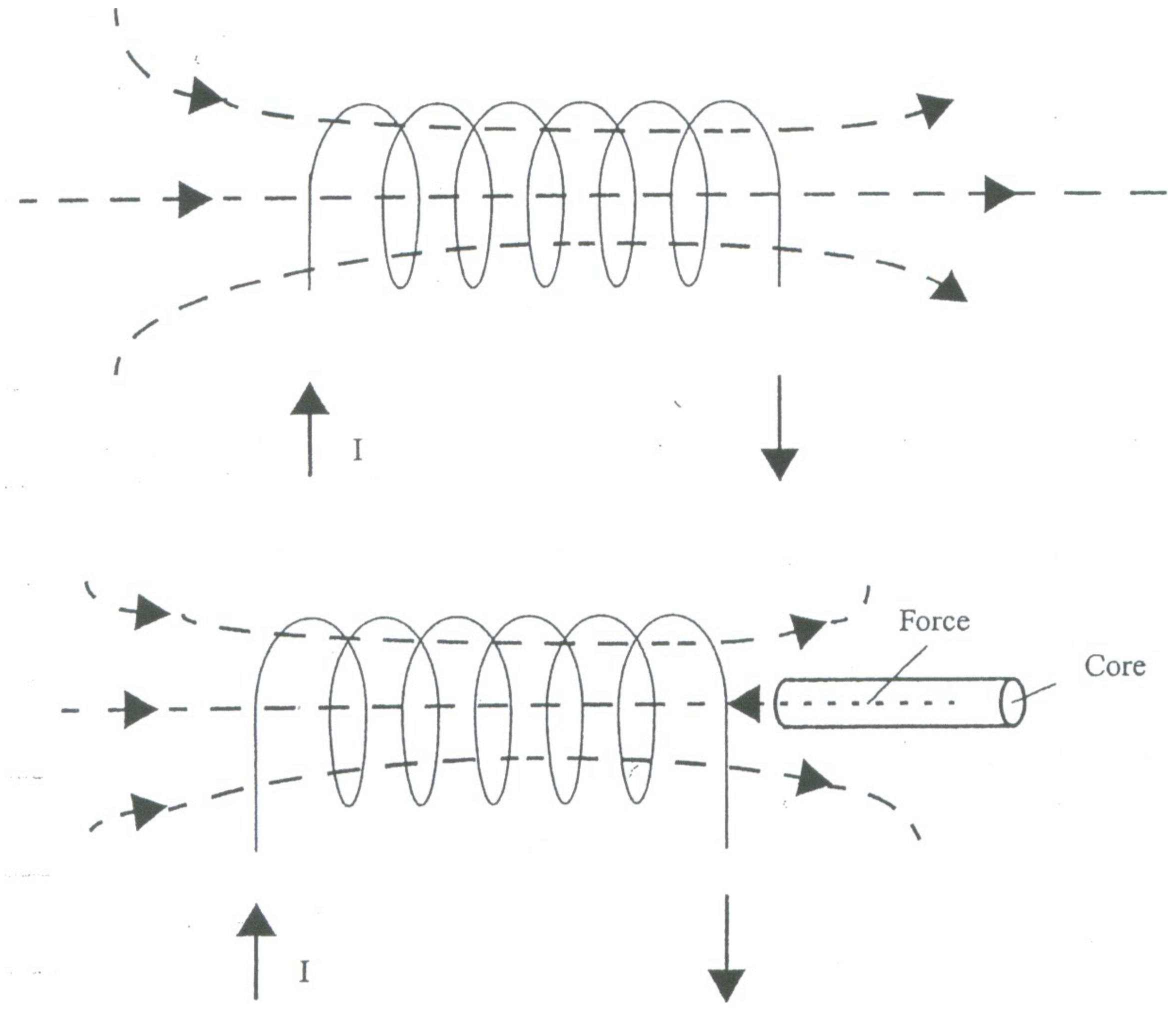
Solenoid

- Electromechanical device to convert electrical energy into linear or rotary motion.
- Components:
  - Coil for conducting current and generating a magnetic field
  - Iron or steel shell or case to complete the magnetic circuit
  - Plunger or armature for translating motion
- Can be actuated by either AC or DC.



Solenoid: Principle of Operation

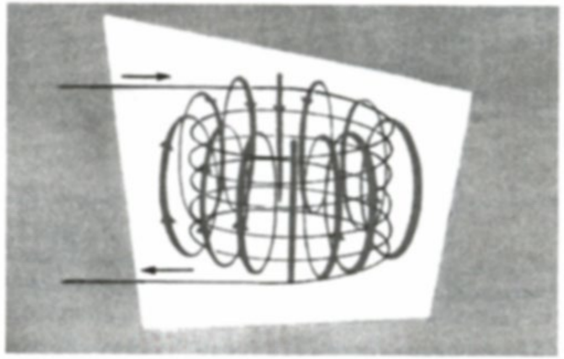
- Current flow through a coil of produces a uniform magnetic field
  - (Another right hand rule)
- Field pulls on a ferromagnetic object to produces a mechanical force



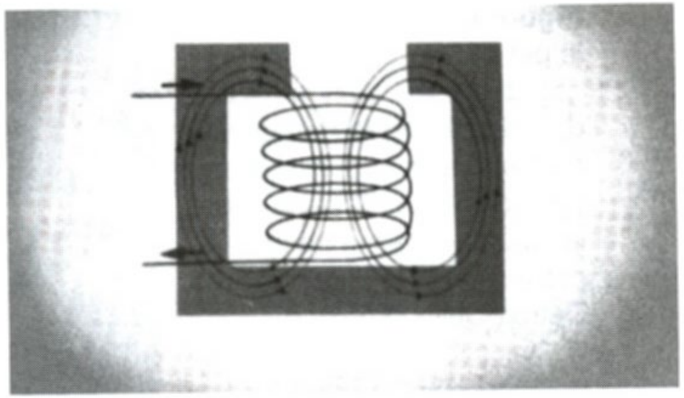
Solenoid: Principle of Operation

- Magnetic field 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 ferrous 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.

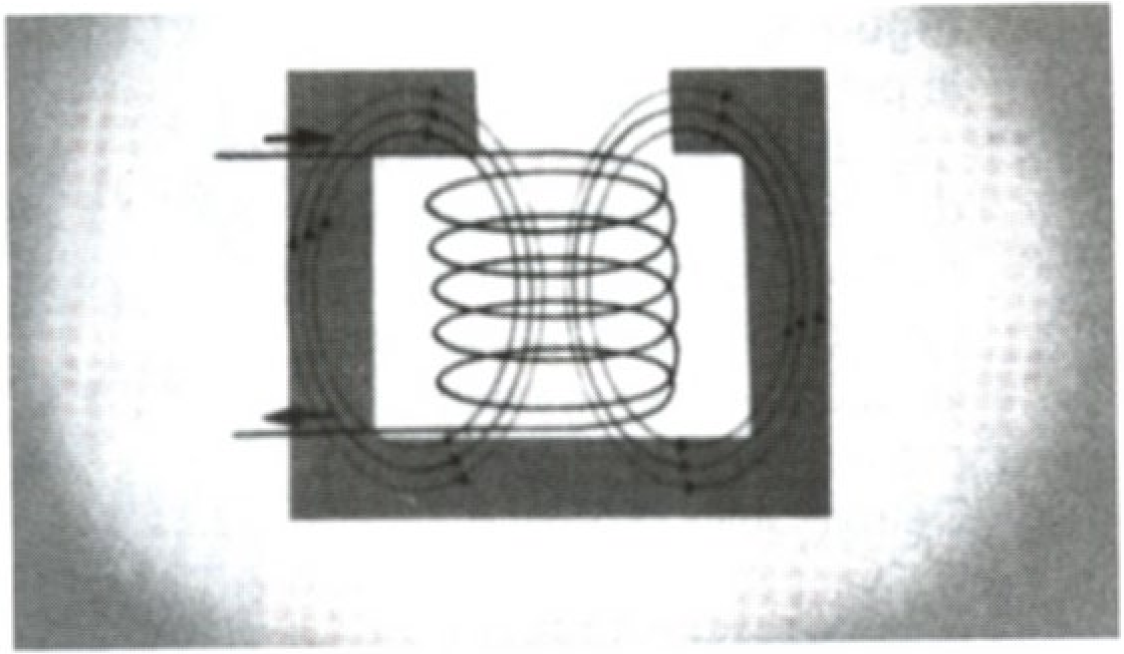


Although this magnetic field will flow in air, it flows much more easily through iron or steel—so we add an iron path, or *C stack*, around the coil that concentrates the magnetism where we want it.

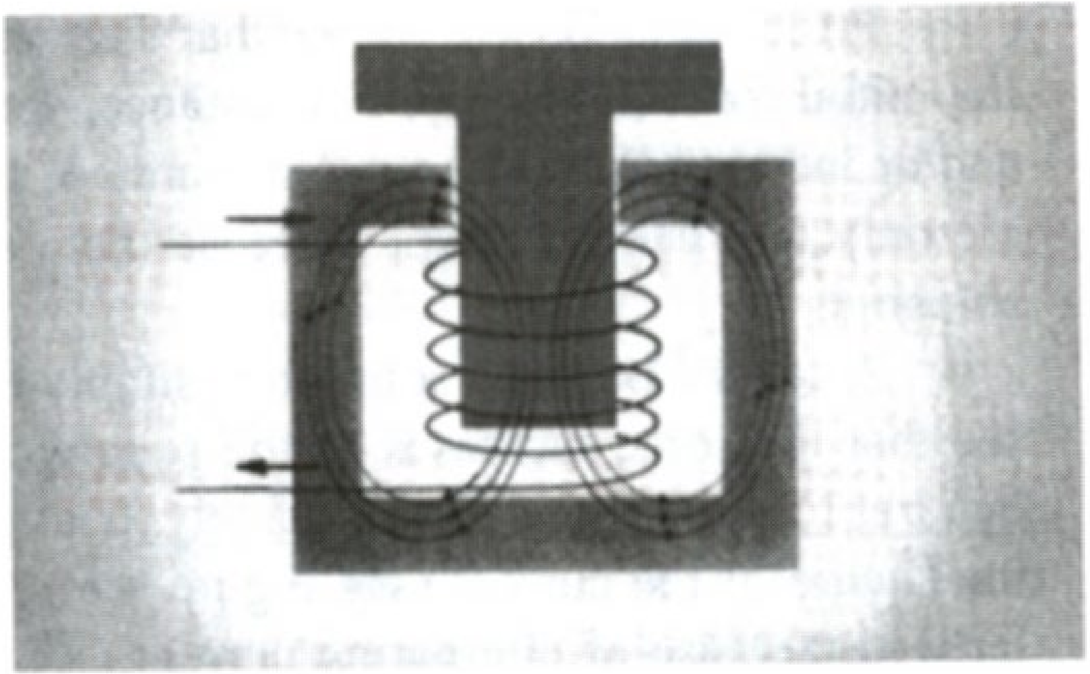


Solenoid: Principle of Operation

- Field draws the ferrous plunger into the coil



Plunger



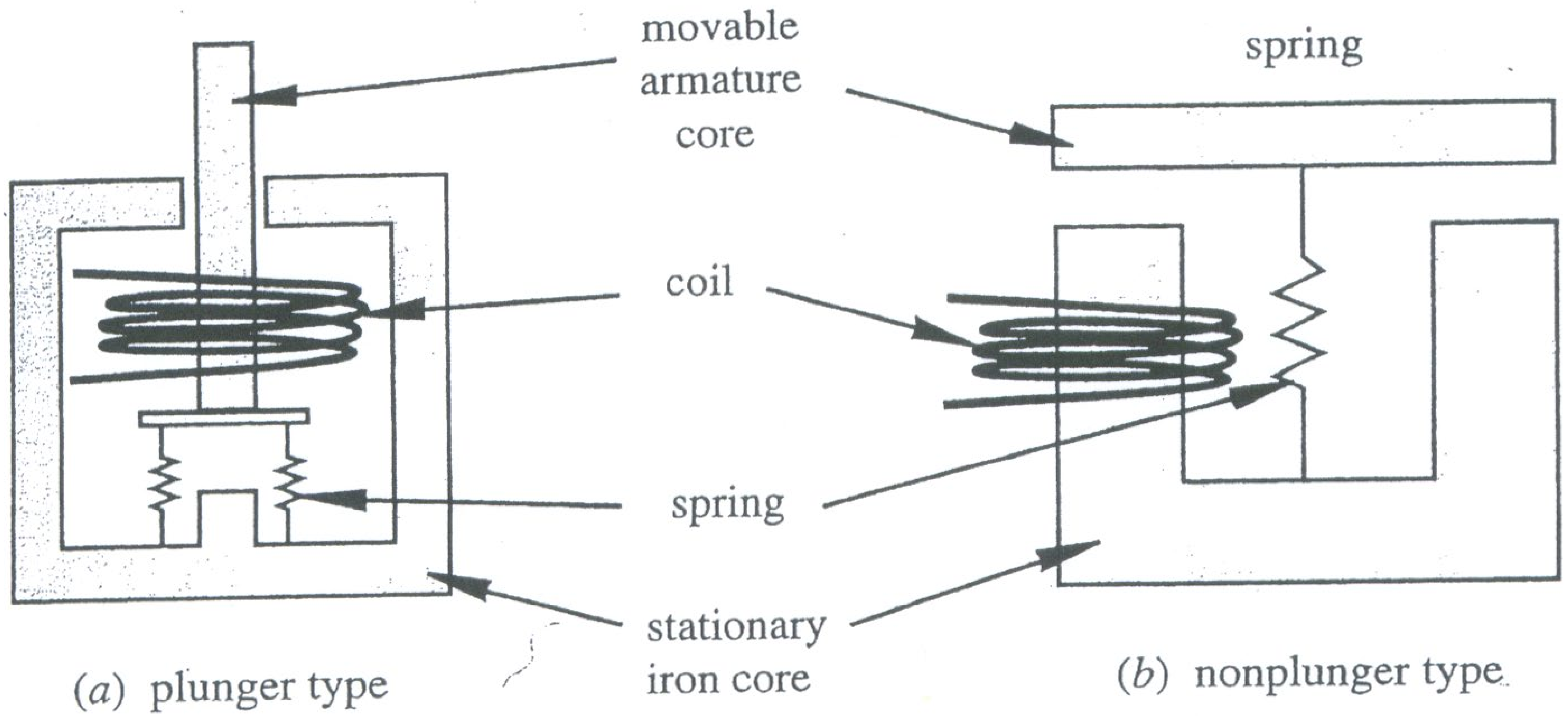
Solenoid: Principle of Operation

- Plunger force is governed by:
  - Coil current
  - # of turns in the coil
  - Plunger material
  - Geometry
  - Distance that the plunger moves (i.e., the solenoid stroke).
- Common specs:
  - Control voltage for coil (3 to 48VDC)
  - Coil current (50mA to 2A)

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

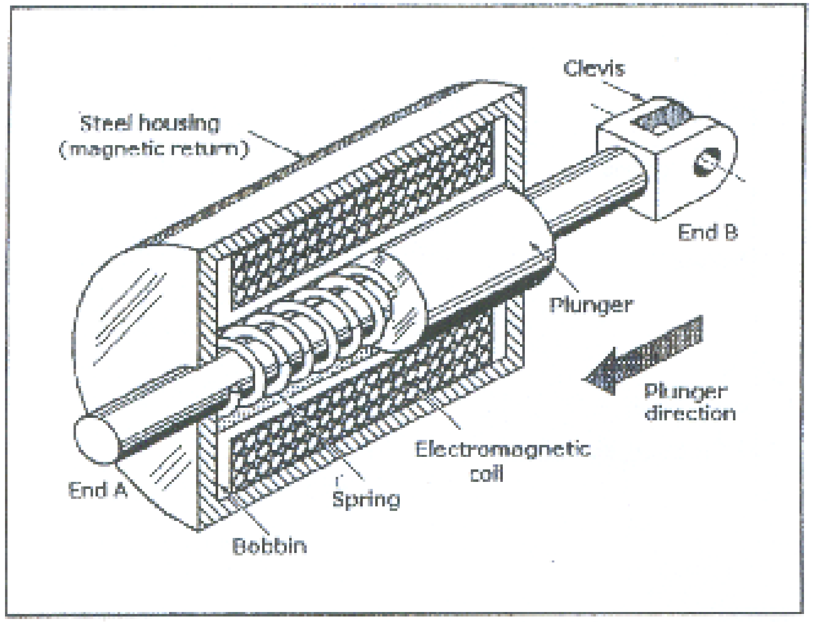
- F: initial solenoid force (N)
- N: # of turns of wire in coil
- I_0: initial current (A)
- μ_0: magnetic permeability of free space ($4\pi * 10^{-7}$ H/m in air)
- A: plunger cross-sectional area (cm^2)
- X: air gap (cm)

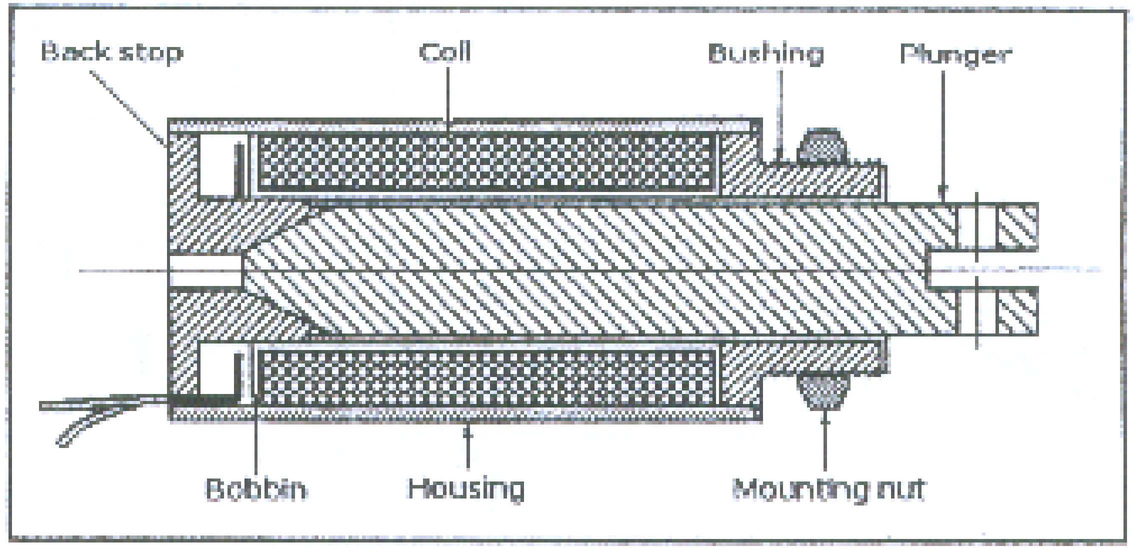
Solenoid: Plunger vs. Non-Plunger



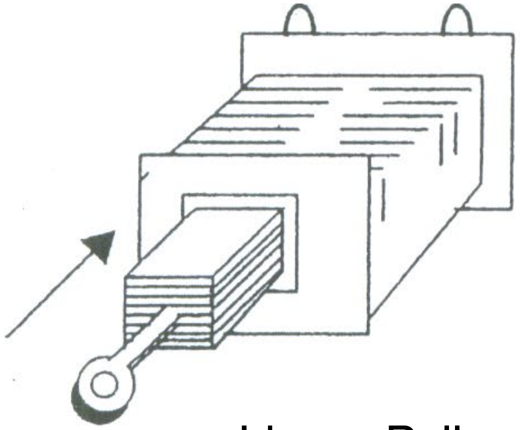
Linear Solenoid

- Linear motion as output
- Conical end of the plunger increases its efficiency.

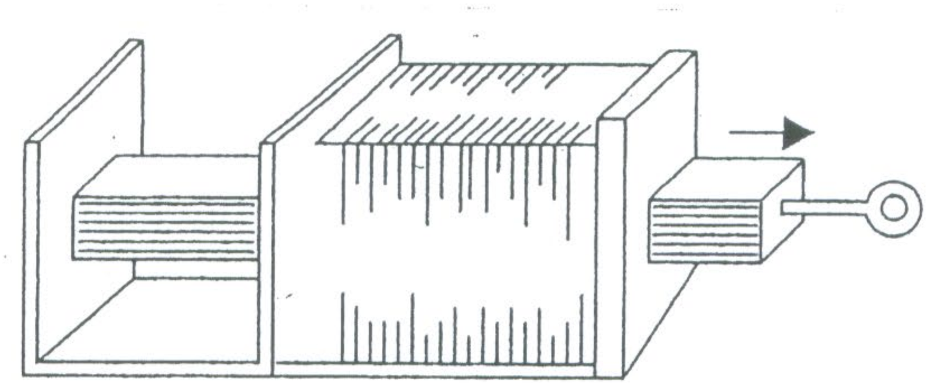




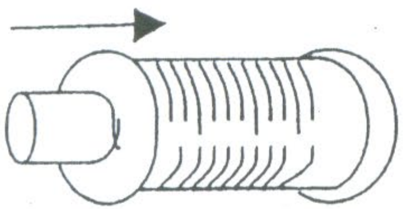
Linear Solenoid: Push vs. Pull



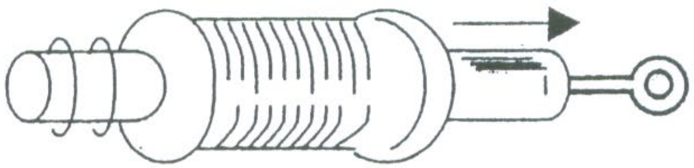
Linear Pull



Linear Push

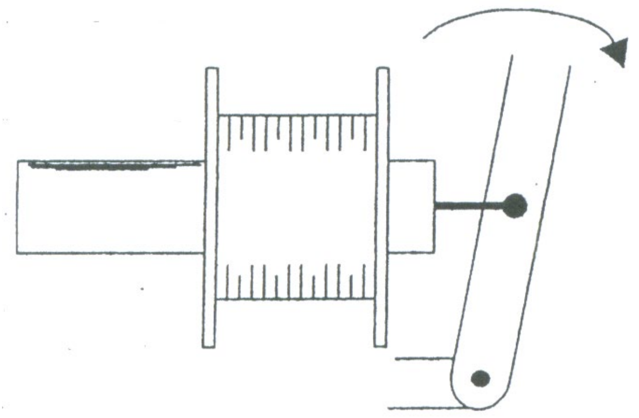


Linear Tubular Pull

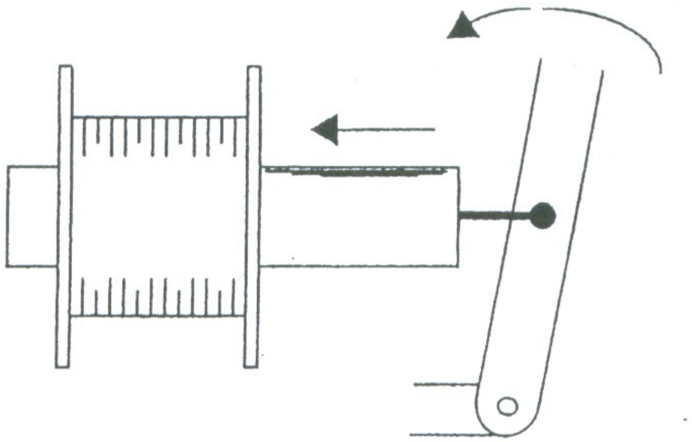


Linear Tubular Push

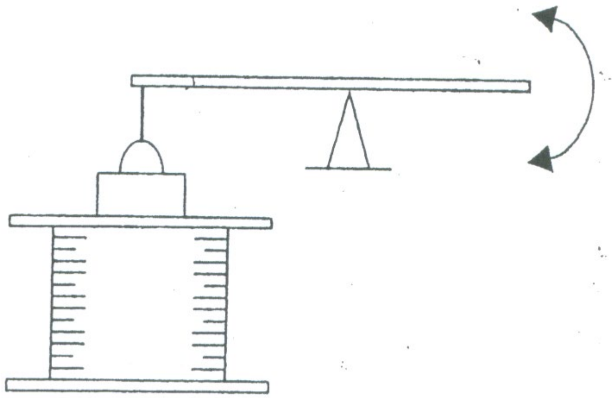
Linear Solenoid: Push vs. Pull



Push solenoid to turn an arm



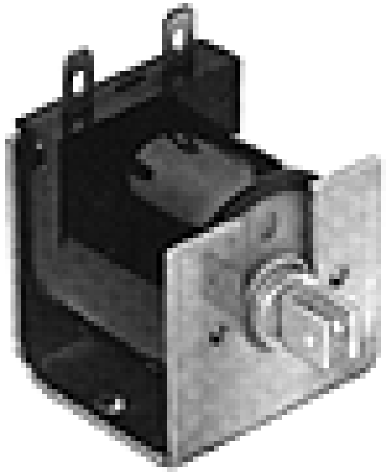
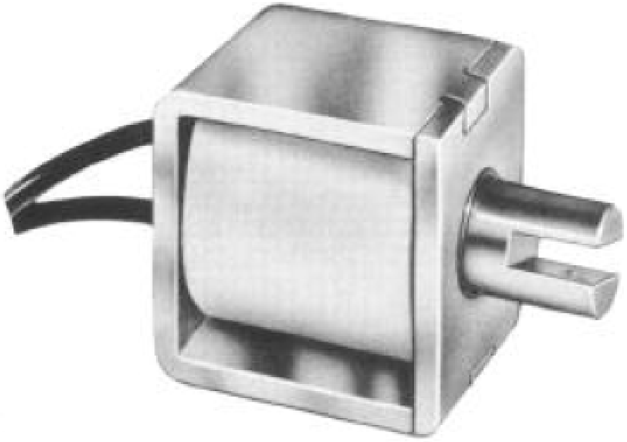
Pull solenoid to turn an arm



Solenoid actuates a level

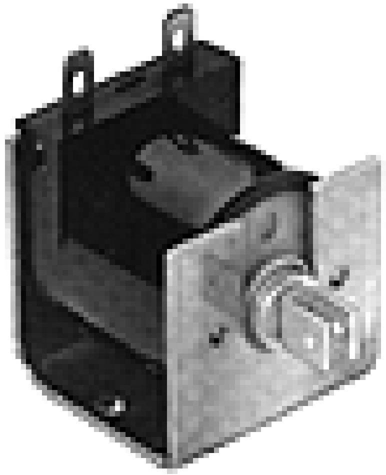
Open-Frame vs. Box-Frame Solenoids

- Open-frame: Exposed elements
- Box-frame: Enclosed elements

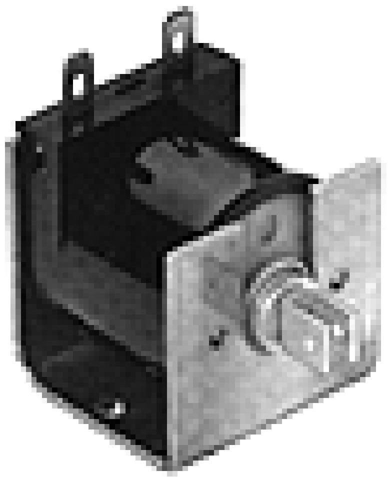
Open-Frame Solenoid

- Simple to manufacture, cheap
  - Open steel frames, exposed coils
  - Movable plungers centered in their coils.
- Not for applications that require long life and precise positioning



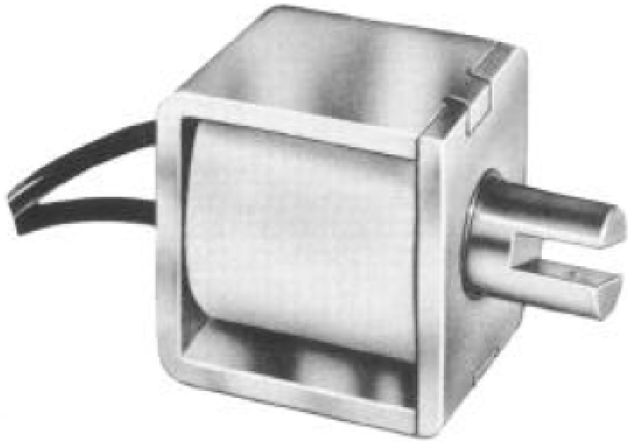
Open-Frame Solenoid: C-type/C-Frame

- Low-cost commercial solenoids for light-duty applications
- Frames are typically laminated steel formed in the shape of the letter C to complete the magnetic circuit through the core
  - Coil windings lack complete protective cover but are usually potted to resist airborne and liquid contaminants.
- Plungers are typically made as laminated steel bars
- Found in appliances, printers, coin dispensers, security door locks, cameras, and vending machines.
  - Can be powered with either AC or DC current.
- C-frame solenoids can have operational lives of millions of cycles
- Standard catalog models are capable of strokes up to 0.5 in.



Open-Frame Solenoid: Box-type/Box-Frame

- Steel frames that enclose their coils on two sides, improving mechanical strength.
    - Some box-type solenoids use stacks of thin insulated sheets of steel to control eddy currents and keep stray circulating currents confined in solenoids powered by AC.
- Coils are wound up on phenolic bobbins
- Plungers are typically made from solid bar stock.
- For higher-end applications compared to C-type:
    - Tape decks, industrial controls, tape recorders, and business machines

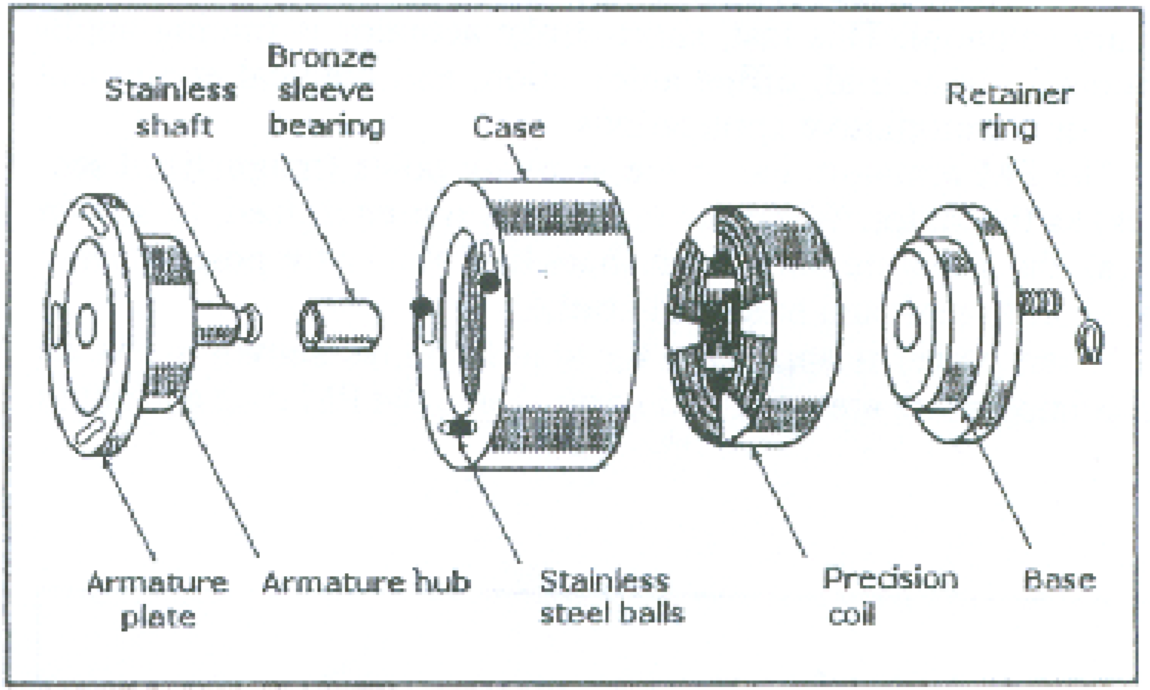


Tubular Solenoids

- The coils of **tubular solenoids** are completely enclosed in cylindrical metal cases
  - Improved magnetic circuit return
  - Better protection against accidental damage or liquid spillage.
- Tubular DC solenoids offer highest volumetric efficiency of any commercial solenoids
  - For industrial and military/aerospace equipment where space is limited.
- For printers, computer disk-and tape drives, and military weapon systems; both pull-in and push-out styles are available.

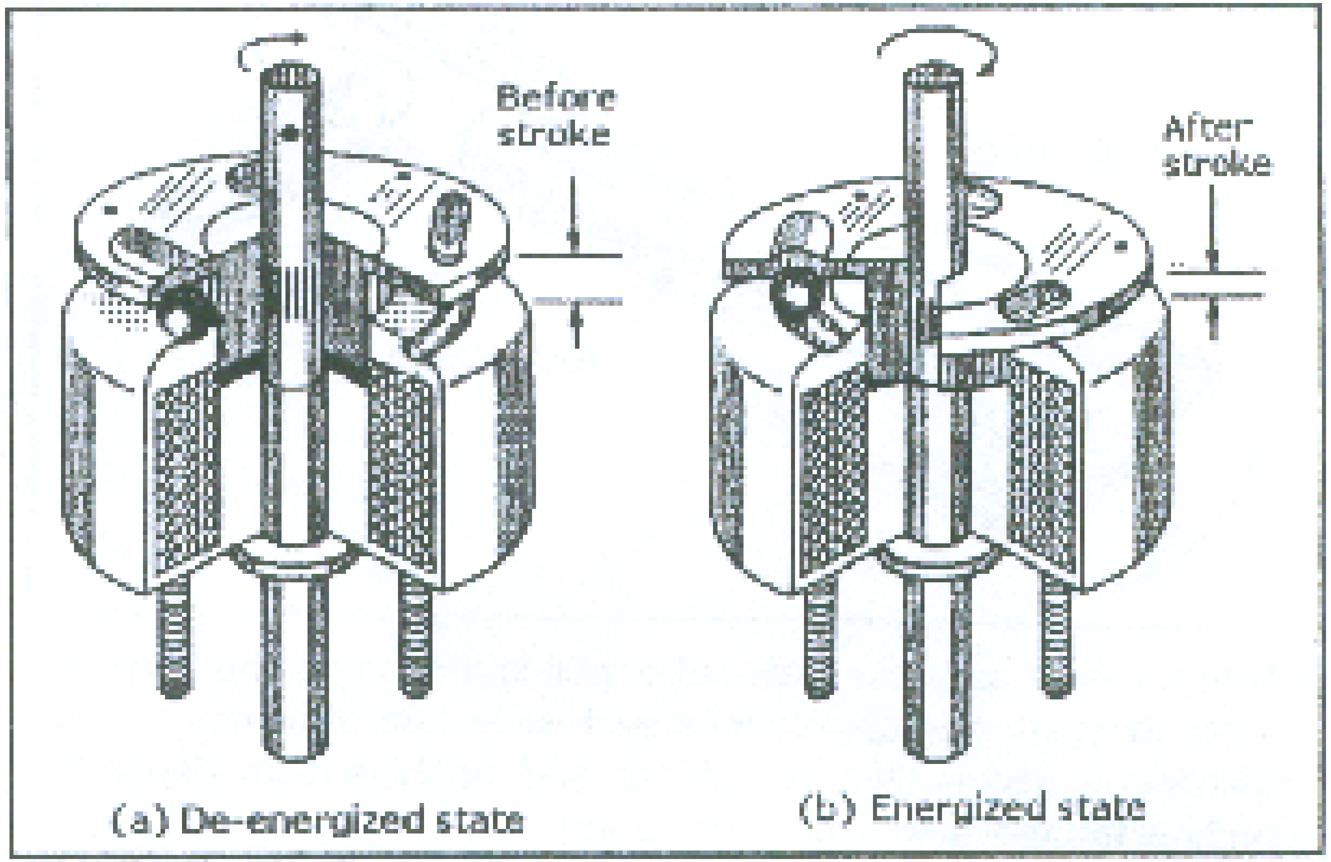
Rotary Solenoids

- Rotary motion as output



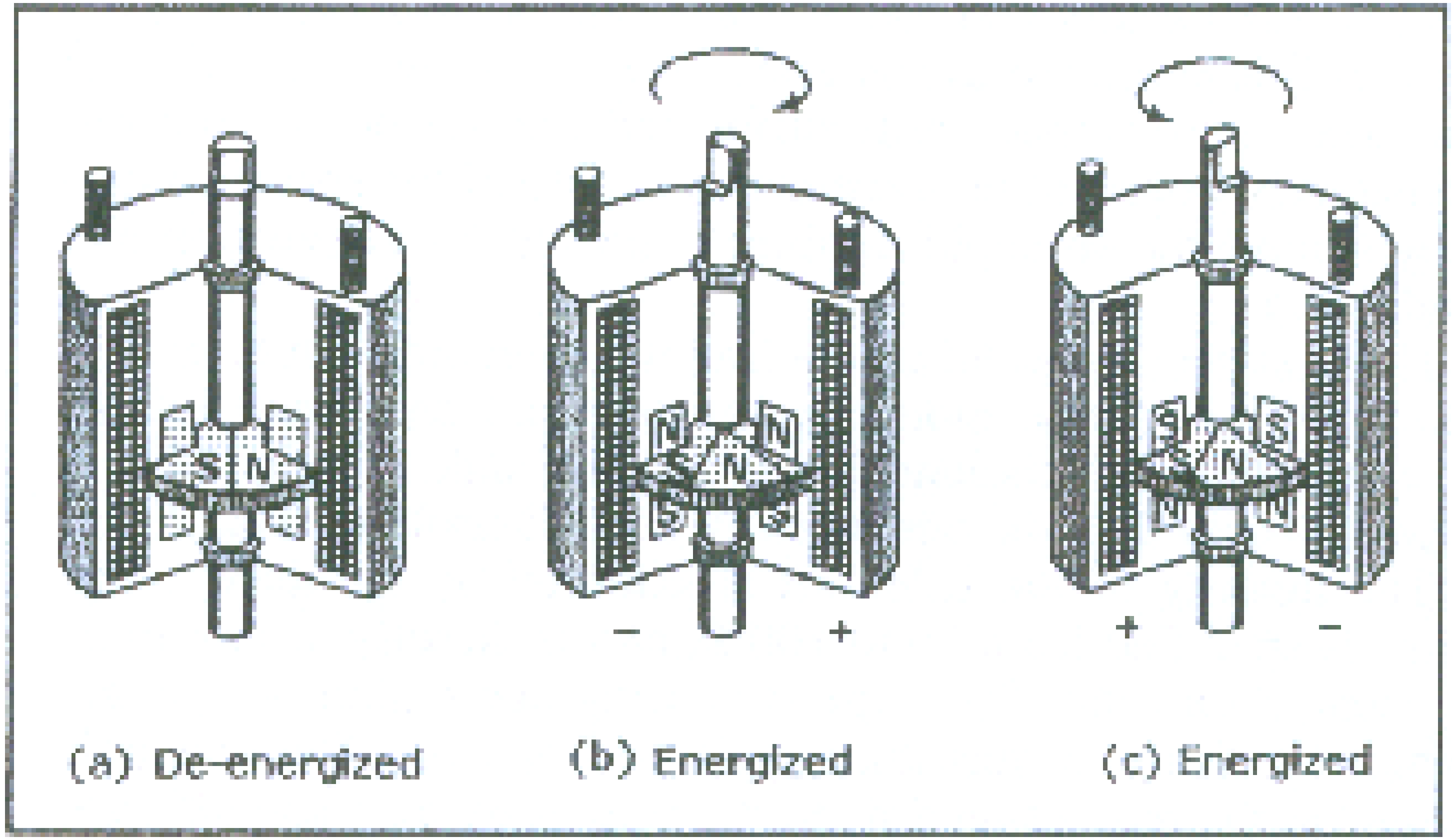
Rotary Solenoids

- Linear motion of armature causes three ball bearings to roll into the deeper ends of the lateral slots on the faceplate

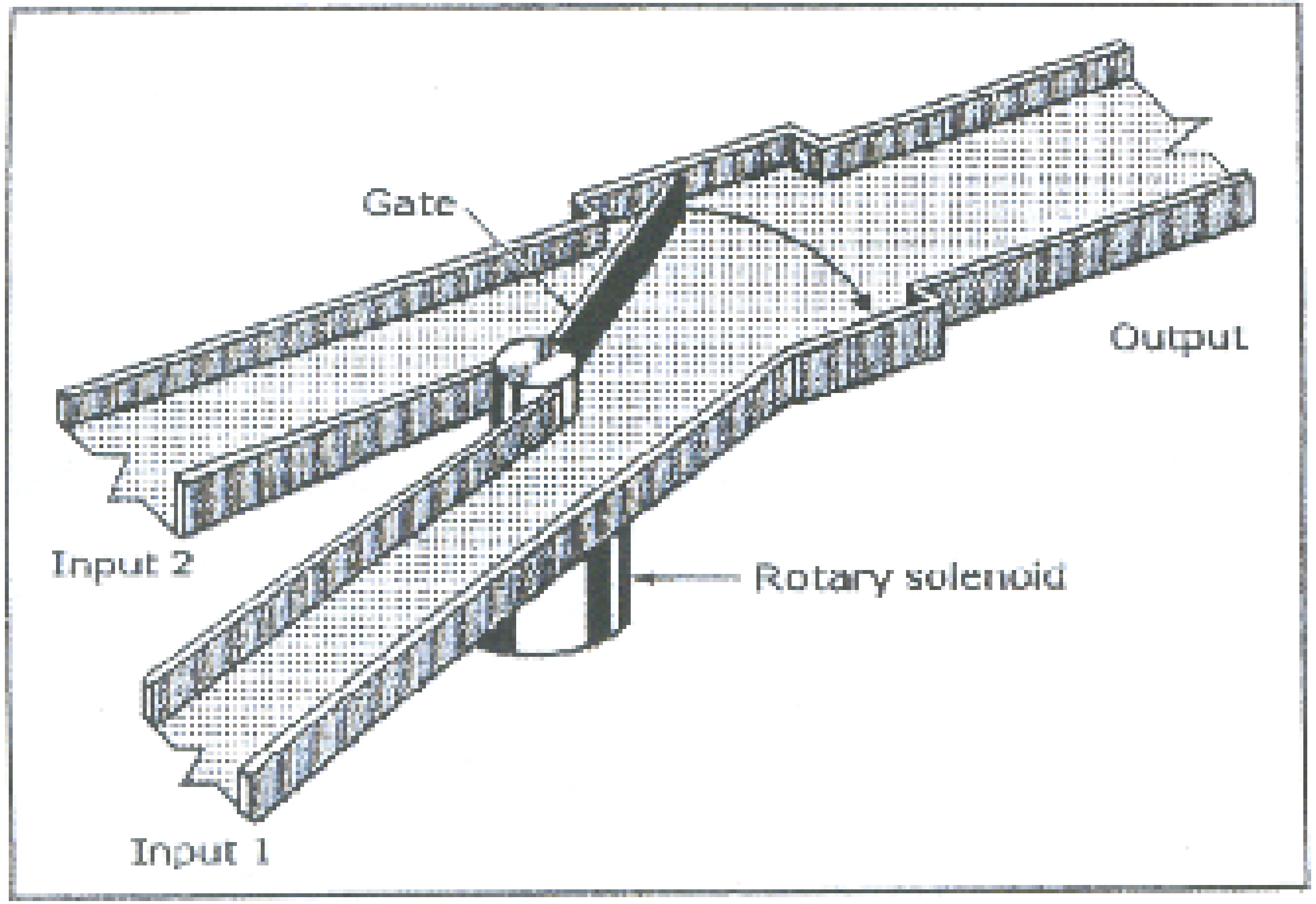


Rotary Solenoids: Bi-directionality with Magnet

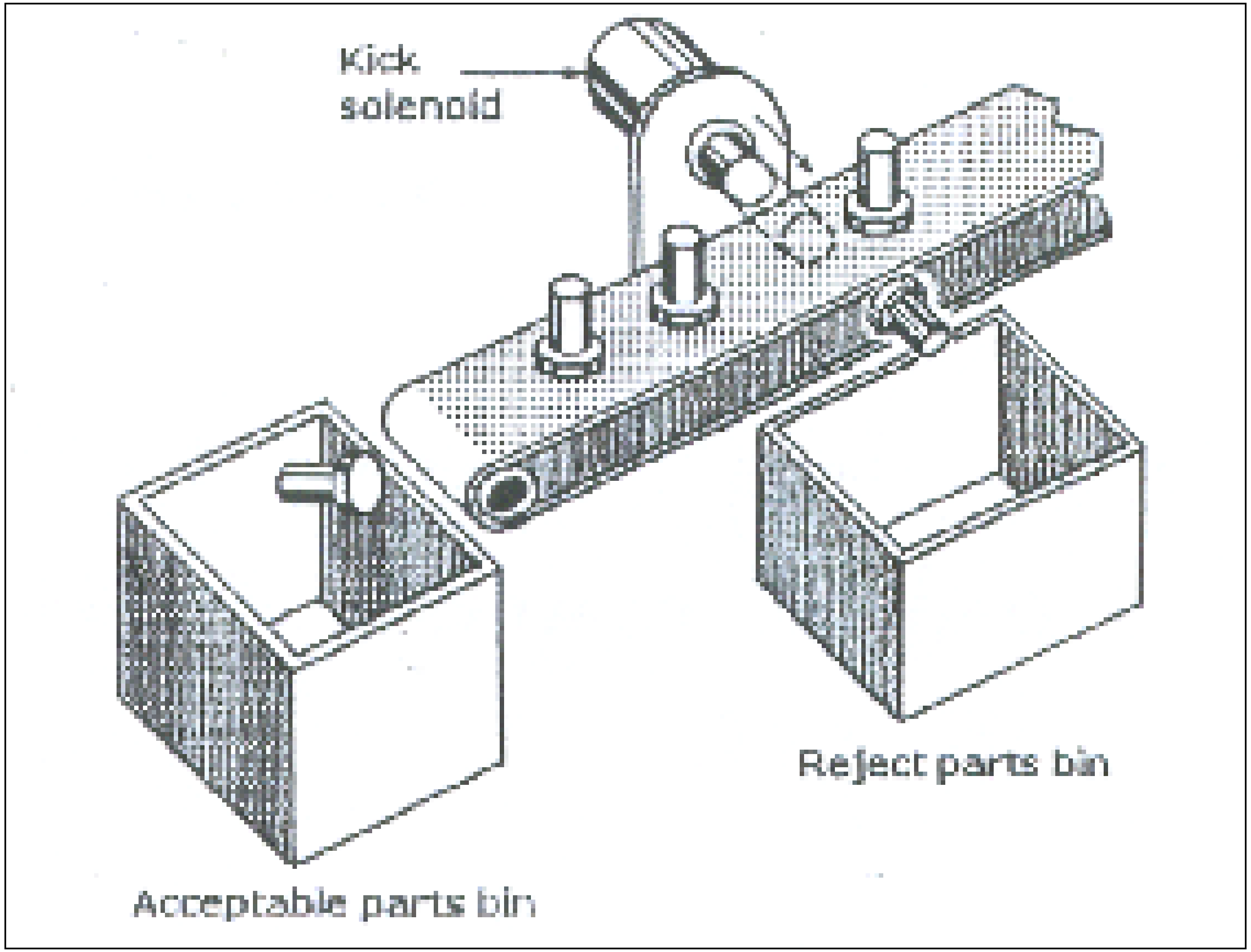
- Electromagnetic flux from the actuator's solenoid interacts with the permanent magnetic field of a neodymium-iron disk magnet attached to the armature but free to rotate. (Attraction vs. Repulsion)



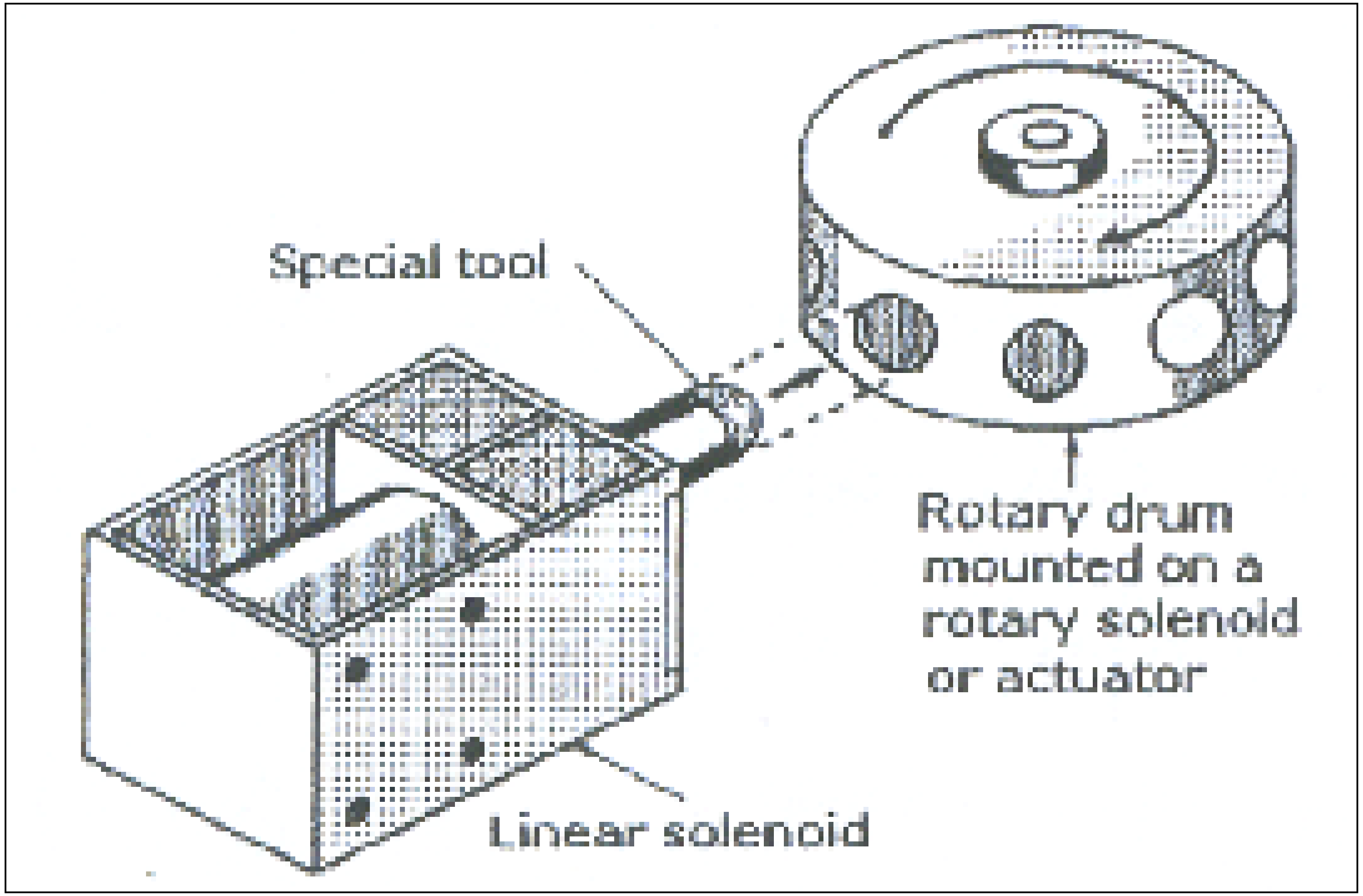
Solenoid Examples: Parts or Material Diversion



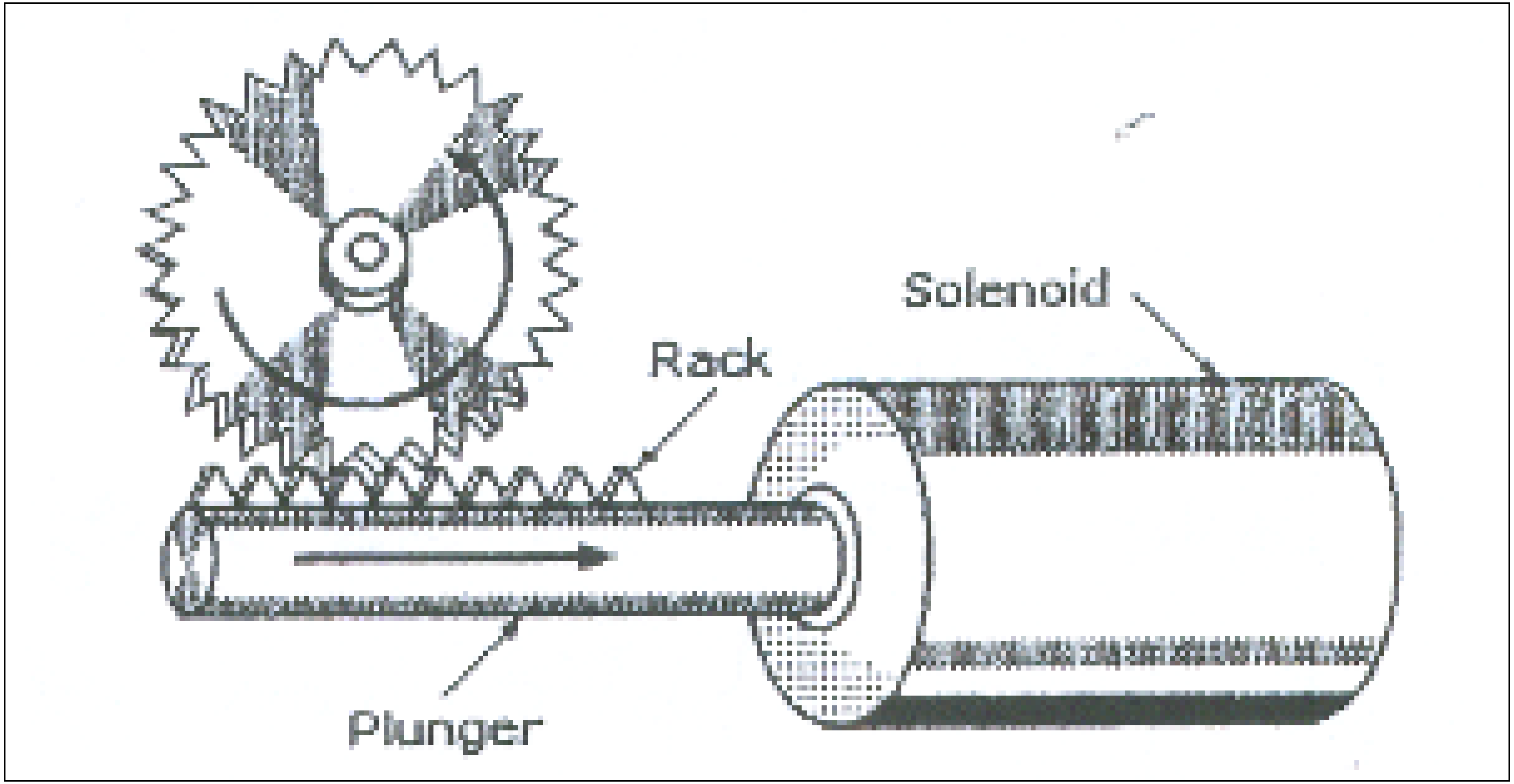
Solenoid Examples: Parts or Material Diversion



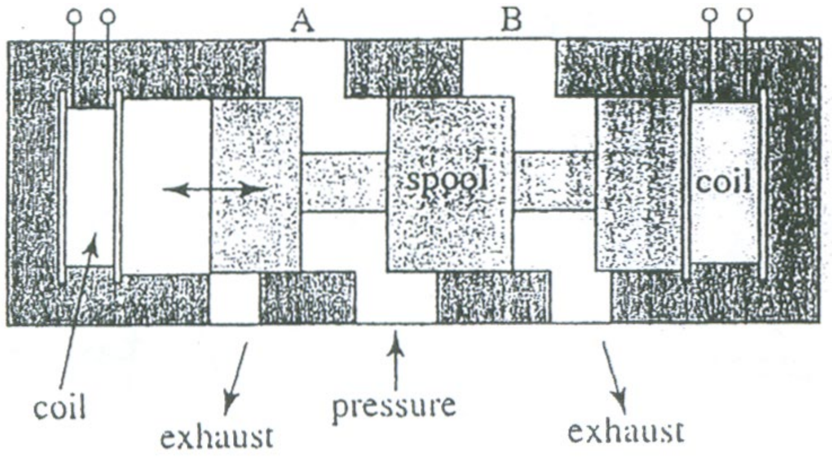
Solenoid Examples: Rotary Position Indexing



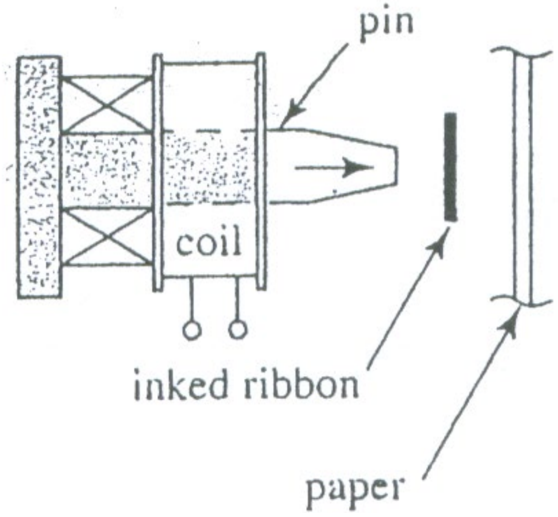
Solenoid Examples: Ratcheting Mechanism



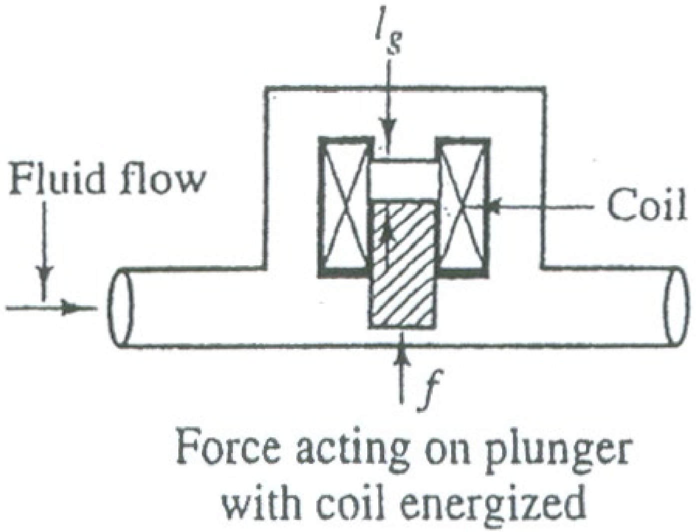
Solenoid Examples: Valve



Solenoid operated valve



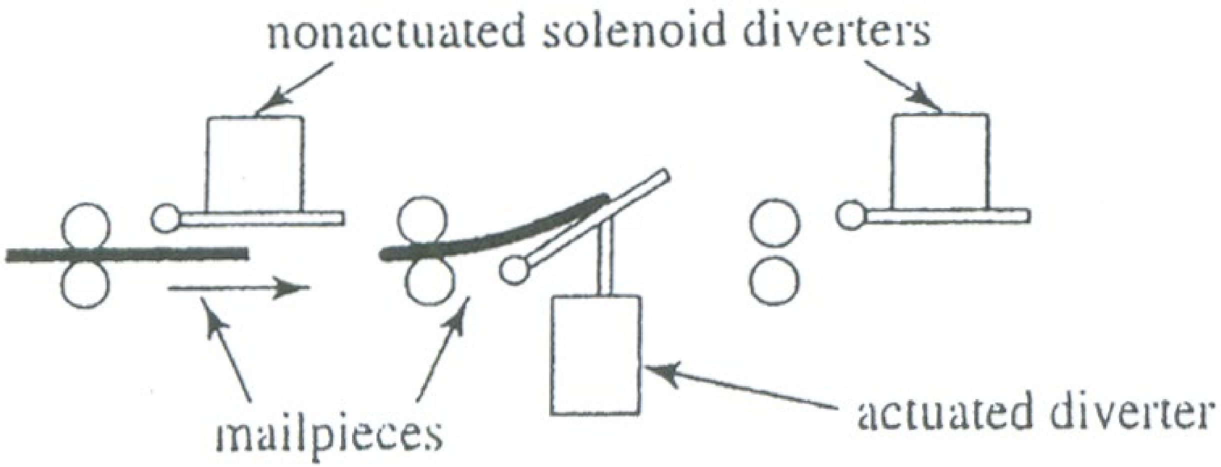
Printer pin solenoid



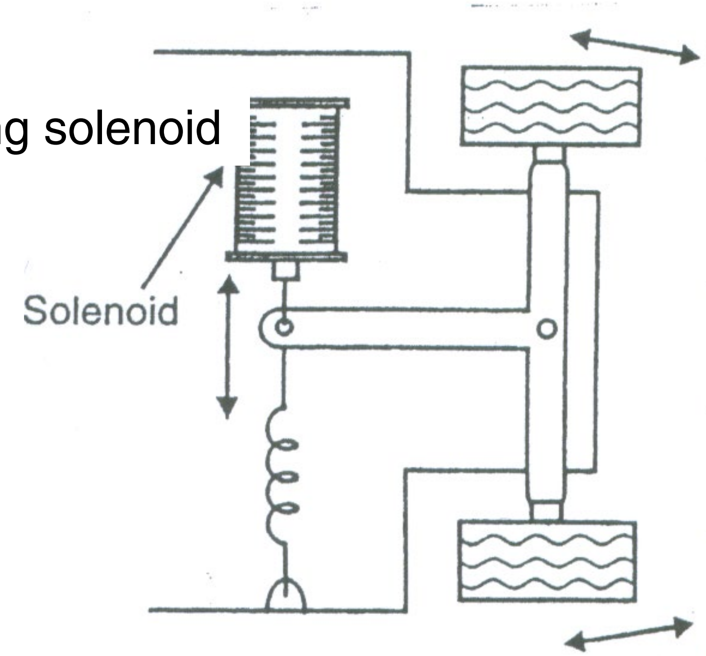
Solenoid valve

Solenoid Examples: Mail Diverter and Robot Steering

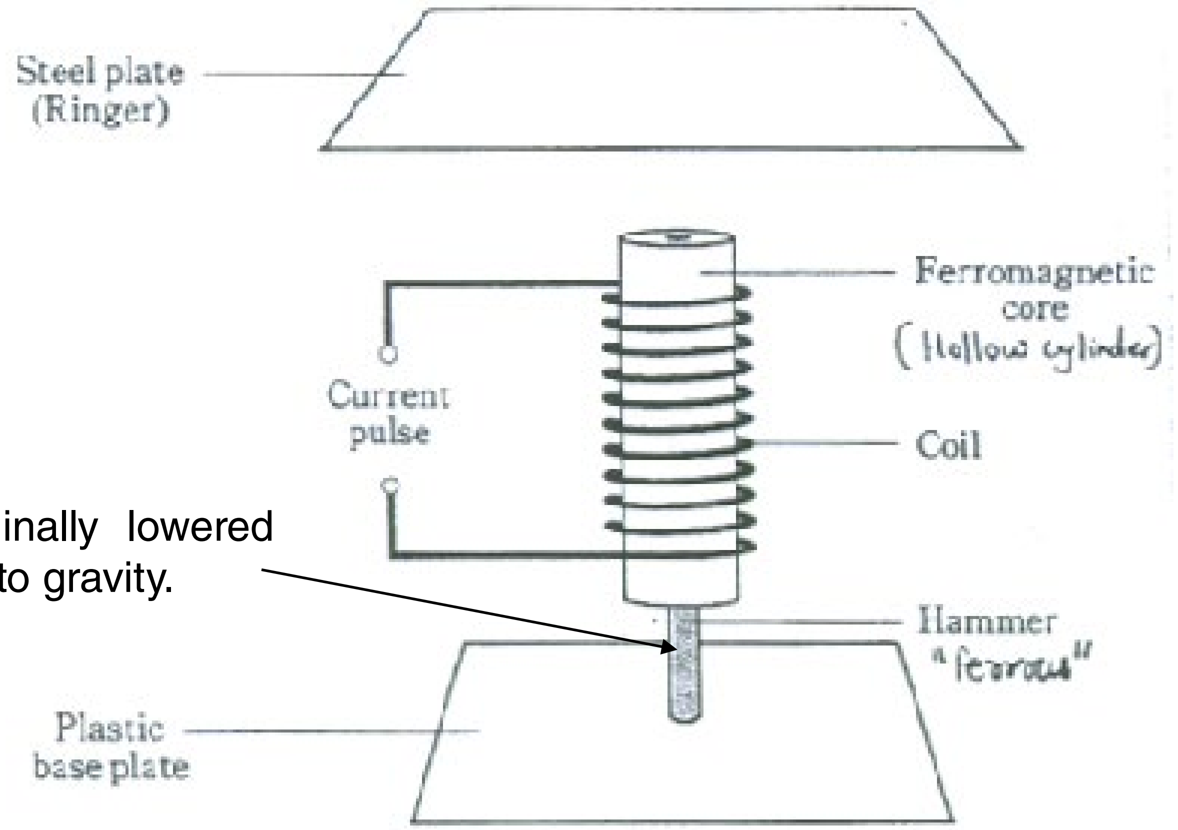
Mail diverter



Robot steering control using solenoid



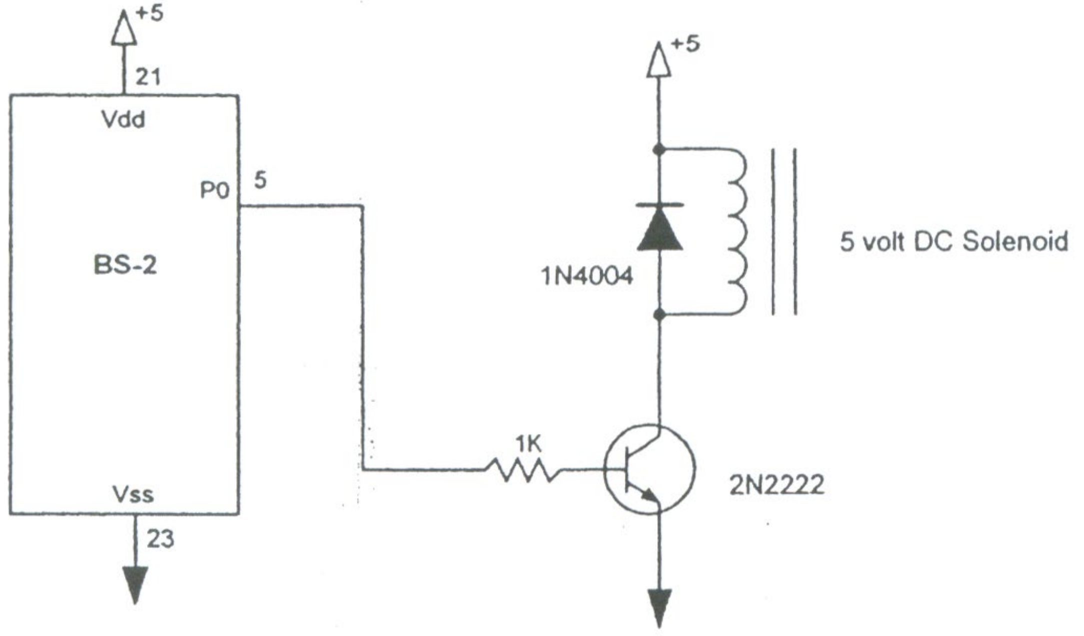
Solenoid Example: Door bell



Nominally lowered
due to gravity.

Interfacing Solenoids with BS2

- NPN BJT switches a low voltage solenoid.
- Diode protects BS2 from the voltage spike created by collapsing magnetic field.



A simple NPN transistor solenoid driver circuit

Interfacing Solenoids with BS2

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

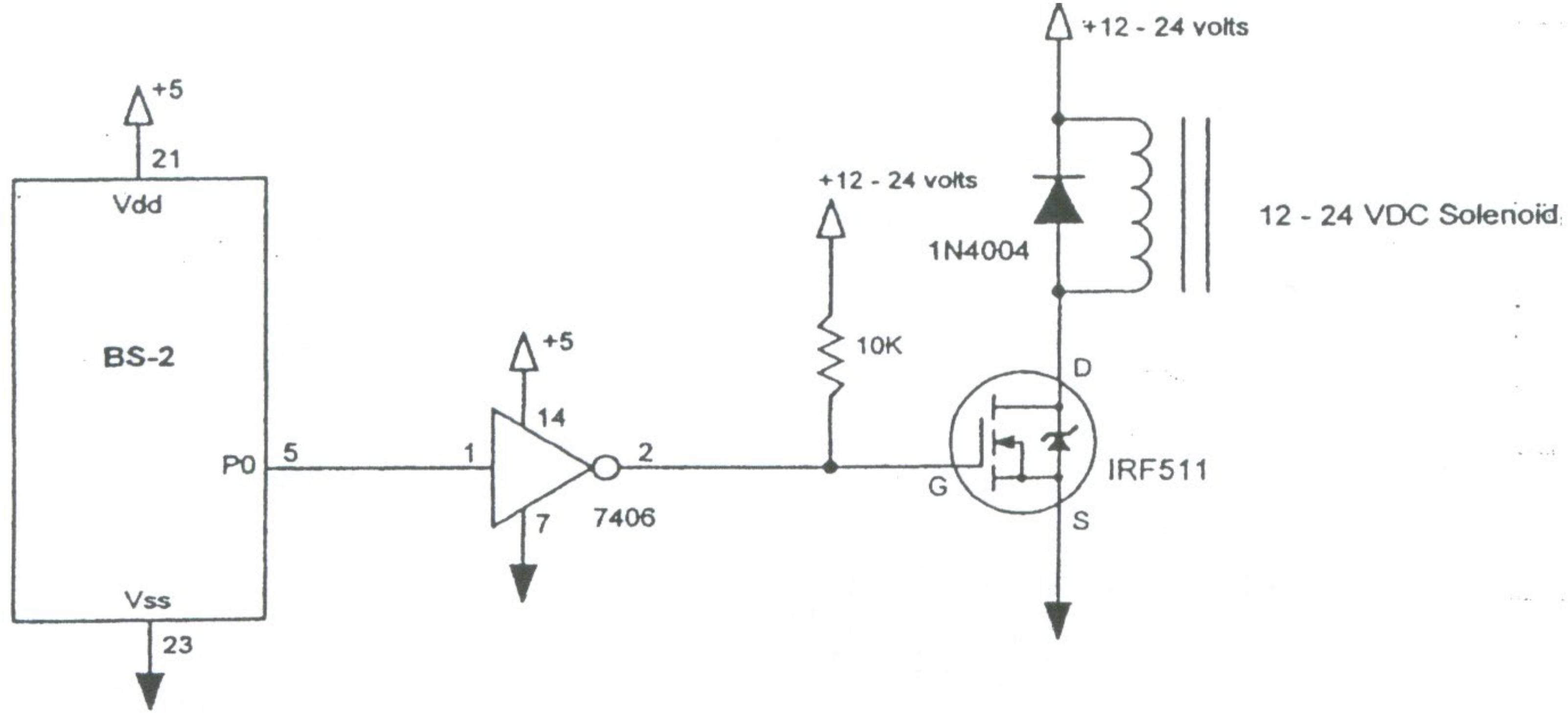
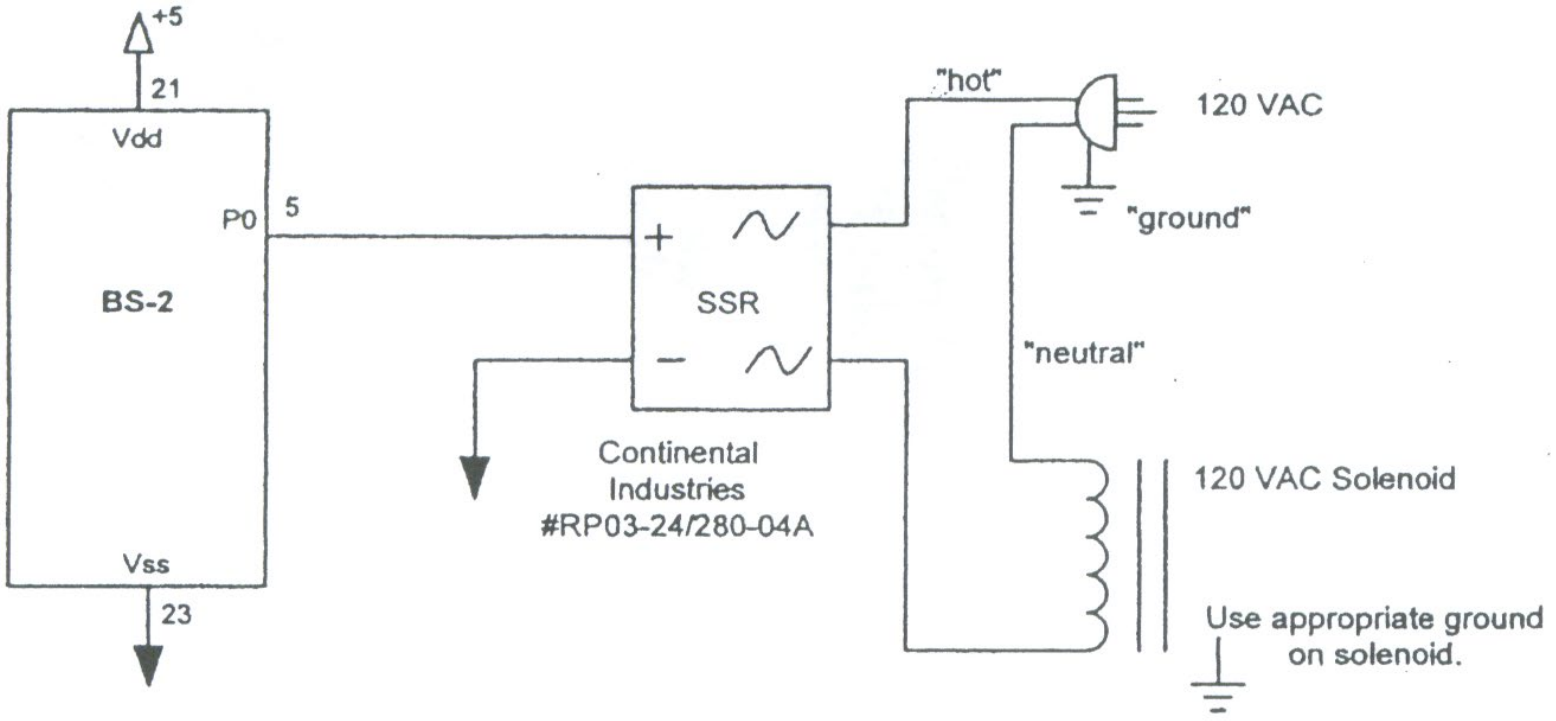


Figure
Driving a high current solenoid

Interfacing Solenoids with BS2

- A SSR and an 120VAC solenoid is used for high-power application



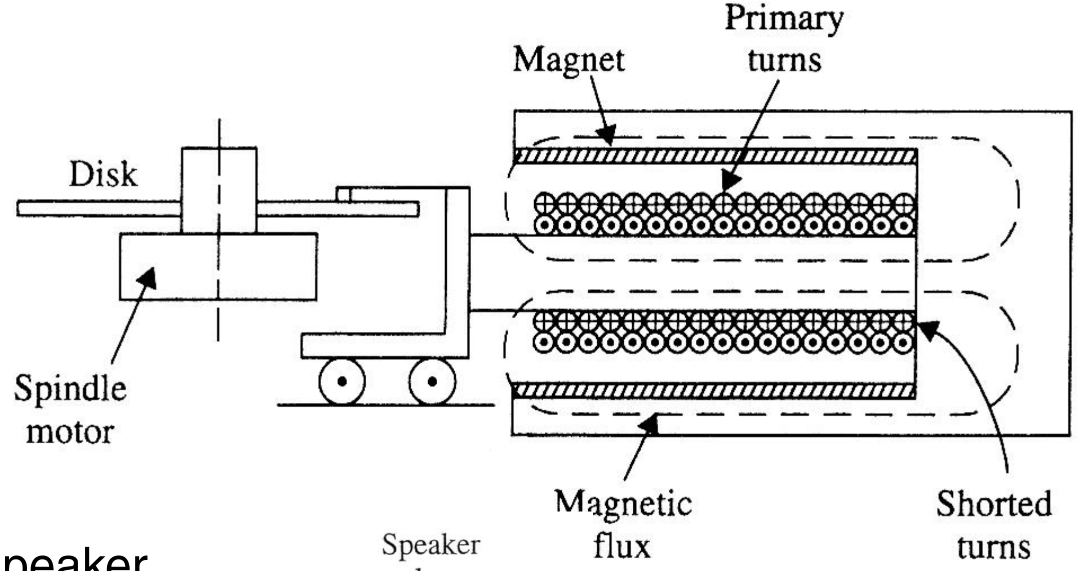
Driving a 120VAC solenoid

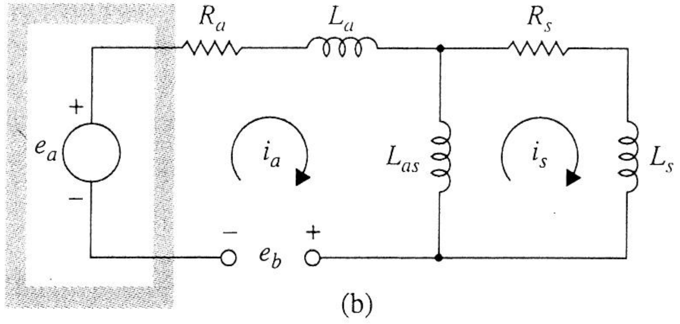
Solenoid Summary

- Most common solenoid types:
  - **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.** 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.

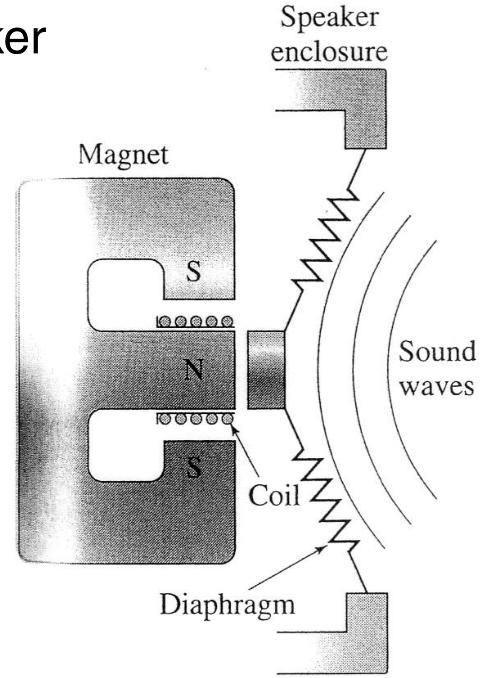
Beyond On/Off Solenoids

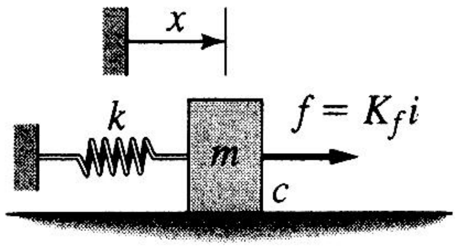
Read/Write Head

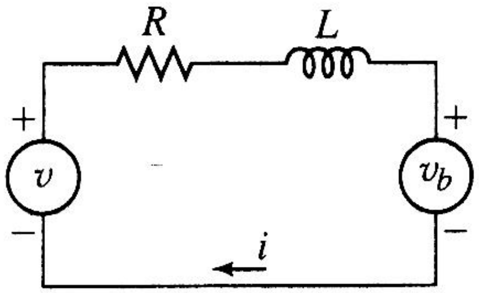




Speaker

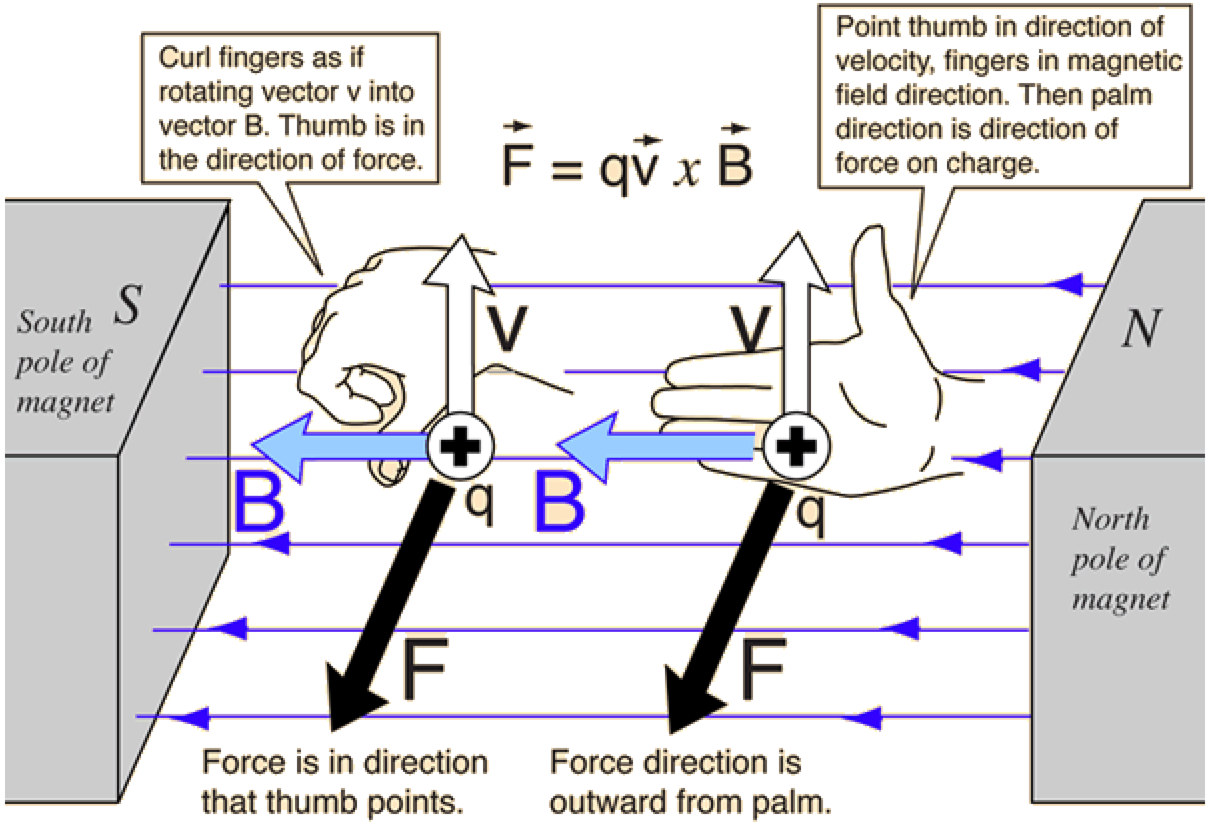


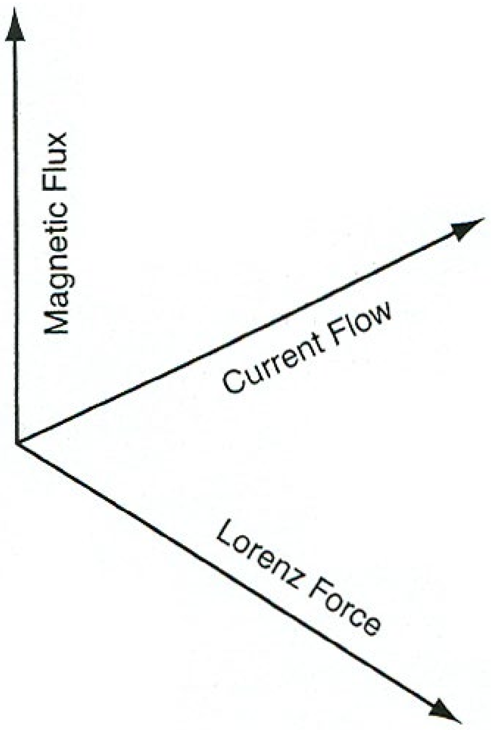




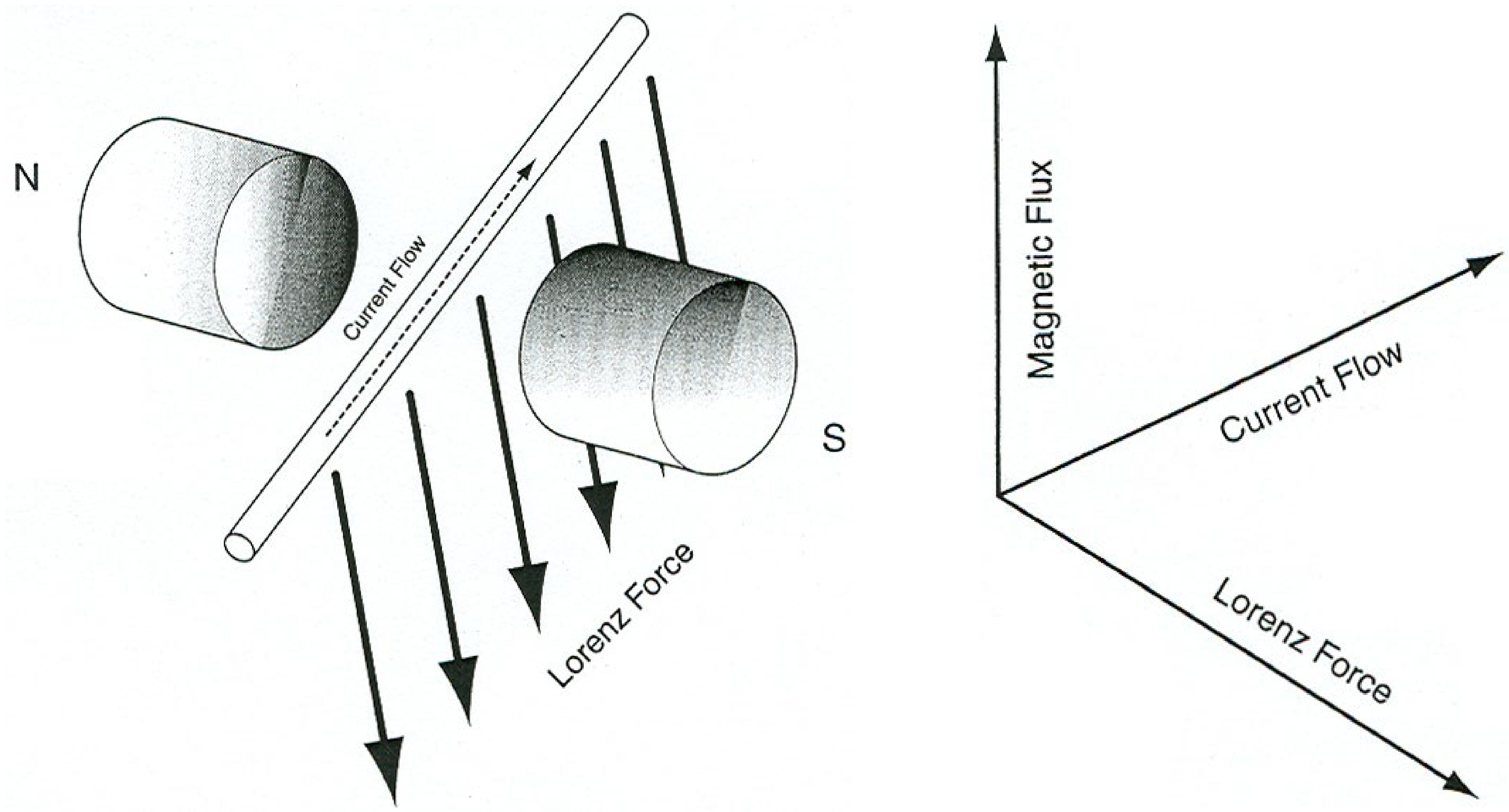
Lorenz Force

- Right-hand rule



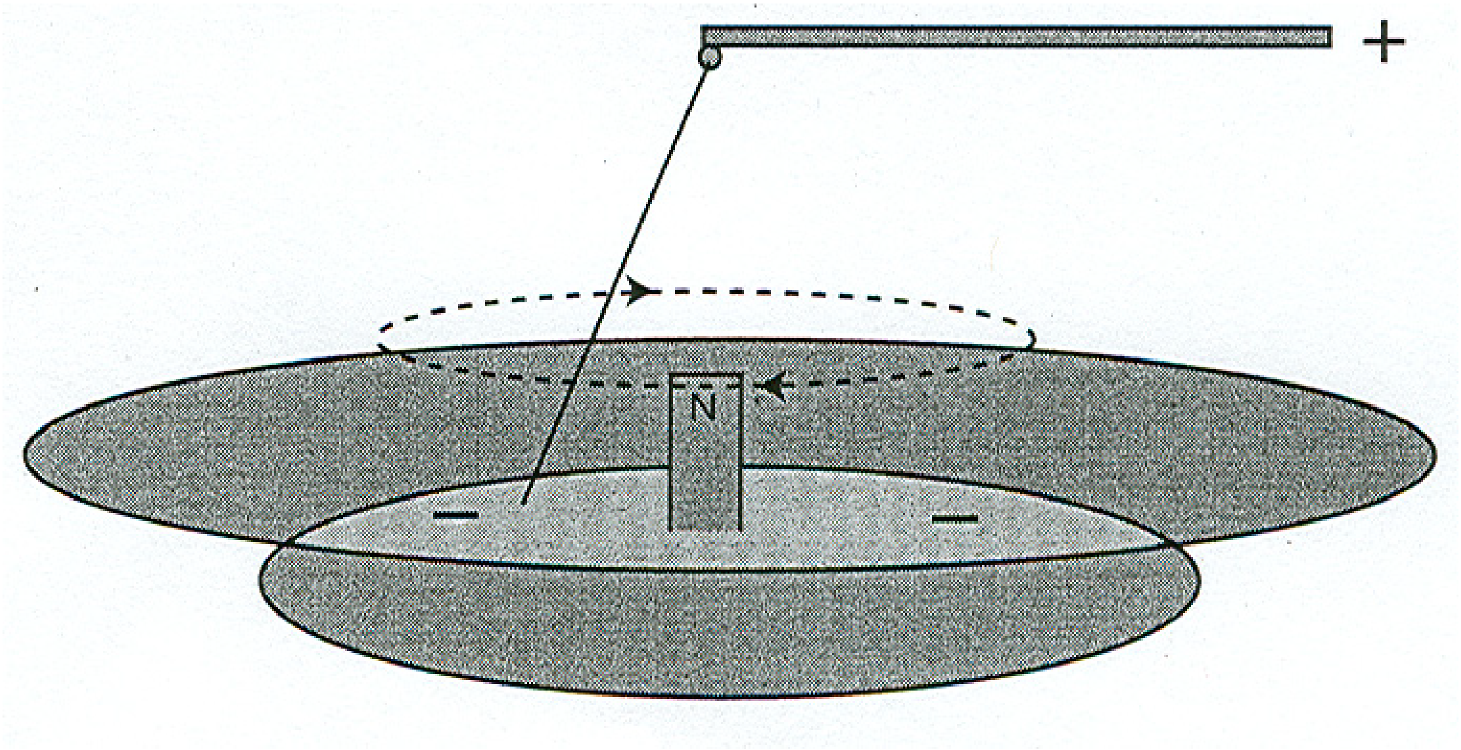


Force on a current-carrying wire

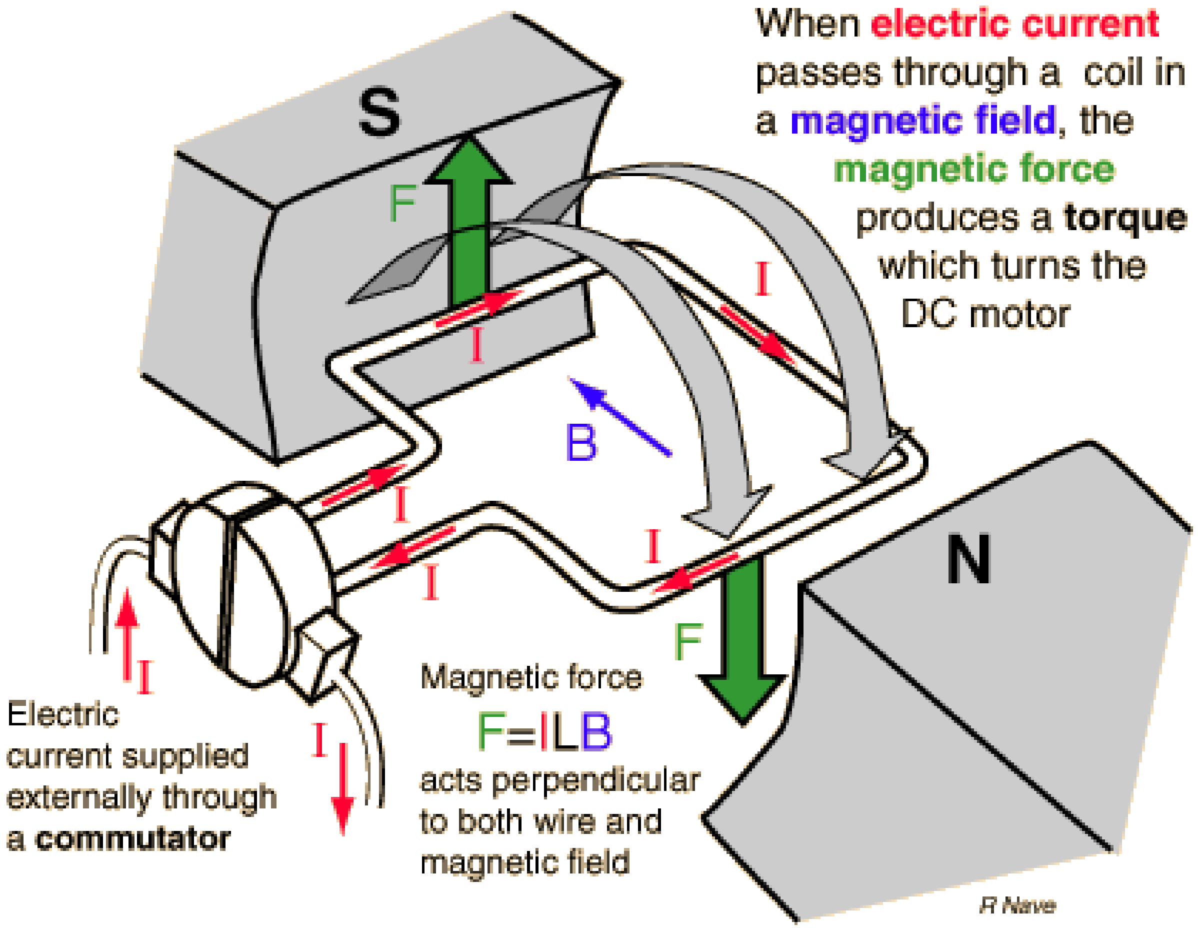


DC Motors: Faraday's Motor (1821)

- Wire spins around a pool of mercury (conductive)



DC Motors: Split-ring Commutator



DC Motors

- Simple two-lead, electrically controlled devices.
  - Comes with a rotary shaft on which gears, wheels, pro
    mounted.
  - Produce significant angular velocity for their size.
- Direction:
  - Direction of rotation of a motor depends on the direction of current flow through it.
  - Reversing motor connections reverses rotation direction
- Yield little torque and allow minimum position control at low speeds.

DC Motors

- Available in many different shapes and sizes.
- Rotational speed range (5000-8000 rpm)
  - Gear train or other mechanism can be used to obtain specific angular velocity
- Voltage limits:
  - 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: Speed + Torque, Voltage + Current

- **Speed** depends on operating conditions (applied voltage and applied load)
  - No load or constant load condition: **no-load speed** increases with voltage.
  - Constant voltage input: speed decreases with increasing load.
  - Most efficiently controlled by pulse-width modulation (PWM).
- **Torque rating** (lb-ft, g-cm, or oz-in): amount of force a motor can exert on a load.
  - **Stall torque:** maximum torque a motor can apply (motor is stalled by a load at given voltage)
- **Current** drawn by motor depends on operating conditions
  - No load: motor draws little current
  - As load increases, the current 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 Motor

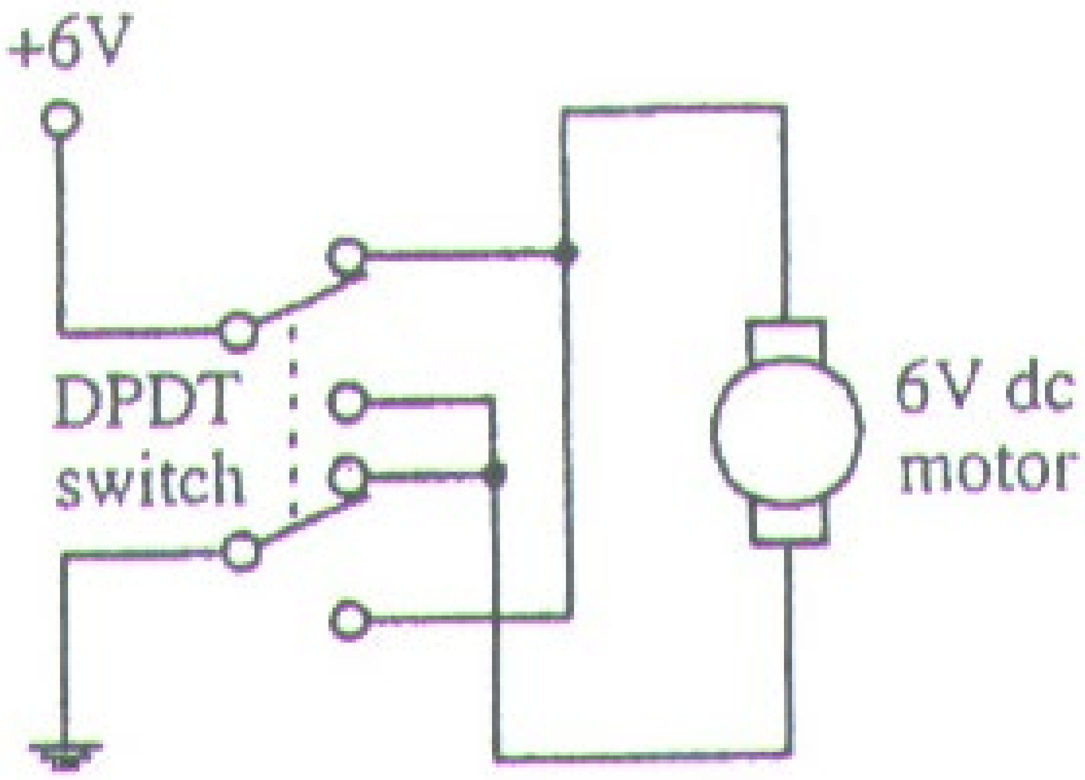
- Like relays and solenoids, DC motors can also produce reverse voltage spikes when voltage applied across motor coil is removed.
- Inductive kickback can damage sensitive **motor drive** circuitry (e.g., BS2-based driver)
  - Important to use a separate power source to drive motor and use diodes to prevent damage due to reverse spike

DC Motor: Drive Circuit

- Some **motor drive circuit** or **driver** is needed for basic control:
  - On/off
  - Rotation in both directions
  - Speed control

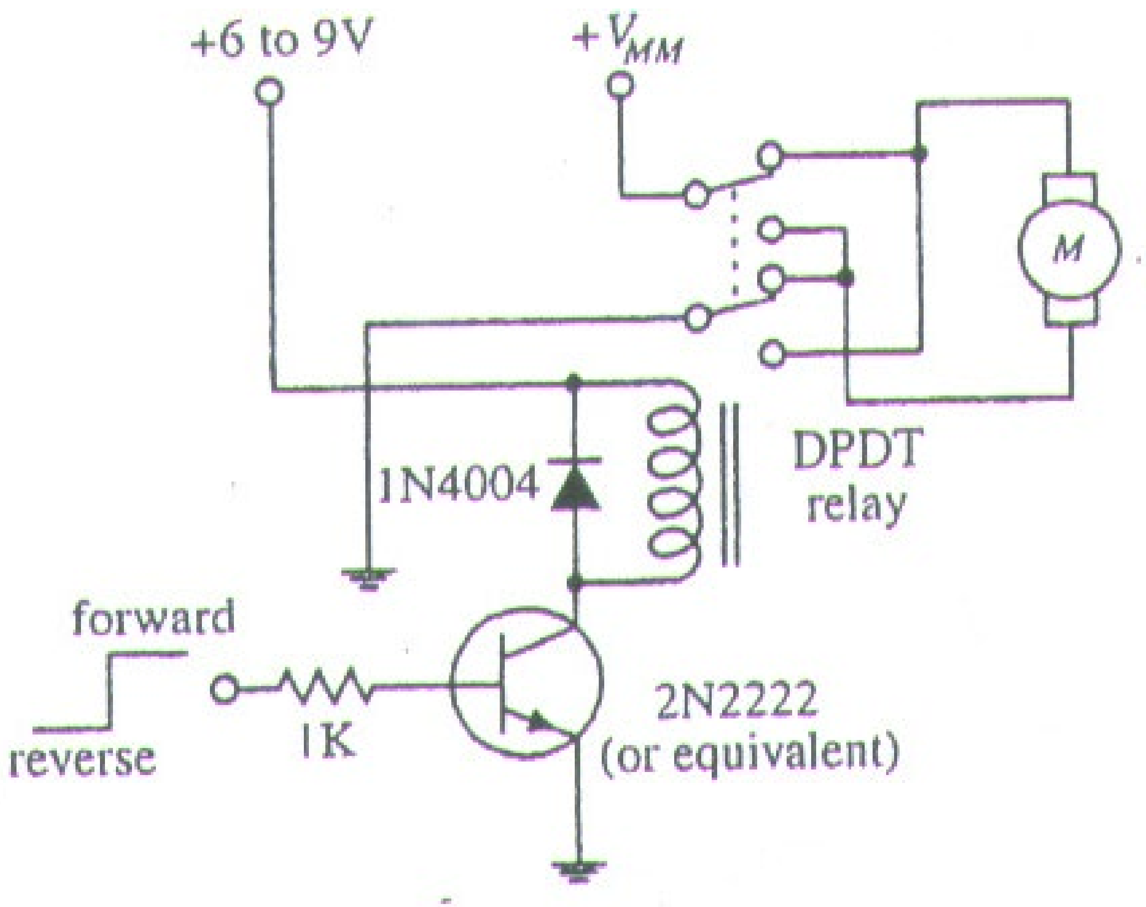
DC Motor: Bi-directional Drive Circuit

- Manual control only
  - Can also use relays (but they are bulky)



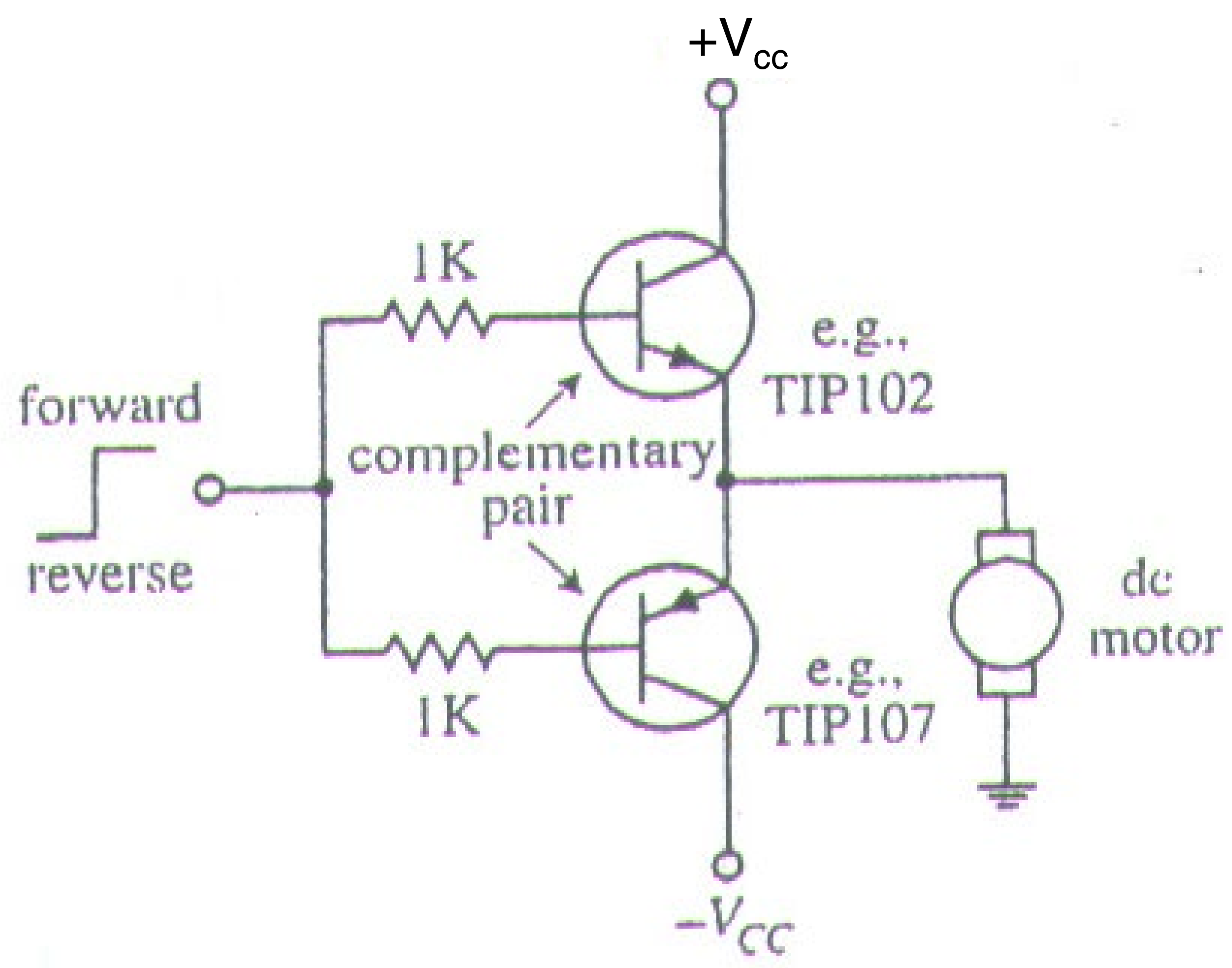
DC Motor: Bi-directional Drive Circuit

- Logic-based control with transistor and relay



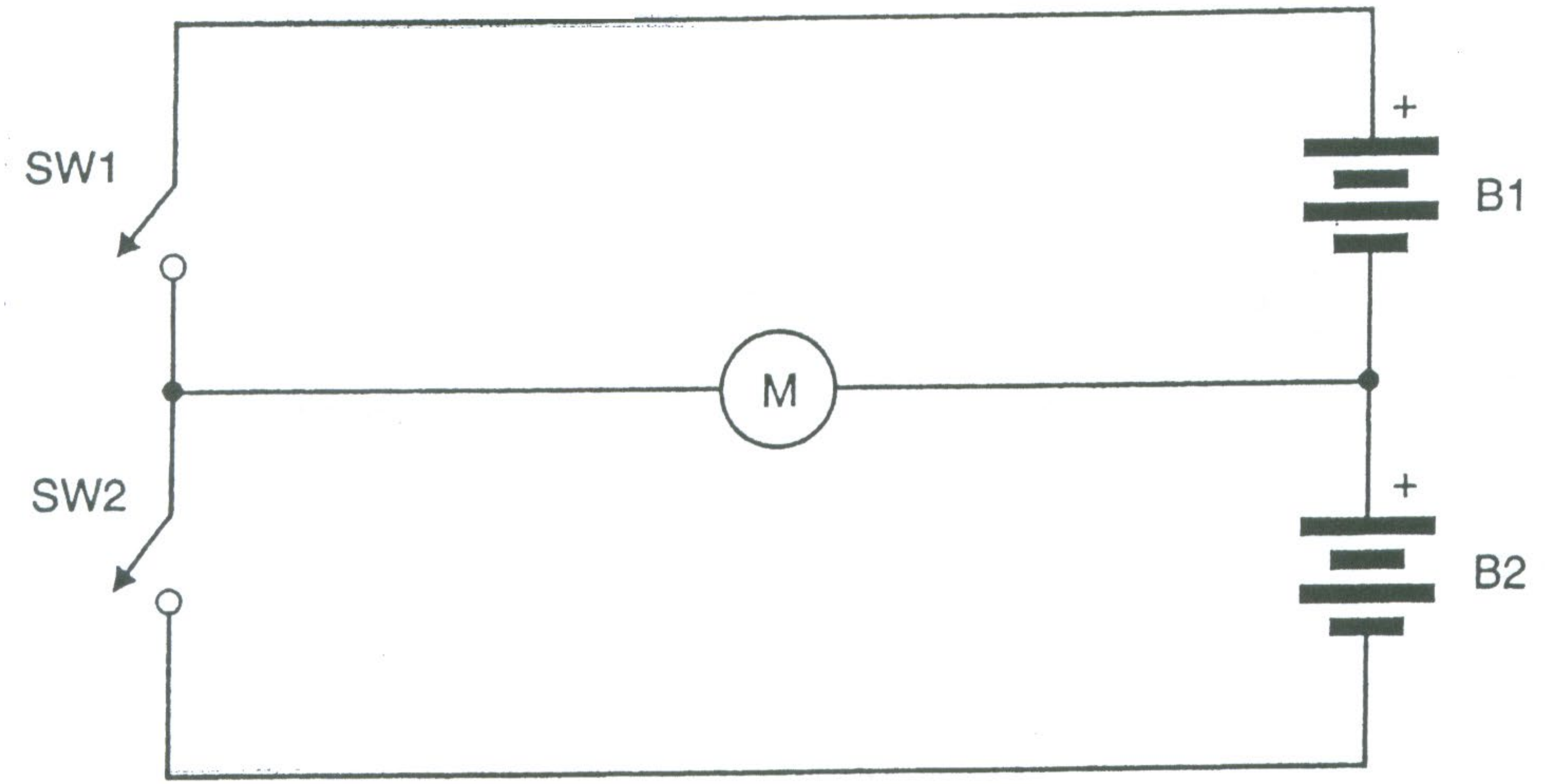
DC Motor: Bi-directional Drive Circuit

- Logic-based control with pair of transistors
- Rotation direction controlled by push-pull transistor circuit
    - Upper transistor: npn power Darlington
    - Lower transistor: pnp power Darlington.



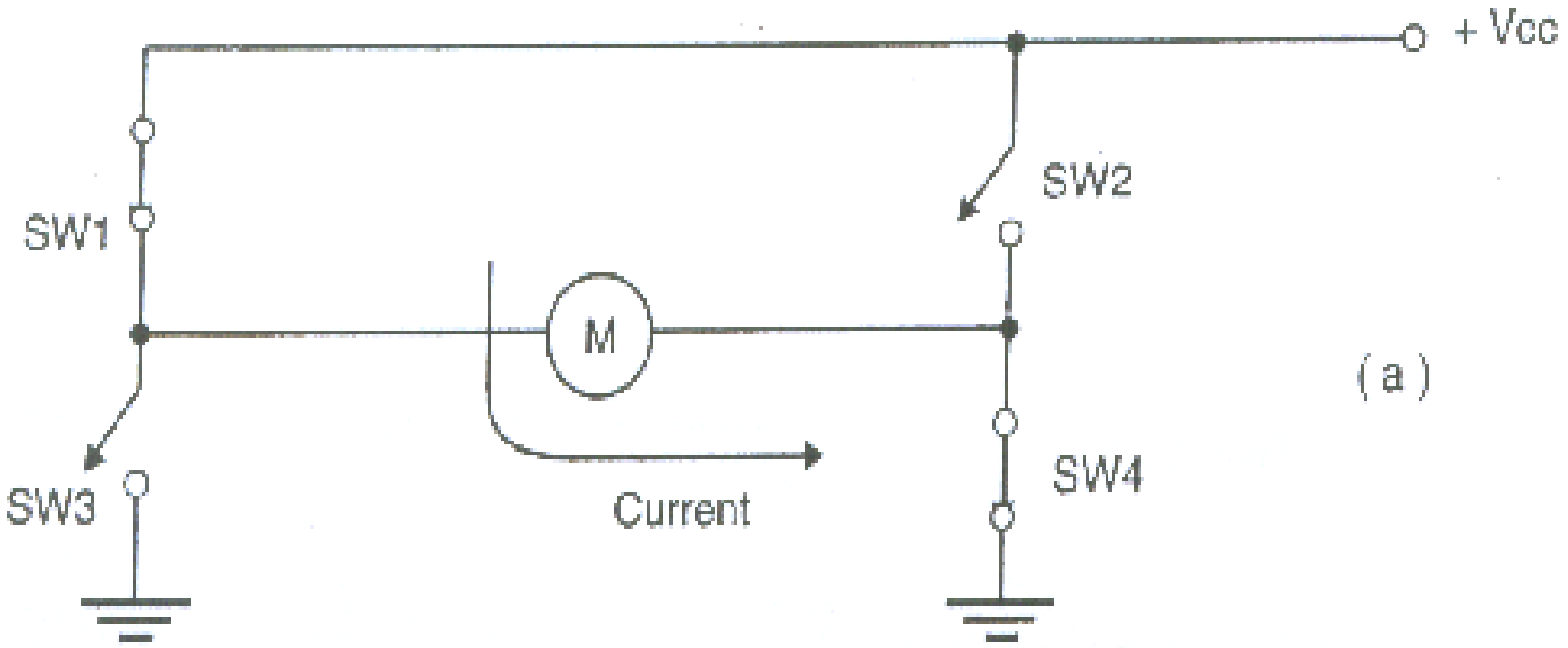
DC Motor: Half Bridge

- Downside of two voltage sources



DC Motor: Full-Bridge (H-Bridge)

- Single voltage source
- Must avoid **shoot-through** (when switches 1, 3 or 2, 4 are closed at the same time)



DC Motor: Full-Bridge (H-Bridge)

- Single voltage source
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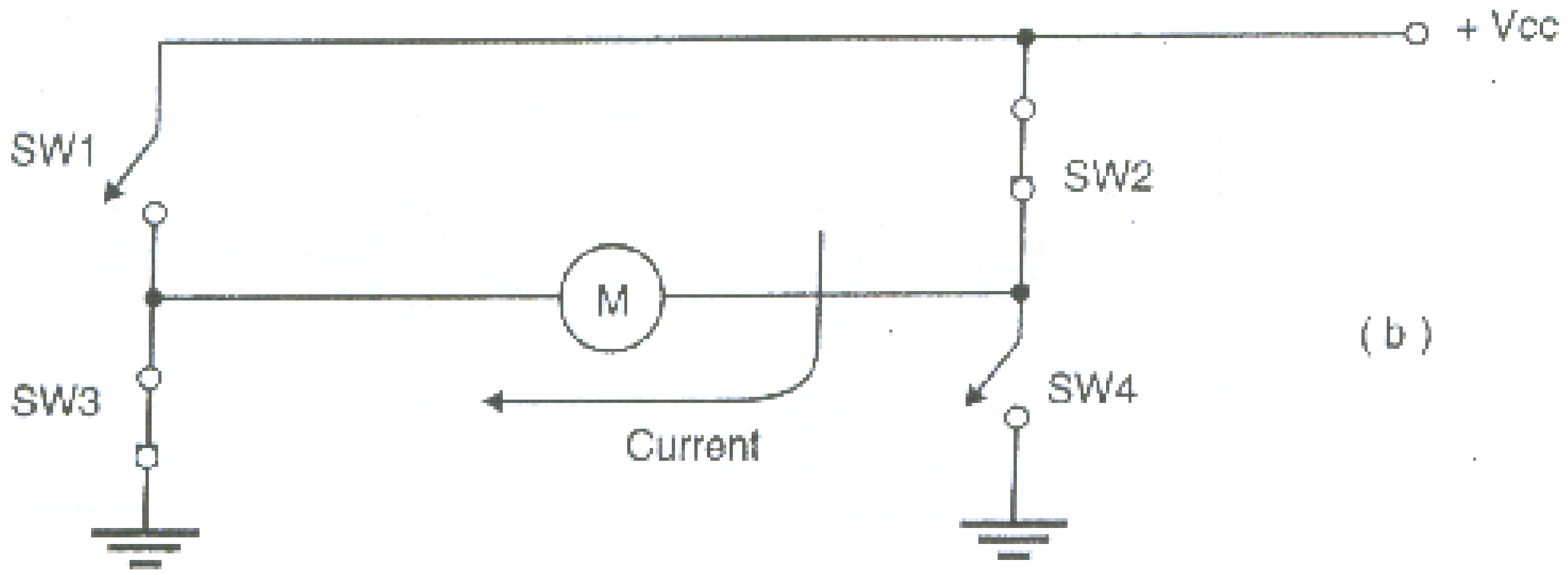

Hands-on Exercises: Digital Input

What's in a Microcontroller? V3.0 Controlling Motion: Activities #1 – #6	Chapter 4