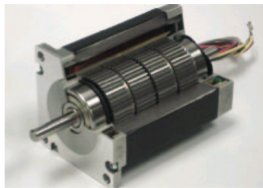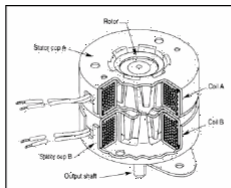# Actuators: Stepper Motors

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Outline

The Big Picture

- Electric motors - used for rotary motion
- Many different kinds - induction (AC), DC, servo, stepper
- This lecture will cover some details of a stepper motor. Lab 1 deals with control of a stepper motor.

So, what is a stepper motor?

Stepper motors are DC motors whose position can be changed in discrete steps. In most applications stepper motor moves in steps instead of rotating continuously

How a DC motor works?

Let us start with a simple DC motor

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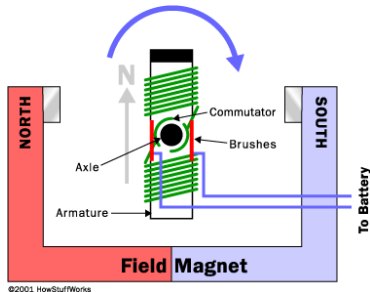
- A permanent magnet stator
- Windings on the rotor (armature)
- Electromagnet created on the rotor by passing current
- Direction of current needs to be changed for rotation
- How to pass current to a rotating body?
- How to reverse connections? - Brushes!

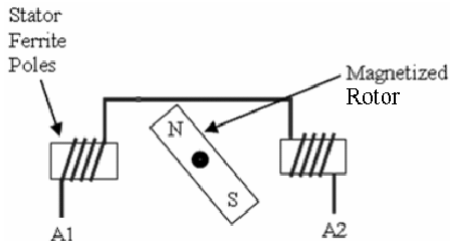# Problems with Brushed DC motors

Problems:

- Brushes have mechanical wear out
- Cause spark and electromagnetic interference

Alternative:

- Have permanent magnet on the rotor
- Electromagnet on the stator
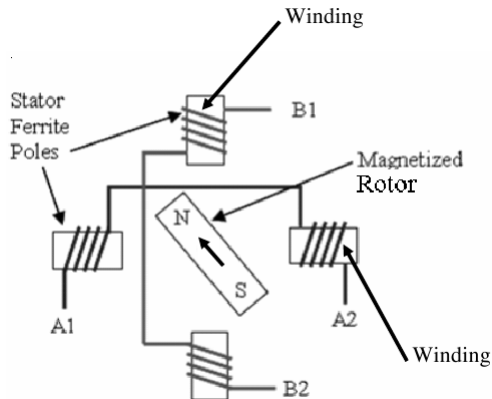- But how do we rotate the field?

Let us see how this alternative works!

Brushless DC Motor with 1 Winding (phase)

- How do we rotate the magnetic field?
- What happens if we add one more winding (phase) to the stator?

Brushless DC Motor with 2 Windings (phases)

Step 1: Apply V_{cc} to B1, GND to B2

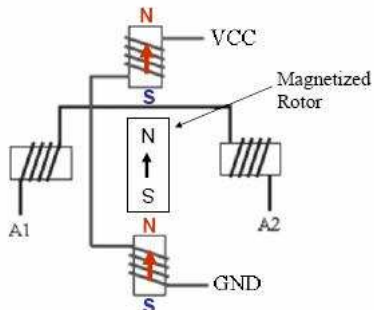Figure: Step1: Apply V_{cc} to B1, GND to B2, (A1, A2 are NC

NOTE: Here NC means "Not Connected"

Step 2: Apply V_{cc} to A2, GND to A1

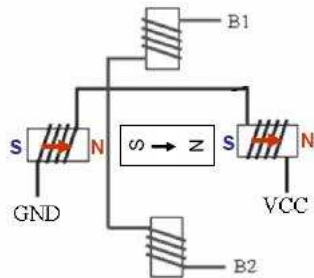Figure: Step 2: Apply V_{cc} to A2, GND to A1, B1=B2=NC

Step 3: Apply V_{cc} to B2, GND to B1
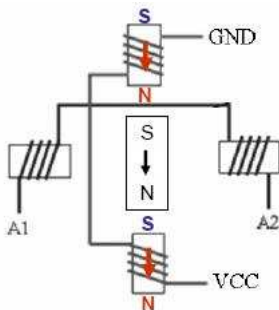
Figure: Step 3: Apply V_{cc} to B2, GND to B1, A1=A2=NC

Step 4: Apply V_{cc} to A1, GND to A2
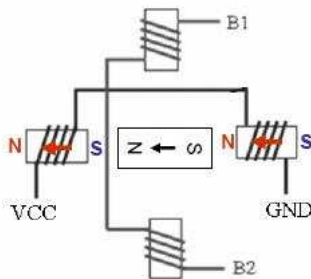
Figure: Step 4: Apply V_{cc} to A1, GND to A2, B1=B2=NC

Step 5: Apply V_{cc} to B1, GND to B2
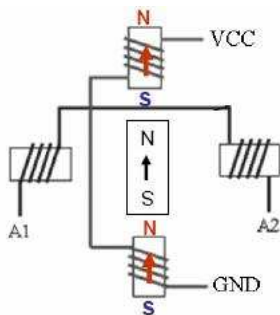
Figure: Step5: Apply V_{cc} to B1, GND to B2, A1=A2=NC

NOTE: Step 5 is identical to Step 1!

Summary: Stepper Control Sequence (CW)

Step	A1	A2	B1	B2
1	NC	NC	+	−
2	−	+	NC	NC
3	NC	NC	−	+
4	+	−	NC	NC

NC = Not Connected

Equivalent Stepper Control Sequence

Step	A1	A2	B1	B2
1	−	−	+	−
2	−	+	−	−
3	−	−	−	+
4	+	−	−	−

Alternative Full Step Control

Consider what happens when voltage is applied
to both windings at the same time?
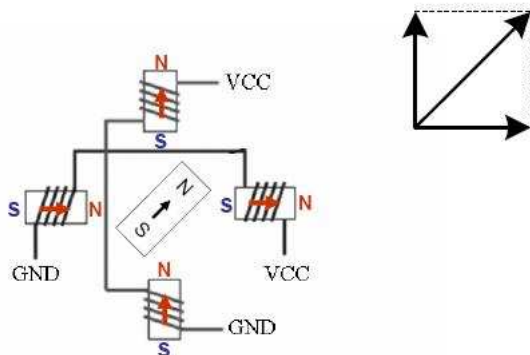
Results in higher torque than energizing only one winding!

Full step drive (two phases on)

This is the usual method for full step driving the motor. Both phases are always on. The motor will have full rated torque. Using the first method, the stepper motor will typically have less then the fully rated torque.

Exercises

1. Write down the full step sequence when both windings are energized at every step.
2. What is the resolution of both Full Step Controls?
3. How do you reverse direction?

Improving Resolution

Current Limitations

- The motor described above has two poles (one N one S)
- Its step resolution is 90°

How can we increase resolution (decrease step size)?

1. Increase number of phases on stator
2. Increase number of permanent magnets on rotor
3. Half Stepping
4. Micro-Stepping

# Improving Resolution with More Phases on the Stator
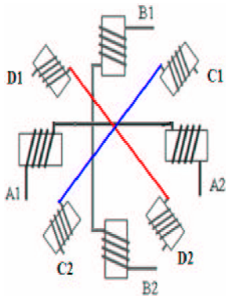
3 Phase Stepper Works but has limits:

The problem with this approach is that the number of wires (and thus control signals) needed to control the motor has increased.

How else can we increase resolution?

We can look at increasing rotor magnet poles. The motor above has two poles (one N one S).

Improving Resolution with More Permanent Magnets
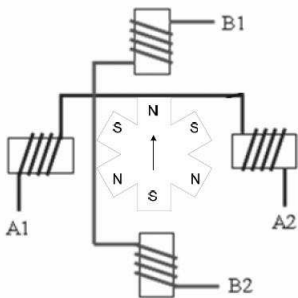
Advantages and Limitations:

The *advantage* is that we keep same number of control signals with increased resolution.
This *disadvantage* is increased cost of permanent magnets.

How do we move (Full Step) this motor?

This motor has 6 poles (3 N, 3S) and 2 phases on the stator.
The Control is the *almost* same as before! (How does it differ?)
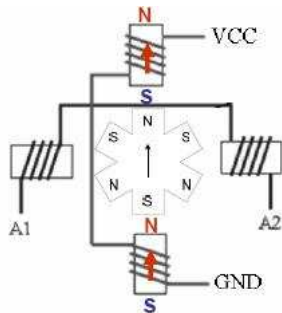
Step 1: Apply V_{cc} to B1, GND to B2

Figure: Step 1
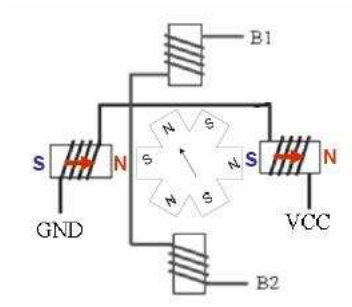
Step 2: Apply V_{cc} to A2, GND to A1

Figure: Step 2
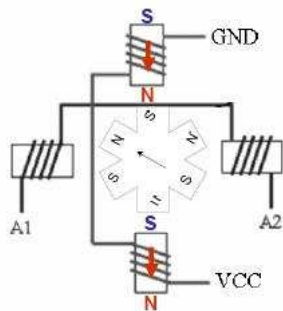
Step 3: Apply V_{cc} to B2, GND to B1

Figure: Step 3

Step 4: Apply V_{cc} to A1, GND to A2
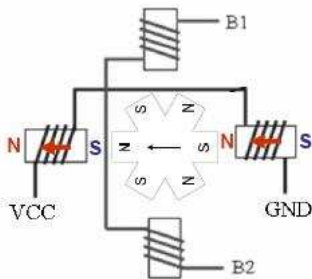
Figure: Step 4

Step 5: Apply V_{cc} to B1, GND to B2
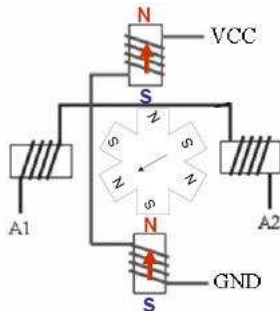
Figure: Step 5

Stepper Motor Full Step Resolution

Resolution is sometimes given in the number of steps required to complete a revolution (360 degrees)

- 2-pole motor takes 4 steps
- 6 pole motor takes 12 steps

$$\text{Angular Resolution} = \frac{360°}{\text{\# of steps}}$$

- 2-pole motor had resolution of $90°$
- 6-pole motor had resolution of $30°$.

Equation for angular resolution of 2 phase motors is:

$$\text{Angular Resolution} = \frac{360°}{2 \times (\text{\# of poles})}$$

Stepper Motor Full Step Resolution

In general a stepper motor can have more than 2 phases (recall 3 phase stepper above).

In this case we can generalize our formula for full step angular resolution to:

Equation for angular resolution of an *n* phase motors is:

$$\text{Angular Resolution} = \frac{360°}{n \times (\text{\# of poles})}$$

Half-Stepping

Basic Concept:

Alternate 2 phase and single phase Full Step control steps

Result:

Double the resolution (1/2 the step size) with no change to control wiring.

Note though that to keep torque consistent in 1/2 steps you need to increase current in the winding when in a single phase 1/2 step.

Half-Stepping Sequence

Step	A1	A2	B1	B2
1	−	−	+	−
2	−	+	+	−
3	−	+	−	−
4	−	+	−	+
5	−	−	−	+
6	+	−	−	+
7	+	−	−	−
8	+	−	+	−

Exercises:

1. Describe the behaviour of a 6-pole stepper motor given the sequence above

2. Consider the torque the stepper motor produces when using half stepping
   a) When one winding is on
   b) When both windings are on

   - Considering this, which 4 steps (out of the 8) would you prefer to use when performing full steps? Does this depend on the application?

Microstepping: Overview

Recall that we turned on one phase then two phases to move a half step. Then turned off one phase to move another half step.
This is Bang-bang control - a phase is either full current, or no current.

Question: What if vary the phase currents in smaller steps?

**Answer:** We get microstepping!
See this animated at:
http://en.nanotec.com/steppermotor_animation.html

Magnetic Reluctance

Magnetic reluctance

- *Magnetic reluctance*, or *magnetic resistance*, is a concept used in the analysis of magnetic circuits.
- It is analogous to resistance in an electrical circuit (although it does not dissipate magnetic energy).
- In likeness to the way an electric field causes an electric current to follow the path of least resistance, a magnetic field causes magnetic flux to follow the path of least magnetic reluctance.
- The smaller the air gap between ferro-magnetic materials becomes, the lower the magnetic reluctance becomes.

Step 1: Energize Coil 1
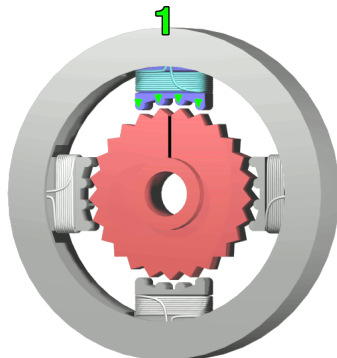
Step 1: Energize Top Coil (1)

Energizing the top coil creates a magnetic field that causes the rotor gear teeth to align with the top stator's teeth to minimize the air-gap
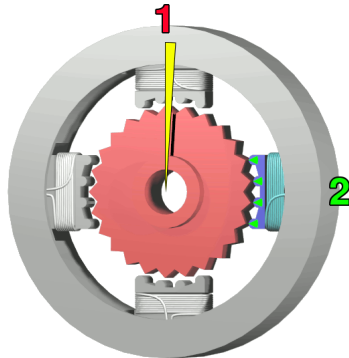
Step 1: Discussion

- Energizing Coil 1 attracts the nearest tooth of the gear-shaped iron rotor.
- With the teeth aligned to electromagnet 1, they will be slightly offset from electromagnet 2 (next electromagnet CW).
- Note the shortest direction the rotor gear has to rotate to align teeth with electromagnet 2!

Angular Resolution

- There are 25 teeth on the rotor gear (Count'em!)
- There are 4 independent electromagnets

What is the resulting (full step) angular resolution?
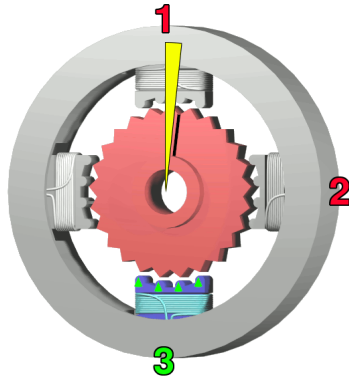
Step 2: Coil 1 Off Then Energize Coil 2

Step 2: Turn off Coil 1 Then Energize Right Coil (2)

The top electromagnet (1) is turned off, and the right electromagnet (2) is energized, pulling the nearest teeth slightly CW. This results in a

Step 2: Discussion

- With Coil 1 off, Energizing Coil 2 attracts the nearest tooth of the gear-shaped iron rotor.
- Now with the rotor gear teeth aligned to electromagnet 2, they will be slightly offset from electromagnet 3!
- Note the shortest direction the rotor gear has to rotate to align teeth with electromagnet 2!
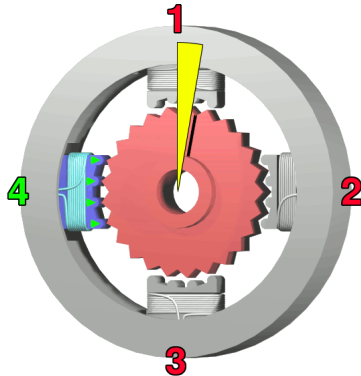
Step 3: Coil 2 Off Then Energize Coil 3

Step 3: Turn off Coil 2 Then Energize Bottom Coil (3)

The right electromagnet (2) is turned off, and the right electromagnet (3) is then energized, pulling the nearest teeth slightly CW. This results

Step 4: Coil 3 Off Then Energize Coil 4

Step 4: Turn off Coil 3 Then Energize Left Coil (4)

The bottom electromagnet (3) is turned off, and the left electromagnet (4) is then energized, pulling the nearest teeth slightly CW. This results

Steps 1-4: Discussion

- When the top electromagnet (1) is again enabled, the teeth in the sprocket 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.

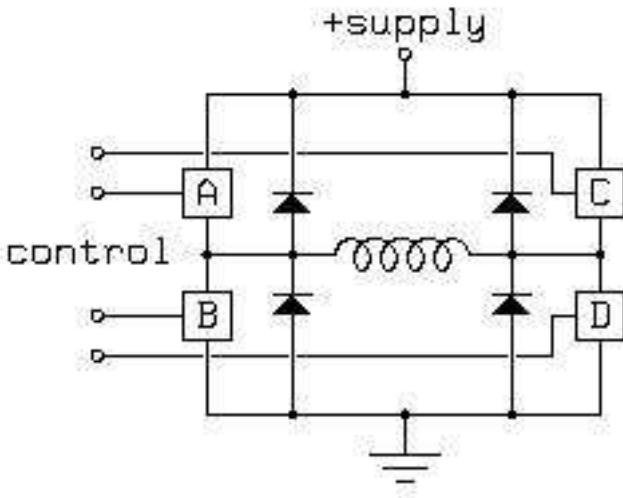There is an animation of a more typical 3 phase variable reluctance motor at:
http:
//www.cs.uiowa.edu/~jones/step/typesf/1anim.html

Control Circuit

- Motors need more current than a typical microprocessor can supply
- Control signals from a microprocessor are connected to a driver circuit
- Output from the driver circuit is connected to the motor
- For a bipolar motor, we need to reverse current through windings of the motor
- This can be done by suitable switches as shown in figure 11
- Electronic equivalent of such switches is called H-bridge
- Forward / reverse modes
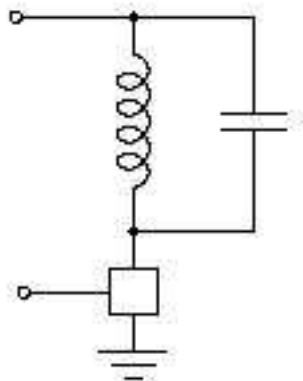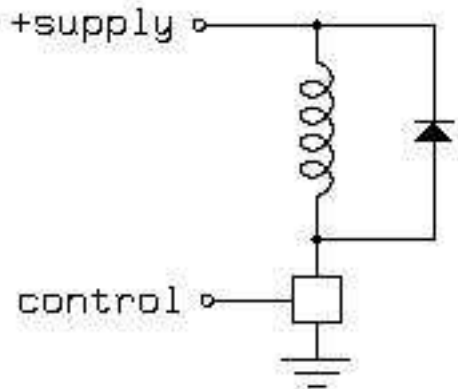
H-Bridge Circuit Equivalent

Protection Circuit

Figure: