# EEC 417/517
# Embedded Systems
# Cleveland State University

## Lab 8

## Stepper Motor Fundamentals and Control

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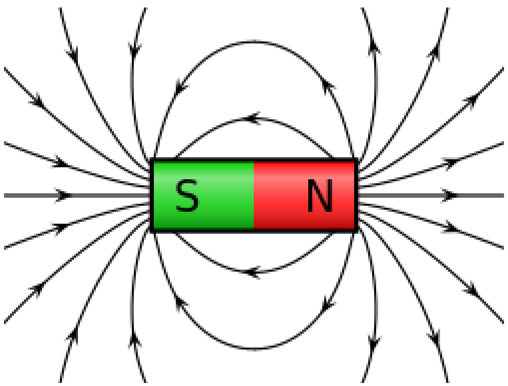
Spring 2018

# Lab 8 Outline

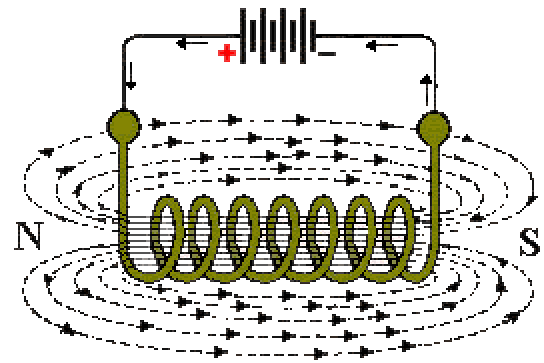
1. **Stepper Motor Fundamentals**
2. Stepper Motor Classifications
3. Full Stepping, Half Stepping, and Micro-stepping
4. Lab 8 Setup

# Stepper Motor Fundamentals

## Pole Convention




Permanent Magnet



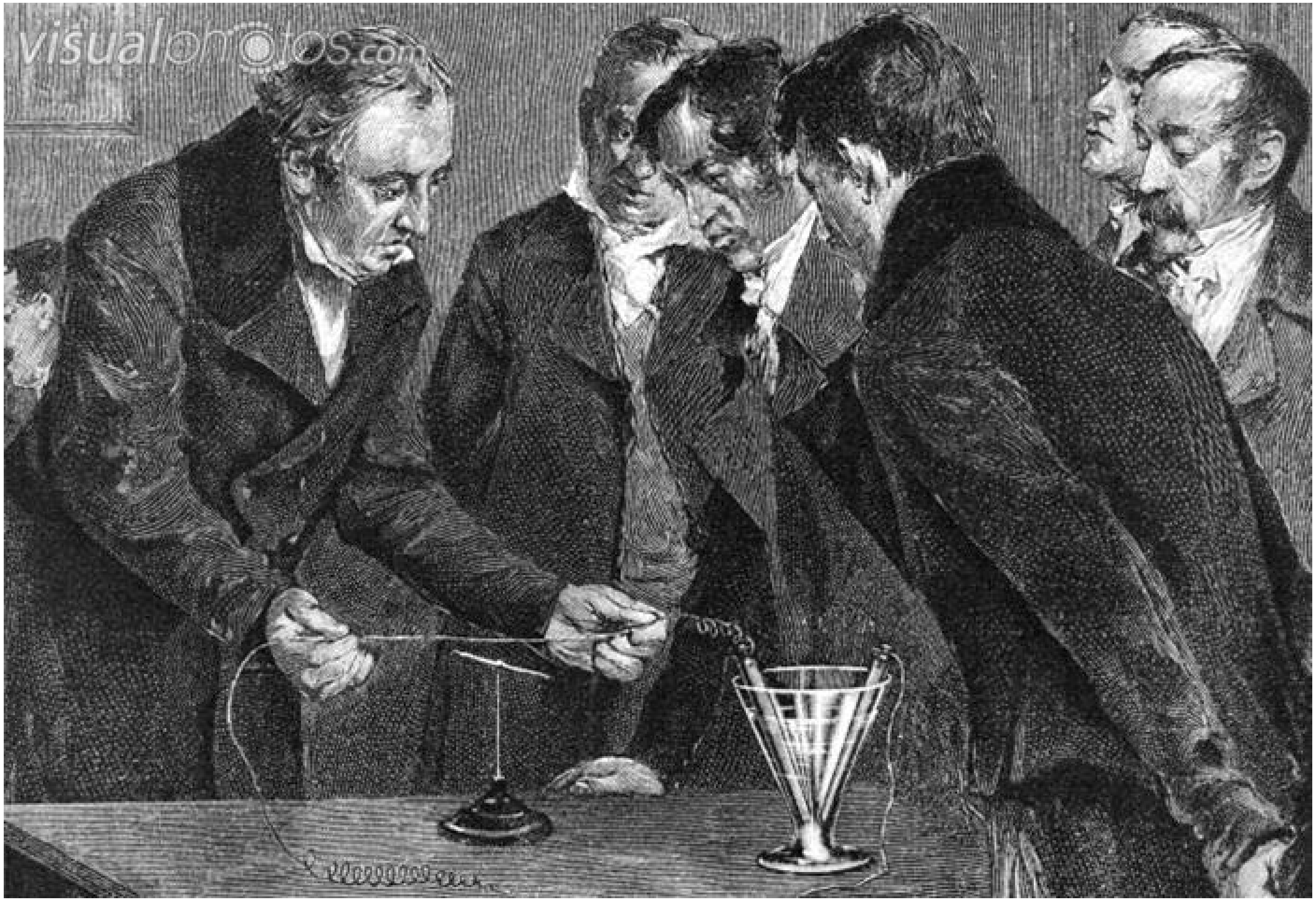

Electromagnet

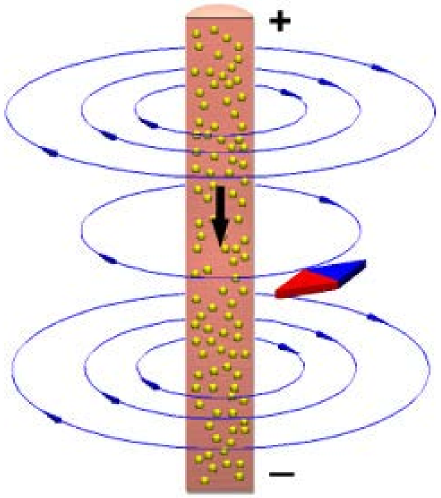
By convention, the north pole of a magnet is the pole where the magnetic field (**B**-field) lines or lines of force **exit** the magnet.

# Stepper Motor Fundamentals

## Electromagnetism

**1820**: Hans Christian Oersted (1777 – 1851) showed that an electric current produces a magnetic field.





# Stepper Motor Fundamentals

## Electromagnetism

**1820**: Biot-Savart Law

Mathematical formula for computing the strength of a magnetic field at a point ***P*** produced by a current ***I*** in a wire

Differential Form

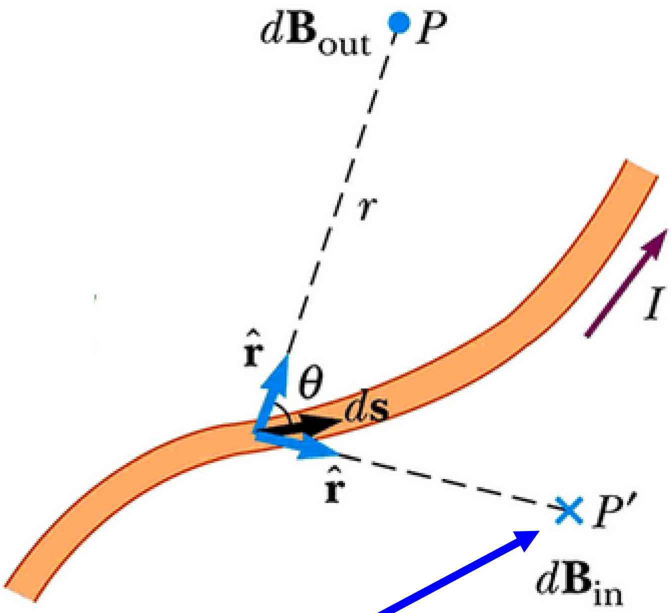
$$\boxed{d\mathbf{B} = \frac{\mu_0 I}{4\pi}\frac{d\mathbf{s}\times\hat{\mathbf{r}}}{r^2}}$$

Line Integral Form

$$\boxed{\mathbf{B} = \frac{\mu_0 I}{4\pi}\int_C \frac{d\mathbf{s}\times\hat{\mathbf{r}}}{r^2}}$$

where $\mu_0$ is the permeability of free space.

Jean-Baptiste Biot (1774–1862)
Felix Savart (1791–1841)




A different point

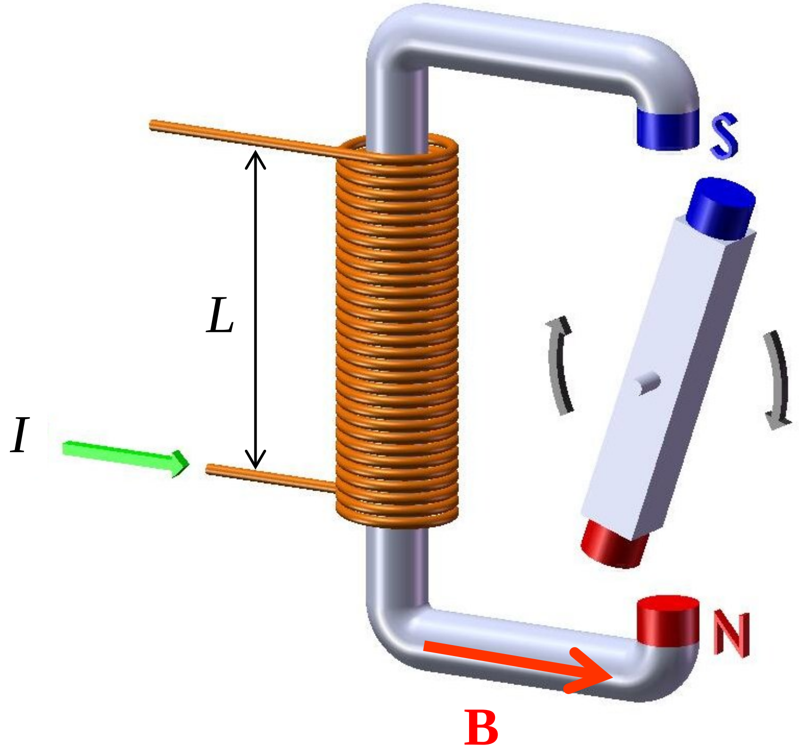
# Stepper Motor Fundamentals

## Electromagnetism

**1826**: Ampere's Law (André-Marie Ampère, 1775 – 1836)

From Ampere's Law, we get the formula for computing the strength of a magnetic field produced by a coil.

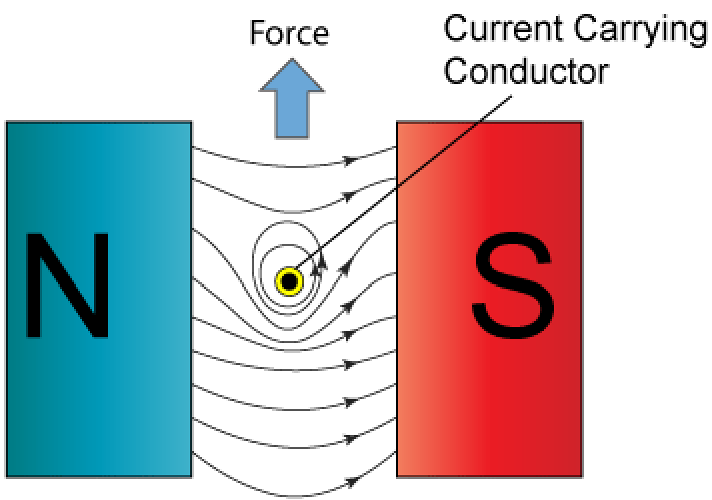
$$\boxed{B = \frac{\mu N I}{L}}$$



# Stepper Motor Fundamentals

## Magnetic Force on a Current

**1830's**: Michael Faraday (1791 – 1867) described the force on a current in terms of **lines of force**.

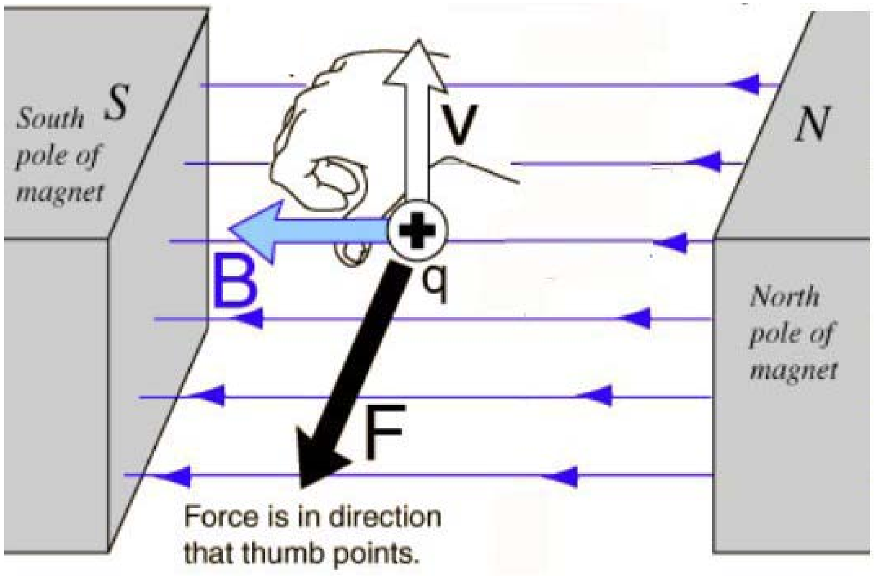



Catapult Field

1. Compression of the lines of force below the conductor produces on upward force on the conductor.
2. This is the basic principle of an electric motor.
3. The distorted magnetic field is called a **catapult** field.
4. First electric motor usually attributed to Faraday.

# Stepper Motor Fundamentals

## Magnetic Force on a Current




**1881**: J. J. Thomson (1856 – 1940)

**1886**: Oliver Heaviside (1850 – 1925 )

**1892**: Hendrik Lorentz (1853 – 1928)

Together derived the mathematical formula for the magnetic force on a moving charge:

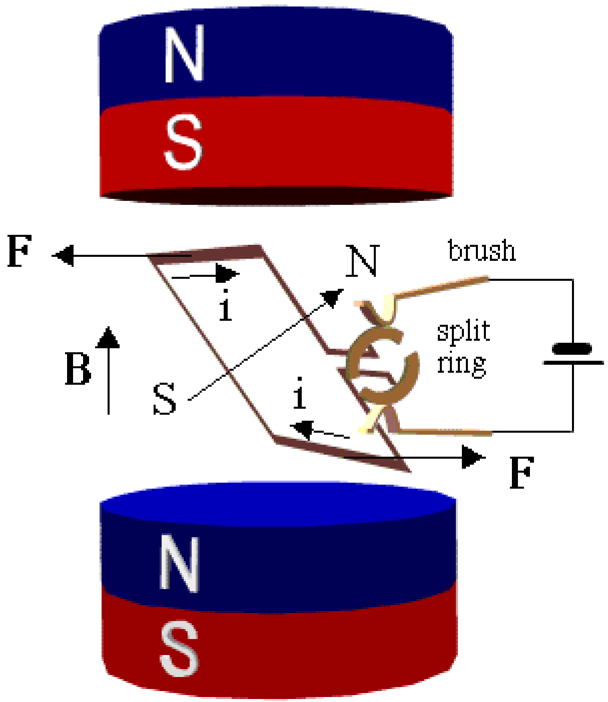
$$\mathbf{F} = q\mathbf{v} \times \mathbf{B}$$

This is the **Lorentz Force Equation**.

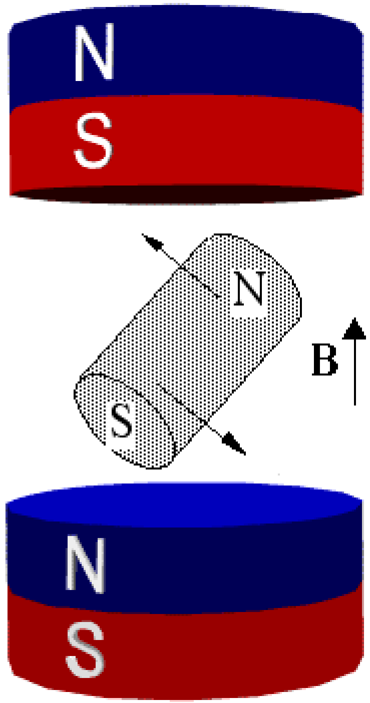
It is the fundamental principle of motor operation.

# Stepper Motor Fundamentals

## Motor Torque




Torque on Loop



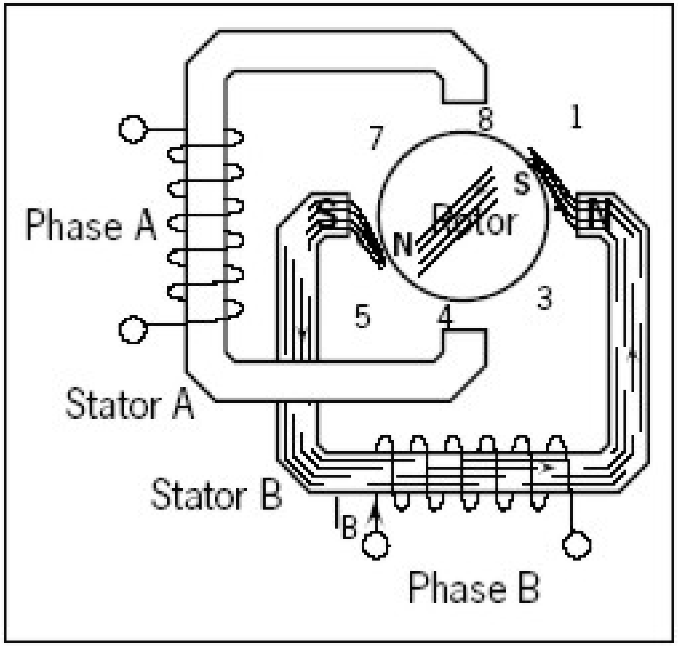

Torque on Permanent Magnet

Left: The current loop can be viewed as a magnetic dipole as indicated by the arrow SN. Right: The magnetic dipole is represented as a permanent magnet with the same torque (North attracts South).

# Stepper Motor Fundamentals

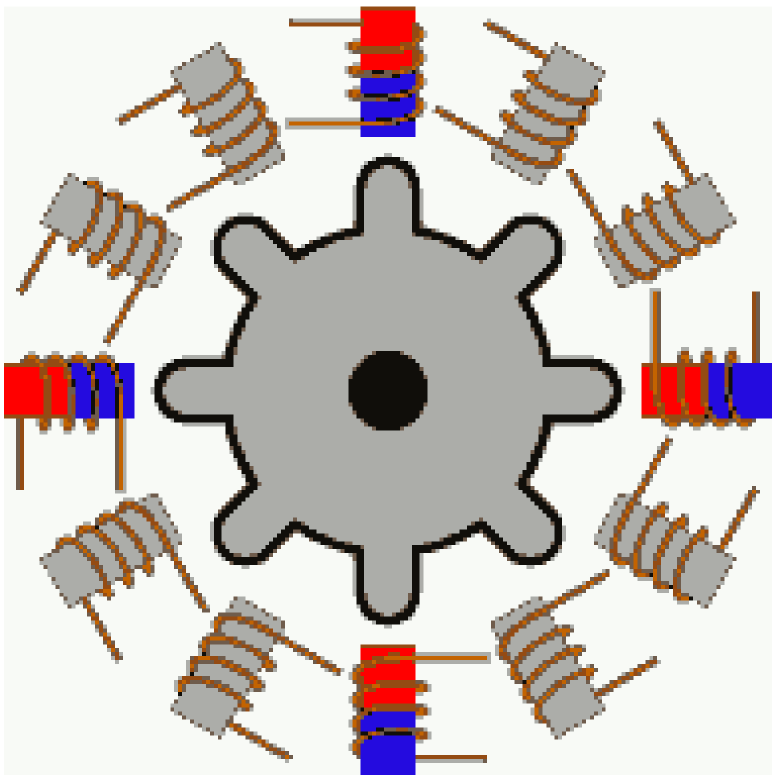
## Motor Torque

1. Faraday's view: Lines of force (flux) or field lines.
2. In rotor position shown, lines of force are "stretched" and "compressed."
3. Rotor will turn to minimize this effect.
4. In magnetic circuits terminology, this stretching and compressing results in increased magnetic resistance or reluctance.
5. Rotor will turn to minimize the reluctance.



# Stepper Motor Fundamentals

What is a stepper motor ?



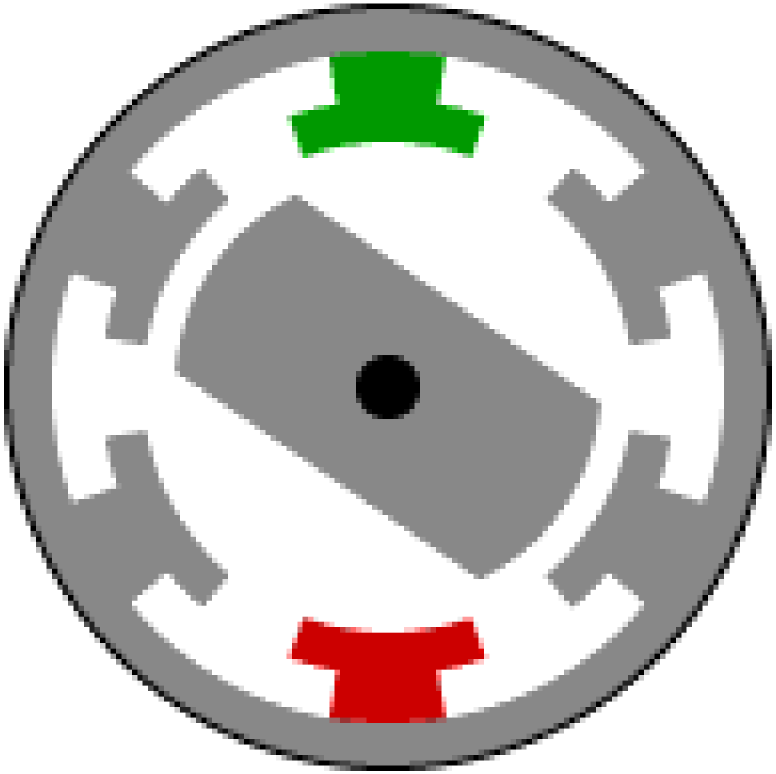
Stepper motors are devices that do not rotate continuously but move in precise steps.

At low speed, low inertia gives "step" motion.

Many different kinds.

(animation: must view in Slide Show mode)
http://pcbheaven.com/wikipages/How_Stepper_Motors_Work/?p=1

# Stepper Motor Fundamentals



(animation)

At higher speed and/or higher inertia, motion appears continuous.

# Stepper Motor Fundamentals

# Lab 8 Outline

1. Stepper Motor Fundamentals
2. **Stepper Motor Classifications**
3. Full Stepping, Half Stepping, and Micro-stepping
4. Lab 8 Setup

# Stepper Motor Classifications

Three basic types of stepper motor:

1. Variable Reluctance
2. Permanent Magnet
3. Hybrid

# Stepper Motor Classifications

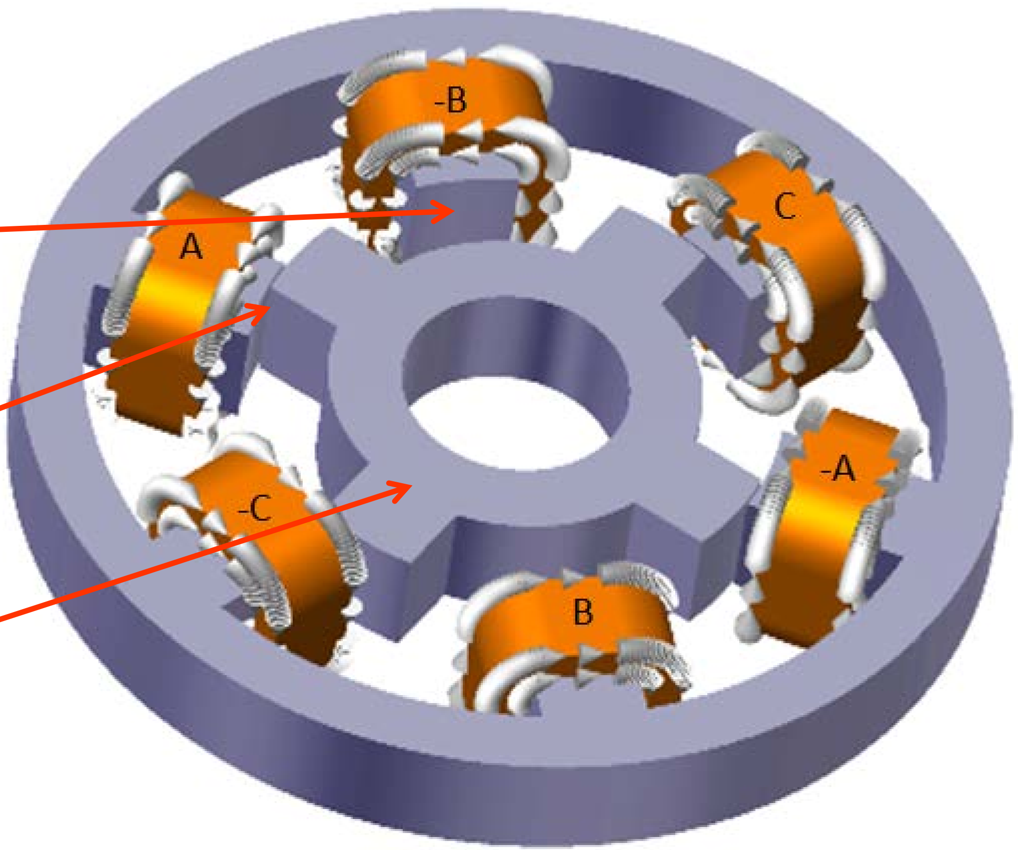
## Variable Reluctance Motor

Reluctance of the rotor varies because of geometric shape.

High reluctance gap

Low reluctance gap

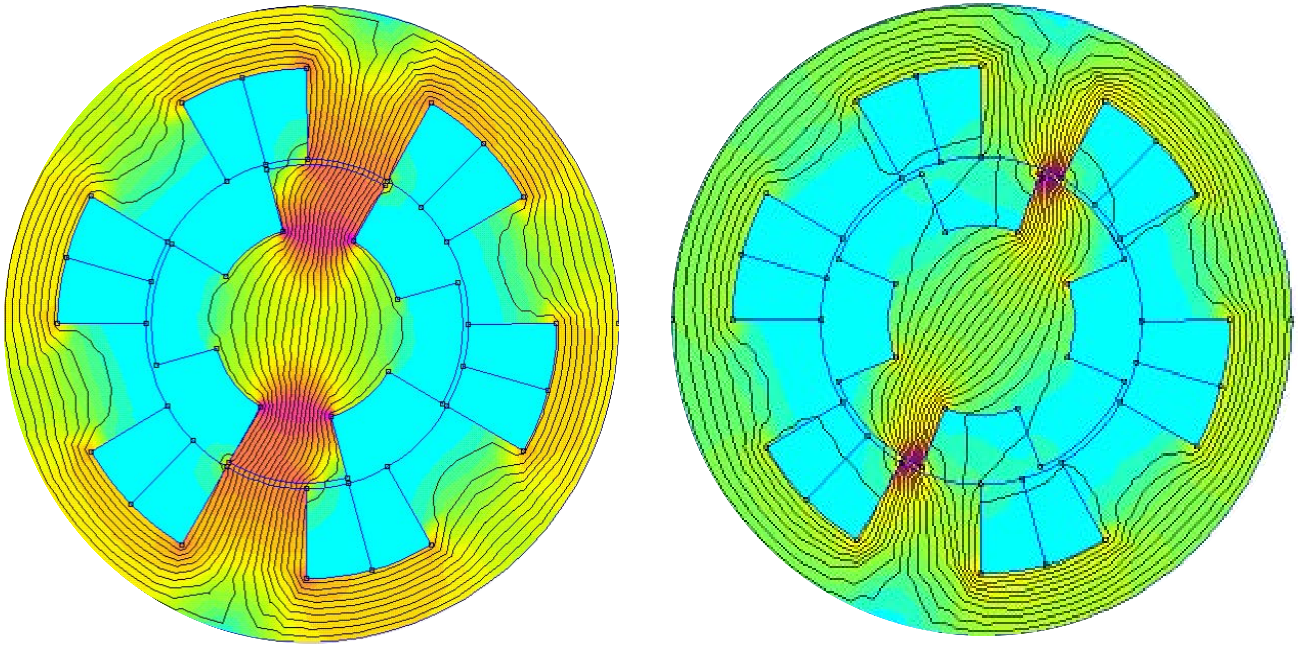
Ferromagnetic Rotor




Rotor will turn in a manner to reduce reluctance.

# Stepper Motor Classifications

## Variable Reluctance Motor

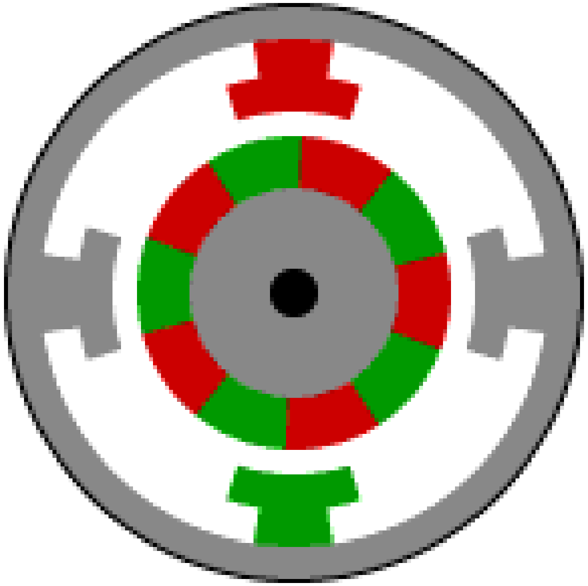


Magnetic flux path

Rotor rotates to try to minimize reluctance = flux resistance.

# Stepper Motor Classifications

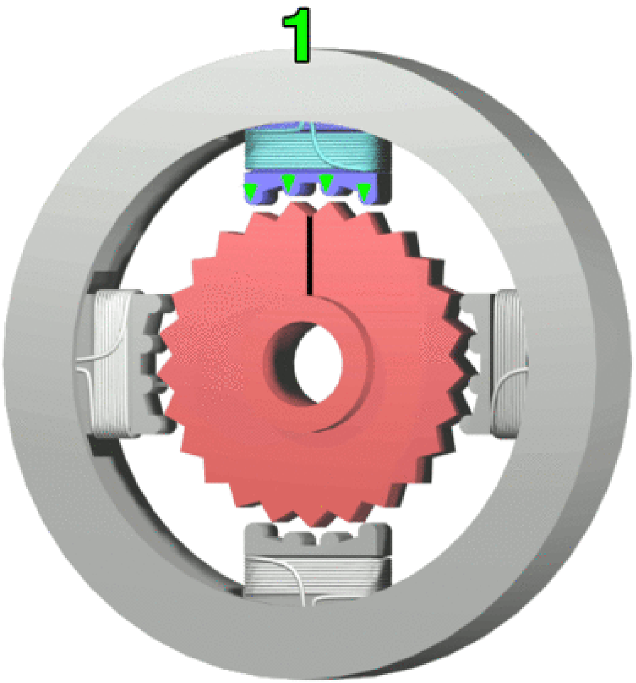
Permanent Magnet Motor



(animation)

# Stepper Motor Classifications

Hybrid Motor

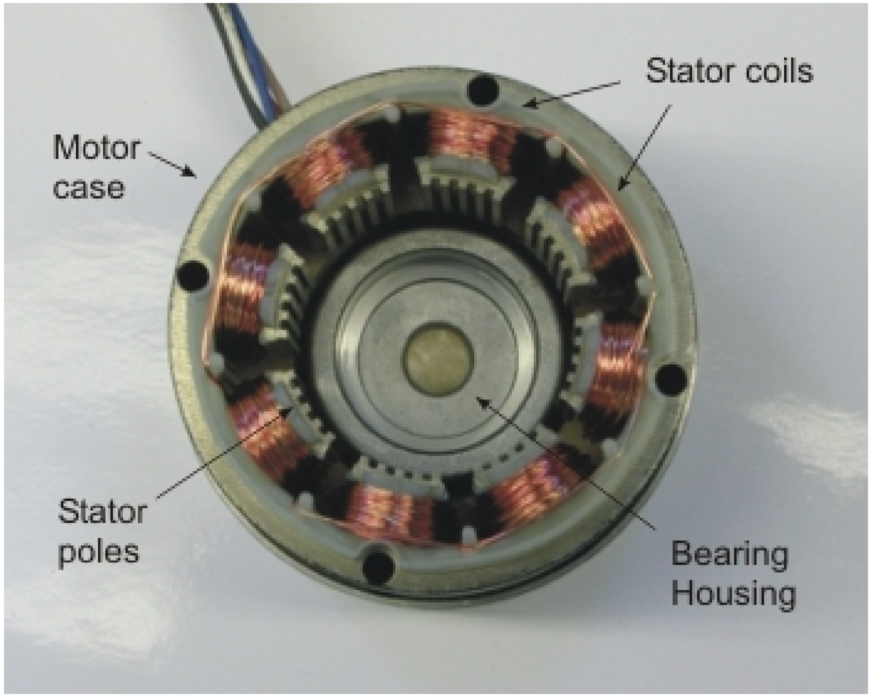


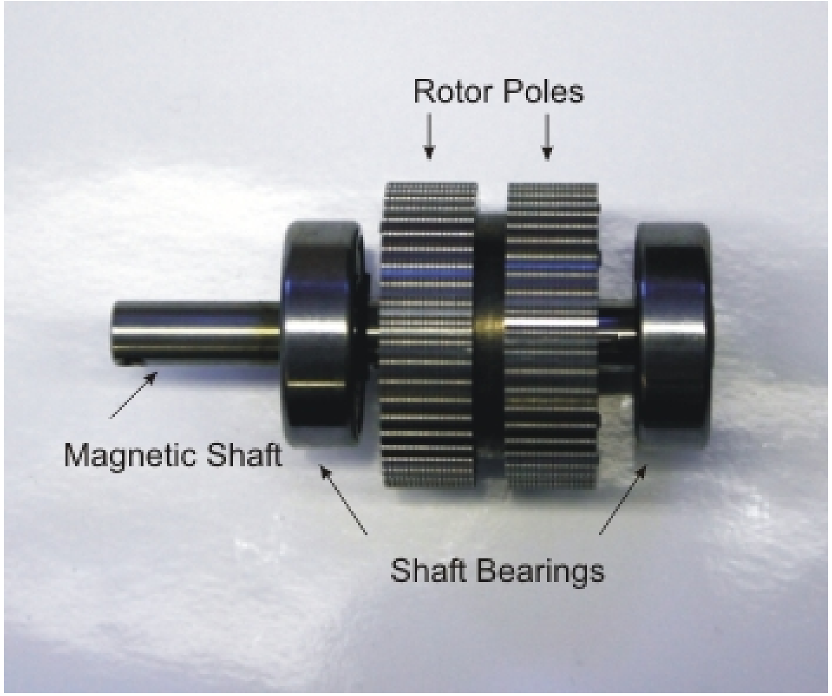

(animation)

Combination of a variable reluctance motor and a permanent magnet motor.

# Stepper Motor Classifications

## Hybrid Stepper Motor

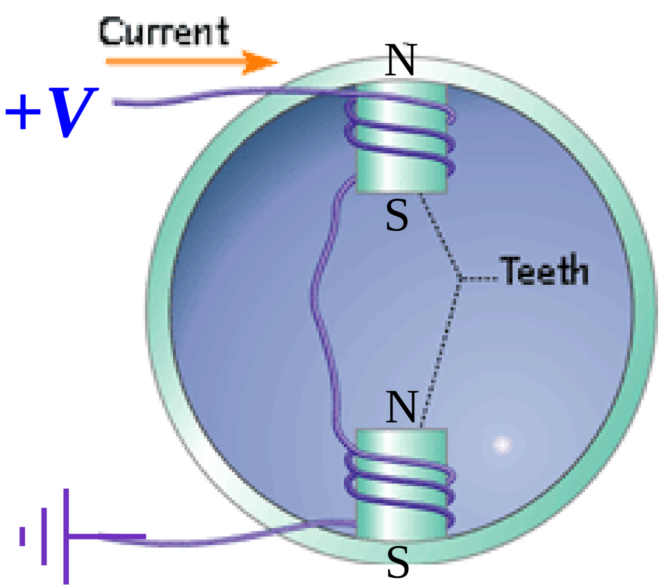


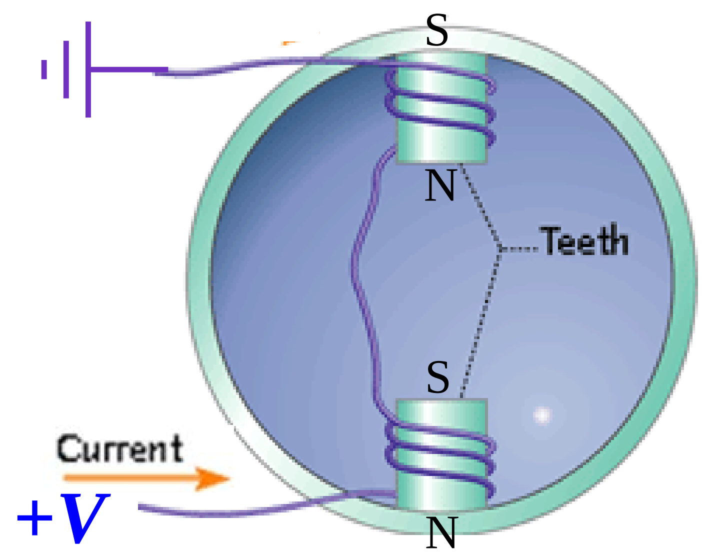



# Stepper Motor Classifications

## Bipolar Stator Windings

- The current though the winding can be reversed by reversing the polarity of the terminal voltage.
- This reverses the polarity of the magnetic poles on the teeth.
- Thus, the stator winding is **bipolar**.

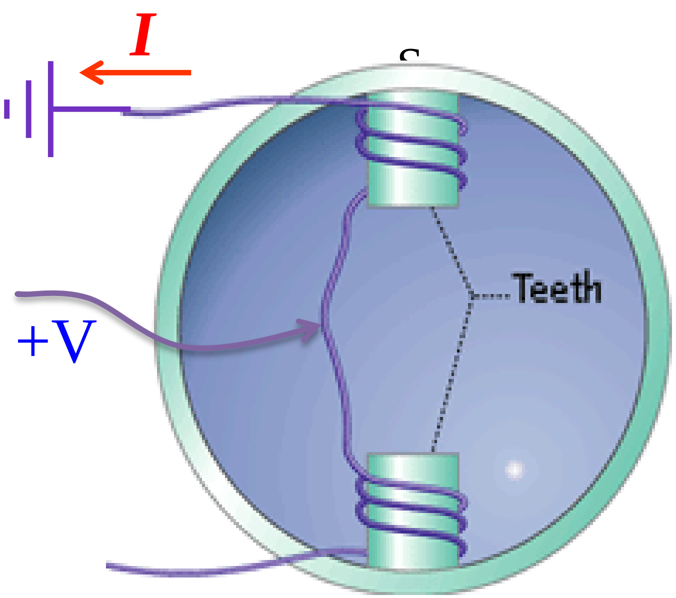


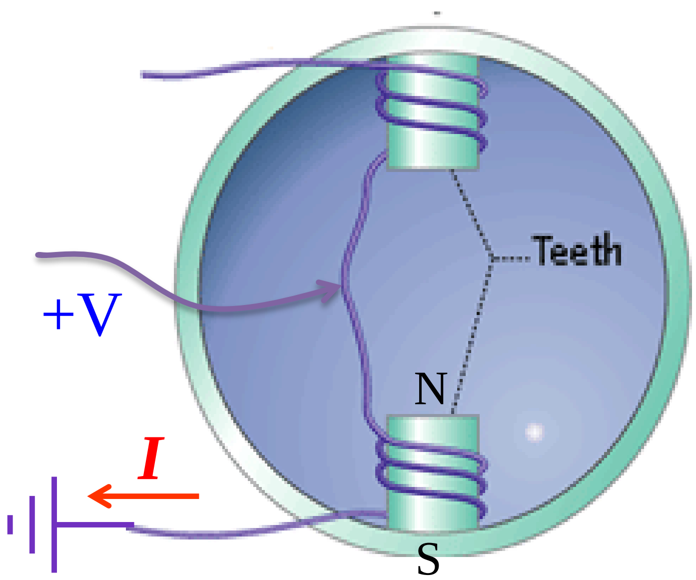



# Stepper Motor Classifications

## Unipolar Stator Winding

- The winding has **center tap**. Each lead is grounded (one at a time) to induce current flow.
- The polarity of the voltage across each segment of the winding does not change, nor does the magnetic polarity on the teeth.
- Thus, the stator winding is **unipolar**.



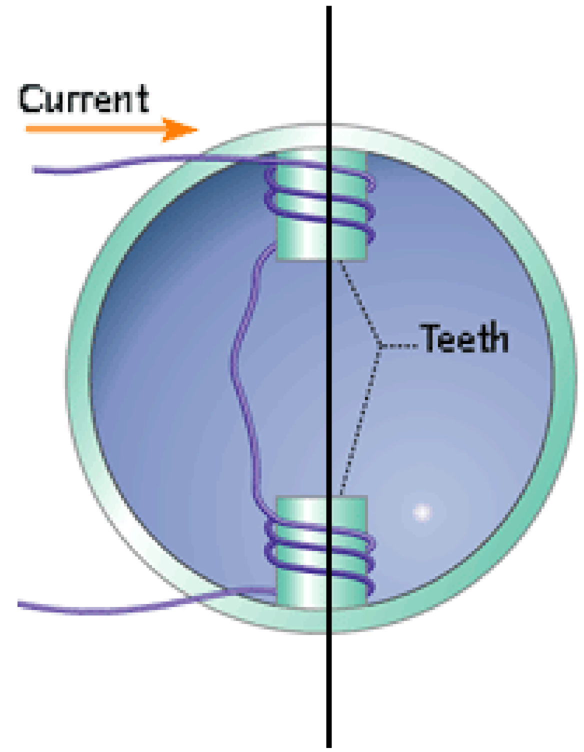
# Stepper Motor Classifications

## Winding Phases

In general, each stator winding determines a **phase** (electrical phase angle), so the diagram depicts the stator winding for a **one-phase** motor.

Note that winding is considered a single winding (or phase) even though it is coiled around two teeth.

Phase 1



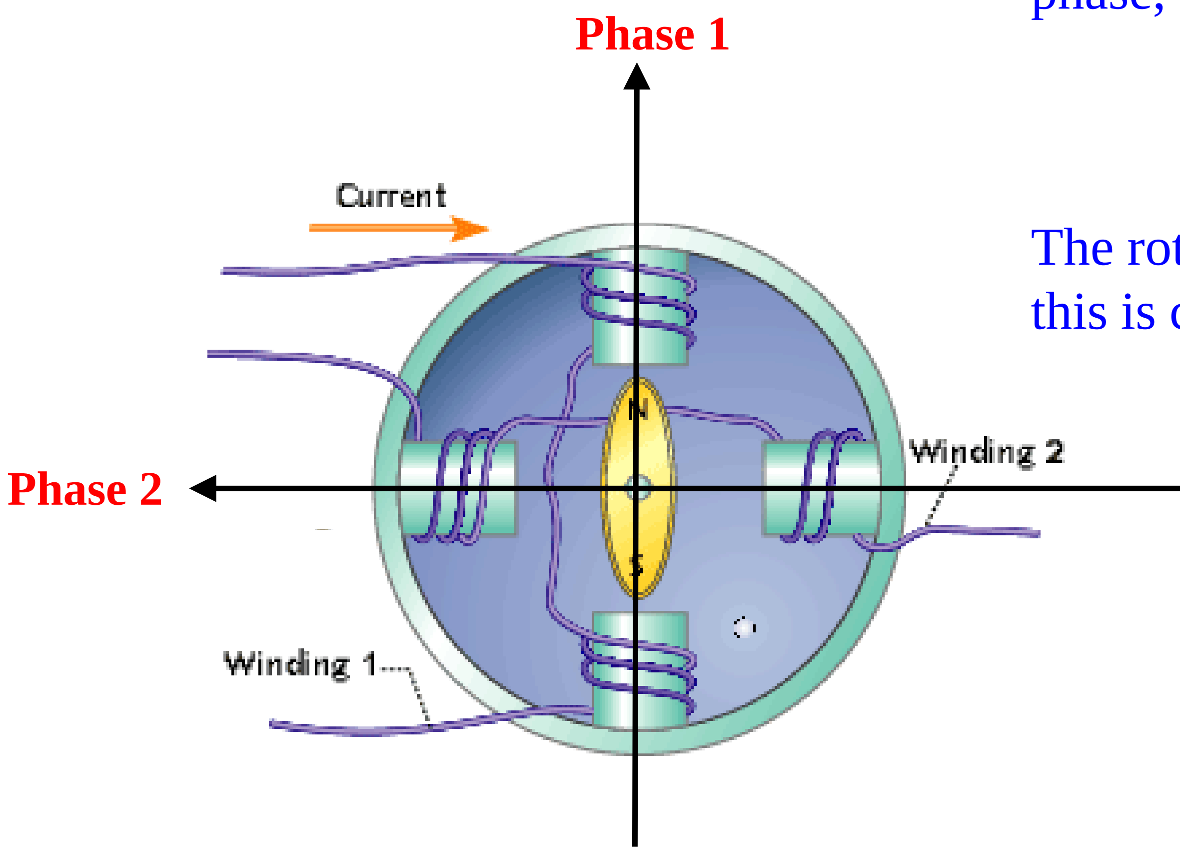

Bipolar Motor Winding

# Stepper Motor Classifications

## Winding Phases and Rotor Poles

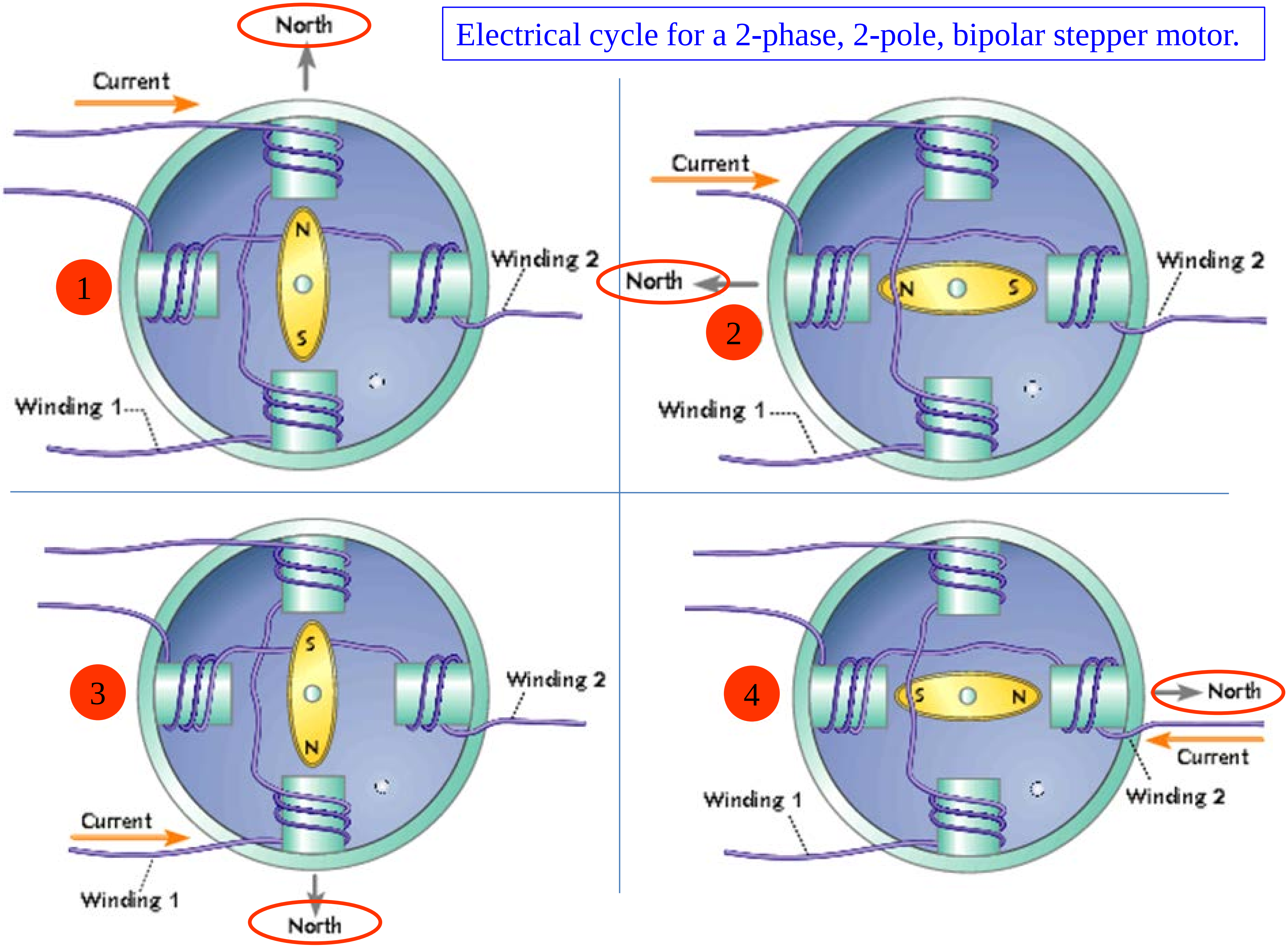
Each winding determines a phase, so this is a **two-phase** motor.

The rotor has two poles (N and S), so this is called a **two-pole** motor.



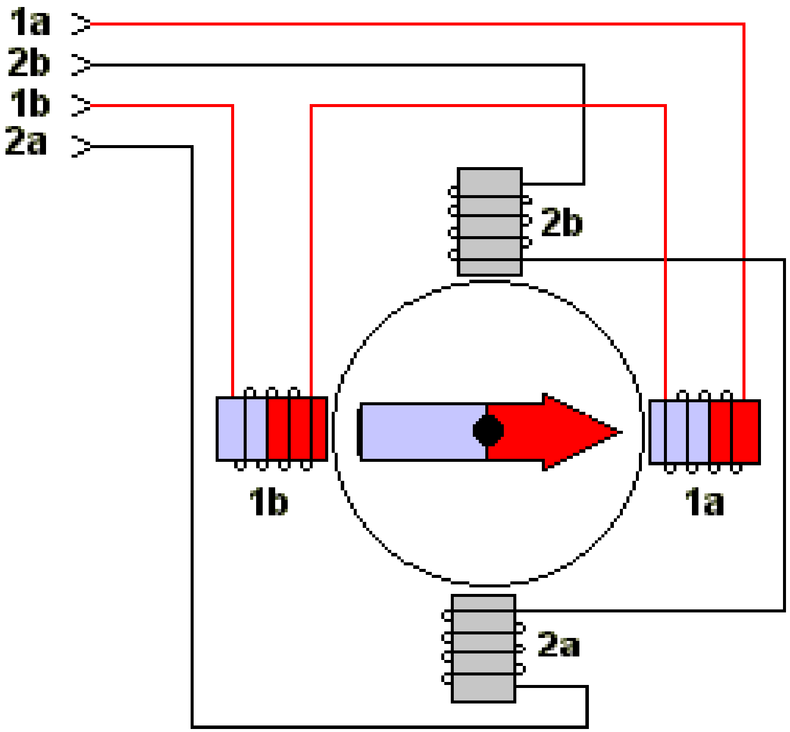

Bipolar Motor Windings

Electrical cycle for a 2-phase, 2-pole, bipolar stepper motor.

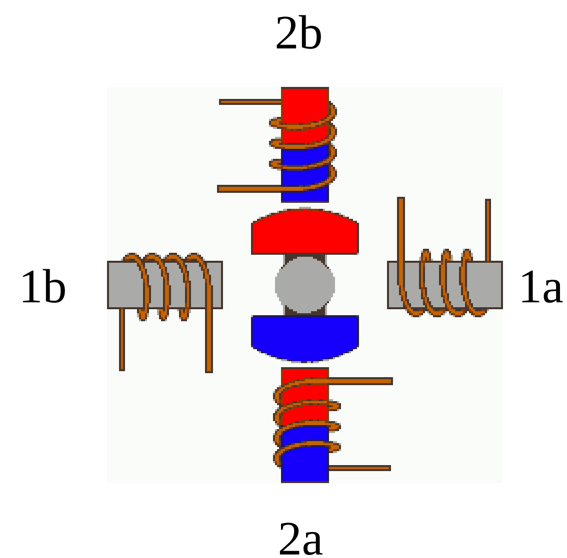


# Conceptual model of a 2-phase, 2-pole, **bipolar** stepper motor.

Driving mode: The coils are activated in sequence to rotate the rotor.




2-phase, 2-pole

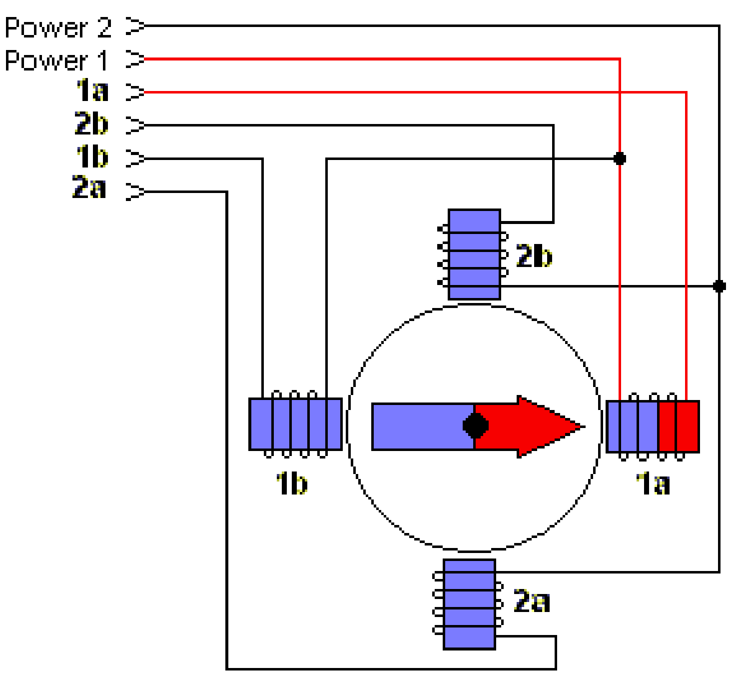


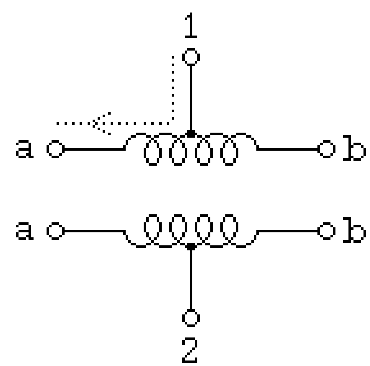

| 1a | 1b | 2a | 2b |
|---|---|---|---|
| 1 | 0 | 0 | 0 |
| 0 | 0 | 0 | 1 |
| 0 | 1 | 0 | 0 |
| 0 | 0 | 1 | 0 |

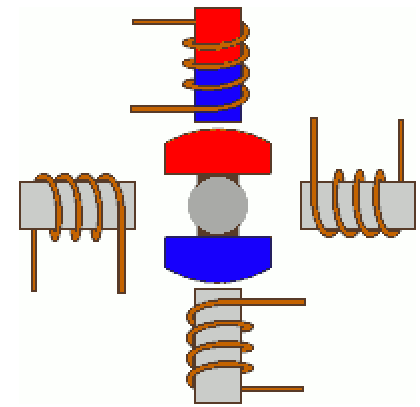
# Conceptual model of a 2-phase, 2-pole, **unipolar** stepper motor.

With the center taps of the windings wired to the positive supply, the terminals of each winding are grounded in sequence to rotate the rotor.

Note: Some sources call this a 4-phase unipolar motor.



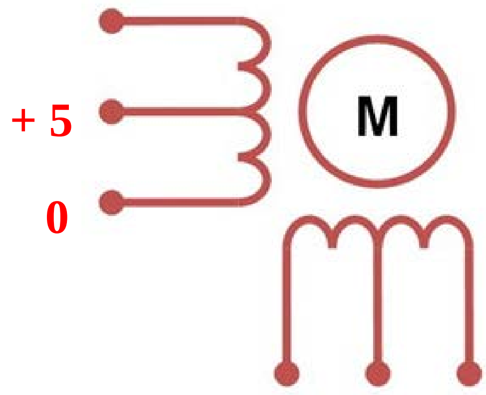



| 1a | 1b | 2a | 2b |
|---|---|---|---|
| 0 | 1 | 1 | 1 |
| 1 | 1 | 0 | 1 |
| 1 | 0 | 1 | 1 |
| 1 | 1 | 1 | 0 |

# 2-phase, Unipolar and Bipolar Schematics

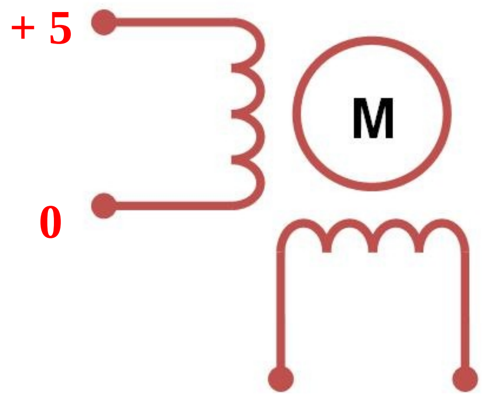
Unipolar




Current flows in **one direction** through winding.

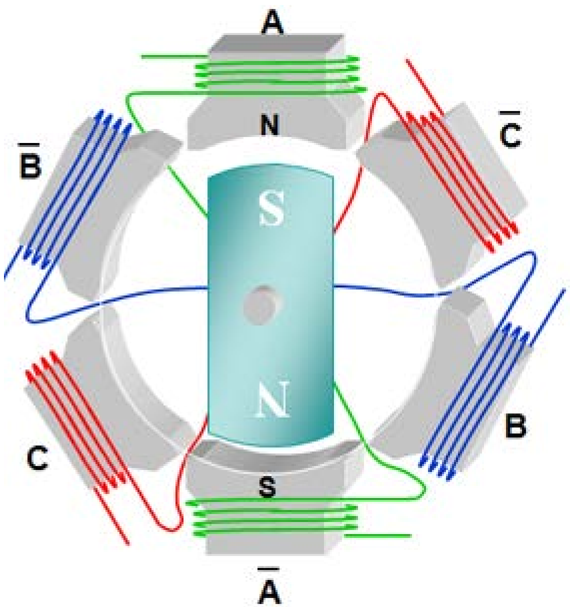
Note: Can be operated as a bipolar motor.

Bipolar

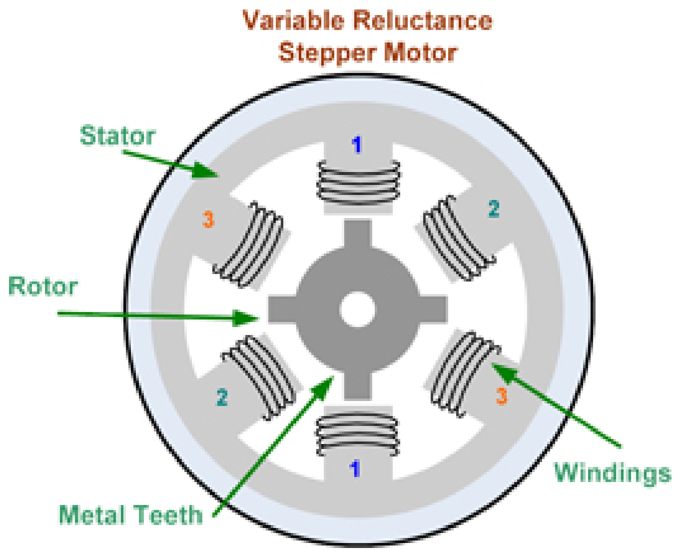



Current flows in **both directions** through winding.

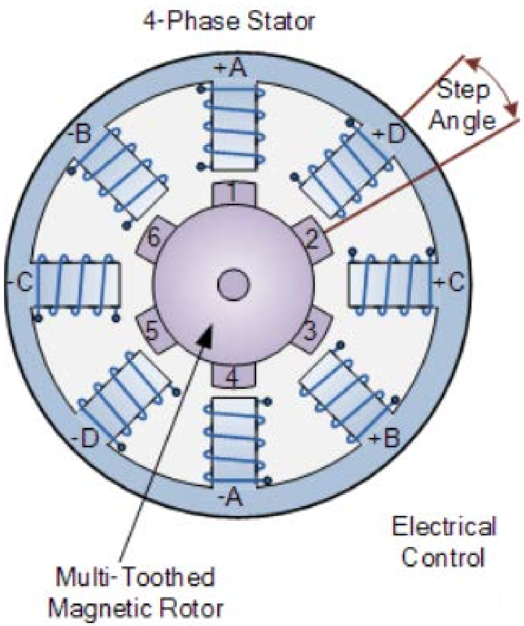
# Stepper Motor Classifications




3-phase, 2-pole, bipolar motor




3-phase, 4-pole, bipolar motor




4-phase, 6-pole, bipolar motor

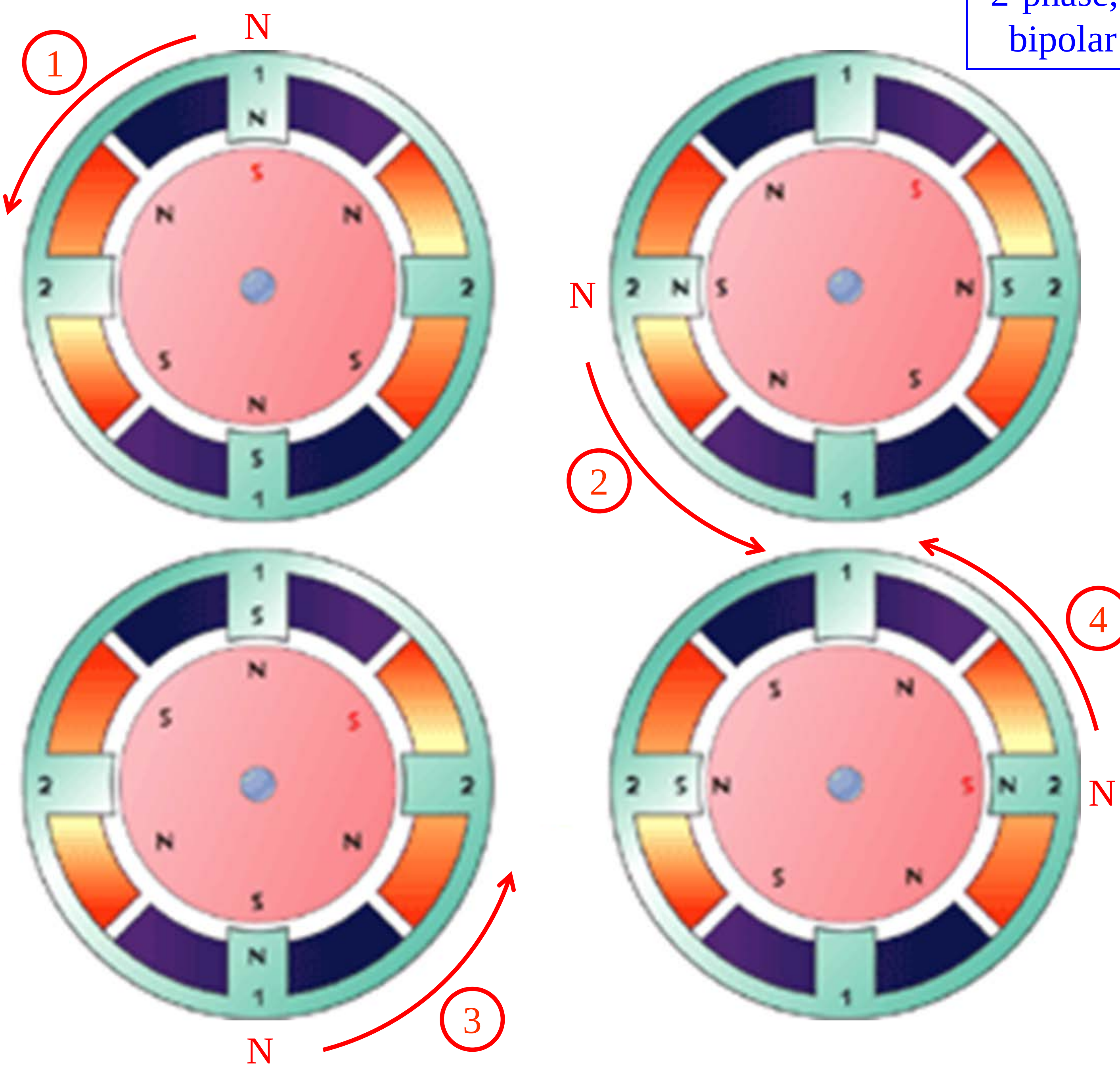
2-phase, 6-pole, bipolar motor

**Electrical Cycle**

Magnetic pole rotates around stator.

After 4 steps, the north pole returns to top of stator.

This is one electrical cycle.



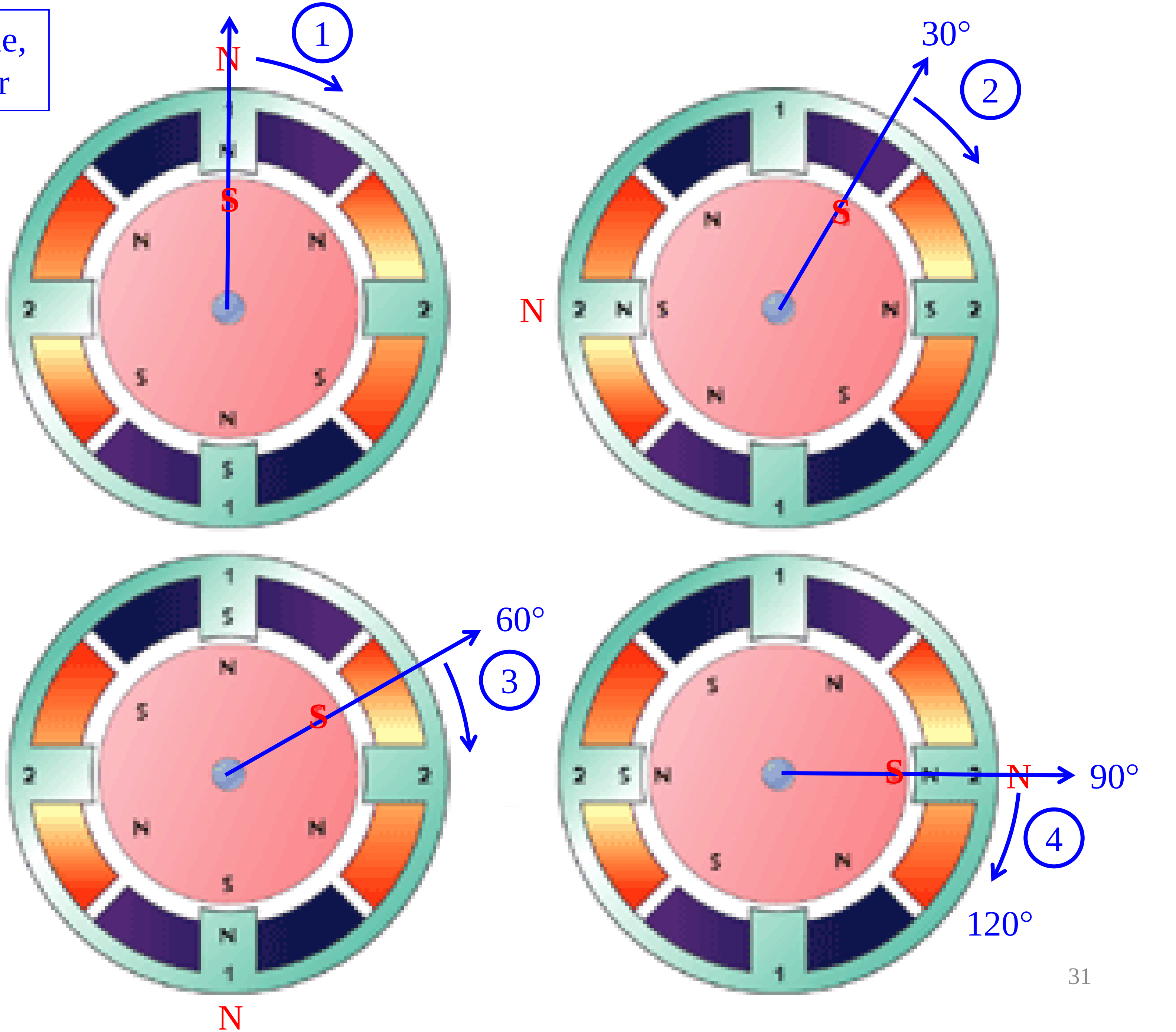
2-phase, 6-pole, bipolar motor

**Mechanical Cycle**

Rotor rotates in opposite direction of stator pole rotation.

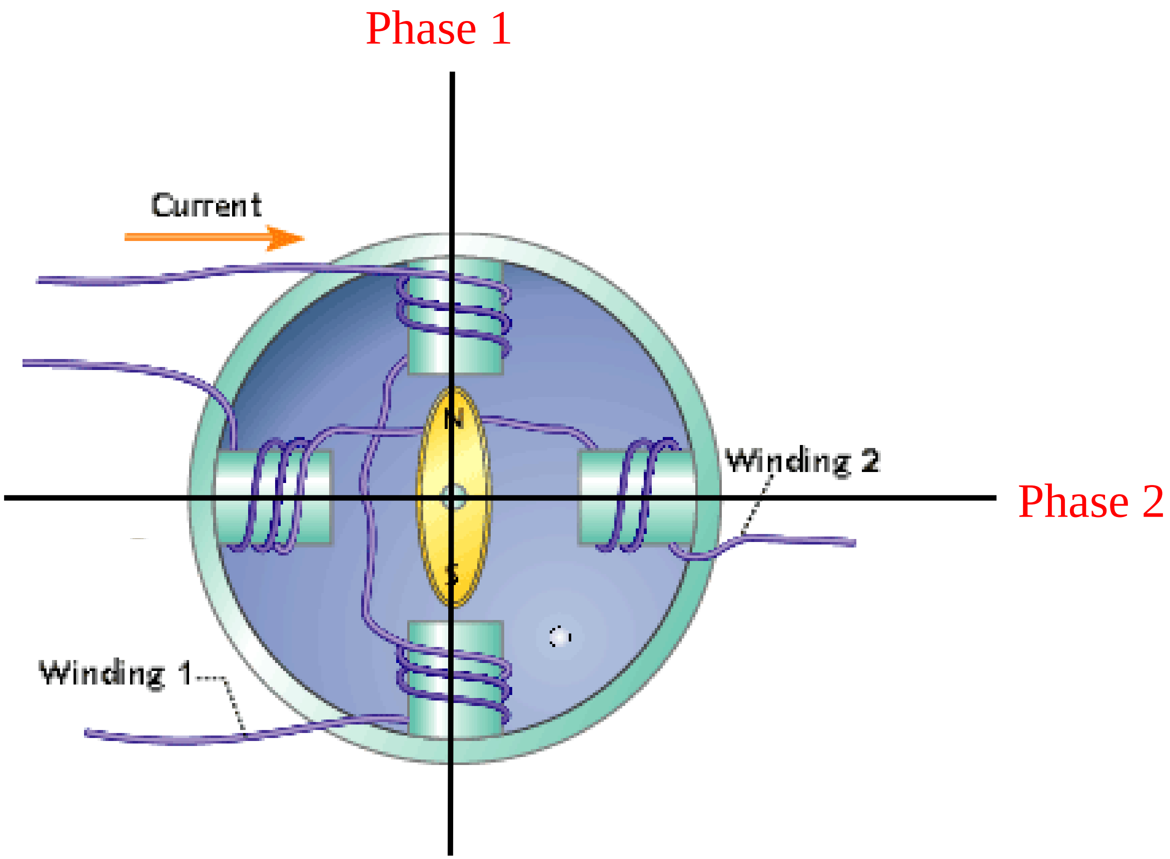
After 4 steps, the rotor is at 120°

This is 1/3 mechanical cycle.



- **Conclusion**: For a 2-phase, 6-pole, bipolar motor, after one electrical cycle (4 steps), the rotor has rotated 120°. So, it takes 3 electrical cycles for the rotor to rotate 360° or 1 mechanical cycle.

- For the 2-phase, 2-pole motor, bipolar below, after one electrical cycle (4 steps), the rotor has rotated 360°. So, it takes 1 electrical cycle for the rotor to rotate 360° or 1 mechanical cycle.



# Summary (bipolar motor)

1. Two-phase, **two-pole** stepper motor ($P$ = 2)

   - 1 electrical cycle = 1 mechanical cycle
   - 1 step = 90 deg = 180 / 2 = 180 / $P$ (deg)
   - $T_e = T_m = T_m\,(2 / 2)$ (sec) ($T$ = period)

2. Two-phase, **six-pole** stepper motor ($P$ = 6)

   - 1 electrical cycle = 1/3 mechanical cycle
   - 1 step = 30 deg = 180 / 6 = 180 / $P$ (deg)
   - $T_e = T_m / 3 = T_m\,(2 / 6)$ (sec)

3. Two-phase, ***P*-pole** stepper motor

   - 1 step = 180 / P (deg)
   - $T_e = T_m\,(2 / P)$ (sec)
   - $f_e = f_m\,(P / 2)$ (Hz)

# Advantages of a Stepper Motor

1. Cost-effective
2. Simple designs
3. High reliability
4. Brushless construction (maintenance-free)
5. If windings are energized at standstill, the motor has full torque
6. No feedback mechanisms required (but may be desirable)
7. A wide range of rotational speeds can be attained as the speed is proportional to the frequency of the input pulses
8. Known limit to the dynamic position error

# Disadvantages of a Stepper Motor

1. Low efficiency (Motor uses substantial amount of power regardless of the load)

2. Torque drops rapidly with speed

3. Prone to resonance

4. Missed steps

5. Cannot accelerate loads very rapidly

6. Motor gets very hot in high performance configurations

7. Motor is noisy at moderate to high speeds

8. Low output power for size and weight

# Stepper Motors – Many Applications

1. **Aircraft** – In the aircraft industry, stepper motors are used in aircraft instrumentations, antenna and sensing applications, and equipment scanning

2. **Automotive** – The automotive industry implements stepper motors for applications concerning cruise control, sensing devices, and cameras. The military also utilizes stepper motors in their application of positioning antennas

3. **Chemical** – The chemical industry makes use of stepper motors for mixing and sampling of materials. They also utilize stepper motor controllers with single and multi-axis stepper motors for equipment testing

4. **Consumer Electronics and Office Equipment** – In the consumer electronics industry, stepper motors are widely used in digital cameras for focus and zoom functionality features. In office equipment, stepper motors are implemented in PC-based scanning equipment, data storage drives, optical disk drive driving mechanisms, printers, and scanners

# Stepper Motors – Many Applications

5. **Industrial** – In the industrial industry, stepper motors are used in automotive gauges, machine tooling with single and multi-axis stepper motor controllers, and retrofit kits which make use of stepper motor controllers as well. Stepper motors can also be found in CNC machine control

6. **Medical** – In the medical industry, stepper motors are utilized in medical scanners, microscopic or nanoscopic motion control of automated devices, dispensing pumps, and chromatograph auto-injectors. Stepper motors are also found inside digital dental photography (X-RAY), fluid pumps, respirators, and blood analysis machinery, centrifuge

7. **Scientific Instruments** –Scientific equipment implement stepper motors in the positioning of an observatory telescope, spectrographs, and centrifuge

8. **Surveillance Systems** – Stepper motors are used in camera surveillance

# Recommended Stepper Motor Videos

Microchip Stepper Motor Video – Part 1 (18 min)

Microchip Stepper Motor Video – Part 2 (12 min)

# Lab 8 Outline

1. Stepper Motor Fundamentals

2. Stepper Motor Classifications

3. **Full Stepping, Half Stepping, and Micro-stepping**

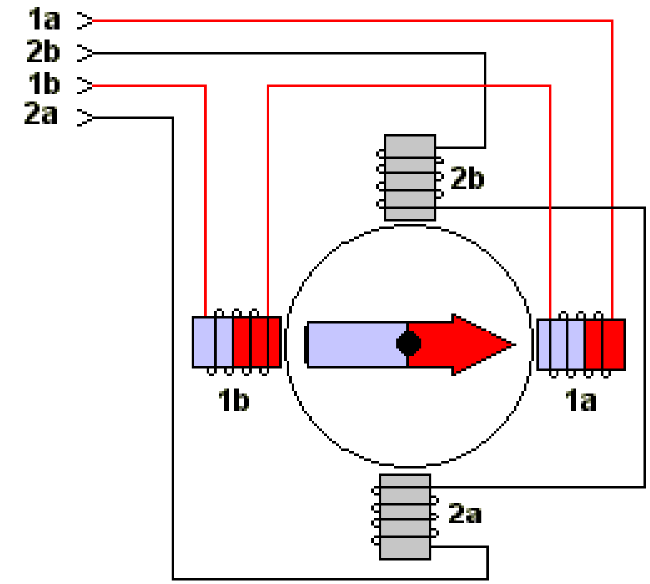
4. Lab 8 Setup

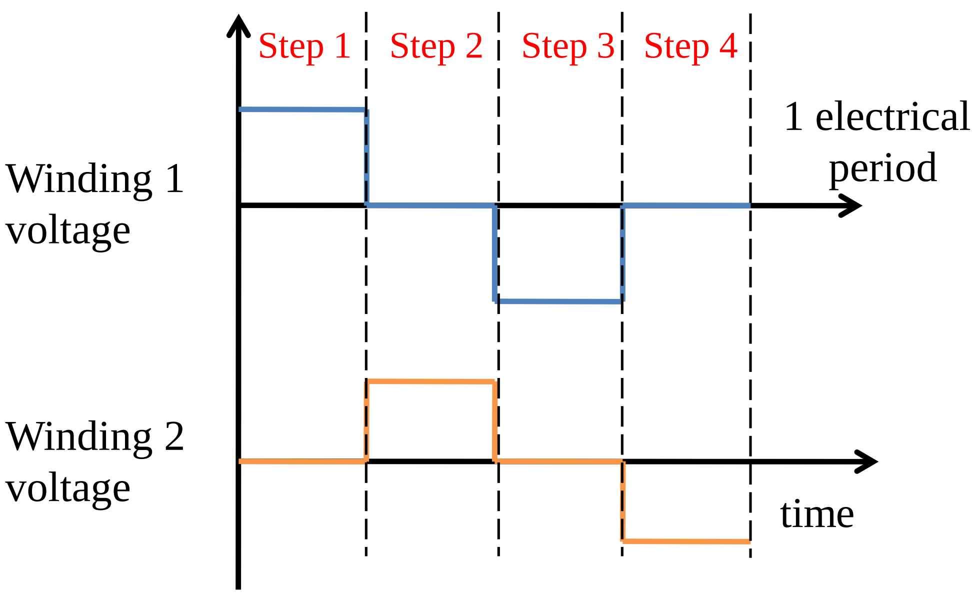
# Bipolar Driving Modes

Two-Coil Excitation
Full Step

Winding voltage: Four steps, one electrical period:

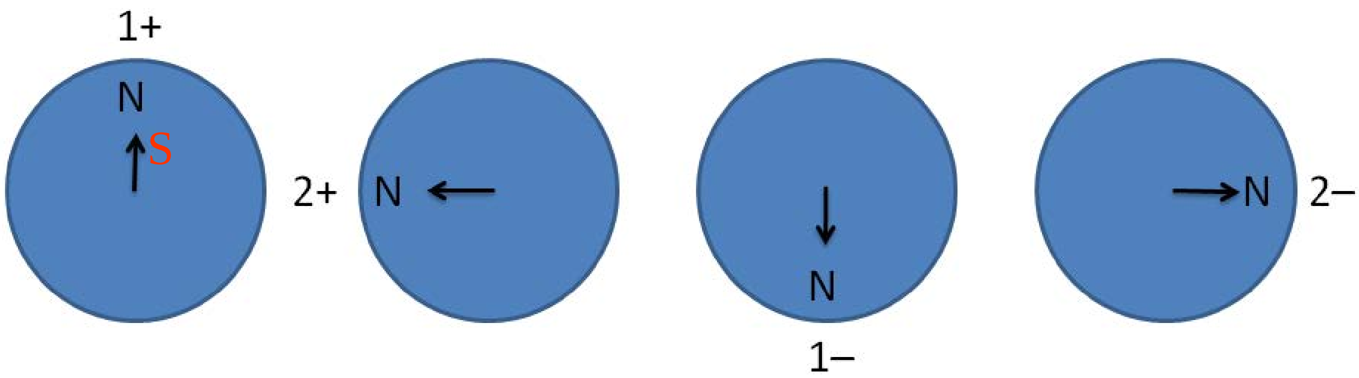
1. Winding 1 positive, Winding 2 zero
2. Winding 2 positive, Winding 1 zero
3. Winding 1 negative, Winding 2 zero
4. Winding 2 negative, Winding 1 zero



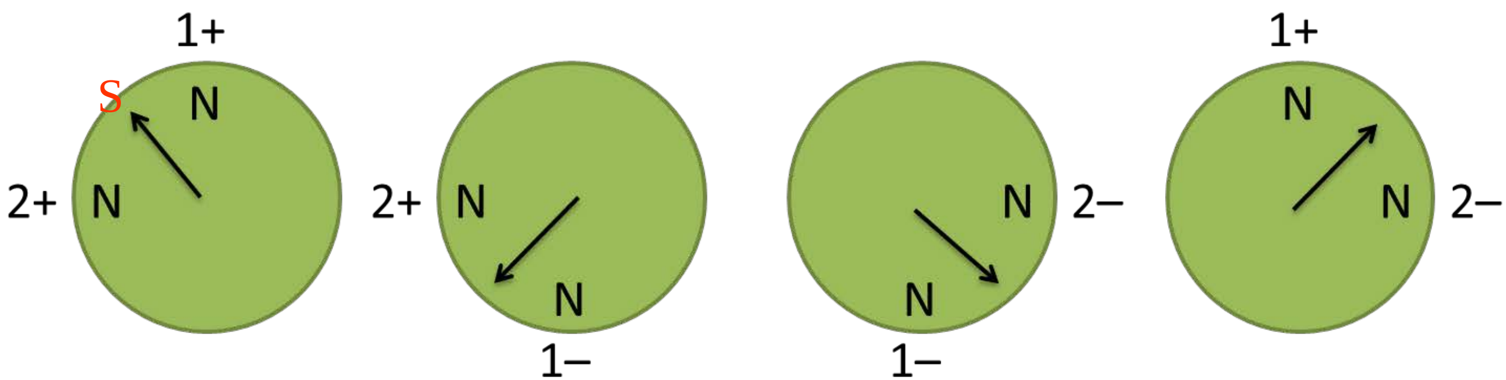




| | 1a | 1b | 2a | 2b |
|---|---|---|---|---|
| Step 1 | 1 | 0 | 0 | 0 |
| Step 2 | 0 | 0 | 0 | 1 |
| Step 3 | 0 | 1 | 0 | 0 |
| Step 4 | 0 | 0 | 1 | 0 |

# Bipolar Driving Modes




Single-Coil Excitation

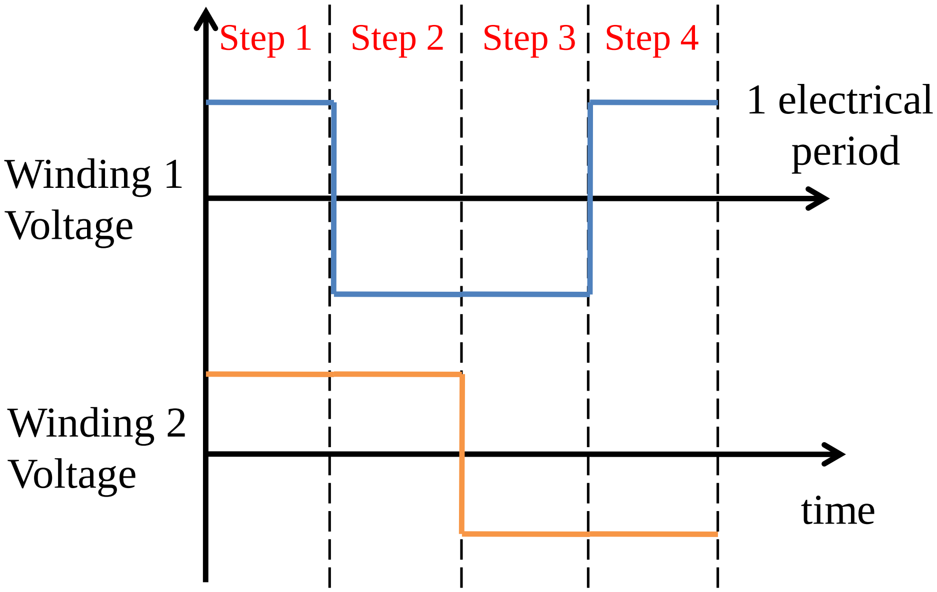



Two-Coil Excitation

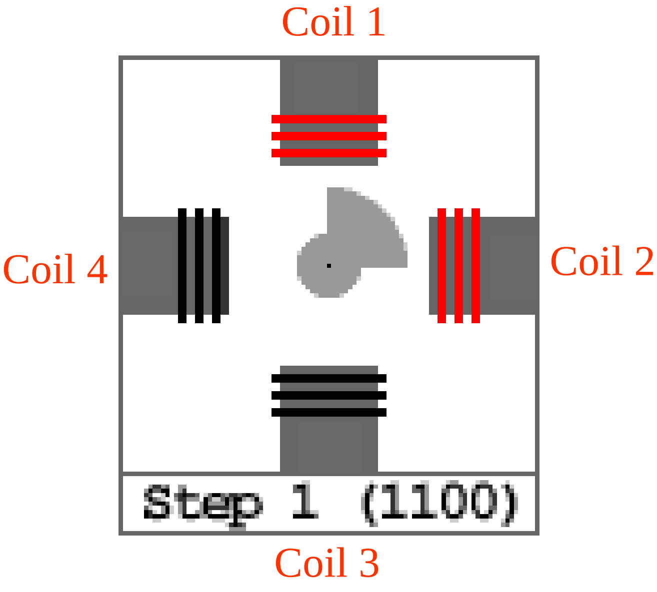
- We can energize two adjacent windings at the same time.
- Is more energy is required?
- Is more torque is obtained?
- "1–" means reverse the current in Winding 1.

# Bipolar Driving Modes

Two-Coil Excitation
Full-Step, High Torque



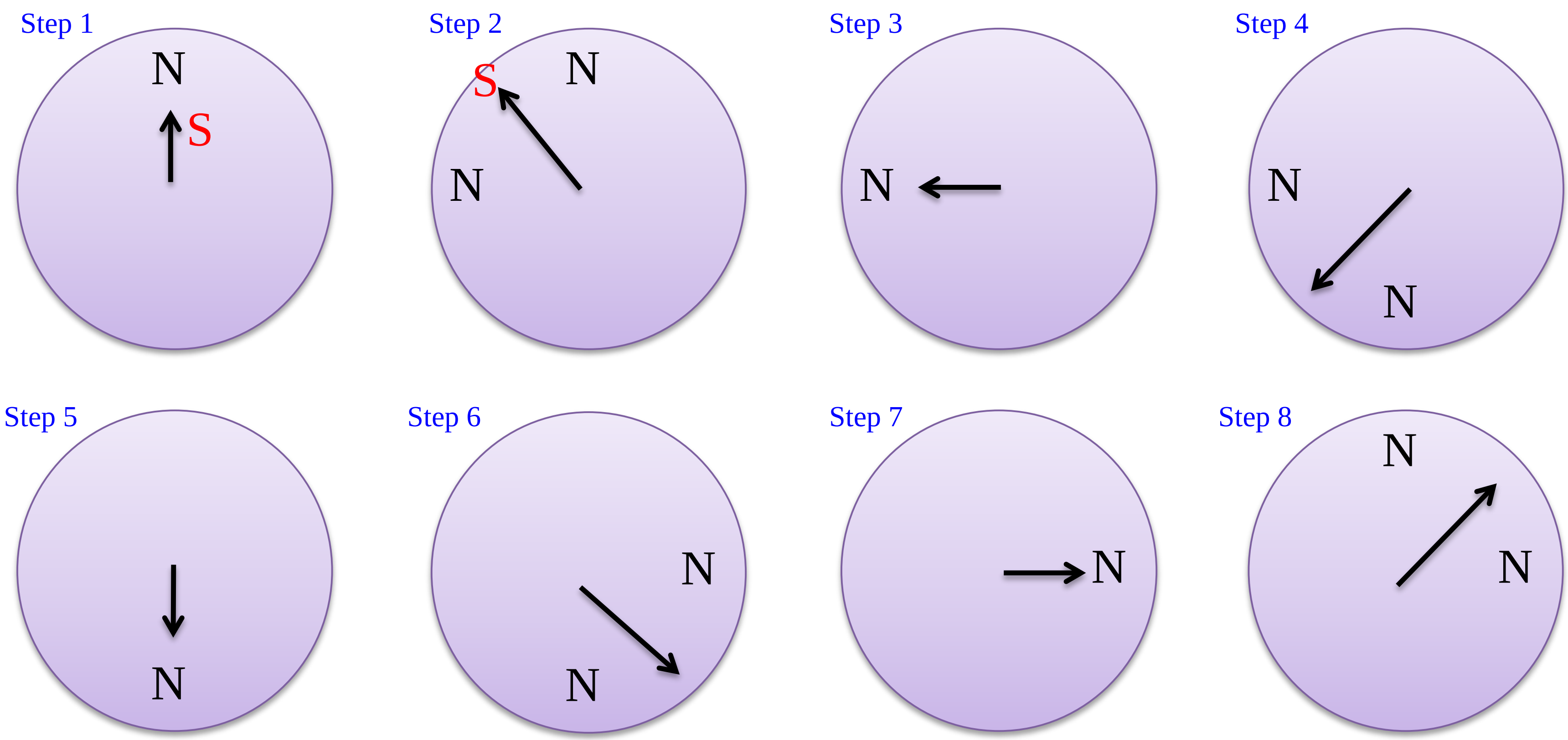

(animation)




| | Coil 1234 |
|---|---|
| Step 1 | 1100 |
| Step 2 | 0110 |
| Step 3 | 0011 |
| Step 4 | 1001 |

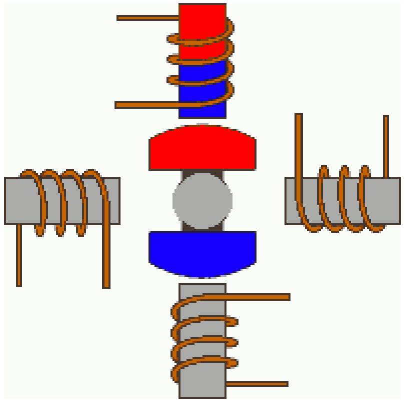
# Half-stepping (bipolar)

**Combine** the two sets of excitations shown previously.



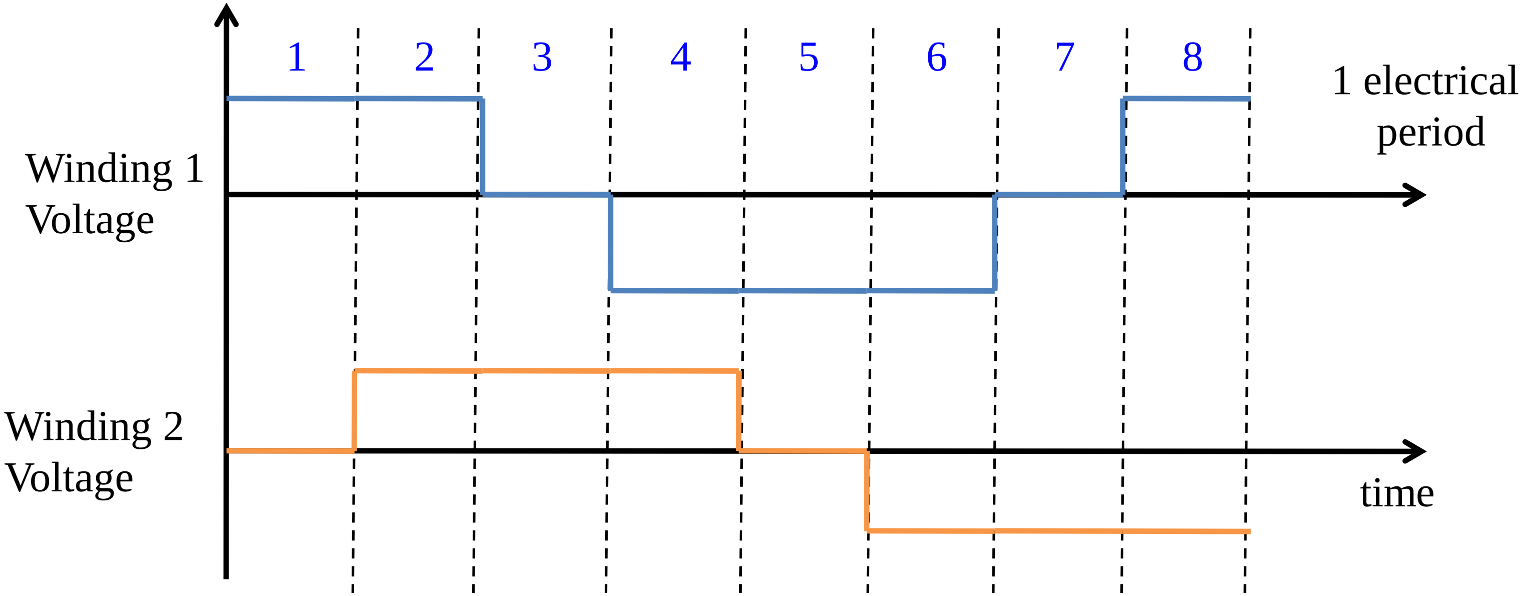

Eight half-steps per electrical cycle.
One half-step = (90 / Poles) degrees.

# Half-step Winding Voltages



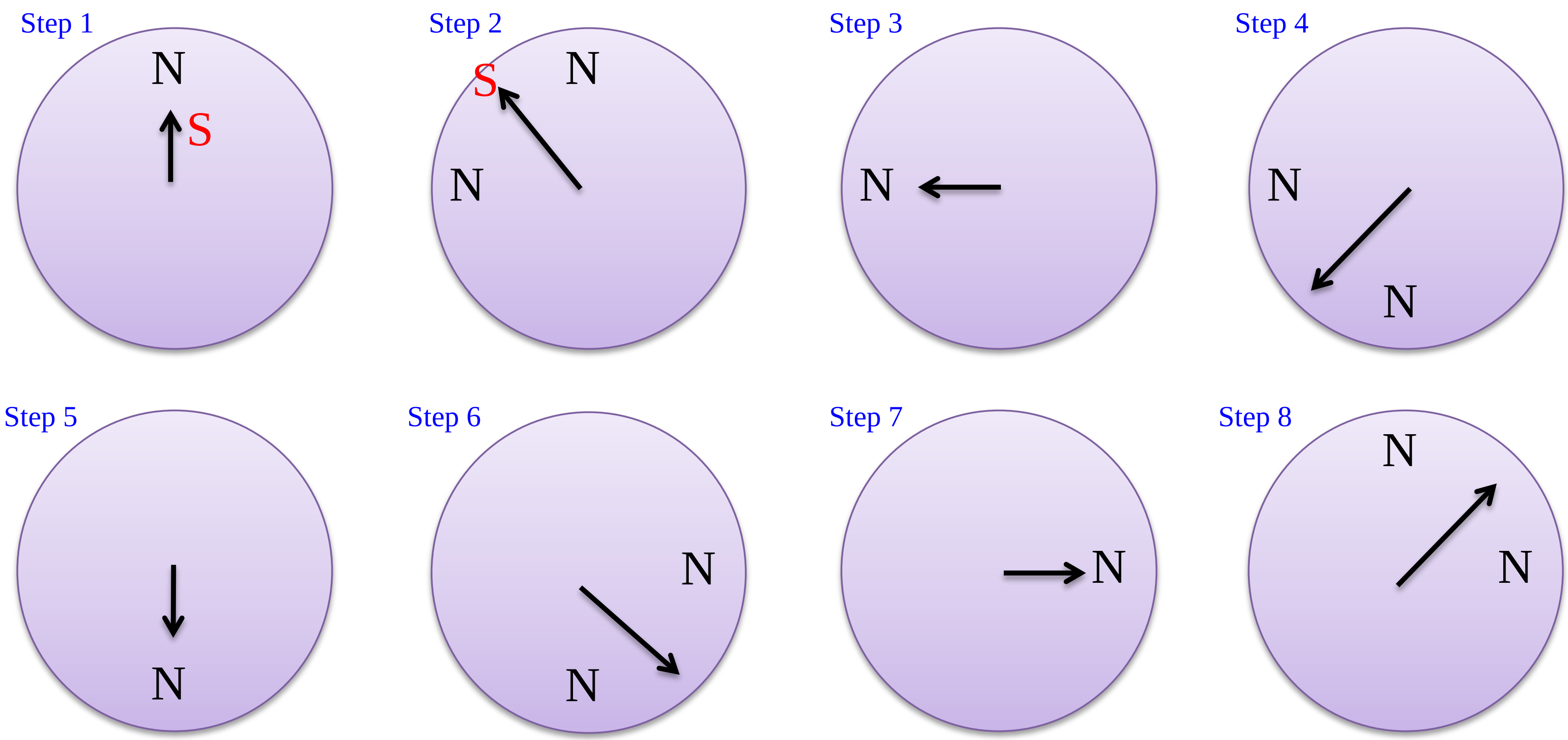
(animation)

Eight half-steps, one electrical cycle



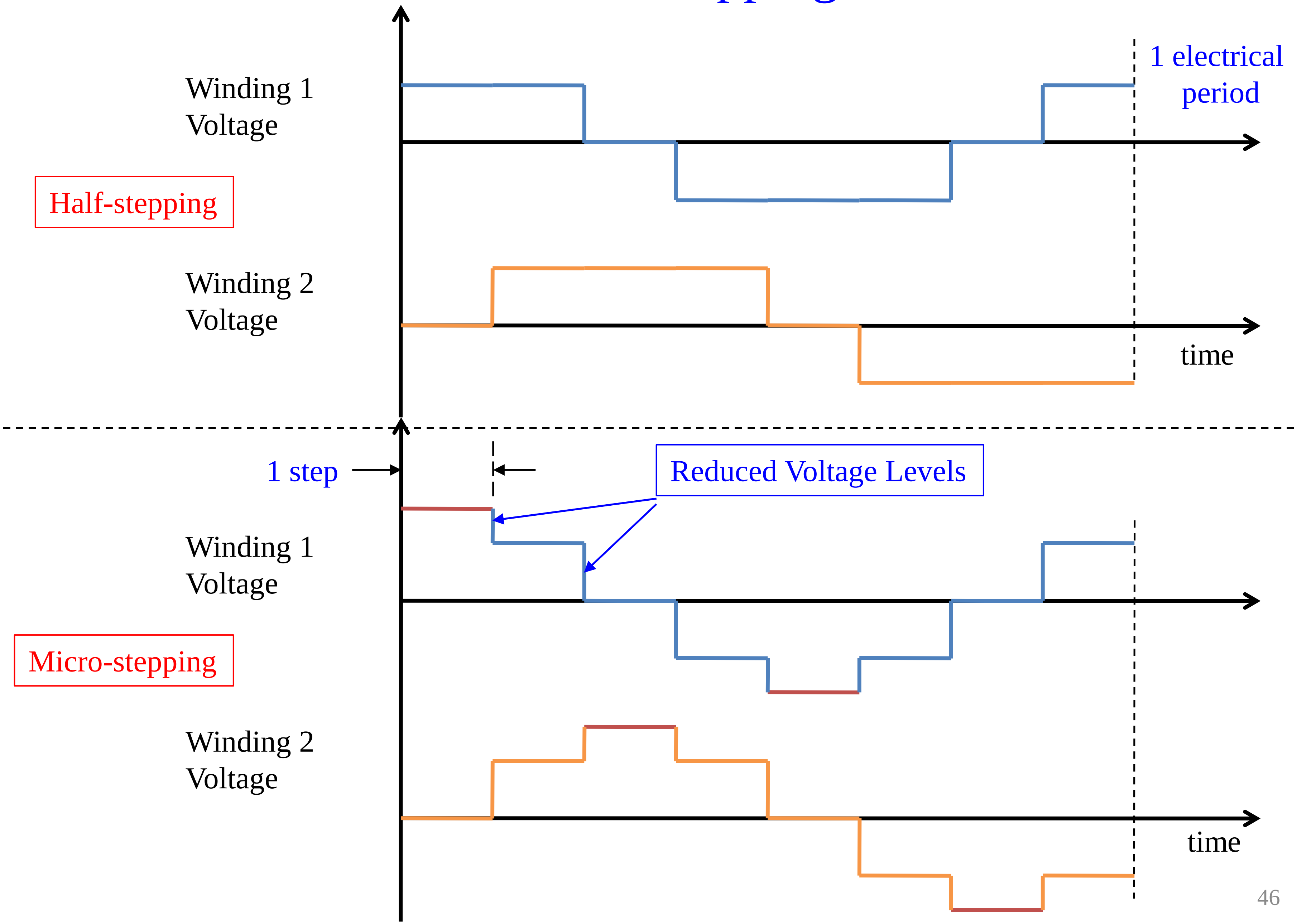
# Micro-stepping

Problem with half-stepping: **Uneven torque**

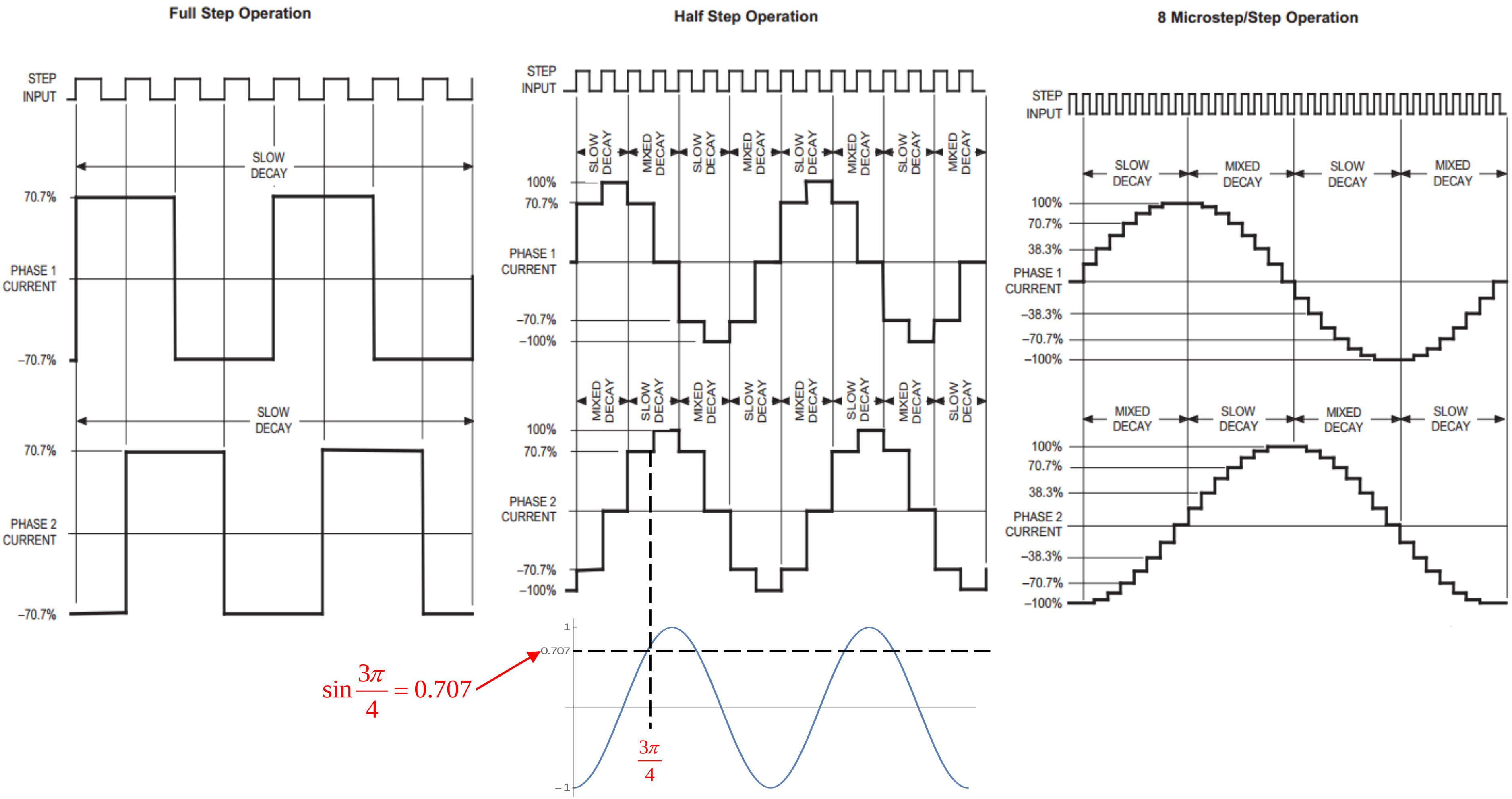



To even out the torque, if one winding is off, increase the current in the other winding. Now what do the waveforms look like? (See next slide . . . )

# Micro-stepping

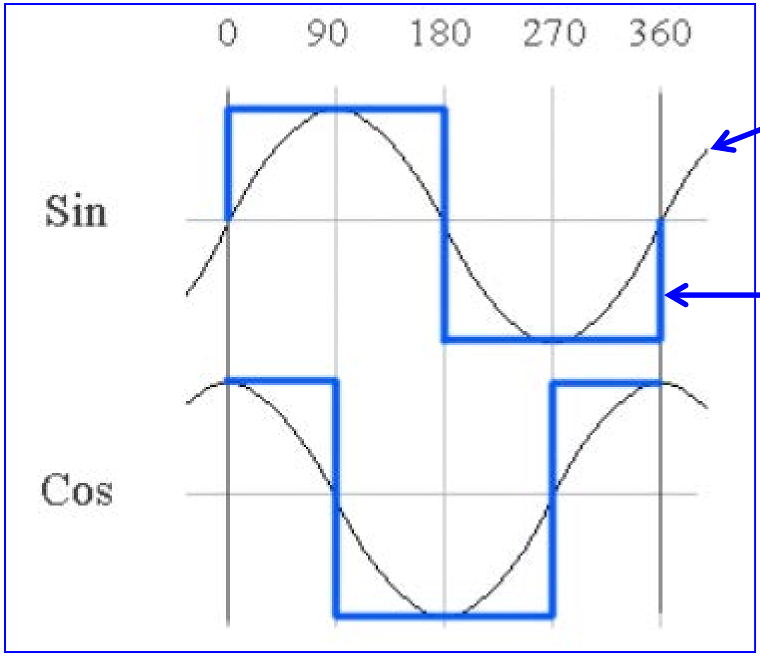


# Micro-stepping



# Micro-stepping

- Two sine waves in '**quadrature**' (90 degrees out of phase) form the **ideal** current drive for a 2-phase, bipolar stepper motor.
- If the two stepper coils follow the sinusoidal waveforms depicted in the diagram, the motor will run quietly and smoothly and the "step" associated with stepper motors will disappear.




Sinusoidal driver current

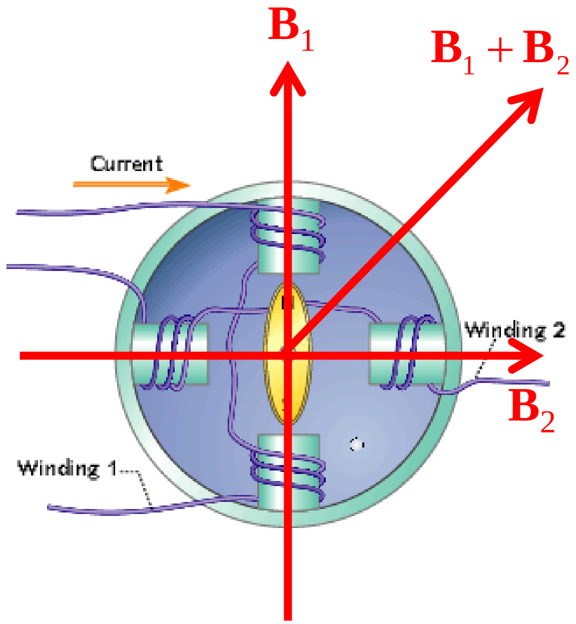
Full-wave, high-torque
“step” driver current

# Micro-stepping

Why is the torque constant with sinusoidal driving current?

The magnitude of the torque on the rotor is proportional to the vector sum of the magnitudes of the **B**-fields in the windings:

$$|\boldsymbol{\tau}| = a\left(|\mathbf{B}_1| + |\mathbf{B}_2|\right)$$




For perpendicular **B**-fields, the magnitude of the torque is given by

$$|\boldsymbol{\tau}| = a\sqrt{|\mathbf{B}_1|^2 + |\mathbf{B}_2|^2} = b\sqrt{I_1^2 + I_2^2}$$

where $a$, $b$ are constants and $I_1$ and $I_2$ are the winding currents.

The magnitudes of the **B**-fields are proportional to the currents.)

If the currents are sinusoidal, of equal magnitude, and 90° out of phase, then

$$I_1 = I_{peak} \sin \omega t \quad \text{and} \quad I_2 = I_{peak} \cos \omega t$$

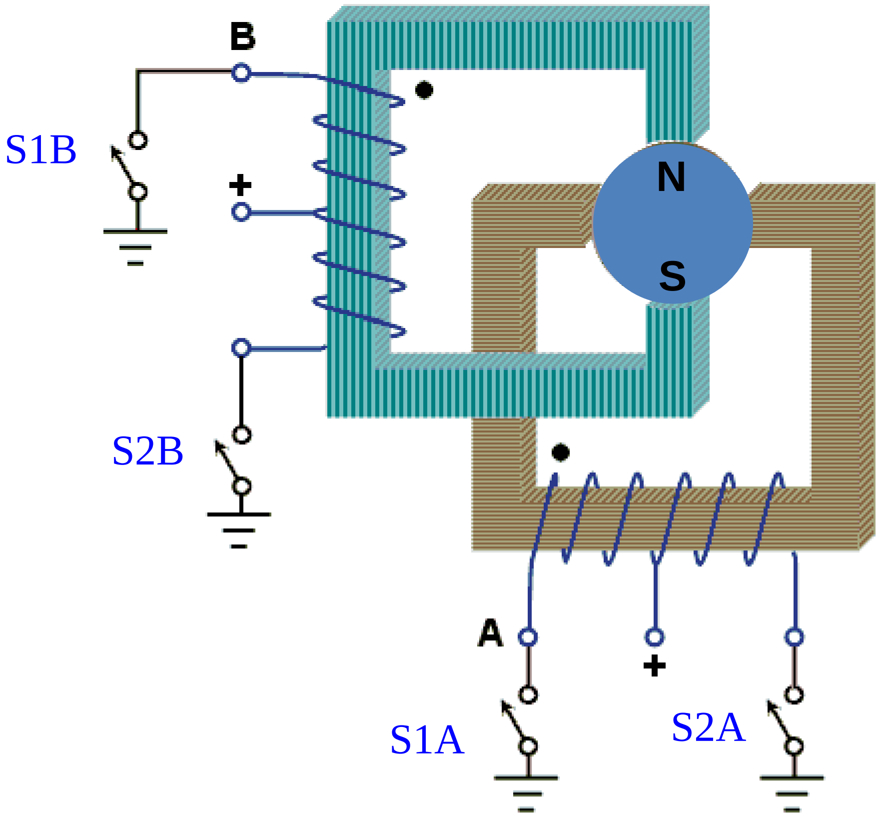
$$\tau = bI_{peak}\sqrt{\sin^2 \omega t + \cos^2 \omega t} = bI_{peak} = \text{constant}$$

# 2-phase, 2-pole Unipolar Motor Drive

Two-Coil Excitation
Full-Step, High Torque

| Step | Winding A | | Winding B | |
|---|---|---|---|---|
| | S1A | S2A | S1B | S2B |
| 1 | 0 | 1 | 0 | 1 |
| 2 | 1 | 0 | 0 | 1 |
| 3 | 1 | 0 | 1 | 0 |
| 4 | 0 | 1 | 1 | 0 |

Logic 0: Switch open
Logic 1: Switch closed

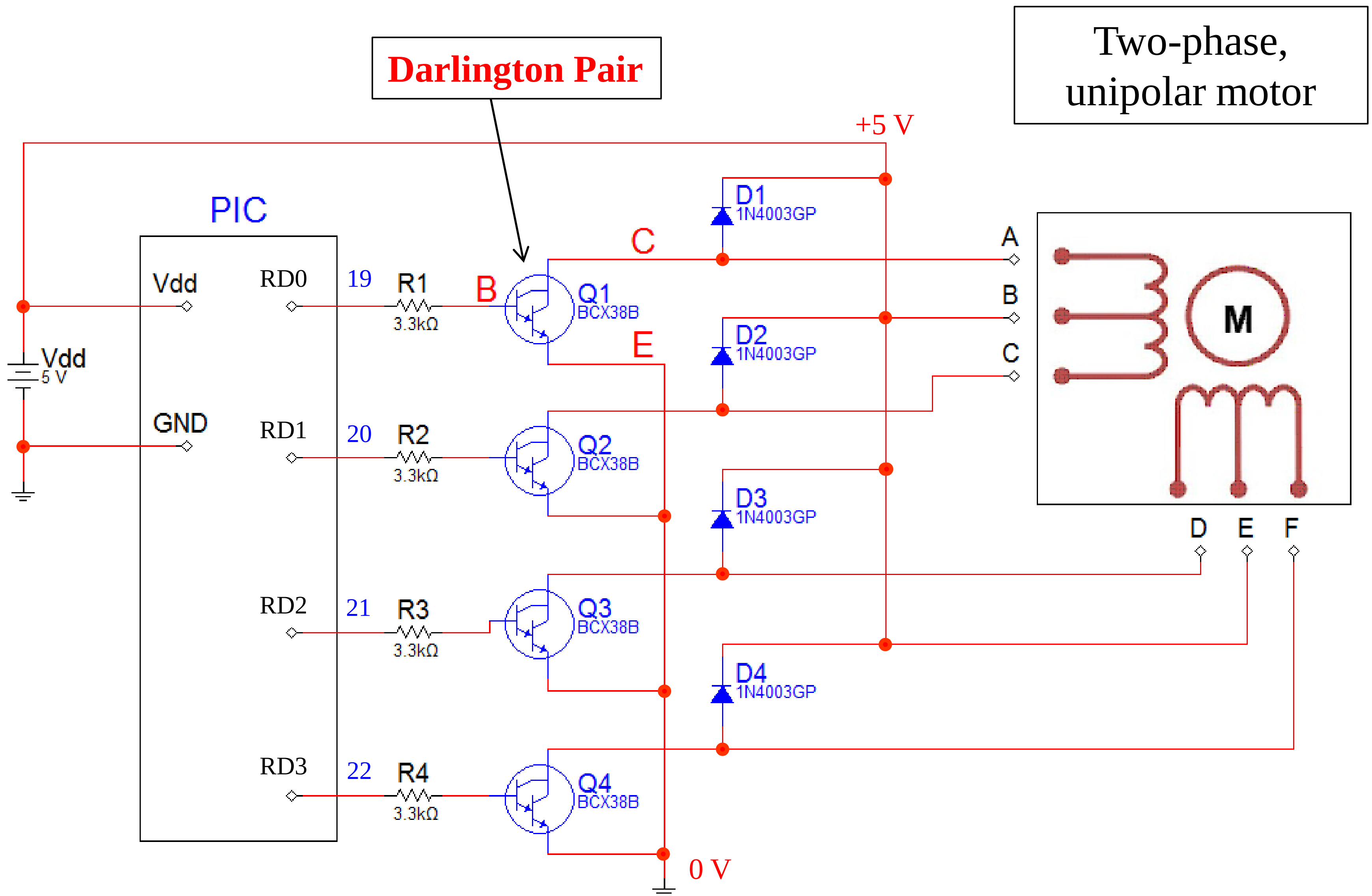



Note: The unipolar motor is being driven in a bipolar mode.

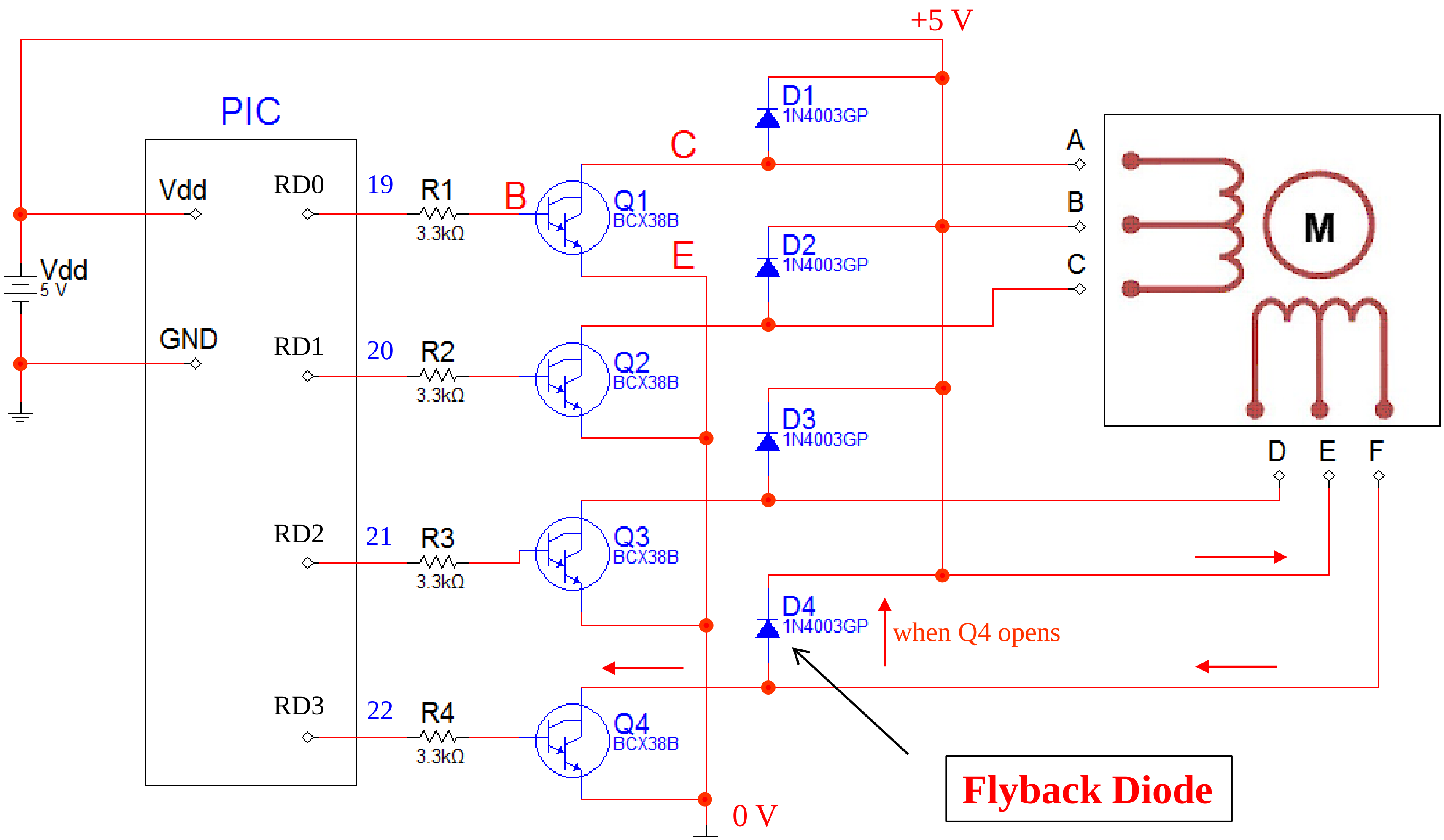
# Lab 8 Outline

1. Stepper Motor Fundamentals
2. Stepper Motor Classifications
3. Full Stepping, Half Stepping, and Micro-stepping
4. Lab 8 Setup

# Lab 8 Schematic



A **flyback diode** (also called a **snubber diode**, **commutating diode**, **freewheeling, or clamping diode**), is a diode used to eliminate **flyback**, which is the sudden voltage spike seen across an inductive load when its supply current is suddenly reduced or interrupted.



# 500 kV Circuit Switch Opening

# Stepper motors in the kits

**Caution**:

1. The stepper motors in the kits are from different manufacturers, often unidentified.

2. The numbers on them might not be part numbers.

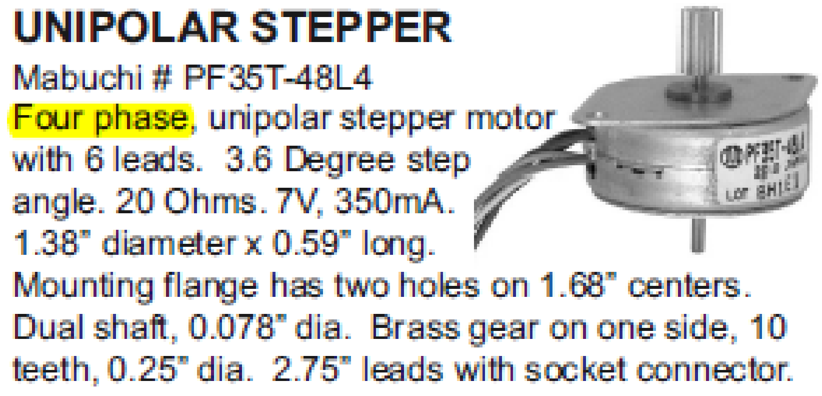
3. The colors of the lead wires vary.

4. Some of the lead wires are very thin stranded wire. They won't make a good connection. **Twisting the leads is not acceptable**. We have header pins that you can crimp on your motor leads.

5. When the program is halted, reset the program, otherwise the PORTD bits will continue to provide power to the motor, and the LM7805 regulator will become very hot depending on the motor specifications. It may also become very hot during motor operation.

# Stepper motors in the kits

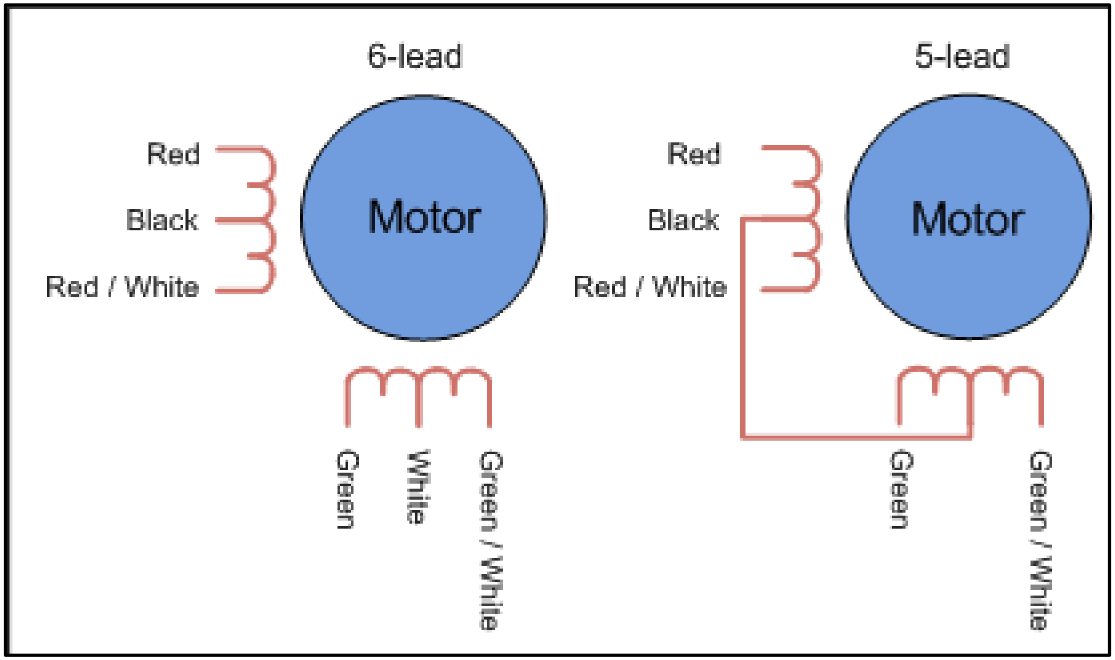
Mabuchi PF35T-48L4



**UNIPOLAR STEPPER**
Mabuchi # PF35T-48L4
Four phase, unipolar stepper motor with 6 leads. 3.6 Degree step angle. 20 Ohms. 7V, 350mA. 1.38" diameter x 0.59" long. Mounting flange has two holes on 1.68" centers. Dual shaft, 0.078" dia. Brass gear on one side, 10 teeth, 0.25" dia. 2.75" leads with socket connector.

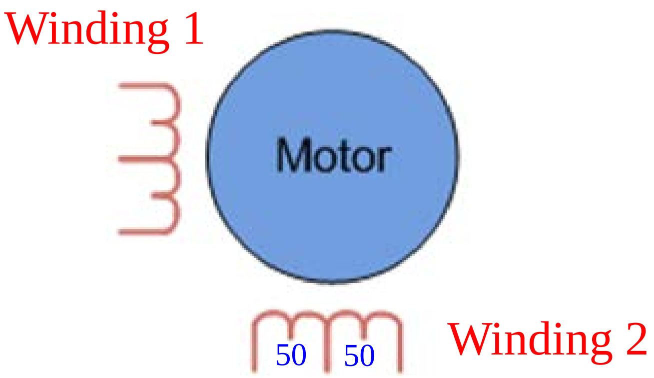
Note: Some manufacturers call
a two-phase unipolar stepper motor
a four-phase motor.

# Two-phase, Unipolar Schematic

Your motor may have 5 or 6 leads.
**Colors may vary.**



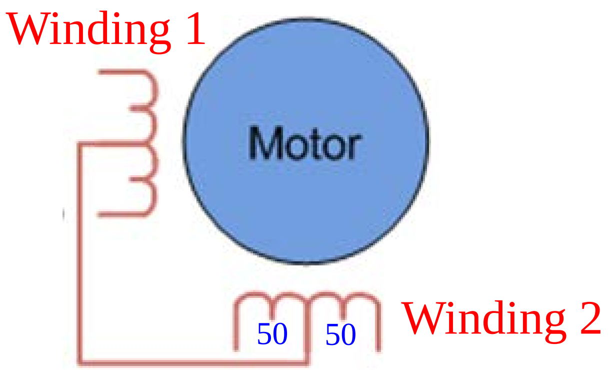
# Determining Lead Connections for 6-Lead Motor




50 ohms is typical. Your motor may be different.

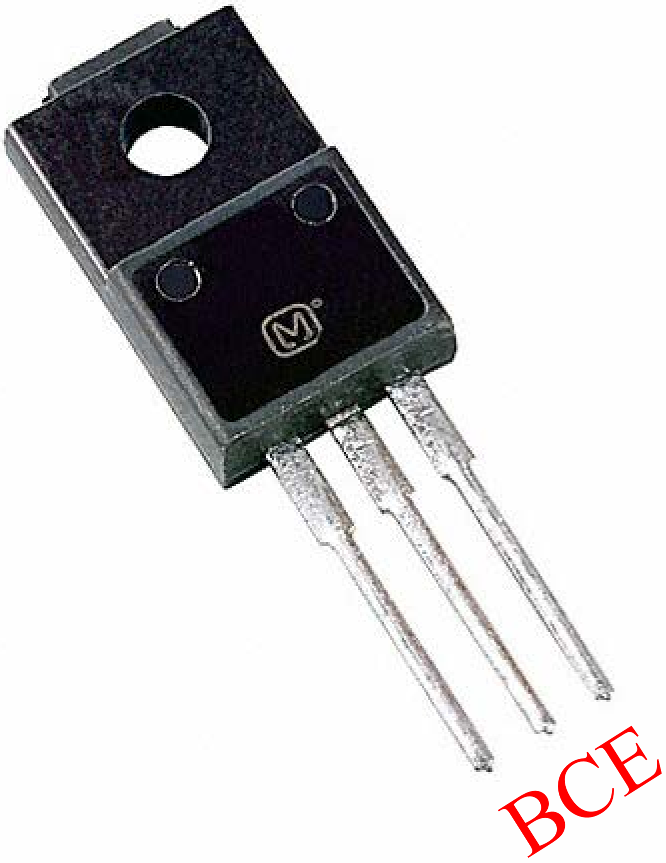
1. Choose any lead X. It will be a center tap or an end lead.
2. Check the resistance between X and any other lead.
3. The resistance will be infinity, 50, or 100 ohms.
4. If two of the resistances are 50 ohms, then X is a center tap.
5. Otherwise, X is an end lead and one of the others is a center tap.
6. After identifying the center taps, the end leads may have to be swapped to obtain proper motor rotation.

# Determining Lead Connections for 5-Lead Motor

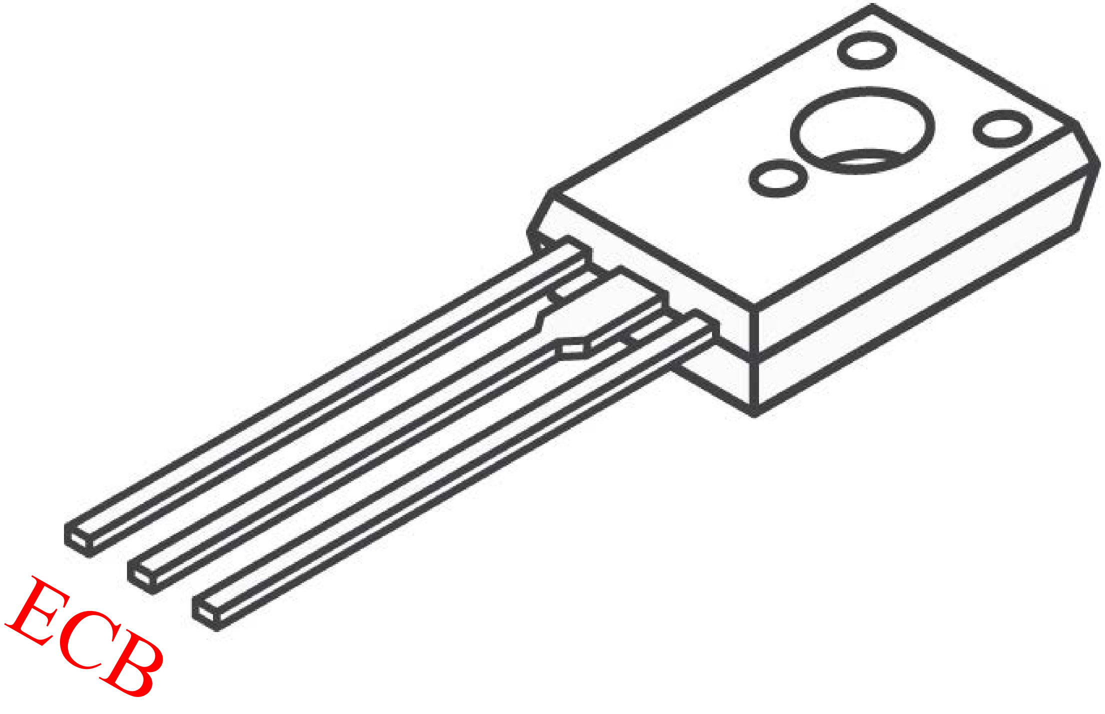


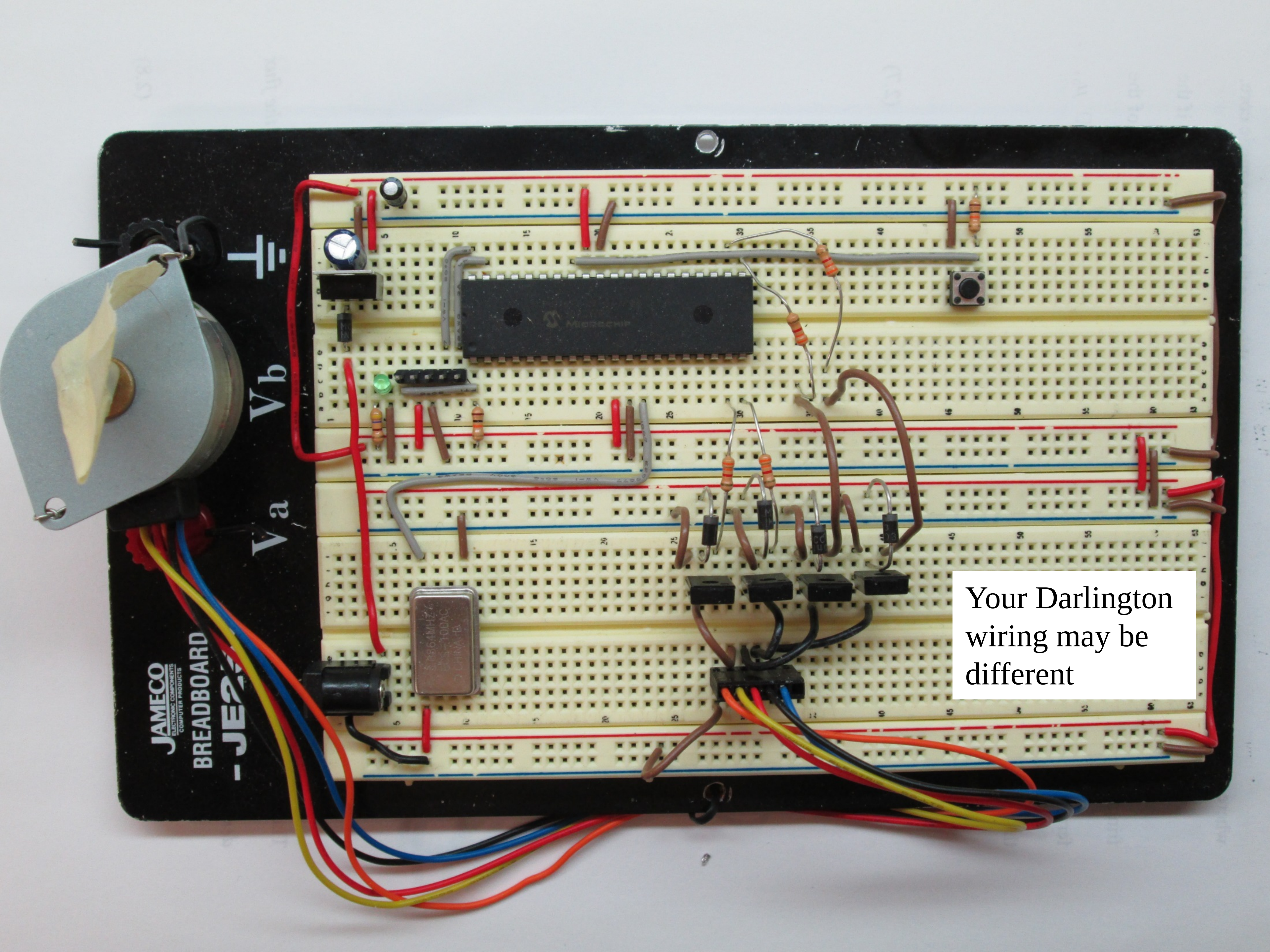

1. Choose any lead X. It will be a center tap or an end lead.
2. Check the resistance between X and any other lead.
3. The resistance will be 50 or 100 ohms
4. If all of the resistances are 50 ohms, then X is the center tap.
5. Otherwise, X is an end lead and one of the others is the center tap.
6. After identifying the center tap, the end leads may have to be swapped to obtain proper motor rotation.

# Panasonic 2SD1276A

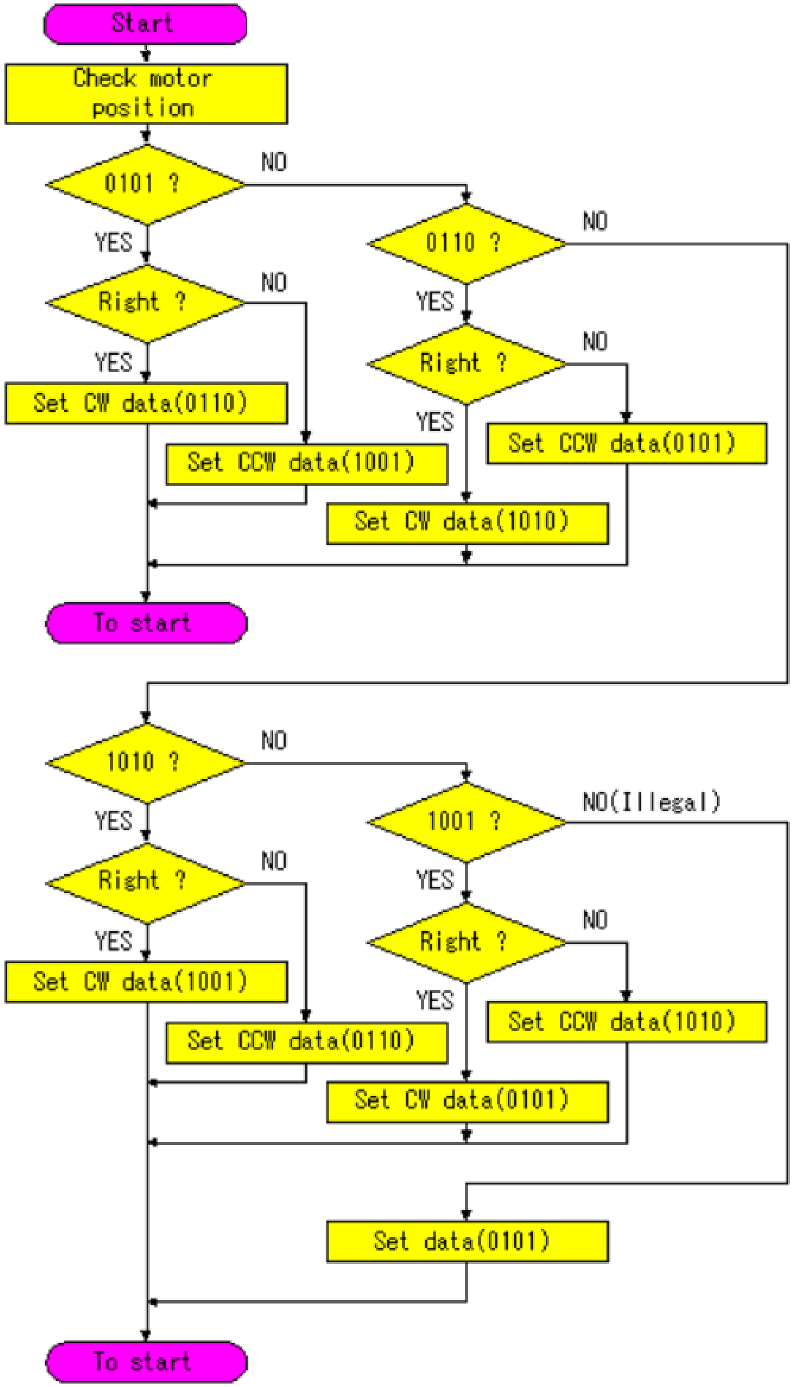


# Fairchild BD679A




Your Darlington wiring may be different
JAMECO
BREADBOARD
Vb
Va

# Step Control Flow Chart Two-Coil Excitation, Full-Step, High Torque




Rotate Left (CCW)

| Winding 1 | | Winding 2 | |
|---|---|---|---|
| Q1 | Q2 | Q3 | Q4 |
| 0 | 1 | 0 | 1 |
| 1 | 0 | 0 | 1 |
| 1 | 0 | 1 | 0 |
| 0 | 1 | 1 | 0 |
| 0 | 1 | 0 | 1 |
| 1 | 0 | 0 | 1 |
| 1 | 0 | 1 | 0 |
| 0 | 1 | 1 | 0 |

Rotate Right (CW)

Modes: CCW, CW, Stop

# Undocumented Instructions

1. Alternative mnemonics for standard instructions
2. Instructions that were not fully implemented/tested
3. Product line mergers/compatibility issues (portability)
4. Used to facilitate development
5. Not recommended for new designs (liability)
6. See MPASM Quick Reference Card for more pseudo-instructions

- Suppose the result of some instruction sets or clears the Z-bit.
- `bz`: (branch if result is zero) **if Z = 1, branch to <label>**

```
bz  <label>  ⇔  btfsc  STATUS, Z
                goto   <label>
```

- `bnz`: (branch if result is not zero) **if Z = 0, branch to <label>**

```
bnz  <label>  ⇔  btfss  STATUS, Z
                 goto   <label>
```

# Lab08a.asm

```
;******************************************************************
;
; Assembler Directives
;******************************************************************
;

WaitTime          equu      d'50'   ; Wait 50 ms between each motor step
```

# Lab08a.asm

```
INIT
        banksel     TRISD               ; Set RD0, RD1, RD2, RD3 as outputs
        movlw       0xF0                ; for motor drive
        movwf       TRISD

        banksel     PORTD
        clrf        mode                ; mode = 0 = stop
        clrf        count1              ; Clear counter
        clrf        count2              ; Clear counter

        movlw       Position1
        movwf       PORTD               ; Write PORTD, move to Position1
Start
        movlw       d'2’              ; mode = 2 = rotate CCW
        movwf       mode
drive
        movf        mode, W           ; Read mode. mode = 0 = stop
        bz          Start             ; Branch on zero. If W = 0, goto Start
```

# Lab08a.asm

```
        movlw   WaitTime     ; Set loop count (1 msec units)
        movwf   count1       ; count1 = WaitTime  = 50 (msec)

loop    call    timer        ; timer = 1 msec delay
        decfsz  count1, F    ; count 1 – 1 = 0 ?
        goto    loop         ; No. Continue

        movf    PORTD, W     ; Read PORTD
        sublw   Position1
        bnz     drive2       ; PORTD != Position1
        movf    mode, W      ; Read mode
        sublw   d'1'         ; CW ?
        bz      drive1       ; Yes. CW
        movlw   Position2
        goto    drive_end    ; Jump to PORTD write
......

drive_end
        movwf   PORTD        ; Write PORTD
        goto    start        ; Jump to start
```

First time through:
mode = 2 = CCW
PORTD = Position1 → Position 2

```
        movlw   WaitTime    ; Set loop count (1 msec units)
        movwf   count1      ; Save loop count
loop    call    timer       ; Wait 1 msec
        decfsz  count1, F   ; count – 1 = 0 ?
        goto    loop        ; No. Continue
        movf    PORTD, W    ; Read PORTD
        sublw   Position1
   1    bnz     drive2      ; Unmatch
        movf    mode, W     ; Read mode
        sublw   d'1’        ; CW ?
   2    bz      drive1      ; Yes. CW
        movlw   Position2
        goto    drive_end   ; Jump to PORTD write
drive1  movlw   Position4   ; Set CW data
        goto    drive_end   ; Jump to PORTD write
drive2  movf    PORTD, W    ; Read PORTD
        sublw   Position4
   3    bnz     drive4      ; Unmatch
        movf    mode, w     ; Read mode
        sublw   d'1‘        ; CW ?
   4    bz      drive3      ; Yes. CW
        movlw   Position1
        goto    drive_end   ; Jump to PORTD write
```

Second time through:
mode = 2
PORTD =
Position2

```
drive3      movlw   Position3   ; Set CW data
            goto    drive_end   ; Jump to PORTD write
drive4      movf    PORTD, W    ; Read PORTD
            sublw   Position3
         5  bnz     drive6      ; Unmatch
            movf    mode, W     ; Read mode
            sublw   d'1'        ; CW ?
         6  bz      drive5      ; Yes. CW
            movlw   Position4
            goto    drive_end   ; Jump to PORTD write
drive5      movlw   Position2   ; Set CW data
            goto    drive_end   ; Jump to PORTD write
drive6      movf    PORTD, W    ; Read PORTD
            sublw   Position2
         7  bnz     drive8      ; Unmatch
            movf    mode, W     ; Read mode
            sublw   d'1'        ; CW ?
         8  bz      drive7      ; Yes. CW
            movlw   Position3
            goto    drive_end   ; Jump to PORTD write
drive7      movlw   Position1   ; Set CW data
            goto    drive_end   ; Jump to PORTD write
drive8      movlw   Position1
drive_end   movwf   PORTD       ; Write PORTD
            goto    start       ; Jump to start
```

Second time through:
mode = 2
PORTD = Position2
→ Position3

End of Lab 8