DC and Stepper Motors, and RC Servos

DC MOTORS

Faraday demonstrated in the mid-19th century

Simple operation:

- More voltage translates to more speed
- Reverse voltage to reverse direction

With the introduction of AC power in the early 20th century, AC motors have displaced DC motors in many applications

Since DC motors are easier to control, they are still retained in difficult control applications

DC MOTORS

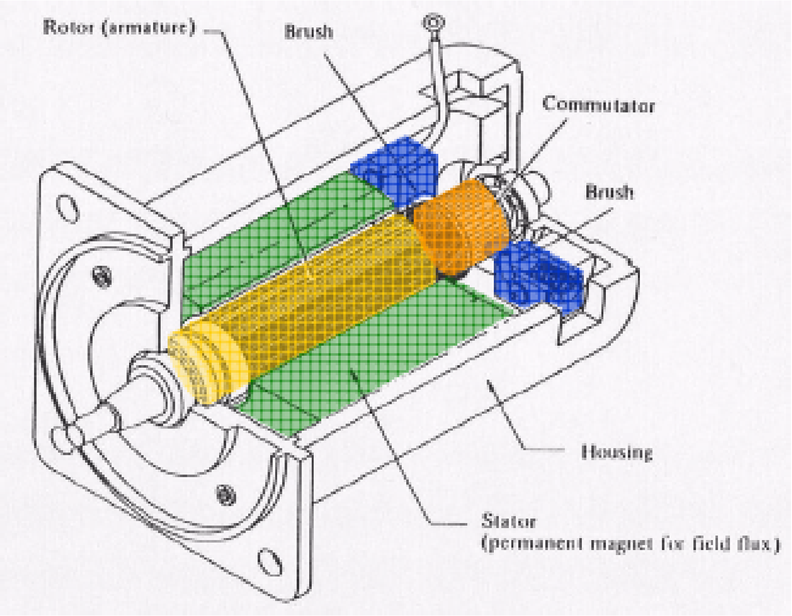
Two basic mode of operation:

- Current (torque) mode – controlling current *through* winding
- Voltage (velocity) mode – controlling voltage *across* winding

Operating principle:

- Torque Generation
  - Current-carrying conductor in magnetic field will induce electro-magnetic force acting on the conductor.
- Back-Electromagnetic Force (EMF)
  - Electric potential will be generated across moving conductor in magnetic field.

DC MOTORS



Motors are actuation devices (actuators) that generate ***torque*** as actuation.

Terminology

Electrical Terms

- **Field System**: the part of the motor that provides the magnetic flux.
- **Armature**: the current-carrying part of the motor that interacts with the magnetic flux to produce torque.

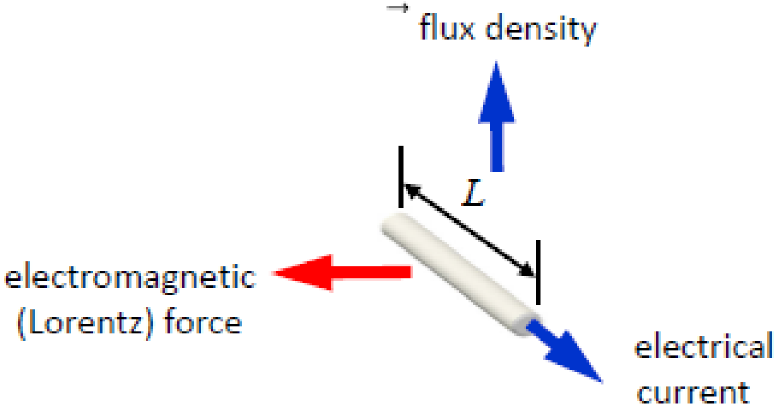
Mechanical Terms

- **Rotor**: rotating part of the motor.
- **Stator**: stationary part of the motor.
- **Commutator**: part of rotor in contact with the brushes
- **Brushes**: part of electrical circuit through which current is supplied to armature.

PRINCIPLES OF OPERATION

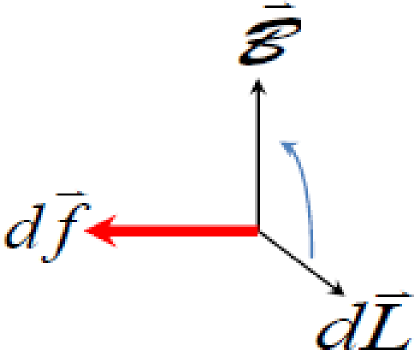
Torque Generation

- Needs two elements:
  - ➢ Magnetic field
  - ➢ Electrical current

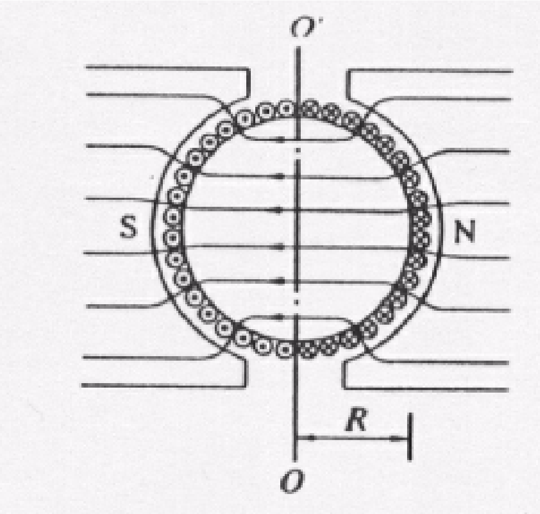


- A conductor in a magnetic field with current flowing through it is subject to a resultant force.

→ →



PRINCIPLES OF OPERATION



Let N be the number of coils in the motor. The total torque generated from the N coils is:

$$\begin{aligned} T_M &= N \cdot (2 \cdot i \cdot B \cdot L \cdot R) \\ &= 2 \cdot (N \cdot B \cdot L \cdot R) \cdot i \end{aligned}$$

For a given motor, (N, $\mathcal{B}$, L, R) are fixed. We can define

$$K_T = 2 \cdot N \cdot B \cdot L \cdot R \qquad [\mathrm{Nm/A}]$$

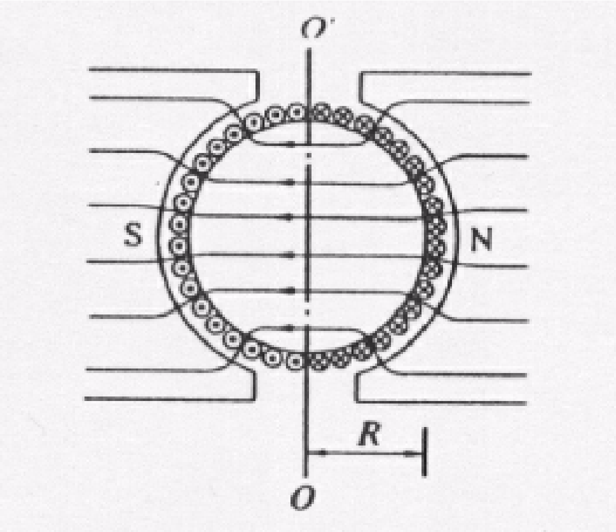
as the *torque constant* of the motor.

The torque generated by a DC motor is proportional to the armature current i_a :

$$\boxed{T_M = K_T \cdot i_a}$$

PRINCIPLES OF OPERATION

For a DC motor, it is desirable to have a large K_T . However, size and other physical limitations often limit the achievable K_T.

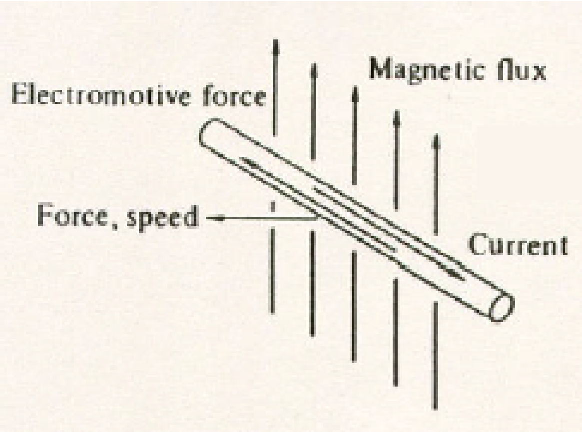


Large K_T suggests:

- Large (N, L, R).
  (N, L, R) are limited by the size and weight of the motor.
- Large $\mathscr{B}$:
  Need to understand the methods of generating flux ...

PRINCIPLES OF OPERATION

Back-EMF Generation



- Electromotive force (EMF) is generated in a conductor moving in a magnetic field:

$$de_{EMF} = (\vec{v} \times \vec{B}) \cdot d\vec{L}$$

- Integrate over the entire length L:

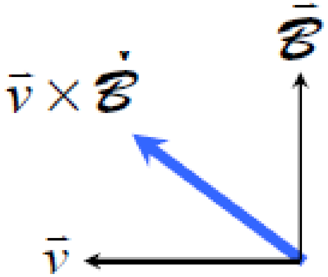
$$e_{EMF} = v \cdot B \cdot L$$

- Since the N armature coils are in series, the total EMF is:

$$V_{EMF} = \underbrace{2N(R\omega)}_{v} BL \;= (2 \cdot N \cdot R \cdot B \cdot L) \cdot \omega$$

- Define the Back-EMF Constant K_{EMF}:

$$K_{EMF} = 2 \cdot N \cdot R \cdot B \cdot L \quad [\mathrm{V/(rad/sec)}]$$



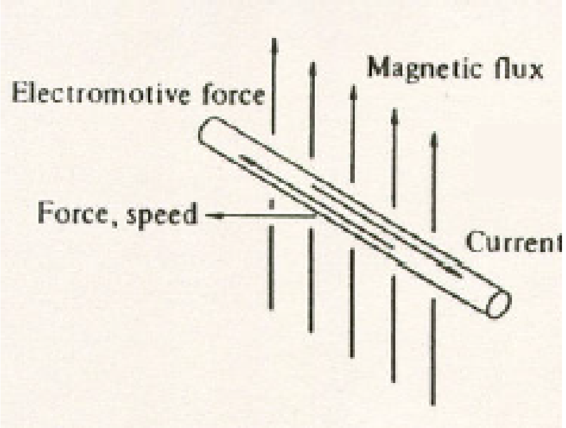
PRINCIPLES OF OPERATION

Back-EMF Generation

- Back-EMF Constant K_{EMF}:

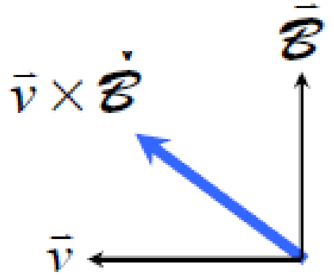
$$K_{EMF} = 2 \cdot N \cdot R \cdot B \cdot L \quad [\mathrm{V/(rad/sec)}]$$

Note: *$K_T = K_{EMF}$ only if SI units are used !*



- Back-EMF generated due to the rotation of the motor armature is opposing the applied voltage and is proportional to the angular speed w of the motor:

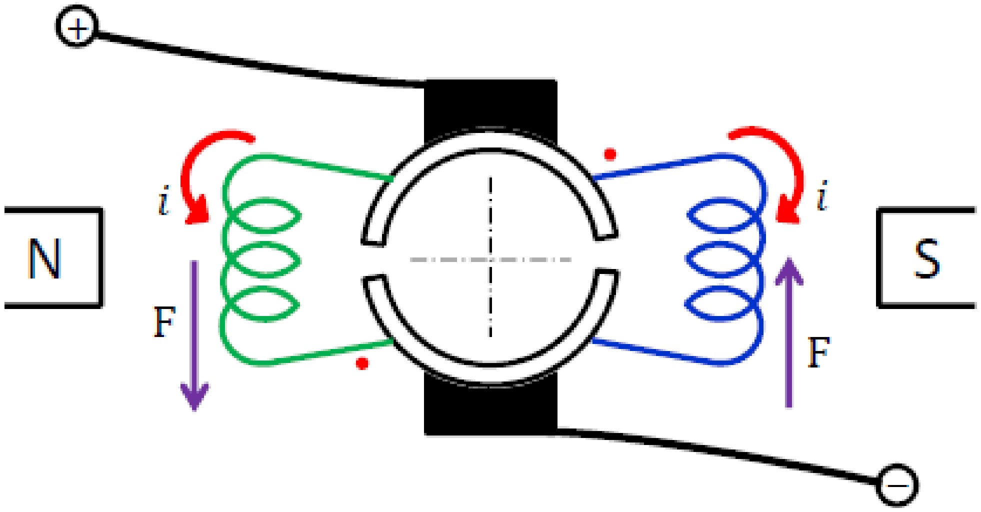
$$\boxed{V_{EMF} = K_{EMF} \cdot \omega}$$



PRINCIPLES OF OPERATION

Commutation

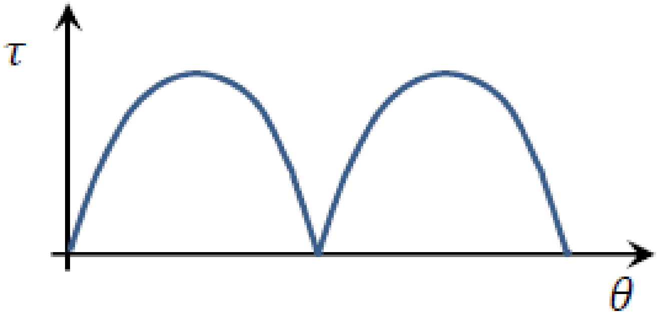
- To keep torque from reversing, the commutator changes current direction at point where torque is zero. This effect is achieved with *brushes*.



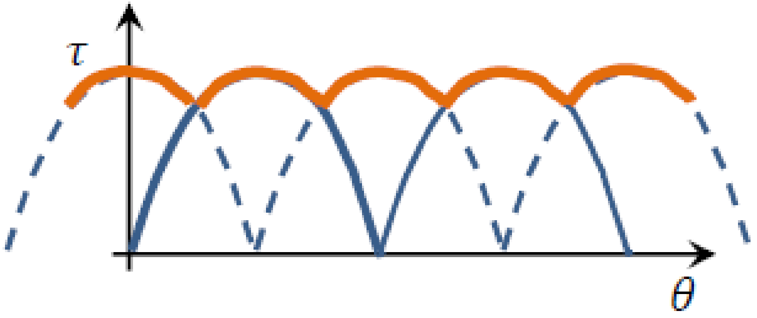
PRINCIPLES OF OPERATION

Commutation

- Brush commutation amounts to a mechanical switching control system.
- To avoid top-dead-center problem and make more uniform torque generation, multi-coil rotors are always used.



Single Phase, Two Pole



Two Phase, Four Pole

OPERATING ISSUES

Brushes

- Wear out
- Generate electrical noise
- Limit maximum voltage

Temperature

- Heat is primary performance limitation for DC motors
- Sources:
  - Electrical losses in windings
  - Eddy current
  - Hysteresis
  - Friction
  - Brush contact resistance
- Detailed analysis needs to separate the rotor and motor housing
- Transient temperature limit is very different from steady-state limits (what is on the spec.)

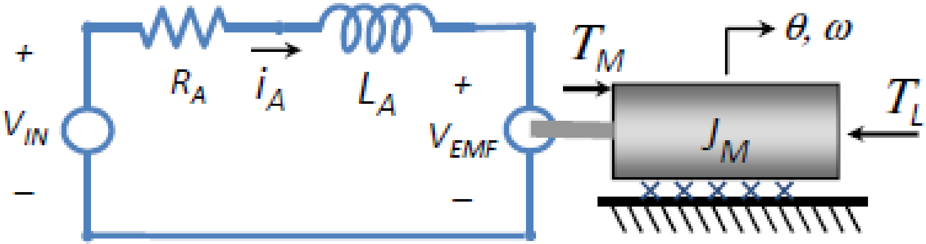
FUNDAMENTAL RELATIONSHIPS

- Torque Generation

$$T_M = K_T \cdot i_A$$

- Back-Electromagnetic Force (EMF)

$$V_{EMF} = K_{EMF} \cdot \omega_M$$



In SI units, $K_T = K_{EMF}$

OPERATING CHARACTERISTICS

From a ***control*** view of a DC motor

- We treat the "motor" as a box that is lossless and stores no energy. In reality, there exist power losses due to internal resistance and friction.

- At steady state (why?), power flow on the mechanical and electrical sides instantaneously match

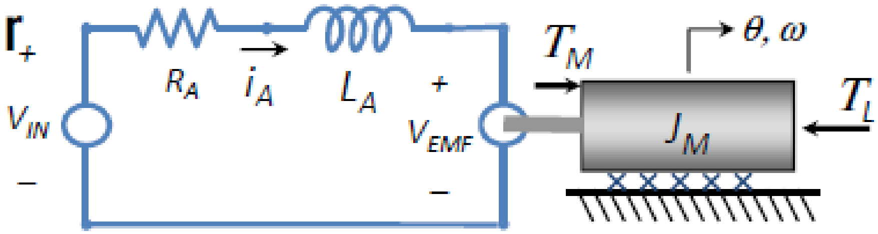
$$P = \underbrace{V_{IN} \cdot i}_{\substack{Electrical \\ power}} = \underbrace{T \cdot \omega}_{\substack{Mechanical \\ power}}$$

During constant speed operation, the input voltage is equal to the back-EMF generated by the motor, since $T = K_T \cdot i$ and $K_{EMF} = K_T$. Hence, by maintaining a constant supply voltage of $V_{IN} = K_{EMF} \cdot \omega$, we can achieve a constant output speed

Q: Does the load on the mechanical side affect the steady-state speed?

TORQUE-SPEED CHARACTERISTICS

Permanent Magnet DC Motor



Equivalent circuit:

$$V_{IN} = i_A \cdot R_A + V_{EMF} + \cancel{L_A \frac{d}{dt}} i_A$$

At steady-state:

$$V_{IN} = i_A \cdot R_A + V_{EMF} = T_M \cdot \frac{R_A}{K_T} + K_{EMF} \cdot \omega$$

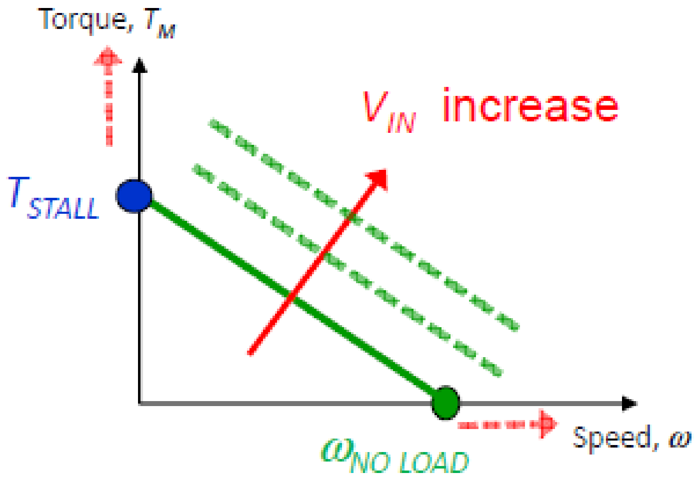
$$\Rightarrow T_M = -\frac{K_T K_{EMF}}{R_A} \cdot \omega + \frac{K_T}{R_A} \cdot V_{IN}$$

- Stall Torque (ω = 0):

$$T_{STALL} = \frac{K_T}{R_A} \cdot V_{IN}$$

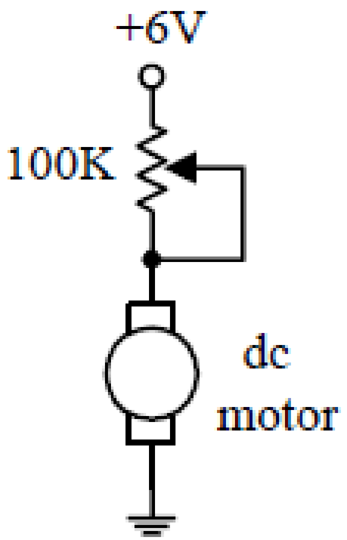
- No-Load Speed (T_M = 0):

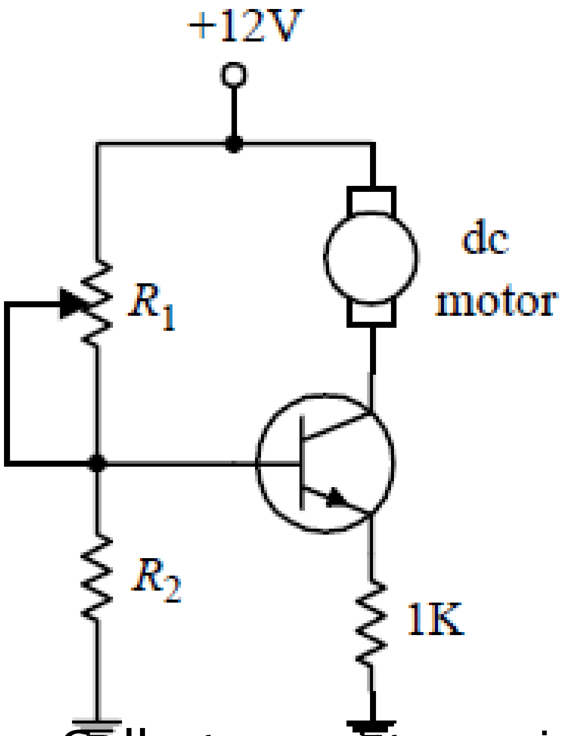
$$\omega_{NO\ LOAD} = \frac{V_{IN}}{K_{EMF}}$$



Speed Control DC Motor

Bad Designs



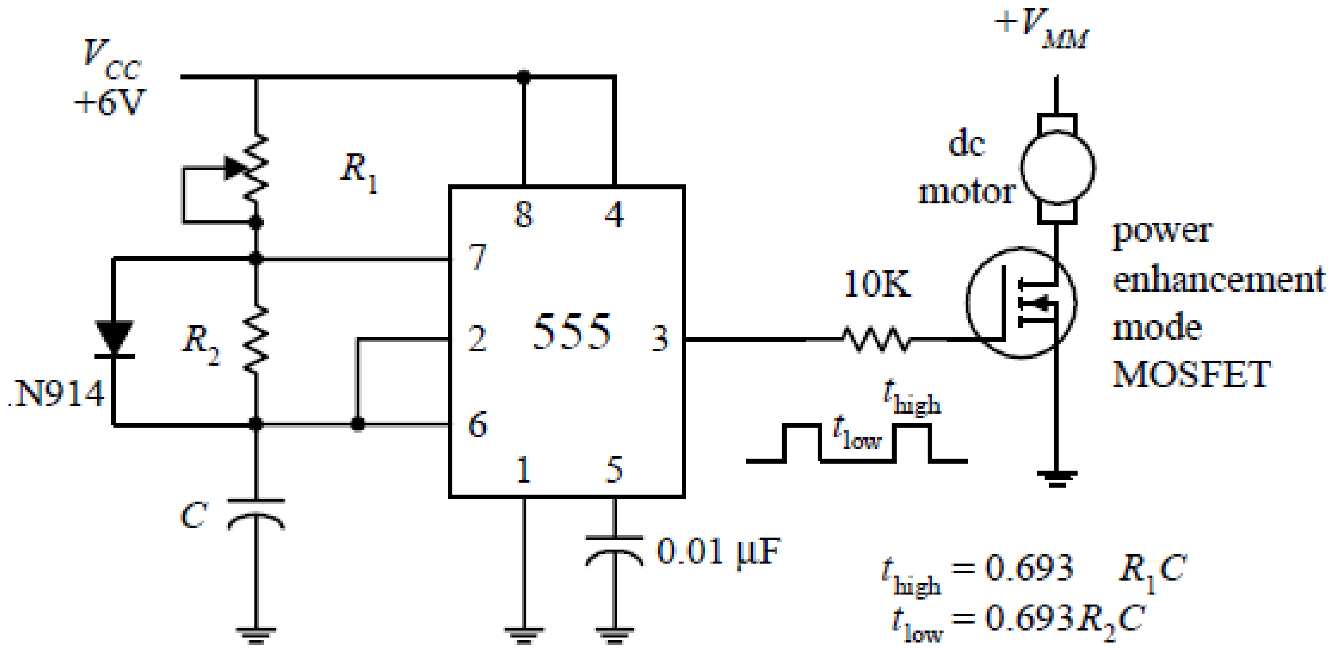


Pot. Resistance increases, the amount of energy that must be converted to heat increases –it consumes supply power and may lead to pot. meltdown

Collector emitter resistance increases, transistor must dissipate considerable amount of heat. This can lead to trans. meltdown

Better Designs.....

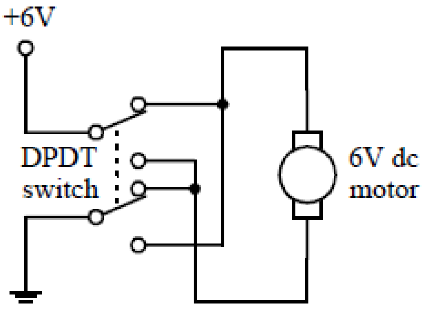
555 Timer/MOSFET Control Circuit

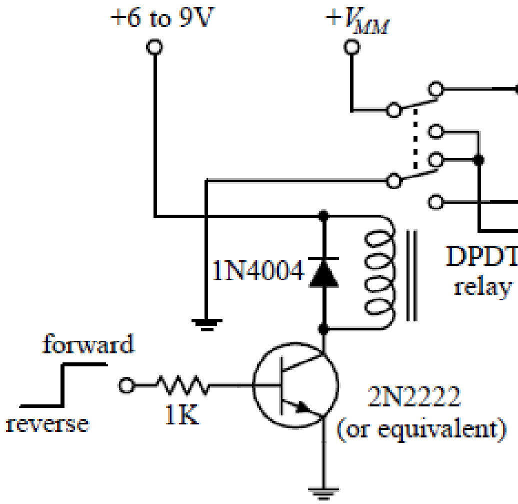


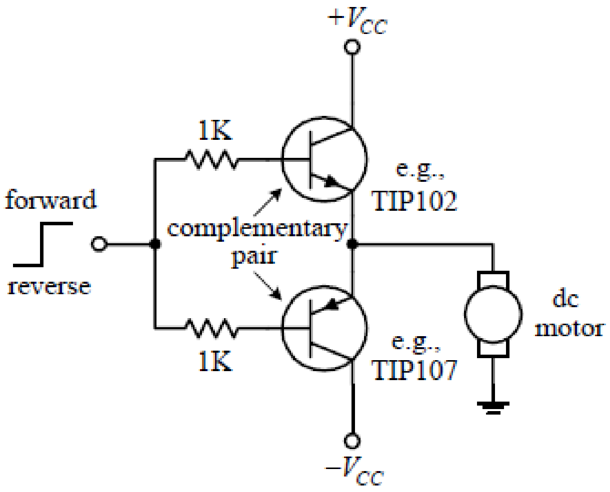
$$t_{high} = 0.693 \quad R_1C$$
$$t_{low} = 0.693R_2C$$

To prevent component melt-down, solution is sending the motor short pulses of current by varying the width and frequency

Directional control of DC Motors

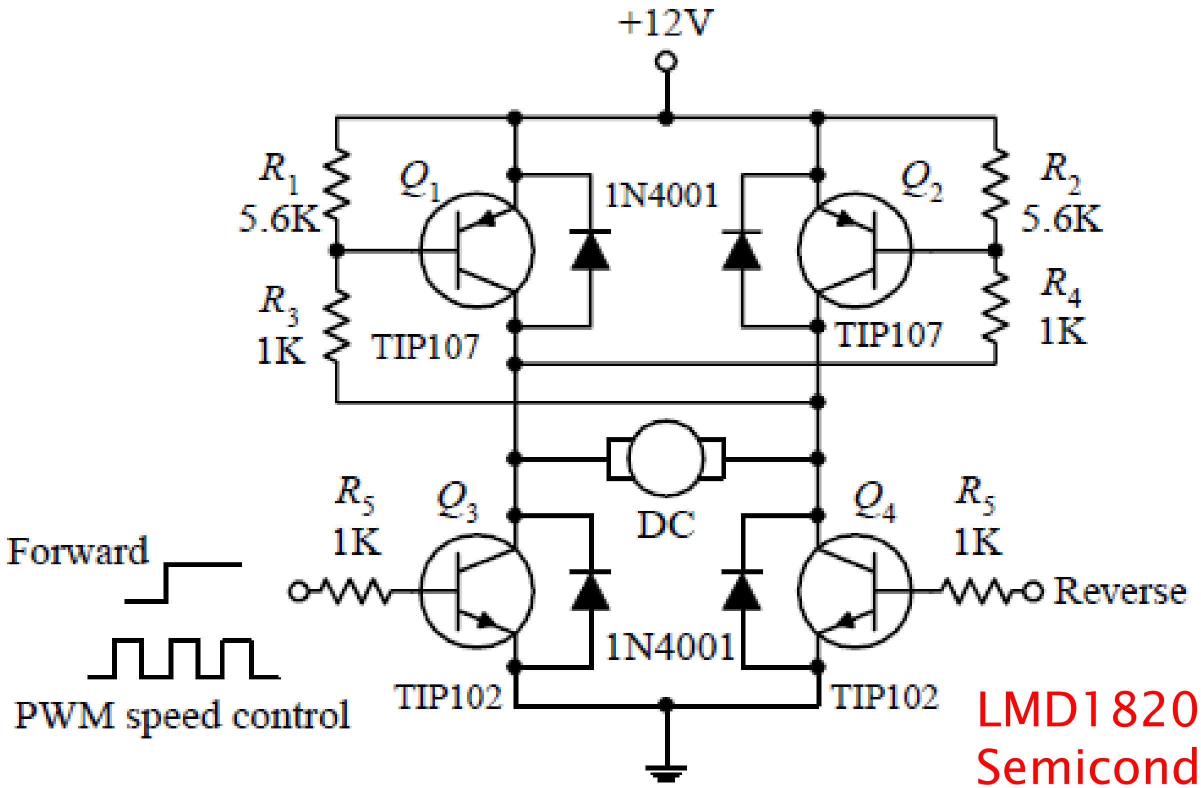




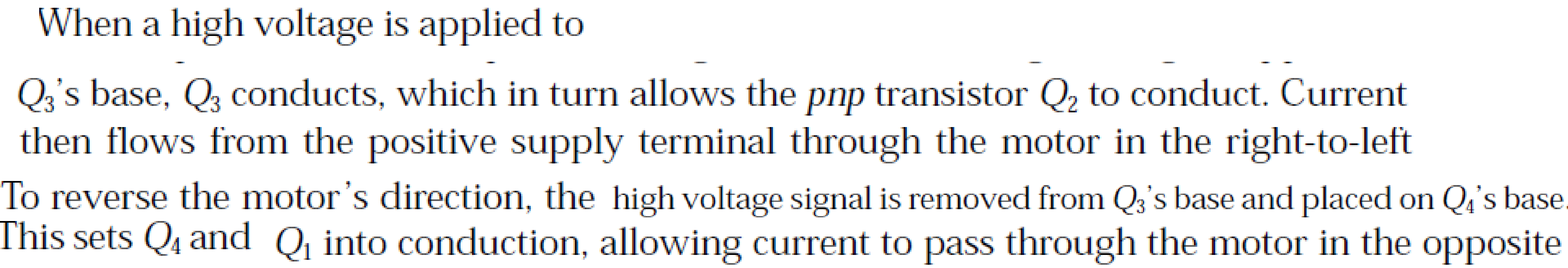


Double Pole Double Throw switch

H-Bridge



LMD18200 National Semiconductor H-Bridge



When a high voltage is applied to

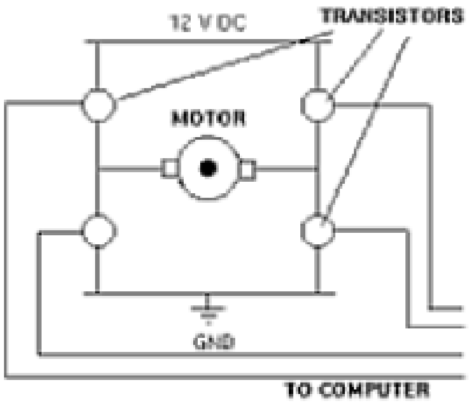
Q_3's base, Q_3 conducts, which in turn allows the *pnp* transistor Q_2 to conduct. Current then flows from the positive supply terminal through the motor in the right-to-left

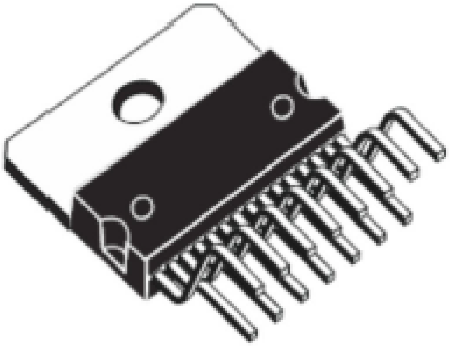
To reverse the motor's direction, the high voltage signal is removed from Q_3's base and placed on Q_4's base. This sets Q_4 and Q_1 into conduction, allowing current to pass through the motor in the opposite

MOTOR DRIVERS (AMPLIFIERS)

PWM Amplifier

- Full H-Bridge
  - Bipolar operation with unipolar supply voltage.
  - PWM operation implies a cooler and more efficient drive.
  - Easily interface with digital control signals.
  - H-Bridge chips, such as the L298, are commercially available.

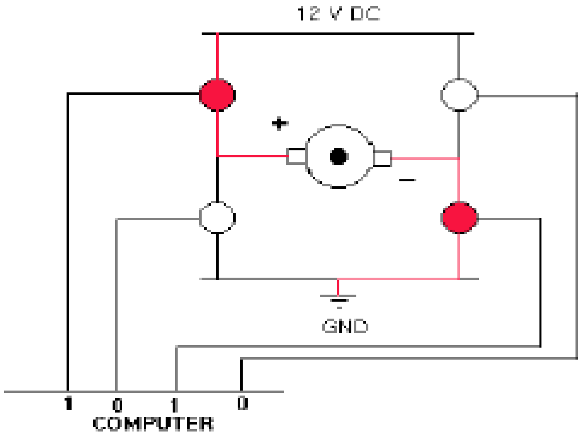




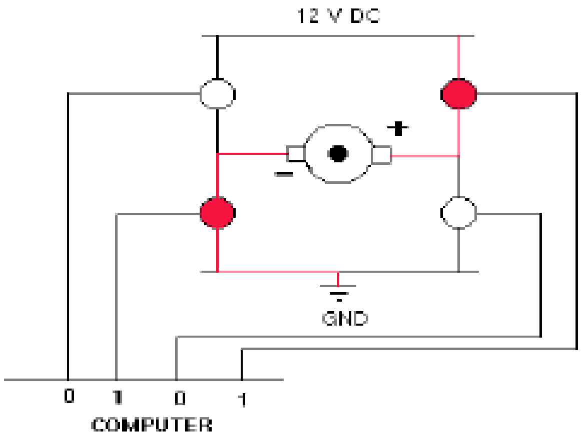
L298 Multiwatt15 package

MOTOR DRIVERS (AMPLIFIERS)

H-Bridge Driver



Forward Operation

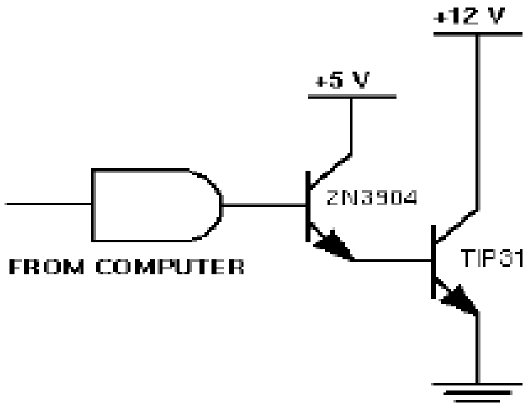


Reverse Operation

MOTOR DRIVERS (AMPLIFIERS)

PWM Amplifier

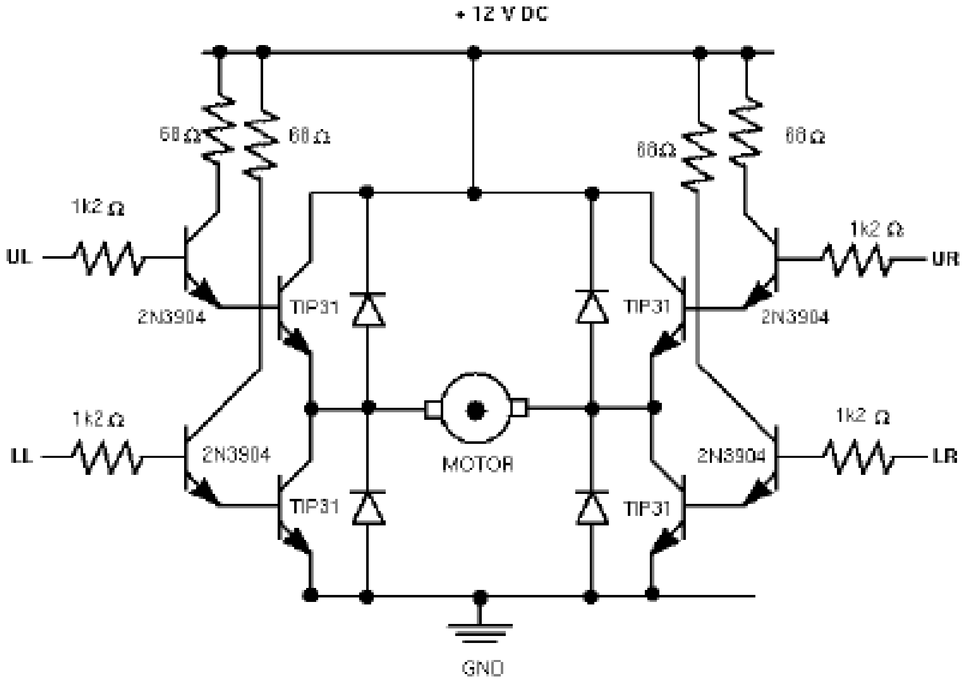
- Full H-Bridge Configuration
  - Darlington Connection
    - For low power applications (less than 0.5 Amp): can connect the digital part directly to analog transistors.
    - Darlington connection uses two stage amplification to bring the current capacity to about 1 Amp.



Darlington Transistor

MOTOR DRIVERS (AMPLIFIERS)

- Circuit Example

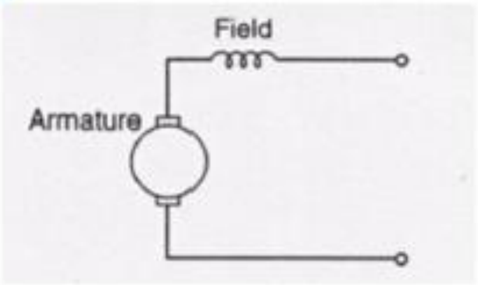


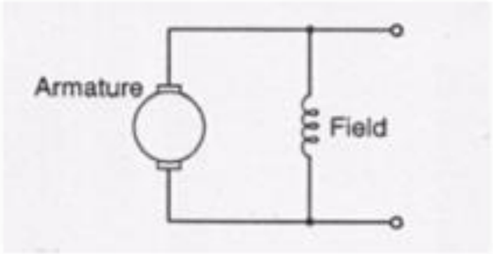
Upper Left	Upper Right	Lower Left	Lower Right	Description
On	Off	Off	On	Forward Running
Off	On	On	Off	Backward Running
On	On	Off	Off	Braking
Off	Off	On	On	Braking

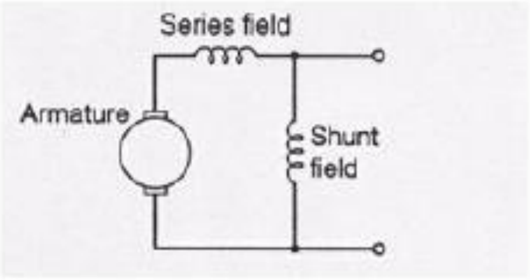
ALTERNATE SOURCES OF MAGNETIC FIELD

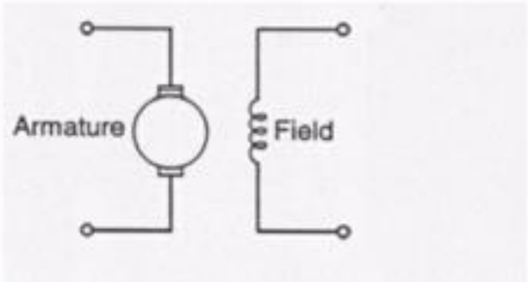
Field Coil Induced Magnetic Field

- Series Wound DC Motor
  - High starting torque and no-load speed
  - Poor speed regulation
  - Good for getting heavy loads moving
- Shunt Wound DC Motor
  - Low starting torque and no-load speed
  - Poor torque regulation
  - Nearly constant speed, regardless of load
- Compound DC Motor
  - High starting torque
  - Good speed and torque regulation
  - Combines good features of series and shunt
- Separately Excited DC Motor
  - High torque capabilities at low speeds





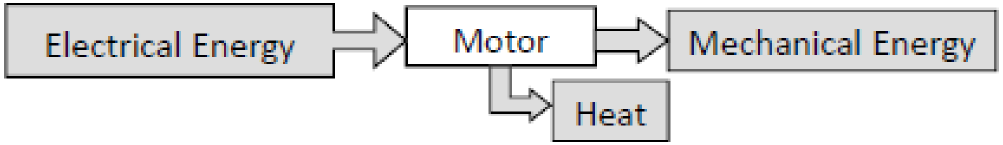




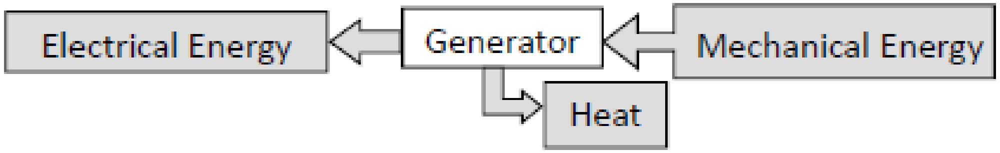
MODES OF OPERATION

Generator/Tachometer

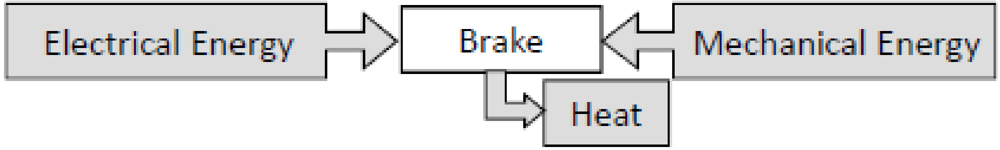
- The operating equations do not depend on direction of power flow:
  - Motor – Electrical power in → mechanical power out.



  - Generator – Mechanical power in → electrical power out.
    - When operated for its output power, it is called a generator.



    - Generator operating mode can be viewed as adding a load. Some application it is called a dynamometer or dynamic breaking.



- Can also be operated as a speed sensor:
  - Back-EMF is proportional to the speed of the rotor.
  - Measure open-circuit voltage across winding – *tachometer*.

Stepper Motor

STEPPER MOTORS

Stepper motors convert digital information to mechanical motion. Stepper motors rotate in distinct angular increments (steps) in response to the application of digital pulses to an electrical drive.

Three types:

- Permanent Magnet (PM)
- Variable Reluctance (VR)
- Hybrid

STEPPER MOTOR

Advantages:

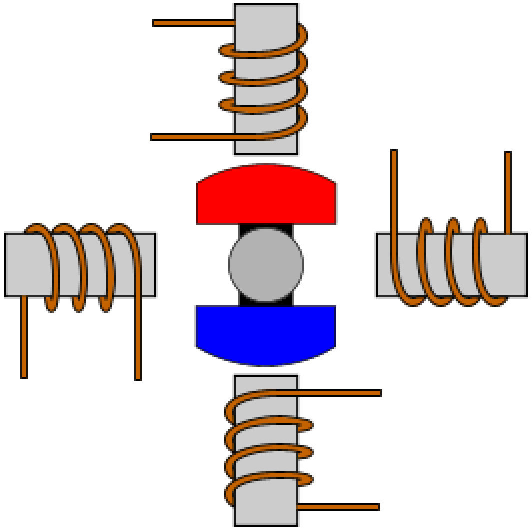
- Simplicity in construction
- Position control without feedback component
- Low maintenance

Disadvantages:

- Resonance effect and long settling time
- Heat (consume current regardless of load condition)
- Slower than servo (DC) systems
- Variable holding torque (cogging)

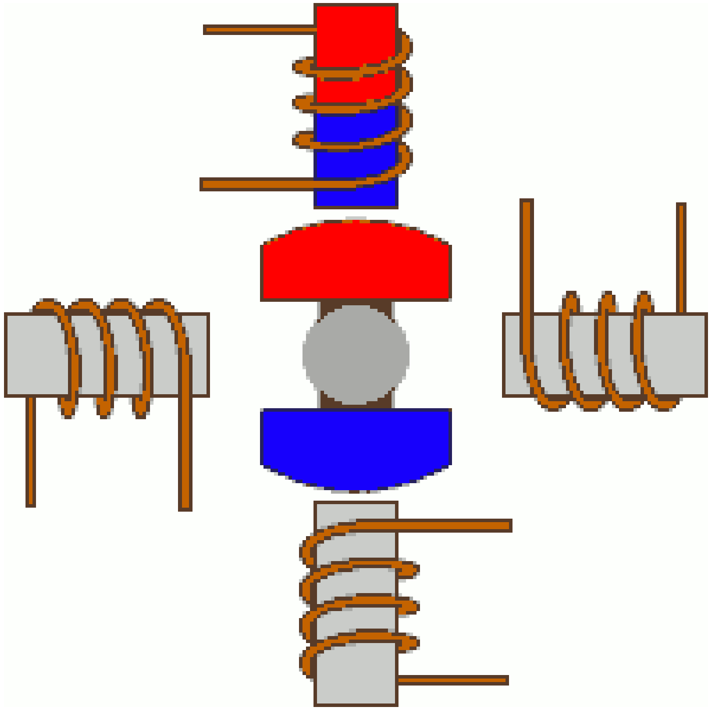
Stepper Motor

- As all motors, the stepper motors consists of a stator an a rotor. The rotor carries a set of permanent magnets, and the stator has the coils. The very basic design of a stepper motor would be as follows:



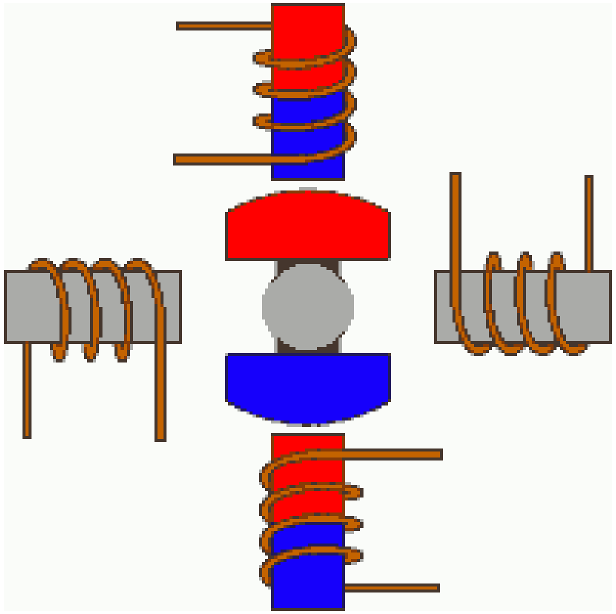
Concept of Operation –Single Coil Excitation

The coils are energized in series, with about 1sec interval. The shaft rotates 90º each time the next coil is activated:



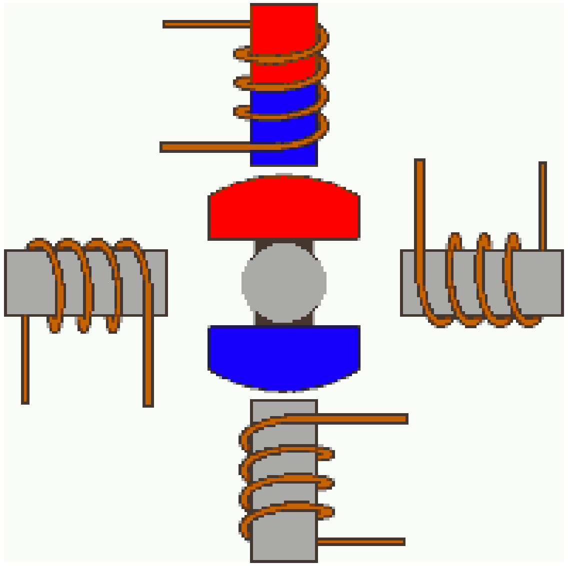
Full-Step Drive

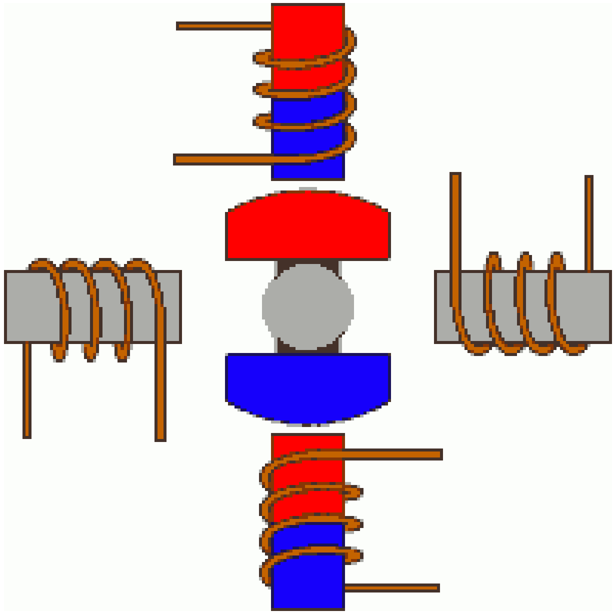
According to this method, the coils are energized in pairs. According to the connection of the coils (series or parallel) the motor will require double the voltage or double the current to operate that needs when driving with Single-Coil Excitation. Yet, it produces 100% the nominal torque of the motor.



Half-Stepping

This is a very interesting way to achieve double the accuracy of a positioning system, without changing anything from the hardware



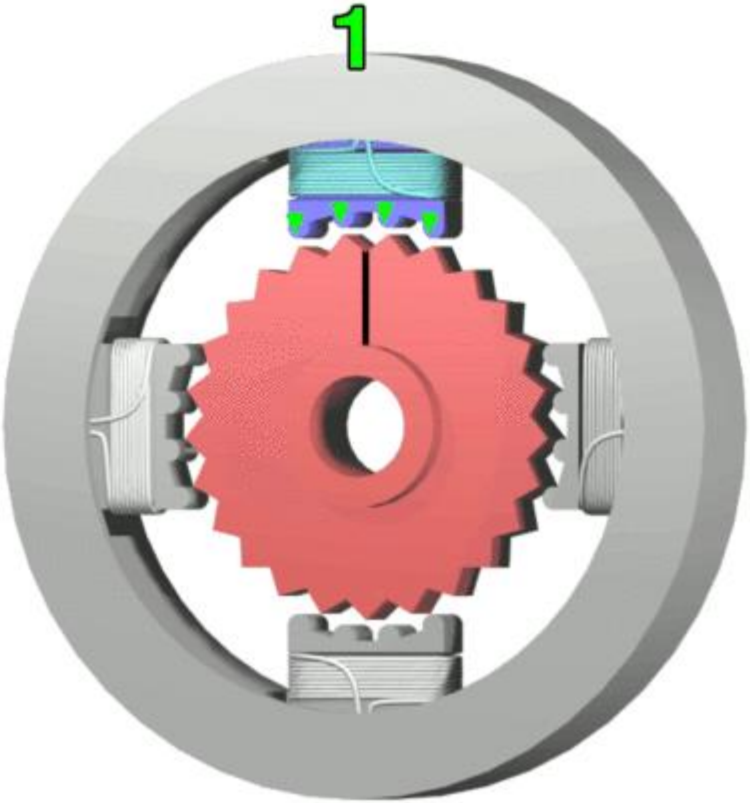


Two-Coil excitation

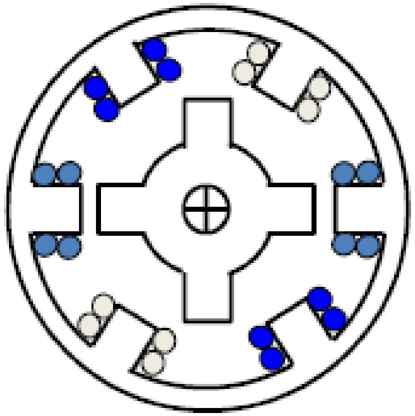
Single-Coil excitation

Simplified unipolar Stepper Motor

Frame 1: The top electromagnet (1) is turned on, attracting the nearest teeth of the gear-shaped iron rotor. With the teeth aligned to electromagnet 1, they will be slightly offset from right electromagnet (2). **Frame 2:** The top electromagnet (1) is turned off, and the right electromagnet (2) is energized, pulling the teeth into alignment with it. This results in a rotation of 3.6° in this example. **Frame 3:** The bottom electromagnet (3) is energized; another 3.6° rotation occurs. **Frame 4:** The left electromagnet (4) is energized, rotating again by 3.6°. When the top electromagnet (1) is again enabled, the rotor will have rotated by one tooth position; since there are 25 teeth, it will take 100 steps to make a full rotation in this example.



VARIABLE RELUCTANCE (VR) STEPPER



Replace the permanent magnet rotor with a teethed ferromagnetic rotor.

The motion and holding are results of minimization of the magnetic reluctance between the stator and the rotor poles.

Advantage:

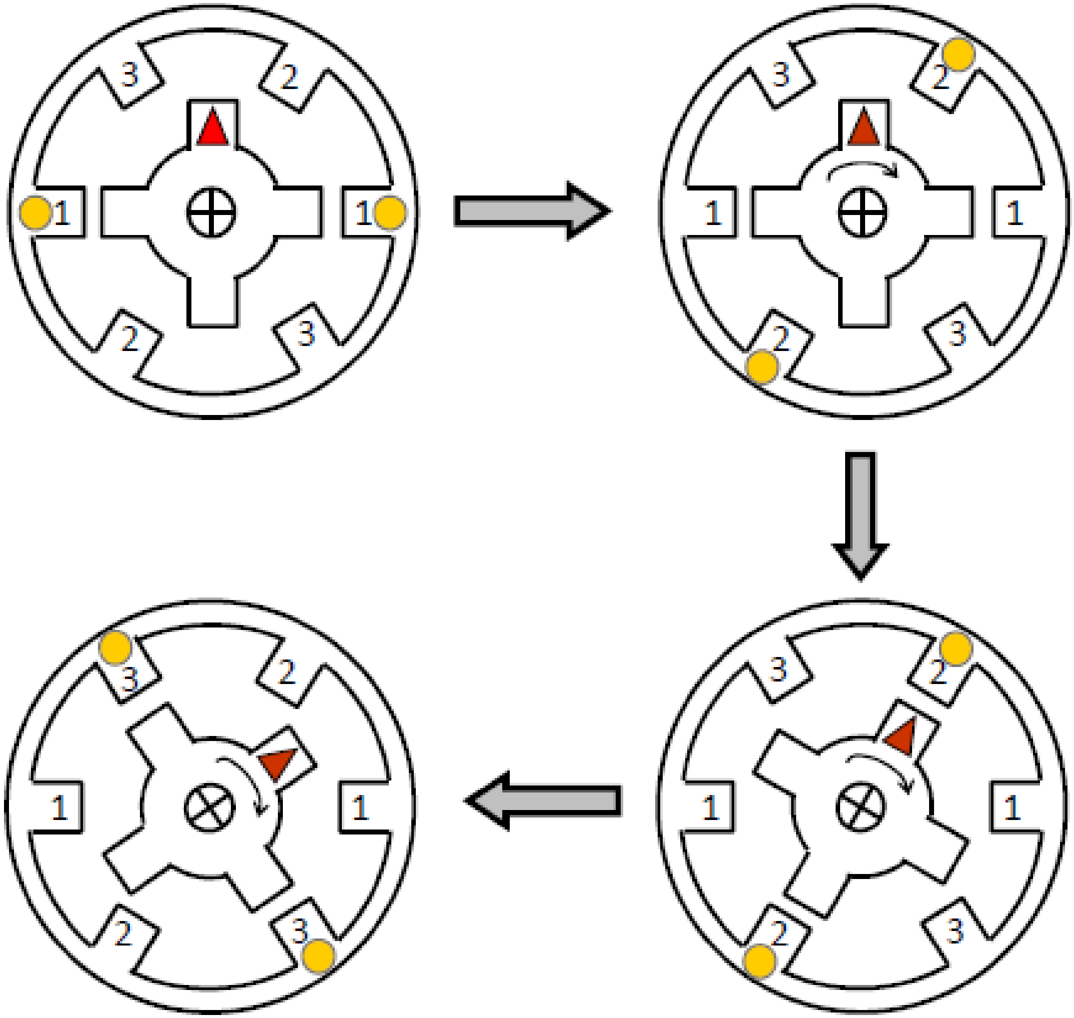
- Lower rotor inertia results in faster dynamic response.
- Gives double the step size for the same number of teeth.

Disadvantage:

- Low allowable load inertia.
- No holding torque when the windings are not energized – no detent torque.

VARIABLE RELUCTANCE (VR) STEPPER

Step Sequence

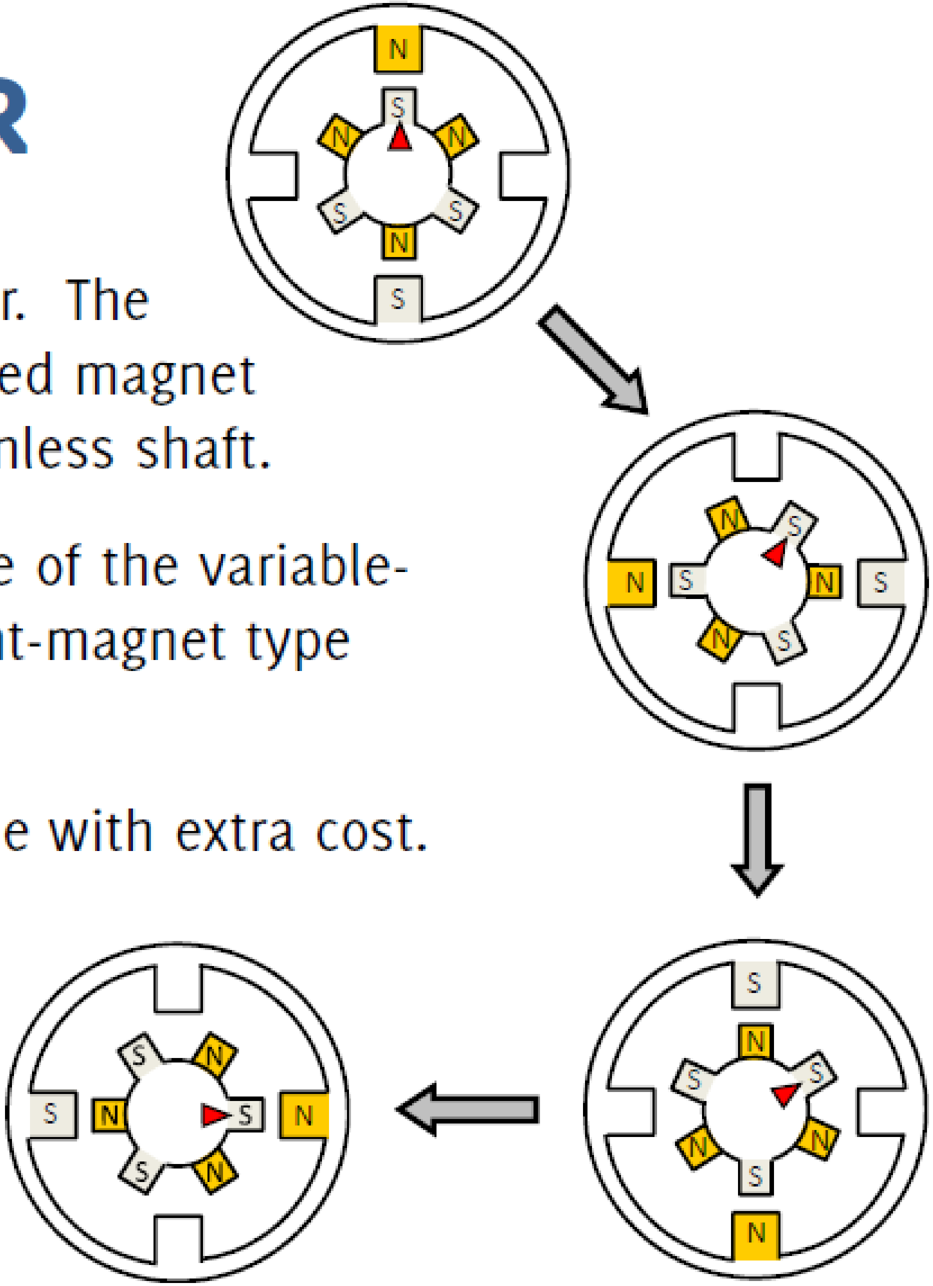


HYBRID STEPPER

Multi-toothed stator and rotor. The rotor has an axially magnetized magnet around its non-magnetic stainless shaft.

The configuration is a mixture of the variable-reluctance and the permanent-magnet type construction.

High accuracy and high torque with extra cost.



STEPPER/BRUSHLESS DIFFERENCES

Feedback

Brushless servomotors run in closed-loop mode, requiring a feedback device. Stepper motors do not require feedback.

Accuracy

If an unexpected load is encountered, a brushless motor will correct its position. A stepper motor will not recognize when its torque limit has been exceeded.

Speed

Brushless servomotors can run at much higher speeds (3000 to 6000 rpm) than steppers (1500 to 3000 rpm), and are not subject to the overheating phenomenon seen in steppers.

Simplicity

Stepper systems are easier to maintain because there are no feedback devices.

Cost

When comparing systems of the same torque capacity, a stepper system costs less than a brushless servo system.

Inertia Sensitivity

Brushless servomotors are more sensitive than stepper motors to fluctuations in load mass.

STEPPER/BRUSHLESS DIFFERENCES

Shaft Power
The largest stepper motors can deliver around 2000 W of shaft power. Brushless servomotors are capable of providing much higher power.

Resolution
Brushless servomotors usually have resolutions between 500 and 4000 counts/rev. Stepper motors are manufactured with nominal resolutions of 200 steps/rev. However, some stepper drives can achieve resolutions of 50000 pulses/rev.

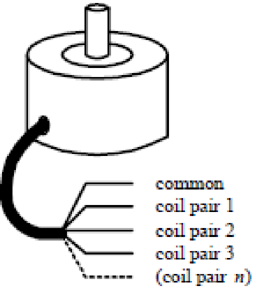
Digital Control
Stepper motors are well-suited to digital control from computers and other digital devices. Most brushless servomotors use an analog controller and resolver or encoder feedback, requiring a more sophisticated and costly controller.

Standardization
Nearly all stepper motors conform to the NEMA flange dimensions so they can be easily be replaced, even between different brands.

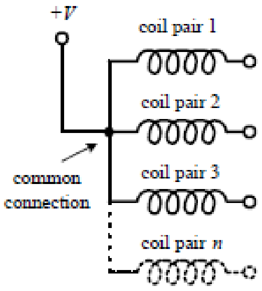
Noise
Stepper motors are inherently noisy, while brushless servomotors don't exhibit this problem.

Power Consumption
Stepper motors apply full rated motor current through the motor windings, no matter the applied load. A servomotor only consumes current as needed to achieve desired rotor positioning.

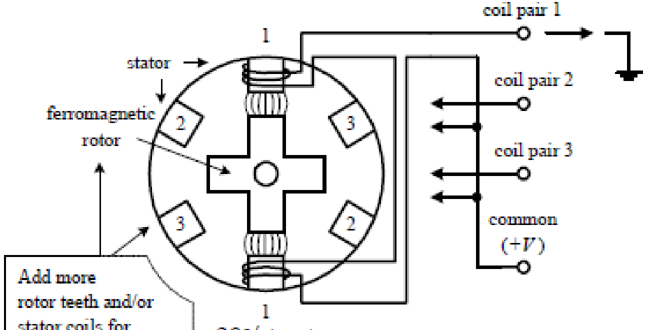
Variable Reluctance Motor



Schematic Diagram



Physical Model



30°/step type

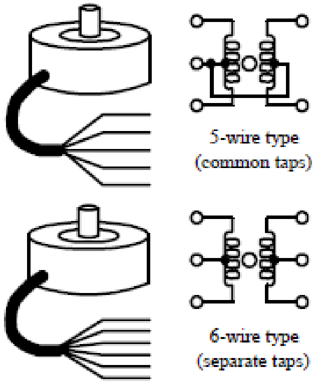
Firing sequence

coil 1	coil 2	coil 3
1	0	0
0	1	0
0	0	1
1	0	0
0	1	0
0	0	1

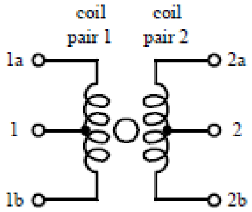
forward ↓ ↑ reverse — repeats after row 3

"1" means to apply current through coil.
"0" means remove current through coil.

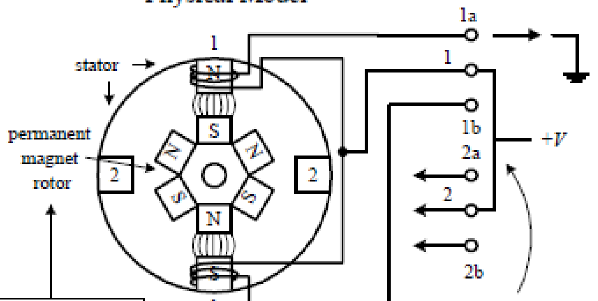
Unipolar Motors



Schematic Diagram



Physical Model



30°/step type

In a 5-wire unipolar, coil pairs 1 and 2 are connected internally.

Types of firing sequences

Single stepping

1a	1b	2a	2b
1	0	0	0
0	0	1	0
0	1	0	0
0	0	0	1
1	0	0	0
0	0	1	0
0	1	0	0
0	0	0	1

Power stepping

1a	1b	2a	2b
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
0	1	0	1

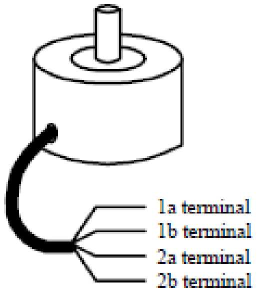
Half-stepping

1a	1b	2a	2b
1	0	0	0
1	0	1	0
0	0	1	0
0	1	1	0
0	1	0	0
0	1	0	1
0	0	0	1
1	0	0	1

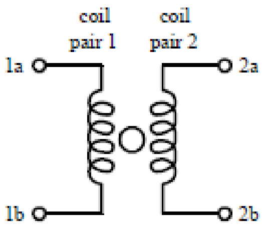
forward ↓ ↑ reverse — repeats

Power stepping provides about 1.4 times the torque but uses twice as much power.

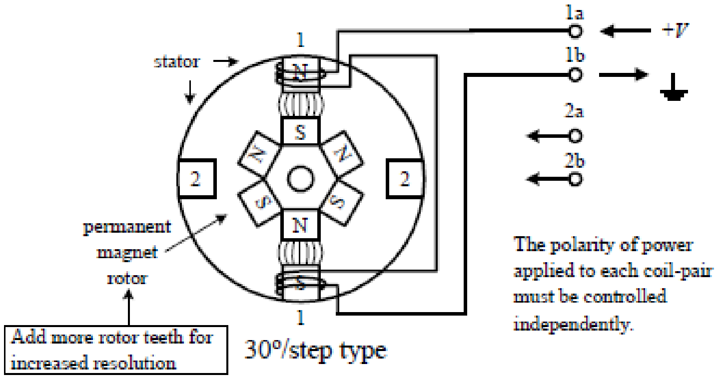
Bipolar Motor



Schematic Diagram



Physical Model



The polarity of power applied to each coil-pair must be controlled independently.

Firing sequence

1a	1b	2a	2b
+	-	-	-
-	-	+	-
-	+	-	-
-	-	-	+
+	-	-	-
-	-	+	-
-	+	-	-
-	-	-	+

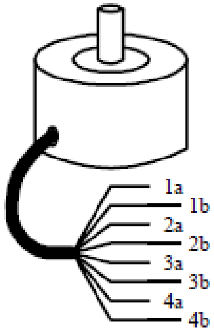
forward

reverse

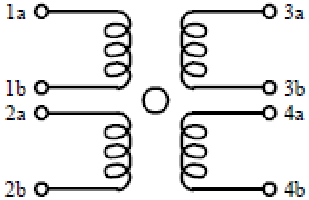
repeats

"+" means to make end of coil-pair positive in voltage relative to its other end whose polarity is denoted as "-."

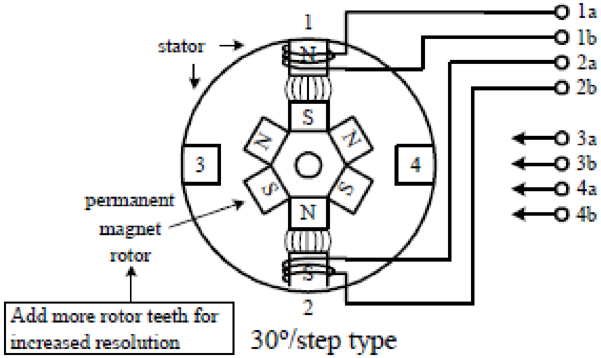
Universal Stepper Motor



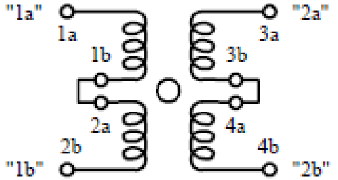
Schematic Diagram



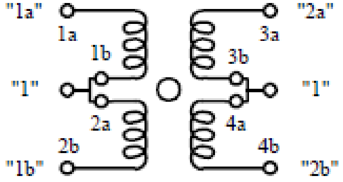
Physical Model



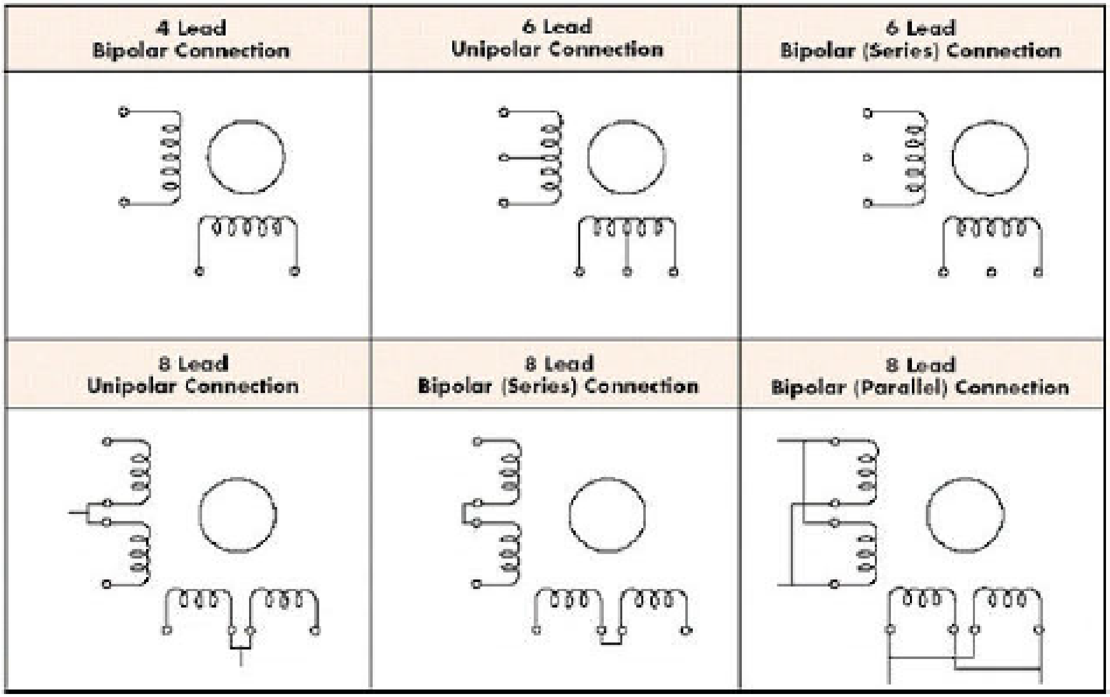
Bipolar setup



Unipolar setup



UNIPOLAR AND BIPOLAR OPERATION



Bipolar

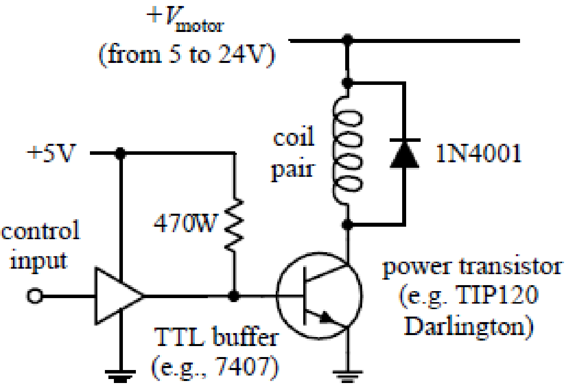
- One winding per phase
- Current through winding must be reversed → needs an H-bridge!
- More torque, but more complex circuitry

Unipolar

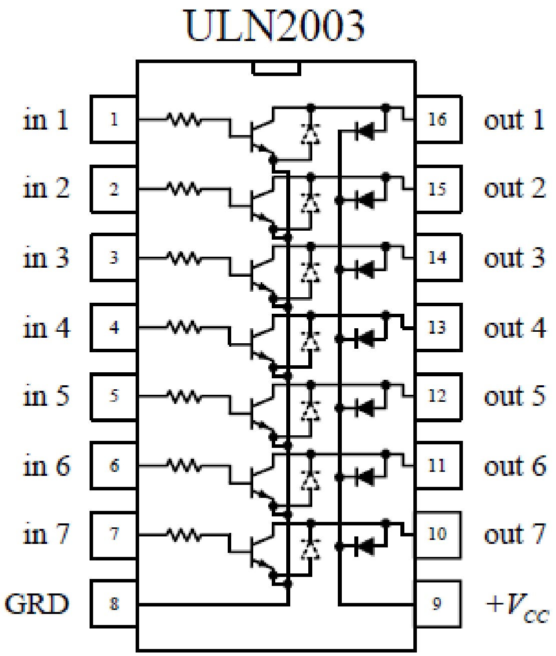
- Center tap (common wire) for each winding
- Simple circuitry
- Thinner wire => more resistance => more power loss

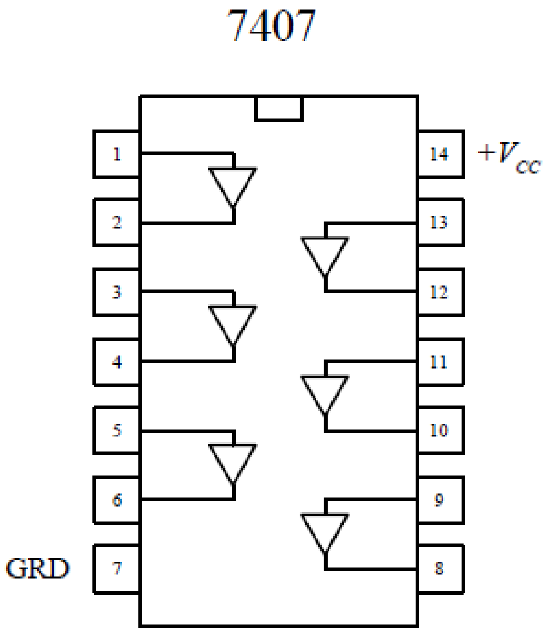
Driving Stepper Motor

Single Driver Section

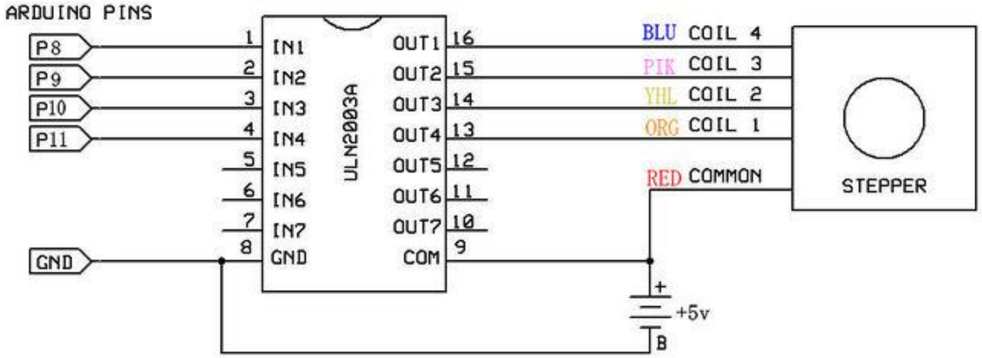


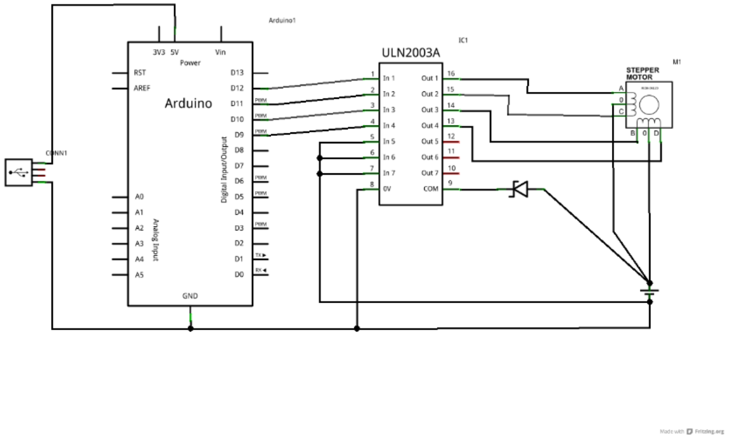
Transistor and Buffer Arrays

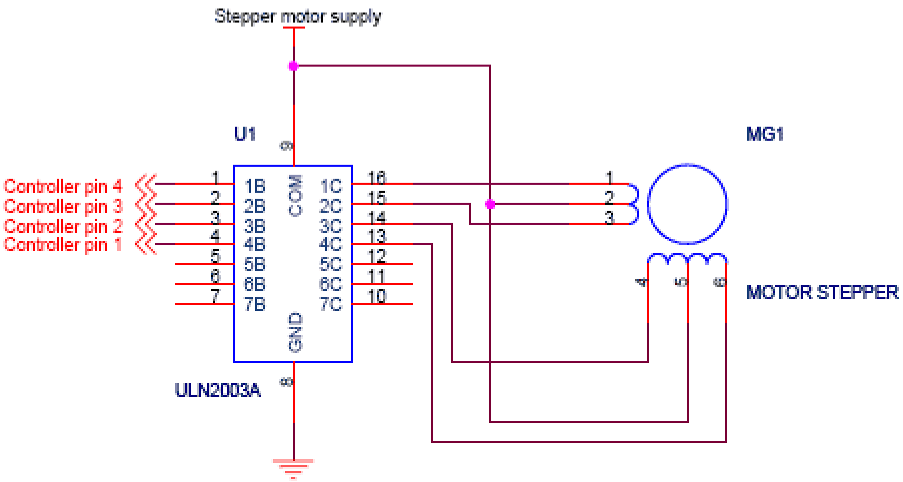


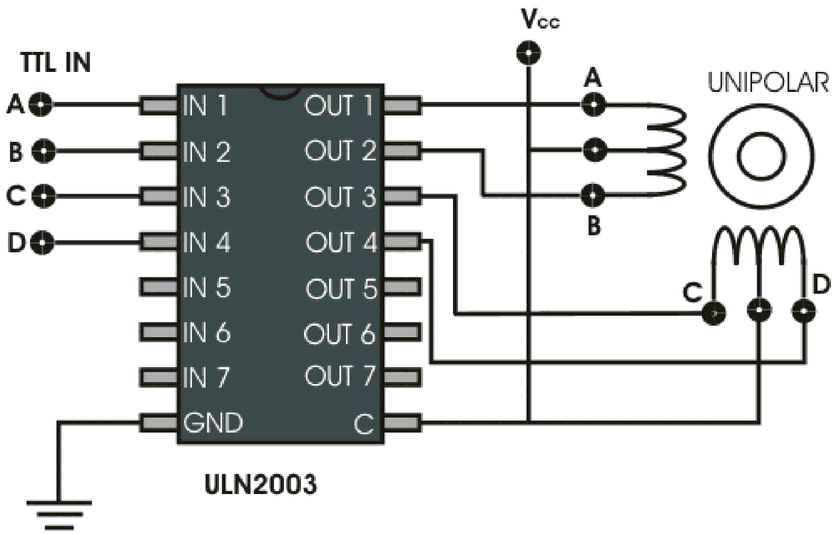


Connecting to Arduino





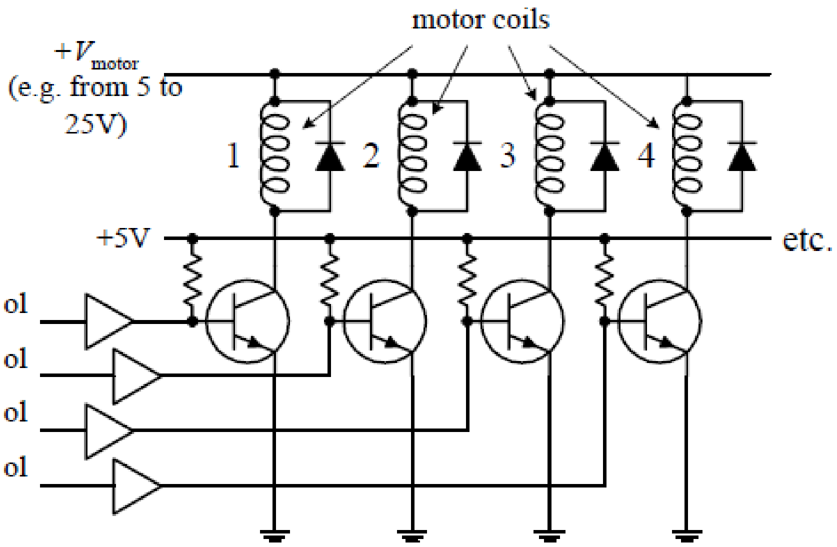




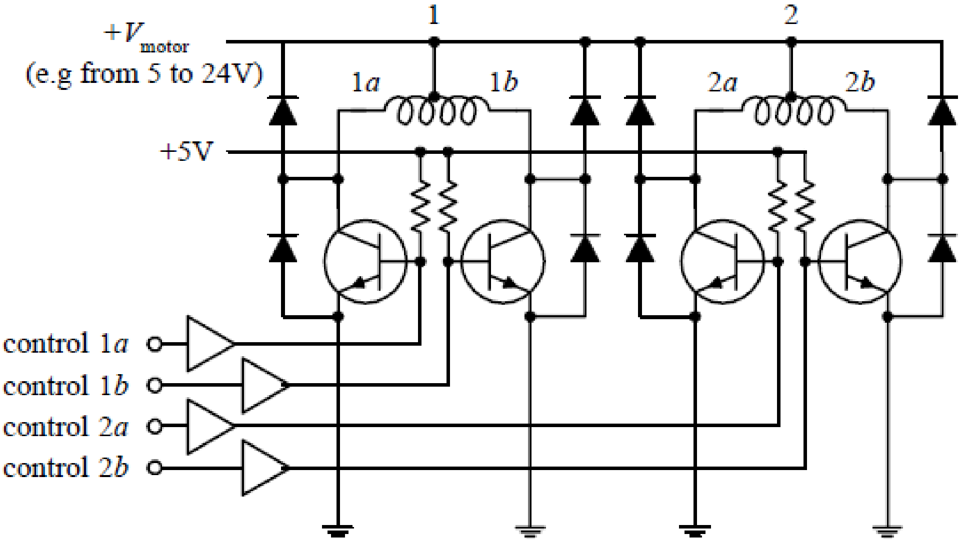
```
#define delaytime 80   //delay time in ms to control the stepper motor delaytime.
                    //Our tests showed that 8 is about the fastest that can yield reliable operation w/o missing steps


void setup() {
  // initialize the 8 pin as an output:
  pinMode(pin1, OUTPUT);
  pinMode(pin2, OUTPUT);
  pinMode(pin3, OUTPUT);
  pinMode(pin4, OUTPUT);
}

void loop(){
  int numberOfSteps = 48;
  step_OFF();         //turning all coils off
  while(numberOfSteps>0){
    forward();        //going forward
    numberOfSteps -- ;//counting down the number of steps
  }
  delay(2000);

  step_OFF();         //turning all coils off
  numberOfSteps = 48;
  while(numberOfSteps>0){
    backward();       //going backward
    numberOfSteps -- ;//counting down the number of steps
  }
  delay(2000);
}
```

Driving Stepper Motor

Variable-Reluctance Driver Network

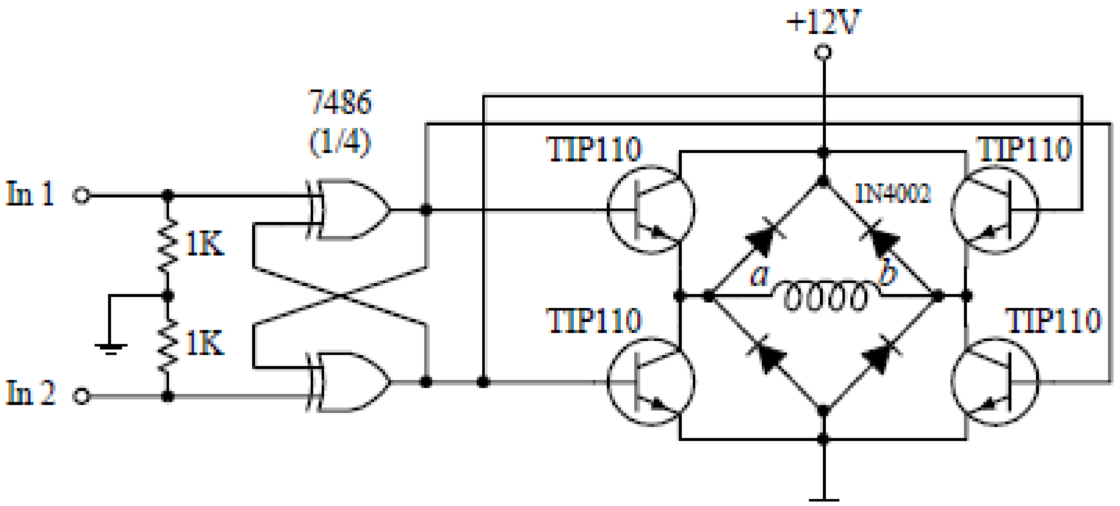


Unipolar Driver Network



Drive Bipolar

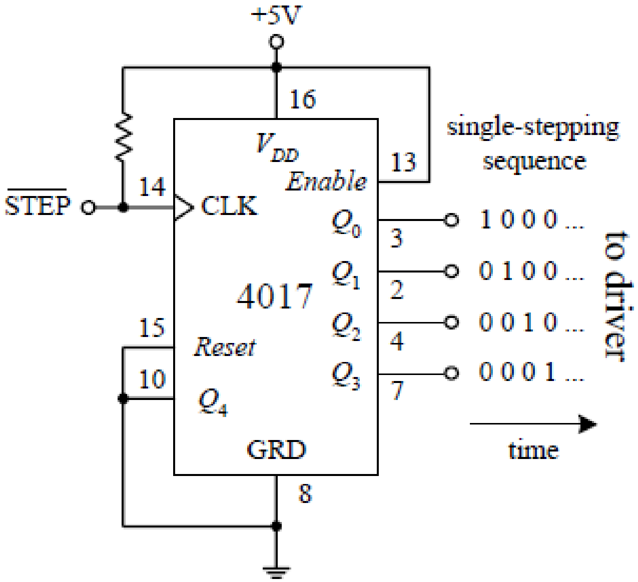
H-bridge used with Bipolar Stepper

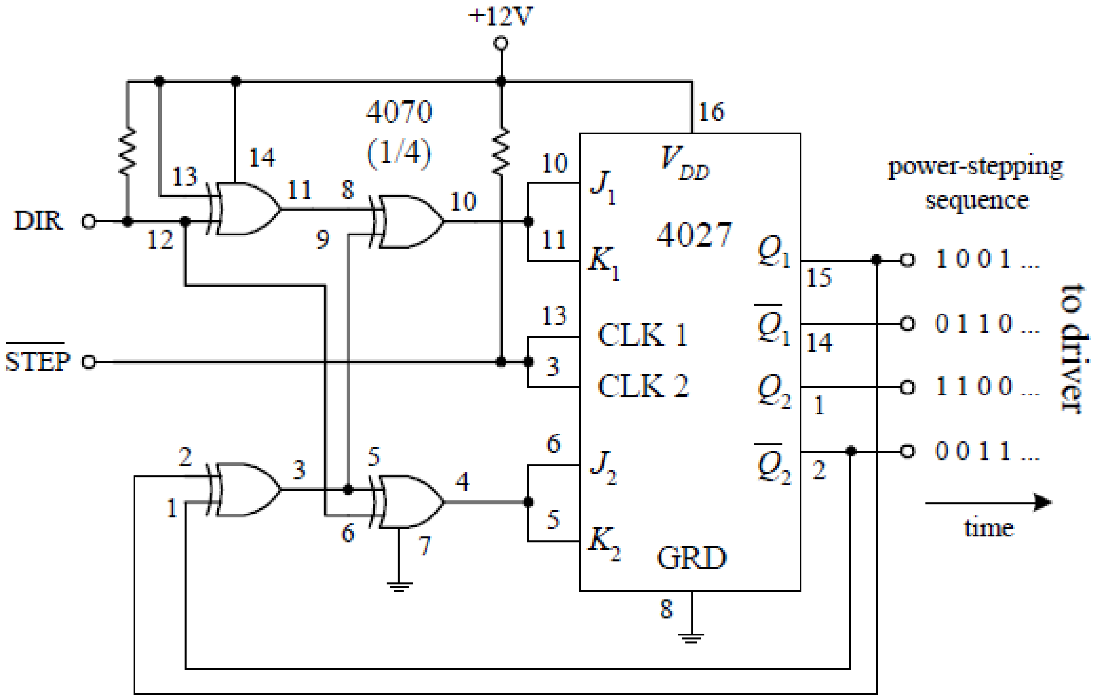


Digital input		Polarity	
In 1	In 2	*a* end	*b* end
0	0	0	0
0	1	-	+
1	0	+	-
1	1	0	0

To prevent two 1’s at the same time, XOR circuit is added to the input otherwise output is shorted to ground

Controlling the Driver with Translator





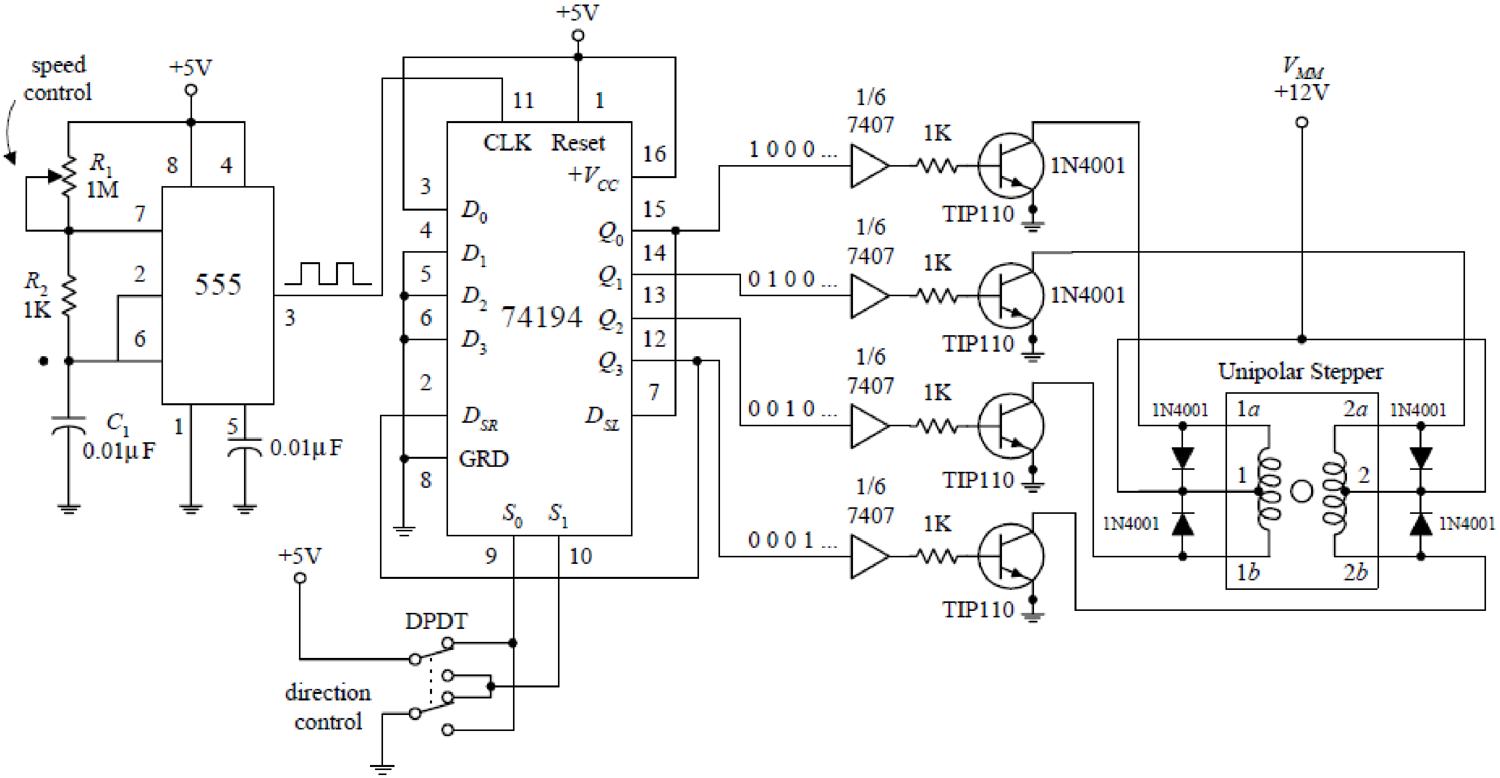
To generate four phase drive pattern :

-Using computer (microcontroller)

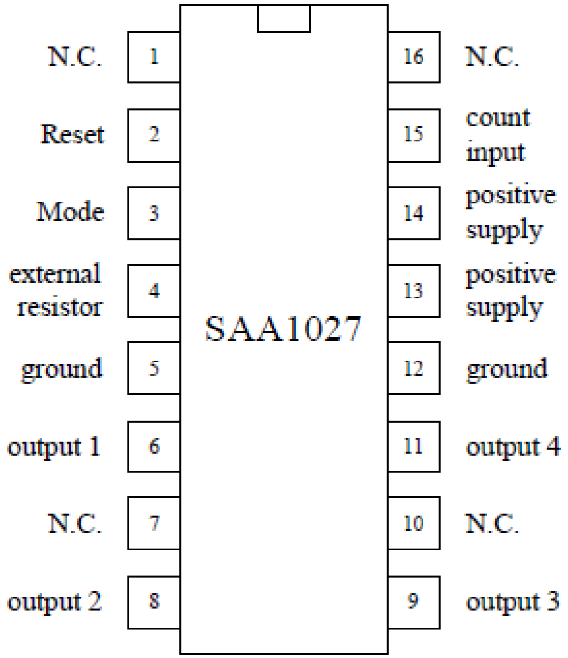
-Use simple circuits like CMOS 4017 decade counter (or 74194 TTL version)

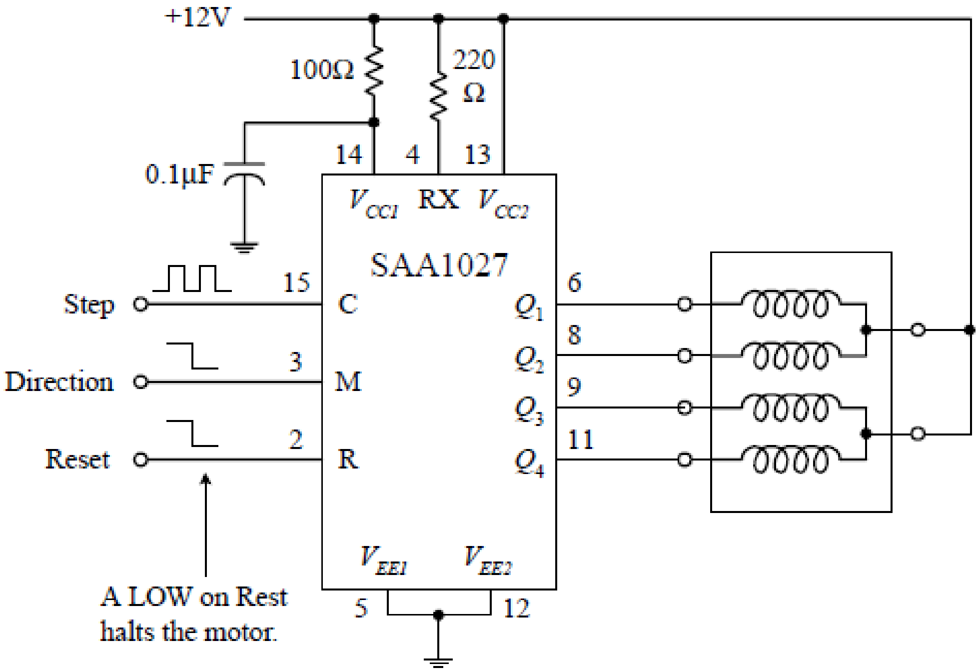
-Use CMOS 4027 dual JK flip flops. The CMOS 4070 XOR is used to step directional control

Complete Circuit



Translator and driver could be in one IC. Classic stepper controller is Philips SAA1027 bipolar IC to drive four-phase steppers





M = 0				M = 1			
Q_1	Q_2	Q_3	Q_4	Q_1	Q_2	Q_3	Q_4
0	1	0	1	0	1	0	1
1	0	0	1	0	1	1	0
1	0	1	0	1	0	1	0
0	1	1	0	1	0	0	1
0	1	0	1	0	1	0	1

FIGURE 13.13

Count input C (pin 15)—A low-to-high transition at this pin causes the outputs to change states.

Mode input M (pin 3)—Controls the direction of the motor. See table to the left.

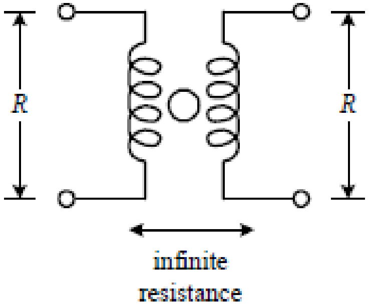
Reset input R (pin 2)—A low (0) at the *R* input resets the counter to zero. The outputs take on the levels shown in the upper and lower line of the table to the left.

External resistor RX (pin 4)—An external resistor connected to the RX terminal sets the base current of the transistor drivers. Its value is based on the required output current.

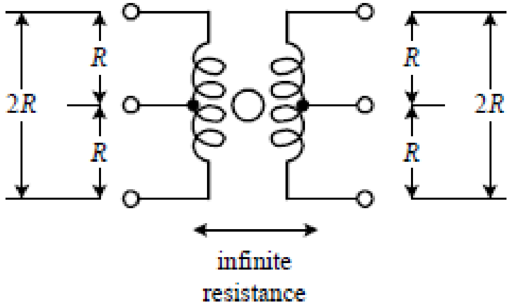
Outputs Q_1 through Q_4 (pins 6, 8, 9, 11)—Output terminals that are connected to the stepper motor.

Identifying Stepper Motor

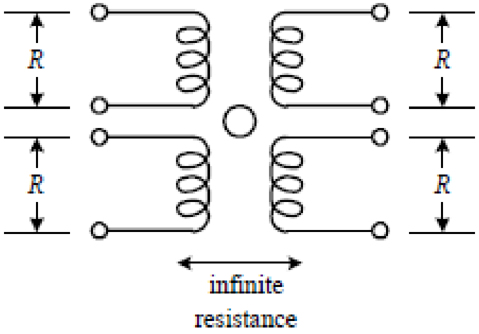
Bipolar



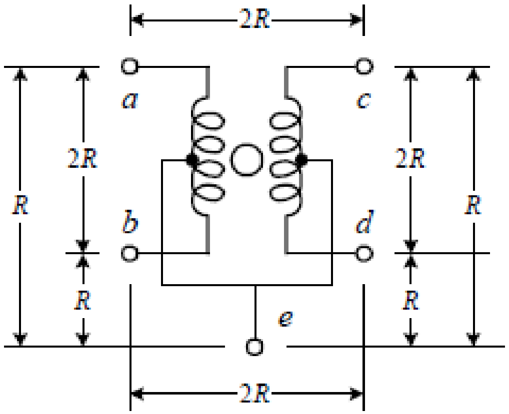
Unipolar (6-wire)



Universal



Unipolar (5-wire)



a	*b*	*c*	*d*	*e*	Resistance
●	●				2*R*
●		●			2*R*
●			●		2*R*
●				●	***R***
	●	●			2*R*
	●		●		2*R*
	●			●	***R***
		●	●		2*R*
		●		●	***R***
			●	●	***R***