DC Motor Armature:

\[ + V_a - \]

\[ \text{Torque } T = L I_a \]

\[ \text{Back EMF } = k \omega = E \]

\[ \omega = \text{shaft speed} \]

In steady state, \( E \propto V_a \)

so speed \( \propto V_a \)

what we want to do:

Drive wheels in either direction

\( \Rightarrow \) need to produce both positive and negative \( V_a \)

From Exp. 2: we obtained max speed at 10V

so let's choose \(-10V \leq V_a \leq +10V\)

Also from Exp. 2: we employed armature currents up to 1A

(and we limited \( I_a \) to 1A under blocked rotor conditions) so let's specify \(-1A \leq I_a \leq +1A\)

We need to design a power amplifier circuit that can do this. Where we are going:

[Diagram showing control flow from microcontroller to power amplifier]
Could we build the power amplifier with an op amp? For ex.,

![Circuit Diagram]

\( V_{cc} = 10V \)

Problems

1. We have a +10V supply but no -10V supply.

   So the op amp can produce only positive voltage.

   A motor can only turn in one direction. How do we get negative voltage?

Solution: A push-pull circuit. Connect the armature differentially between the outputs of two power amplifiers (PA's):

\[ V_a = V_1 - V_2 \]

Even though \( V_1 \) and \( V_2 \) are positive: \( V_{cc} > V_1, V_2 > 0 \) \( V_a \) can be negative: \( V_{cc} > V_a > -V_{cc} \)
There are multiple ways to control the Pts's:

a) \( V_1 = \frac{1}{2} V_{cc} + V \) with \(-\frac{1}{2} V_{cc} \leq V \leq \frac{1}{2} V_{cc}\)

\( V_2 = \frac{1}{2} V_{cc} - V \)

then \( V_a = V_1 - V_2 \geq 2 V \) and \(-V_{cc} \leq V_a \leq +V_{cc}\)

b) To get positive \( V_a \), let \( V_2 = 0 \) and control \( V_a \) using \( V_1 \): \( V_a = V_1 \)

To get negative \( V_a \), let \( V_1 = 0 \) and control \( V_a \) using \( V_2 \): \( V_a = -V_2 \)

We will use (b) in this experiment.

Problem #2:
The power amplifiers need to produce up to 1 A, can the op amp do it? Check TLV272 data sheet (see Exp. 3 Web site). See output current \( I_o \) characteristics, p. 6. With \( V_{pp} = 10 V \),
the op amp produces no more than 13 mA. Also graphs on p. 9; under some conditions it could produce more current, but nowhere near 1 A.

This is typical of commercial op amps. So we need a current boost.

Solution: use a power transistor to increase the current.
The NPN Bipolar Junction Transistor (BJT)

Base - Emitter junction is a diode that controls the device: put current through this diode to operate the transistor.

A simple circuit:

Basic active region equivalent circuit:

Current gain $\beta = \frac{I_C}{I_B}$

Also called $h_{FE}$

Typical $\beta \approx 20$ to $200$
Insert equivalent circuit model:

\[ V_{CE} = V_{CC} - I_c R_c = V_{CC} - \beta I_B R_c \]

Solve circuit (valid for operation in active region):

\[ V_{BE} = \text{diode drop} \approx 0.7 \text{ V} \]

\[ V_{CE} = V_{CC} - I_c R_c \]

The PNP BJT - opposite polarity

Polanities are reversed; negative \( I_B \) forward-biases B-E diode junction, Negative \( V_{CE} \) and \( I_c \) in active region.
Emitter follower circuit

\[ I_c = \beta I_B \]

\[ I_a = I_B + I_c = (1+\beta)I_B \]

If our op amp can produce 10 mA and \( \beta = 100 \) then we can get \( I_a = (101)(10 \text{ mA}) = 1.01 \text{ A} \)

To get positive and negative \( I_a \):

For positive \( I_a \): \( V_{BE} = +0.7 \text{ V} \) so NPN conducts

\[ I_a = \beta_{\text{NPN}} I_B > 0 \]

For negative \( I_a \): \( V_{BE} = -0.7 \text{ V} \) and NPN is cutoff

\[ I_a = \beta_{\text{PNP}} I_B < 0 \]

PNP conducts
The complete power amplifier circuit:

```
Vcc

Q1 NPN + Va -
Q2 NPN

Q3 PNP

Rb1

Rb2

Ia

Ib1

Ib2

Vce

Vbe2

Vbe1
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Limiting the current to |Ia| ≤ 1A.

The data sheet for the KSCU73 NPN (see Exp. 3 web page) says that β ≤ 200. Let's choose Rb1 and Rb2 to limit Ia to 1A under worst case conditions.

**Worst case**
- Rotor is blocked so water armature becomes resistance Ra
- U1 produces max output voltage (nVcc)
- U2 produces min output voltage 0

Under these conditions:
- Fe > 0
- Ib1 > 0 so VBE1 = +0.7 V
  - Q1 operates in active region
- Ib2 < 0 so EbVBE2 = -0.7 V
  - Q2 is cut off
  - Q4 operates in active region
Insert equivalent circuits:

\[ V_{cc} \]

\[ R_{b1} \]

\[ I_{b1} \]

\[ (Q_3 \text{ cutoff}) \]

\[ \beta_{npp} I_{b1} \]

\[ + V_a \]

\[ (Q_2 \text{ cutoff}) \]

\[ I_a \]

\[ R_a \]

\[ R_{b2} \]

\[ R_{b2} \]

\[ \beta_{pnp} I_{b2} \]

\[ (-I_{b2}) \]

\[ Q_4 \]

Solve circuit for \( I_a \)

Choose \( R_{b1} = R_{b2} \) such that \( I_a = 1 \text{ A} \)

With \( \beta_{npp} = \beta_{pnp} = 200 \)