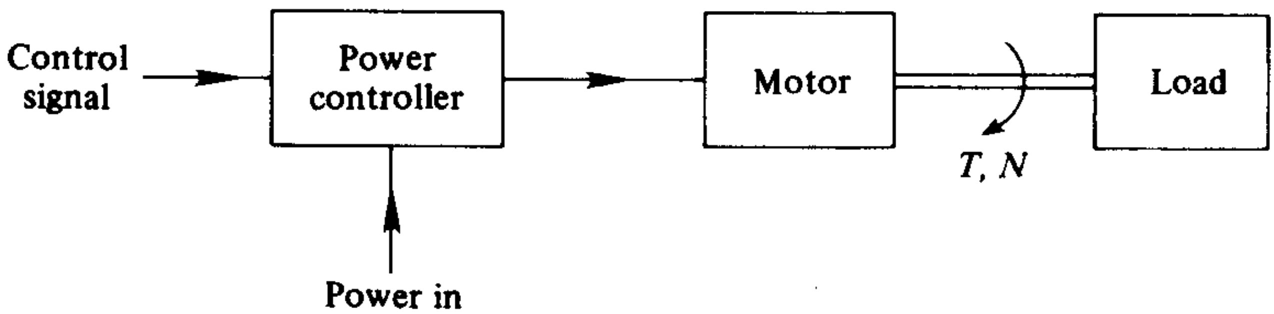
Power Devices and Motor Drivers

The signal to control the power and direction of a motor will often originate from a microcontroller

It is impossible for a microcontroller to directly power a motor (absolute maximum pin output current for the Atmel AT89C51AC3 is 10 mA)

Need some form of **power controller** to provide the required (**high**) motor current at moderately high voltages (400 V)



Power semiconductor devices are normally optimised for use in **commutation** mode (either on or off). Most should **not** be used in linear operation

Power MOSFET

- Has high **commutation speed** and **good efficiency**
- Has an **isolated gate** that makes it easy to drive
- Is the most widely used low-voltage (< 200 V) switch
- Can be found in most power supplies, DC to DC converters, low voltage motor controllers

Because of their unipolar nature (there is no need to remove **minority carriers** as with bipolar devices), the power MOSFET can switch at **very high speed**

The switching speed is limited by the internal capacitances of the MOSFET which must be charged or discharged – determined by the **external driver circuit**

Gate Oxide Breakdown

The gate oxide is very thin (100 nm or less), so it can only sustain a **limited voltage,** $V_{gs} \sim 20 \rightarrow 200$ V,

Exceeding this limit can result in a significant **reduction** in the lifetime (or even **destruction**) of the MOSFET, (with little to no reduction of $\mathbf{R_{DSon}}$)

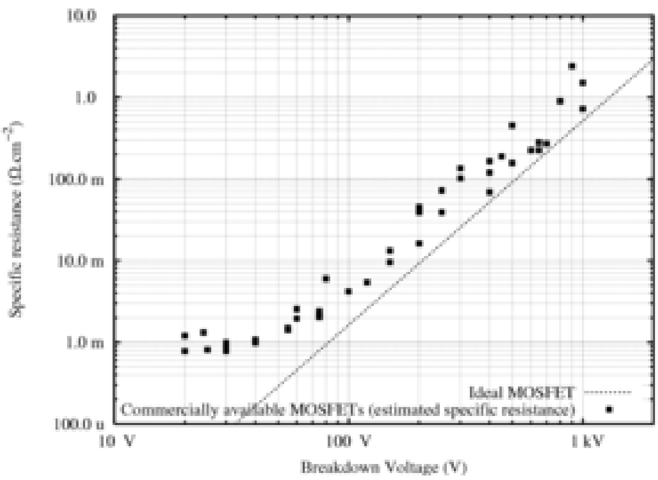
Breakdown voltage/on-state resistance trade-off

Breakdown voltage and R_{DSon} are determined by the doping level and the thickness of the N^- epitaxial layer

The thicker the **layer** and the lower its **doping level**, the **higher** the **breakdown voltage**

But the thinner the layer and the higher the doping level, the lower the $\mathbf{R_{DSon}}$ (and therefore the lower the **conduction losses** of the MOSFET)

There is a trade-off in the design of a MOSFET, between its voltage rating and its ON-state resistance



The R_{DSon} of MOSFETs **increase** with their voltage rating

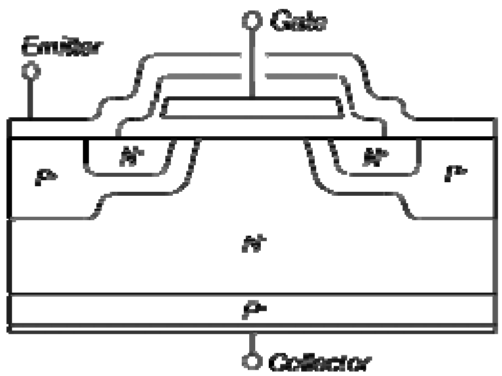
IGBT (Insulated Gate Bipolar Transistor)

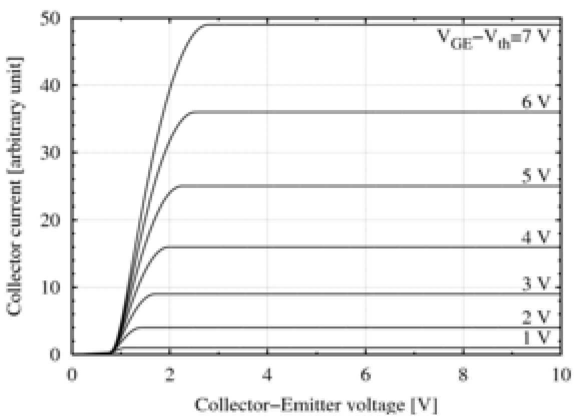
A pnp bipolar transistor driven by a power MOSFET:

- Combines the advantages of being a minority carrier device (**good performance in on-state**, even for high voltage), with the **high input impedance** of a MOSFET

Used in:

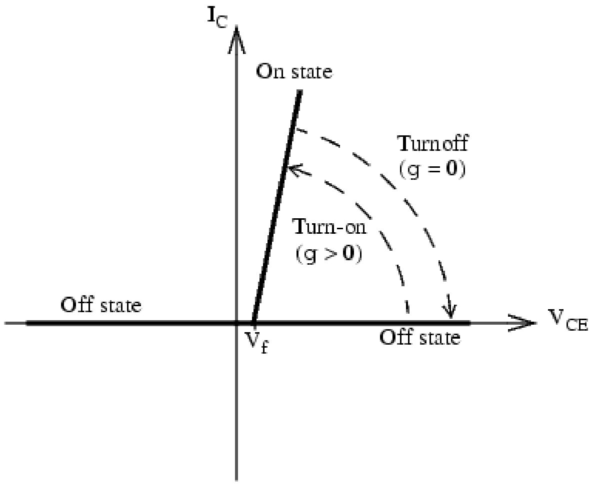
- High voltage hobbyists (Tesla coils)
- Electric vehicles and hybrid cars (Toyota's Prius has a 50 kW IGBT inverter controlling the motors)
- Audio amplifiers





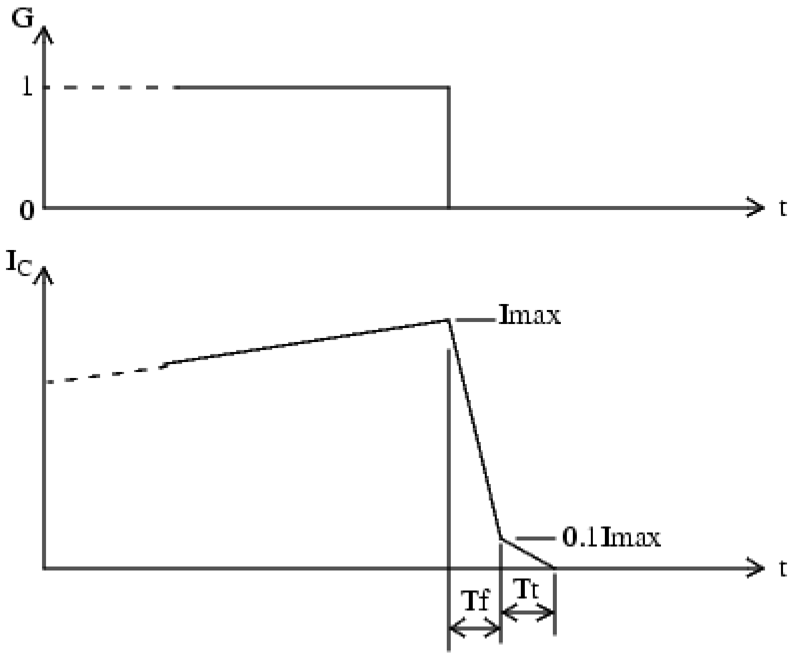
The IGBT turns on when **V_{CE} is positive** (> V_f) and a **positive** signal is applied at the **gate** ($V_g > 0$)

It turns off when V_{CE} is positive and a **0 signal** is applied at the gate ($V_g = 0$), or when $\mathbf{V_{CE}}$ **is negative**.



The turnoff characteristic of the IGBT is approximated by two segments:

- When the gate signal falls to 0, the collector current decreases from I_{max} to 0.1 I_{max} during the **fall time** (T_f)
- It then falls from 0.1 I_{max} to 0 during the **tail time** (T_t)



Switching

One of the most common tasks in designing and building robots is the interfacing of logic circuitry to high current loads such as motors, solenoids, or Nitinol wire

These loads can have peak current requirements much greater than 10 amps

Most logic circuitry can sink and source loads in the range of **1 to 20 mA**

Switching is the process of using a **small control** current to activate a much **larger circuit** current

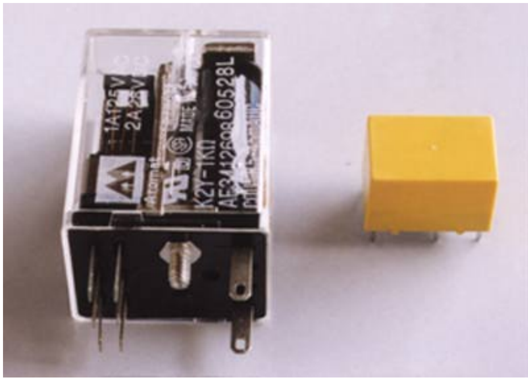
Typical switching components are:

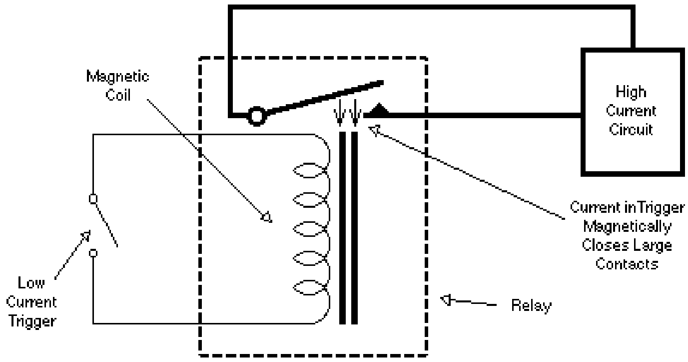
- Relays
- Transistors
- Power transistors
- Thyristors

http://www.acroname.com/robotics/info/articles/drivers/drivers.html

Relays

An electro-magnet closes or opens the contacts of the switch which completes the high-current circuit





Relays can have the high-current contact normally open or normally closed

Can have varying numbers of poles so that numerous high-current circuits can be activated/deactivated

Advantages

- **Easy to design** circuits
- Relays are often “drop-in” replacements in a circuit
- Reasonably priced and easily available

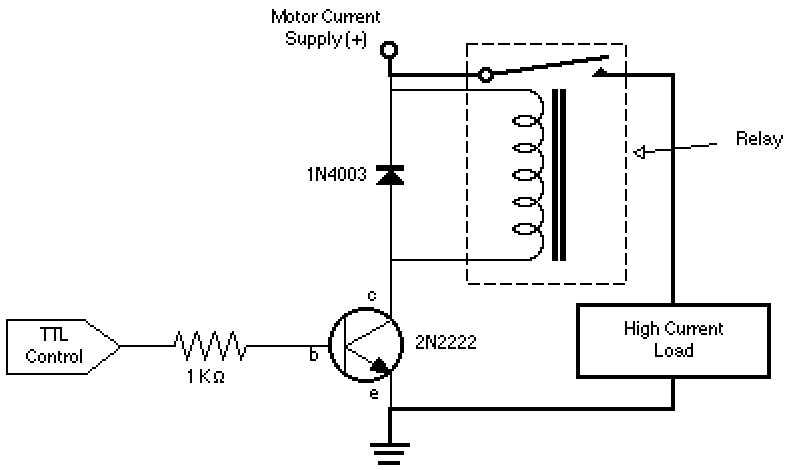
Disadvantages

- Since there are physical contacts in relays, the contacts will tend to **arc** when they are opened or closed
  - Creates **electrical noise**
  - Contacts **degrade** over time and will **wear out**
- Are **very slow** compared to logic circuits
- If the contact needs to stay closed for a period of time, the coil magnet must stay energized which takes appreciable current
  - Shortens the **operating life** of robots running on batteries

Circuit Implementation

Many small relays are available that can be driven directly from logic currents of ~20 mA,

Often a **transistor** is used to amplify the current from the logic circuit to drive the relay



Transistors

The BJT is current controlled, adequate for < 0.5 A, the Darlington pair (dual bipolar) can handle < 400 A

MOSFETs are voltage controlled, adequate to ~100 A
Low voltage (power) drop

Advantages

- No mechanical parts to wear out
- They make **no electrical noise**
- Can be **very fast**
- Are **very small**

Disadvantages

- Limited **voltage range**
- Limited current capability
  - Can **parallel** devices to overcome this

Thyristors

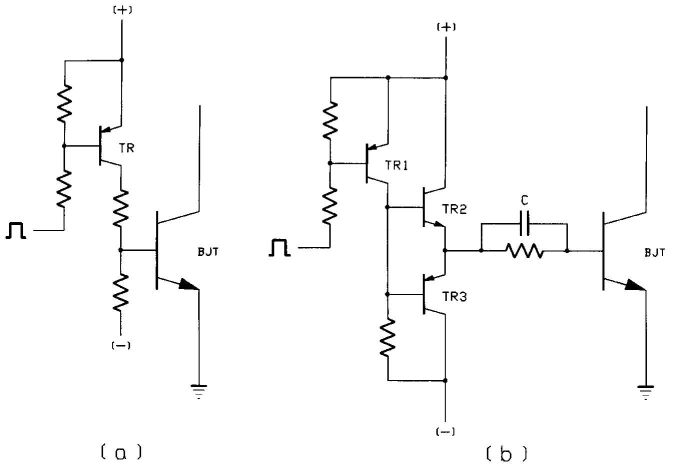
- High power devices
- Can be difficult to turn off
- Often slower than transistors

Switching Device Drivers

Control signals may be generated from digital circuits where the voltage and current supplied are not adequate for device switching (esp. for BJTs)

BJTs are **current controlled** devices

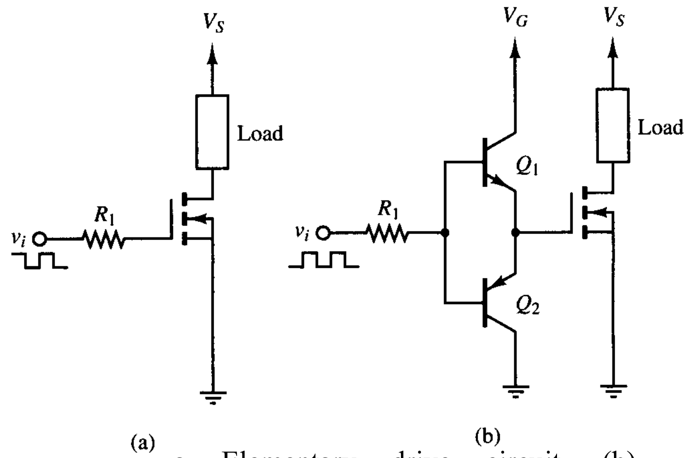
The input digital **voltage pulses** must be converted into **current pulses**



(a) Single transistor driver, (b) driver with class B output stage

MOSFETs, and IGBTs are **voltage controlled**

The drive circuit has to output a **scaled voltage pulse** of enough power to drive the device

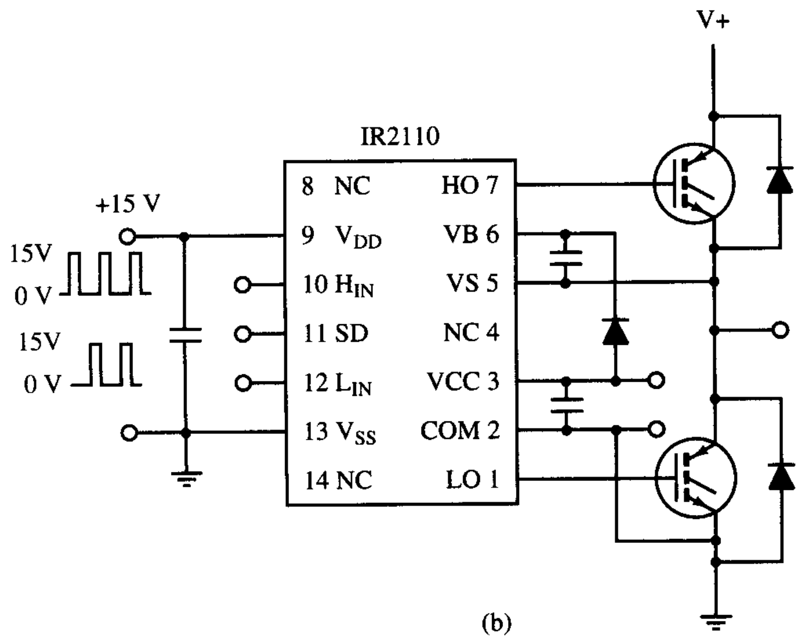


a. Elementary drive circuit, (b) Totem-pole drive circuit

Dedicated ICs exist that provide the appropriate output voltage (or current) to drive the switching device

For example, the IR2110, (International Rectifier) is designed to drive one half of an H-bridge (that uses MOSFETs or IGBTs, i.e. voltage controlled switches)

- Input voltage 3.3 – 20 V
- Output (V+) to 500 V
- Dissipates ~1.6 W



(b)

Inductors

Relays and Motors are inductors

Inductors and electricity similar to mass and movement

If you try to stop the current in an inductor, the inductor will resist it (like stopping a moving car)

When car hits an object, momentum changed to pressure – for the inductor the current is turned into a (large) voltage

Because $V = L\frac{dI}{dt}$ it is not possible to turn the current off instantly, since that would imply an infinite voltage across the inductor's terminals - must interrupt the current flow slowly

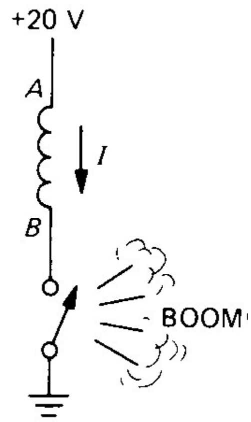
If the current changes quickly, the inductor kicks furiously and the voltage across it suddenly rises until it forces current to flow (**Inductive kick)**

This creates **electrical noise** and shortens the **life of the switch** (or destroys a transistor)

Consider the switch is initially closed and current is flowing through the inductor (relay, motor)

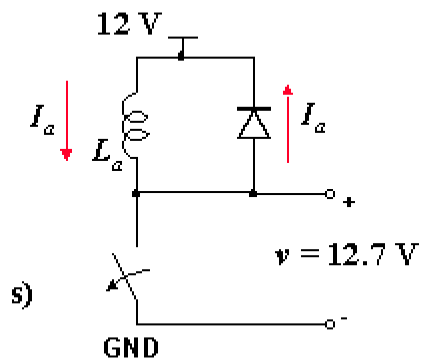
When the switch is open, the inductor tries to keep current flowing from A to B

For $V_s = 20$ V, if the inductor was 1 mH with 1 amp running through it, if the switch opened in 2 μs, the voltage across the switch would be:



$$V = \mathbf{20 + (1\ mH)(1\ A)/(0.2\ \mu s) = 5020\ V!!!!}$$

A **high speed** (response < 0.2 μs) parallel diode can eliminate this spike as any voltage overshoot forward biases the diode and causes the high current to recirculate in the coil (e.g. 1N4004 or 1N4003)

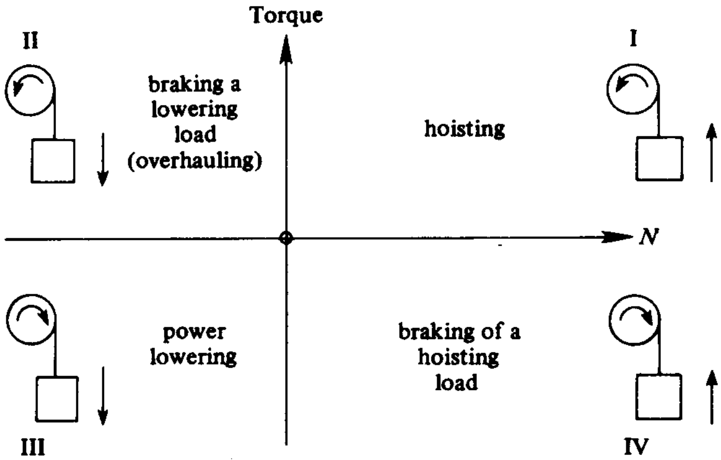


The diode is called freewheeling, flywheel or **flyback.**

Flyback diodes are often incorporated into controller chips and prohibit this large spike from forming and destroying your circuitry

Motor Drivers

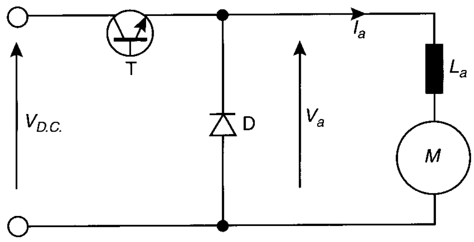
All loads on rotating motors translate to a torque on the motor

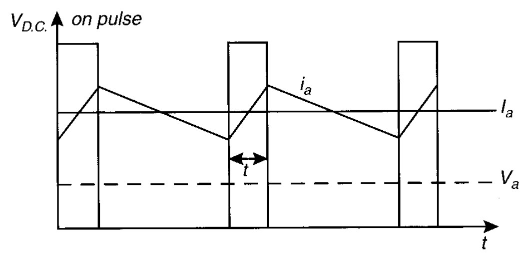


The **four quadrants** of Torque (T) / Speed (N) characteristics of a hoist or winch (the arrows in the pulleys represent the direction of the motor torque)

DC-DC Converters

The basic chopper circuit provides only single quadrant (I) operation



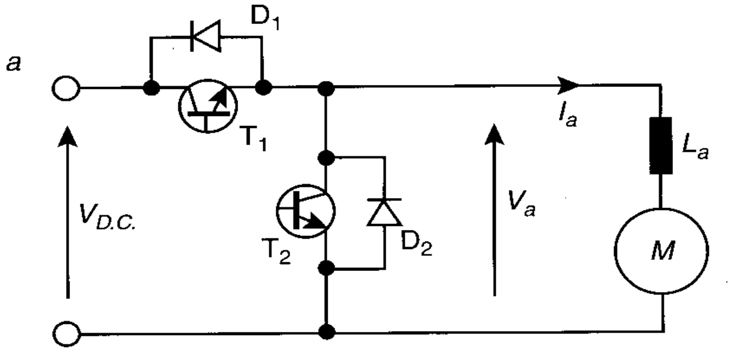


The motor is inductive – the current waveform is significantly smoothed so that continuous motor action is observed

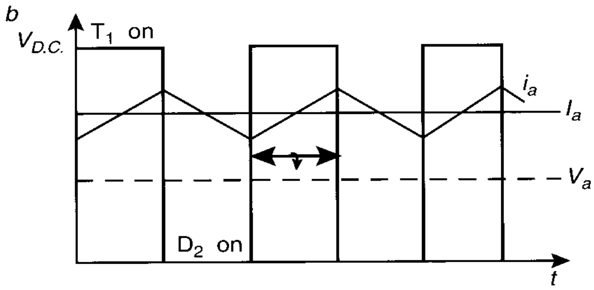
The **flyback diode** (D), carries the current when the transistor is switched off (remember it is driven by a PWM signal)

First and Second Quadrant Chopper

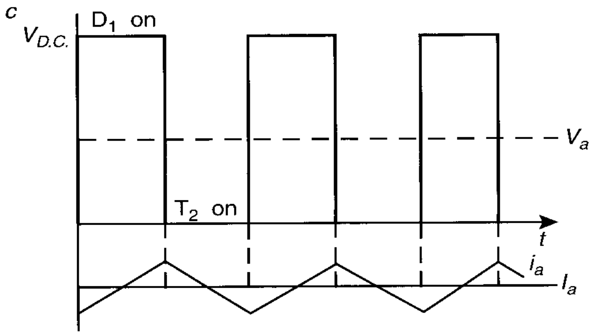
In order to provide quadrant 2 braking, an extra switch and diode are added to the basic chopper



When T_1 is on and T_2 is off, current is provided from the supply to **turn the motor** (original chopper)



When T_1 is off and T_2 is on, the motor is still forward-rotating, but building up a **back emf** so the current builds up in the $-I_a$ direction



When T_2 is switched off, the back emf forces current to flow in the $-I_a$ direction

The only current path allowing this to happen is through D_1, back to the DC supply which sinks the energy **(regenerative)** and **brakes** the motor

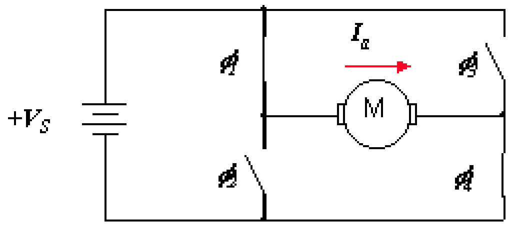
Motor Driver Circuits (Transistor based)

H-Bridge Circuit (4 quadrant operation)

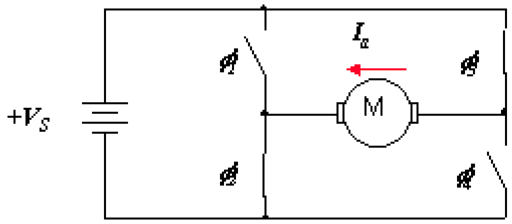
- Four switches control DC voltage applied to motor
- Motor completes the “H”
- Switches must be able to handle **large currents**
- $2^4 = 16$ combinations, but only a few are useful

H-Bridge Circuit Operation

ϕ_1, ϕ_4 on: **forward motor drive**

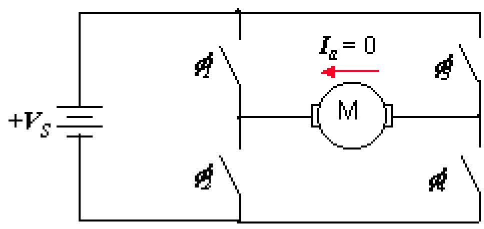


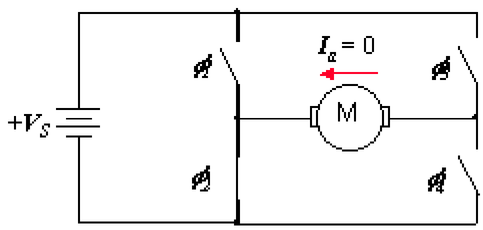
ϕ_2, ϕ_3 on: **reverse motor drive**



Any three switches off: **free running motor stop**

- Viscous damping

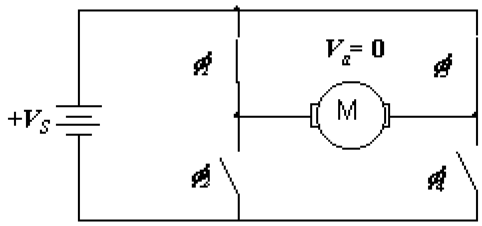


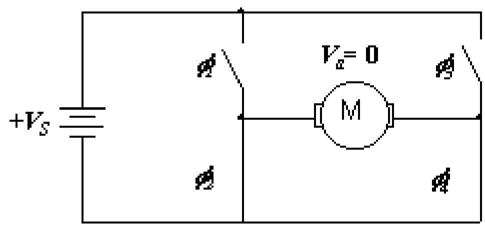


If you connect the two terminals of a motor with a bit of wire (short-circuiting it), you will feel a **resistance torque** if you try to turn the shaft of the motor by hand – the back emf generated by the motor rapidly reduces its speed

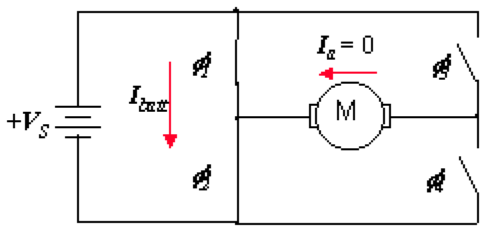
The motor acts like a damper with $\boldsymbol{T = b\omega}$ where T is the torque you feel, b is the damping constant and ω is the motor's angular velocity

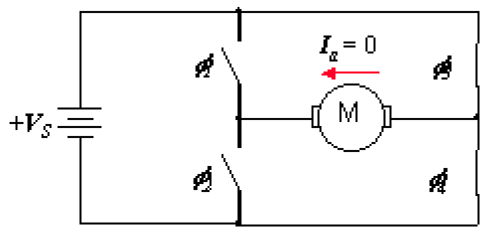
So with ϕ_1, ϕ_3 on or ϕ_2, ϕ_4 on: **braking (fast) motor stop**





ϕ_1, ϕ_2 on or ϕ_3, ϕ_4 on: **shorts out battery** (pretty sparks)





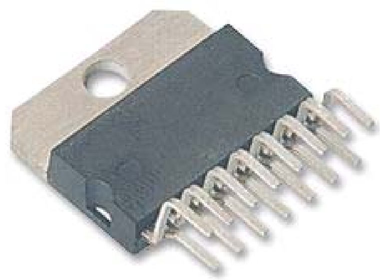
In summary, there are four useful combinations:

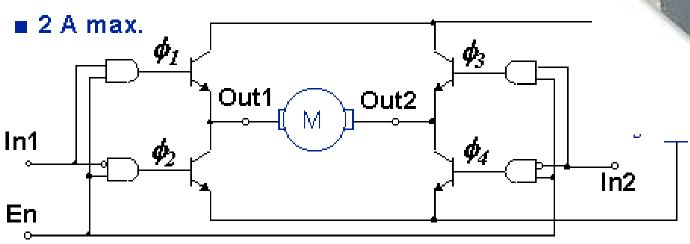
combination	polarity	effect
A & D	forward	Motor spins forward
B & C	reverse	Motor spins backward
A & B	fixed	Motor acts as a brake
None	free	Motor floats freely

There are many chips that combine all the discrete components of an H-Bridge into a single package

The L298 Dual Full Bridge Driver Circuit

- Bipolar transistors act as high-current switches
- Logic prohibits **invalid operation**
- 2 A maximum





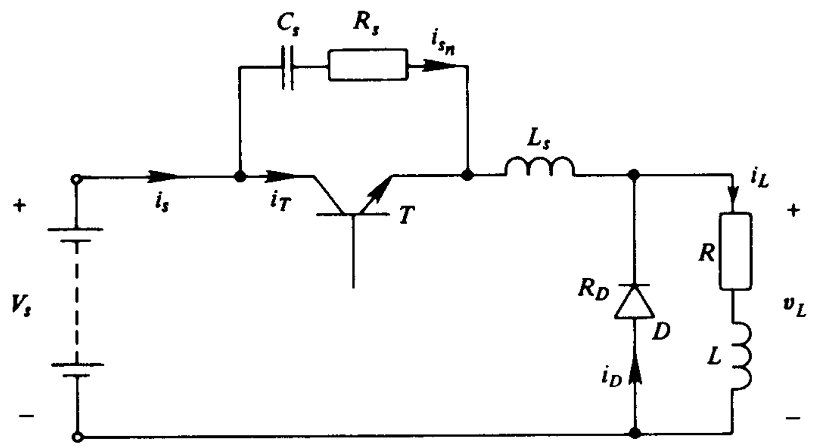
En	In1	In2	
H	H	L	forward
H	L	H	reverse
H	L	L	fast brake
H	H	H	fast brake
L	X	X	free running stop

Snubbers

Snubbers are devices that effectively **limit** switching times so that damage does not occur

Important when you want to suppress the **rapid rise** in voltage across a thyristor, preventing the erroneous **turn-on** by limiting the rate of rise in voltage

A snubber can consist of a small resistor in series with a small capacitor connected across the output terminals of the switching device



Can be used with either **DC or AC** loads

A flyback diode is also an example of a snubber

Metal-oxide varistors are used as transient suppressors

Available at voltage ratings from 10 – 1000 V and can handle transient currents up to thousands of amperes

A Tranzorb is a silicon based surge protector with a **very fast** clamping reaction

It can trigger at **low voltages** making it suitable for protection of circuits which could be damaged by high current surges of relatively low voltage (e.g. data buses)

One of our robots uses a Transzorb transient protector in parallel with an RC snubber (100 Ω, 10 nF) in inverse-parallel with a Zener

You can **NEVER** be too careful when dealing with motors

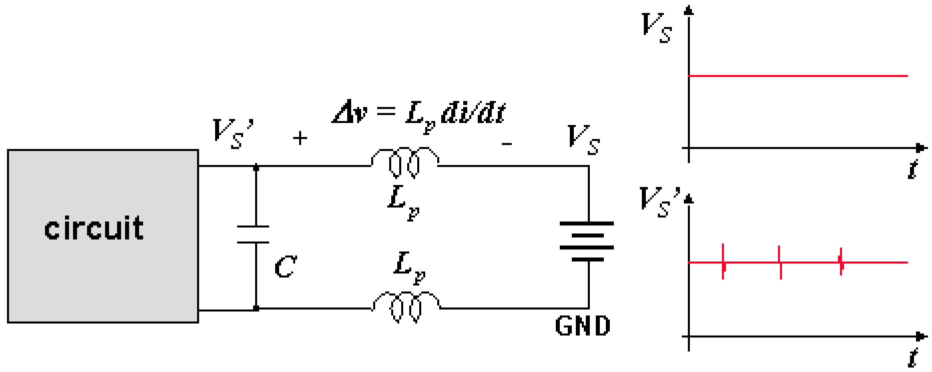
Bypass Capacitors

Place close to driver chip

Shunt high-frequency current

Suppresses propagation of **AC voltage glitches**

- Motor commutation
- Motor control switching
- Digital switching



Motors frequently suffer from severe **in-rush currents** during starting

Need to ensure all components can handle this current

Fuses

A fuse will go open-circuit if a certain current is exceeded

By limiting the maximum circuit current, damage to expensive electronics can be avoided (a new fuse is much cheaper than a new relay, driver chip, etc.)

Slow-blow – the current must be exceeded for a certain (long) length of time

Fast-blow – as soon as the current rating is exceeded, the circuit will "blow"

Place a fuse inline from your driver to the high-current loads

During prototyping, common to use **fast-blow** fuses

Once the circuit is debugged and in use, should use a slow-blow as there is often a large current transient at turn-on (due to rapid charging of the power-supply capacitors)

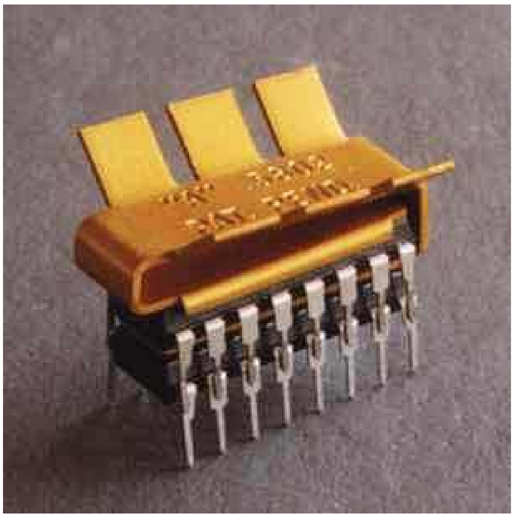
Externally accessible fuse-blocks can be very convenient

Heat

Driving **high-current** loads generate heat

This heat can reduce the **efficiency** of the driver and can even **ruin** it if it gets too hot

Some devices can be put in **parallel** or stacked to handle more current and therefore dissipate more heat



Heatsinks and venting are often necessary

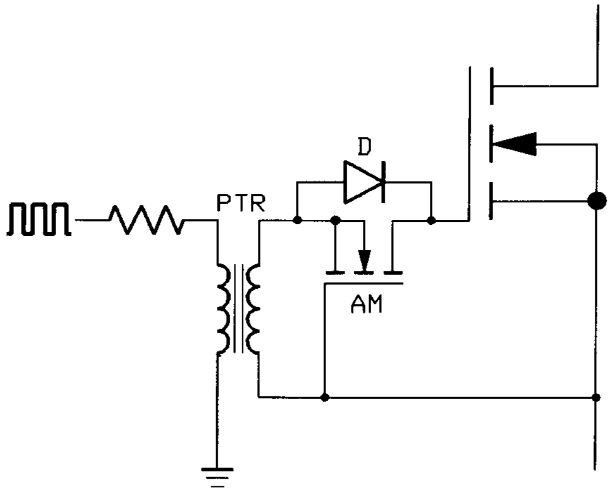
In extreme cases, small fans can be employed but these consume power and generate noise

Put venting holes above and below a hot drive circuit before you put holes on the sides

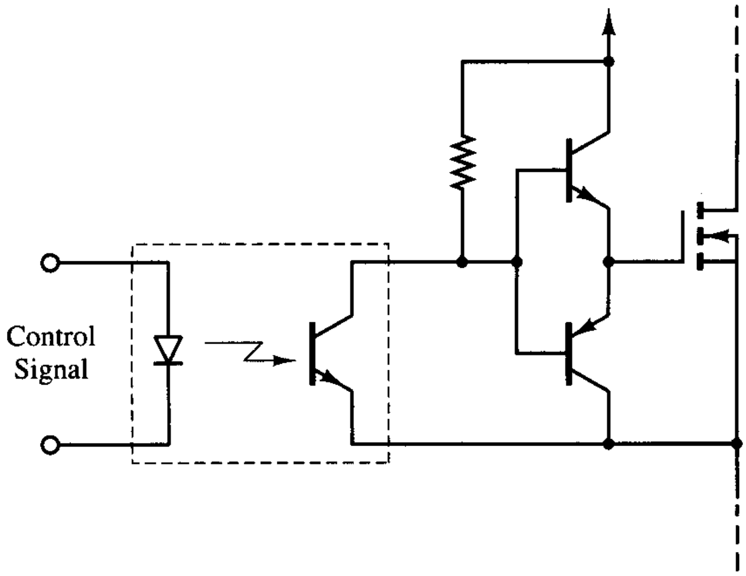
Signal Isolation

To reduce noise, the high current electronics may need to be **isolated** from the rest of the circuit

This is normally **transformer** or **optical** based



Transformer isolation of a MOSFET driver



Optical isolation of a MOSFET driver