Introduction to Autonomous Electric Vehicles

Lecture 1

- EV Modules
    - Electrical and mechanical sub-systems
- Vehicle Modeling

EEE department, BITS-Goa

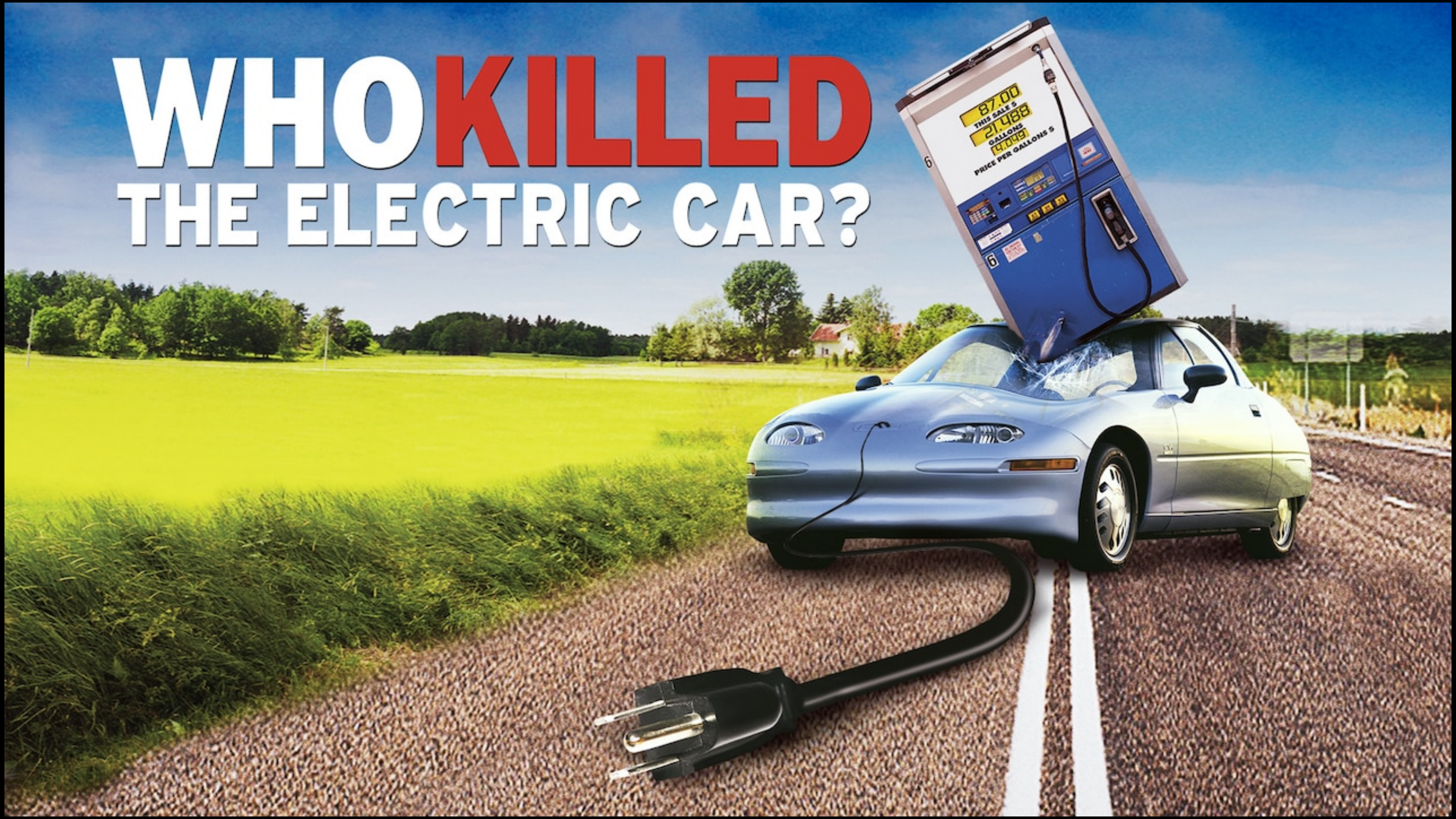
27-March-2021

Course Instruction

- Background about the course
    - Learnings from a cargo AV start-up
- Course structure
    - 6 lectures 90 minutes each
    - Breadth-over-depth
        - Individual topics can span semester-long class!
    - Primary emphasis on software: Autonomy and Control
    - High-level overview of EV modules and vehicle-design choices
- Supplemental readings and non-graded assignments

Today’s Plan

- Introduction (Leisurely) - 15 min
- Batteries and BMS - 20 min
- Electric Motors - 20 min
- Break - 5min
- Vehicle design - 10 min
- Vehicle modeling - 20 min


WHO KILLED
THE ELECTRIC CAR?

Factory Workhorse

Agile service Bot

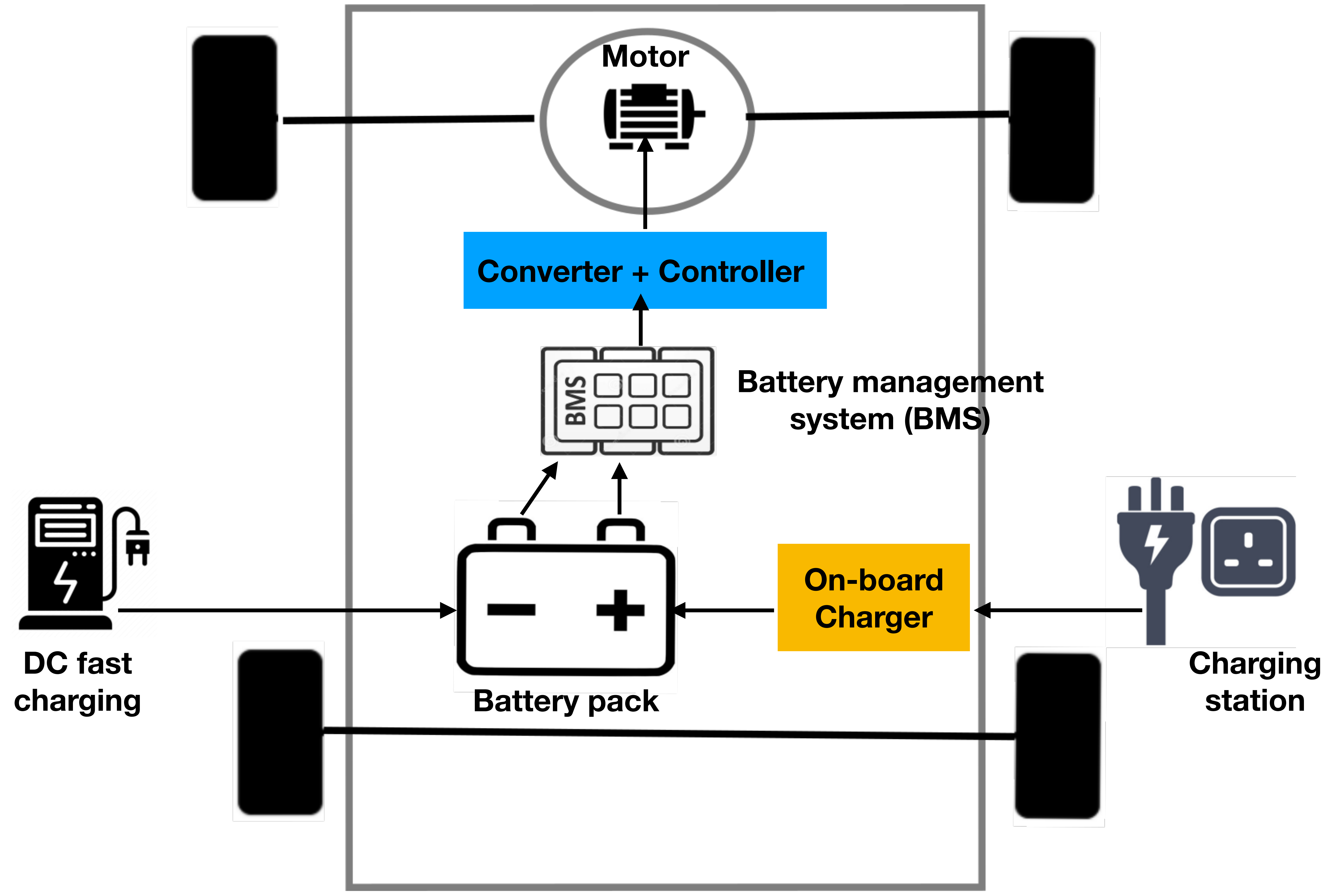
Contactless patient care in CoVID hospitals

EV sub-systems

Electrical modules

Overview

- Battery Pack
  - Li-ion
  - Need for BMS
  - Newer battery tech
- Motors
  - DC Motor
  - Motor controller

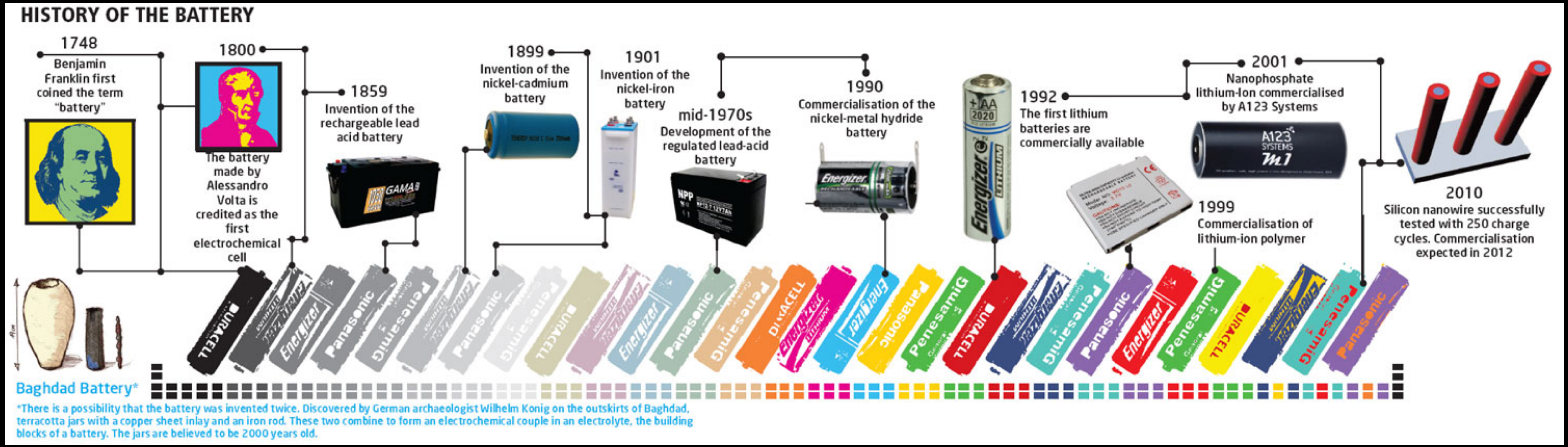


Objectives for today

1. Requirements: Vehicle + payload weight, terrain, inclination, maximum speed/ desired acceleration, duration before recharging
2. Calculate Torque needed - Peak/ continuous
3. Select Motor to deliver calculated Torque
4. Select Battery size based on Motor and driving range

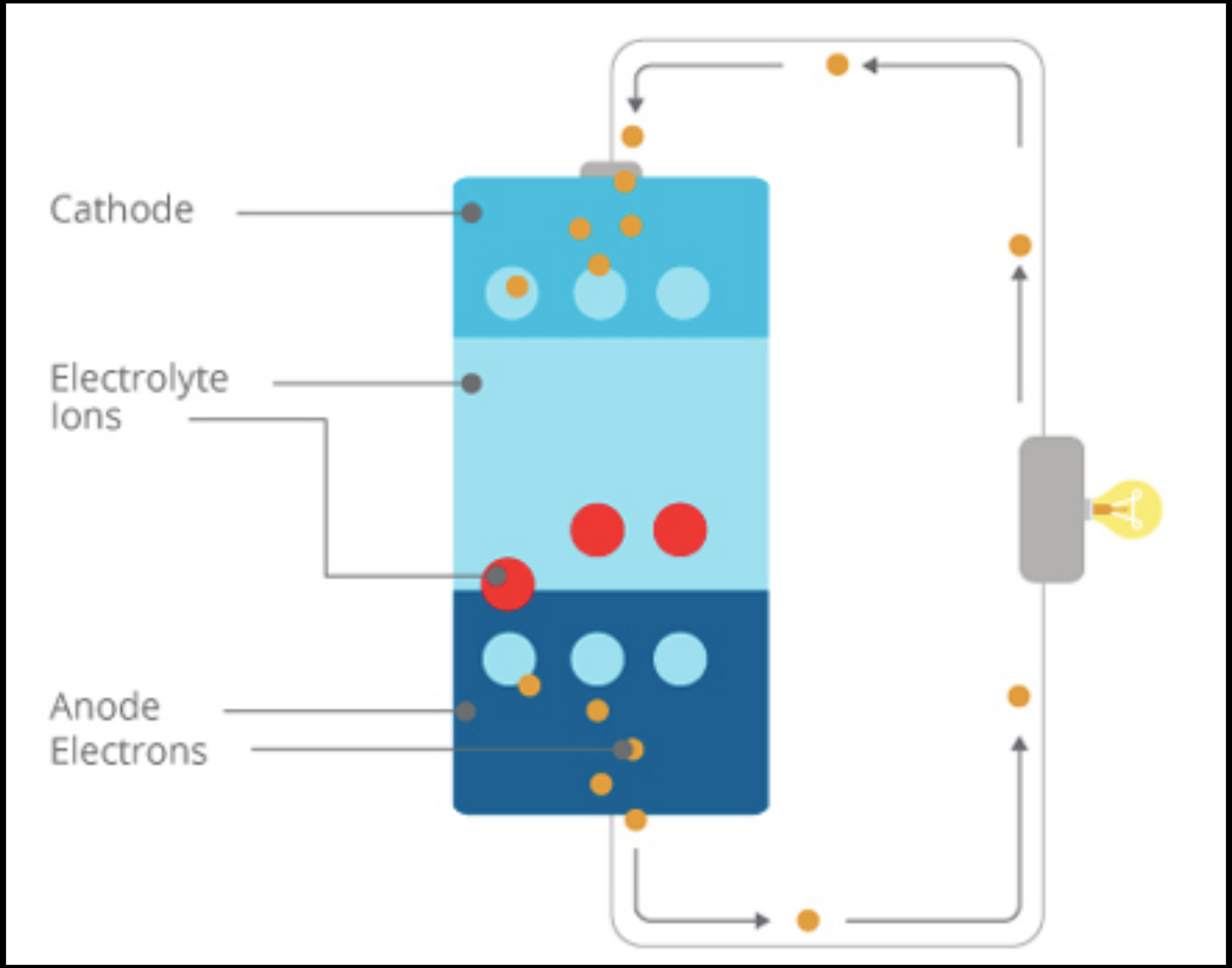
Battery Pack
Battery Management System

Battery is the new oil



- Lead-acid / Ni-Cd/ Ni-H batteries - > 100 years
- Li-ion batteries commercially available ~25-30 years
    - Li light metal, 3.5x energy density of Lead-acid
    - De-facto choice for EVs today
    - Next few slides - practitioner’s perspective
- Briefly talk about other promising battery tech
    - Supercapacitors / Fuel Cells

Simple battery schematic



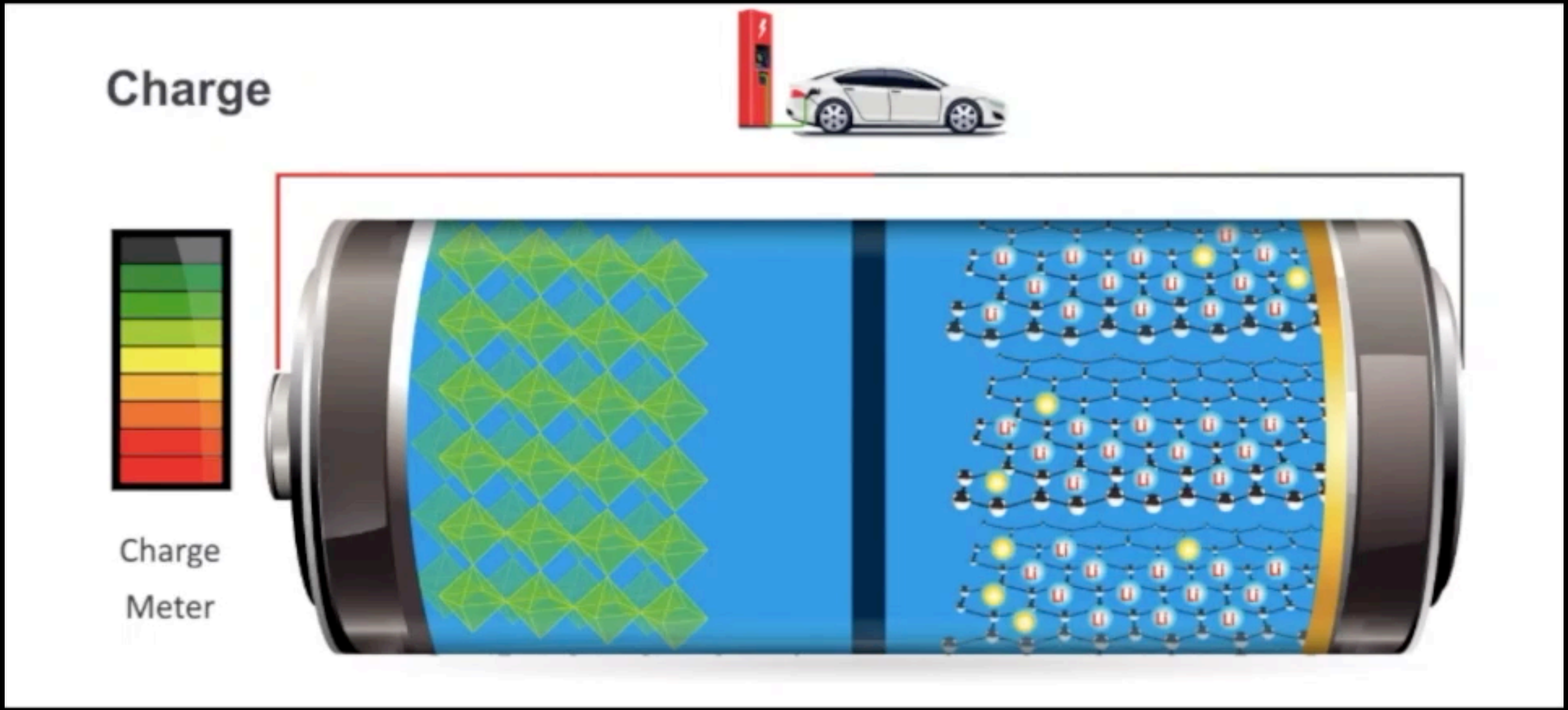
Discharge

- Ions in Electrolyte + Anode = release free electrons
- Free electrons absorbed by Cathode
- Separator = blocks electron movement between Cathode-Anode

Charging = Reverse action

Source: https://www.bhphotovideo.com/explora/photography/buying-guide/batteries-101

Charge-Discharge cycle animation



Source:
https://www.energy.gov/eere/articles/how-does-lithium-ion-battery-work

Enough chemistry!

How to dimension battery packs and use them in design?

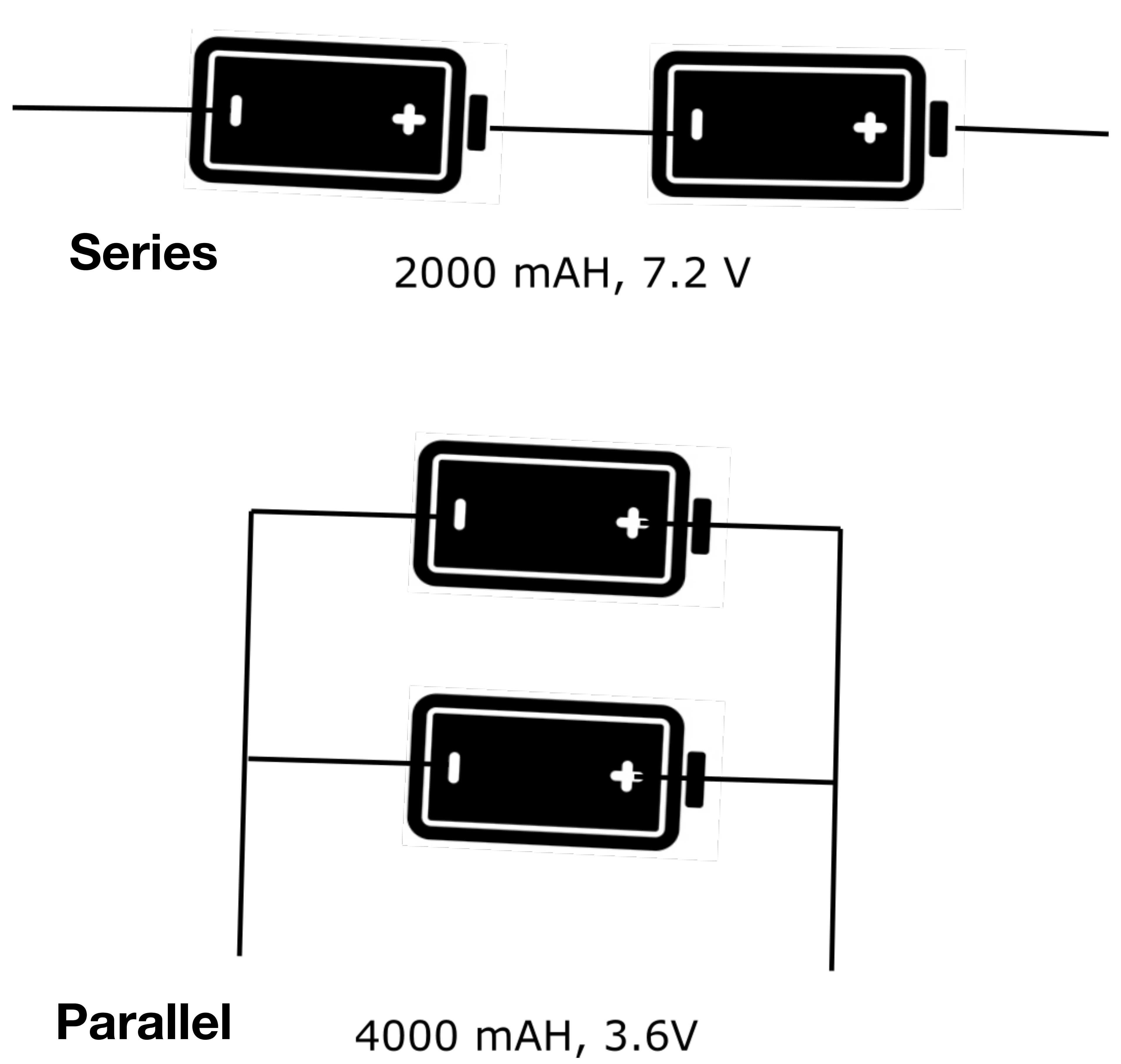
Tesla Model-S battery pack

Battery voltage and capacity

- Voltages
    - Fully Charged ~ 4.2V
    - **Nominal** ~ 3.6V
    - Fully discharged ~ 3.2V
- **Cell Capacity (mAH)**

  2000 mAh => Battery lasts 1 hour @ 2A discharge

  Battery lasts 2 hours @ 1A discharge
- Nominal energy stored = 2 x 3.6 = 7.2 Wh
    - Cars would need much more!
    - Energy needed for 100 Watt bulb @ 1hour = 100 Wh
- Battery packs
    - Combination of cells in series and parallel
    - Parallel cells => capacities get added
    - Series cells => voltages get added



Tesla

- 96s x 74p
- Fully charged voltage = 96 *4.1 ~ 390V
- Capacity = 74 * 2.8 ~ 207.2 AH
- Energy stored ~ 81 kWH
- Can drive a **81kW** motor for an hour

Battery current

- 2000 mAh => Battery lasts 1 hour @ 2A discharge
  Battery lasts 2 hours @ 1A discharge
- Best capacity results when lower currents drawn
  - Can walk 20 miles at a stretch, cannot run that much
- High current electronics
  - Contactors and Cables have be heavy
  - High I^2R losses - heat sinks needed
- **C-rate** = specified max current that can be drawn

Cut-off circuitry needed to ensure max current is not drawn for prolonged periods

Design Summary

- Capacity comes from desired range
  - Max vehicle speed and range gives desired discharge duration
- Nominal voltage depends on the motor
    - DC-DC converter to address motor-specific voltage requirements
- Current - Peak/ nominal current drawn depends on motor's peak/ rated power

Additional factors in battery pack design

- Weight of the battery pack
    - @ 48 g / cell ~350 Kgs for batteries alone
    - with casing, cable + cooling units, battery can take 50% of car weight!
- Cost of the battery pack
    - $1.50 /cell ~10K$ for the batteries alone in Tesla

Reading datasheet: Samsung 18650-25R

Type		Spec.	Typical INR18650-25R
Chemistry		NCA	NCA
Dimension (mm)	Diameter	18.33 ± 0.07	18.33 ± 0.07
	Height	64.85 ± 0.15	64.85 ± 0.15
Weight (g)		Max. 45.0	43.8
Initial IR (mΩ AC 1kHz)		≤ 18	13.20 ± 2
Initial IR (mΩ DC (10A-1A))		≤ 30	22.15 ± 2
Nominal Voltage (V)		3.6	3.64
Charge Method (100mA cut-off)		CC-CV (4.2±0.05V)	CC-CV (4.2±0.05V)
Charge Time	Standard (min), 0.5C	180min	134min
	Rapid (min), 4A	60min	55min
Charge Current	Standard current (A)	1.25	1.25
	Max. current (A)	4.0	4.0
Discharge	End voltage (V)	2.5	2.5
	Max. cont. current (A)	20	20
	Max. momentary pulse (A, <1sec)	100	100
Rated discharge Capacity	Standard (mAh) (0.2C)	2,500	2.560
	rated (mAh) (10A)	2,450	2.539

Battery selection example

Say, we selected a Motor that is rated at 1KW and 50V

Vehicle weight = 500Kg

Top speed = 40Kmph

Desired range = 200Kms

Battery and Motor efficiency ~ 80%

What is the battery capacity needed?

Nominal current I = 1KW/ 50V = 20 A

Adjusted current ~ 1.1*I = 22A

- Accounts for stop-start traffic

Power needed = 22*50 = 1.1kW

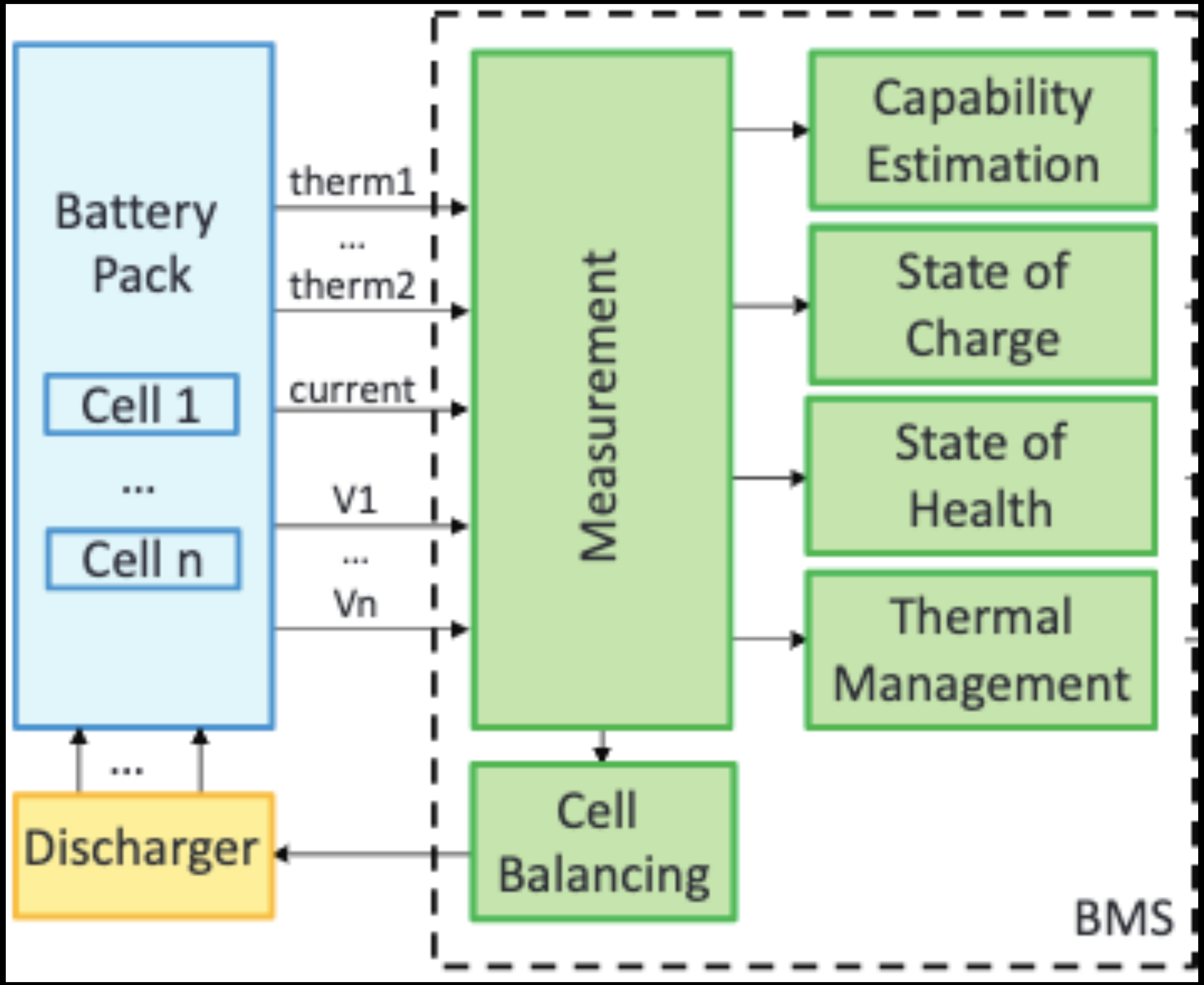
Duration = 200/40 = 5hours

Storage capacity needed =

1.1*5/(0.8*0.8) ~ 8.6 kWh

You can now select MxN 18650 battery pack!

Need for BMS



- Lithium very unstable
  - Overcharging can cause explosions
  - Excess discharge cause battery damage

What does BMS do?

- Safety
  - Overheat cut-off circuitry
- Perf Optimization
  - Regulate charging/ discharging
- Predictive Maintenance
  - Cell Balancing

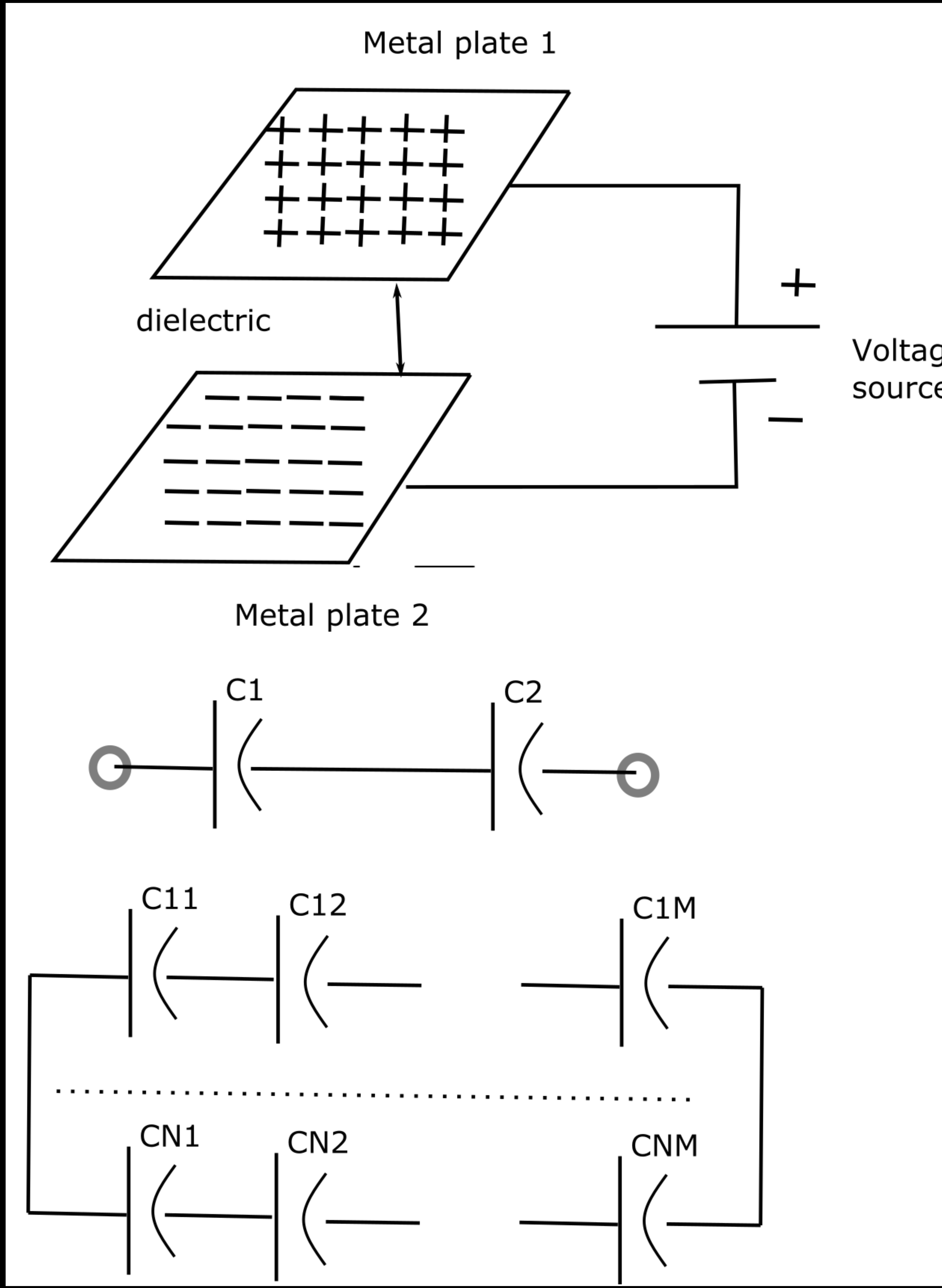
Source: L. Buccolini et al “BMS simulation environments for EVs”, 2016

Super-capacitors

$$Q \propto V \qquad\qquad C = \frac{\epsilon A}{d}$$

$$E = \frac{1}{2} C V^2$$

- No chemical reactions involved
- Larger storage -> larger form factor
- Super-capacitor = carbon electrodes + electrolyte
  - High shelf-life
  - Rapid charge-discharge, used in region braking
- M x N array => realizes higher voltage and energy
  - Energy increases as MxN
  - Voltages increases as M



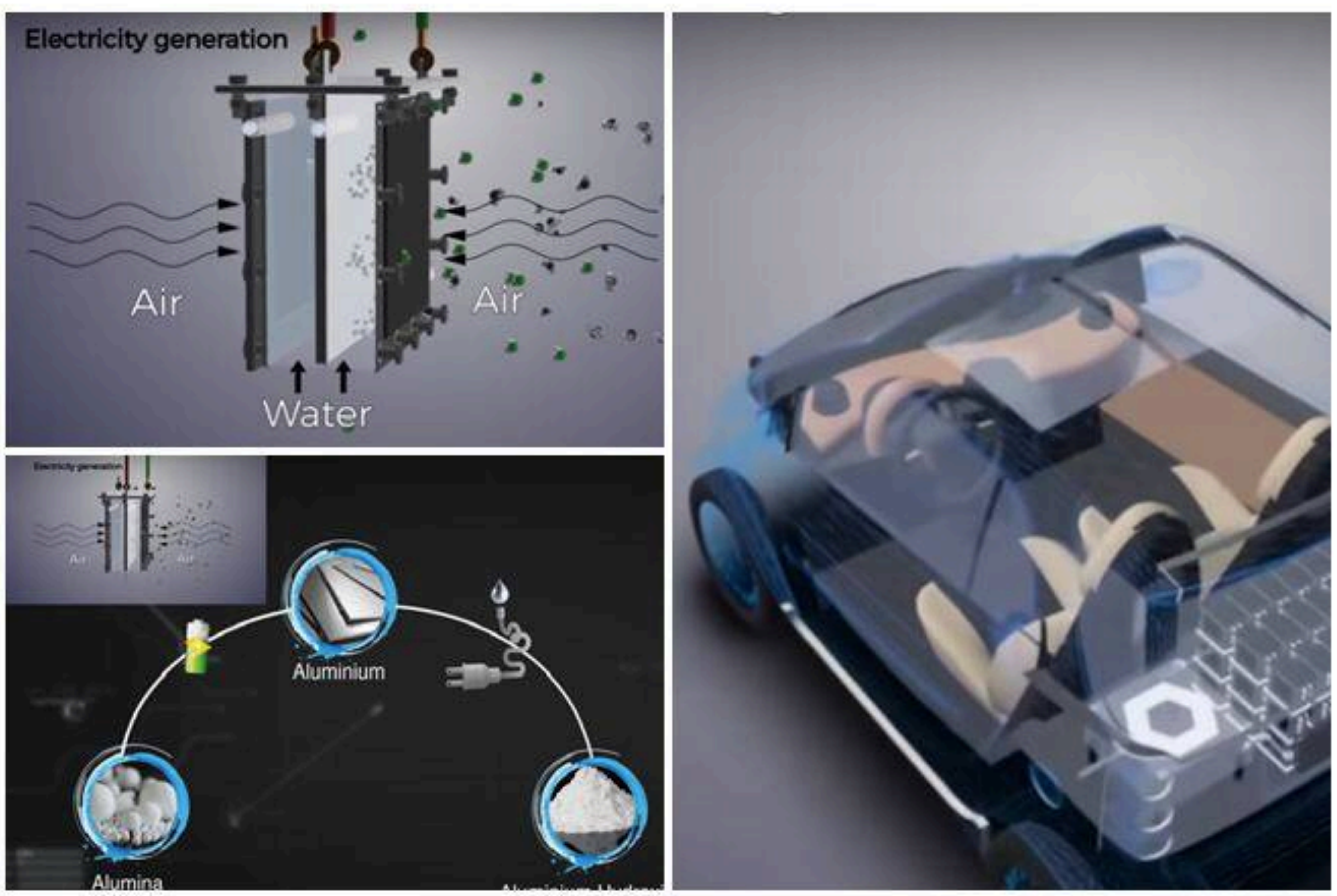
Source: ESE 471, Lecture 4, Oregon State

Super-capacitors vs Batteries

- Sprint-like
- High Power
- Short Bursts
- HEVs use in regenerative braking, back-up UPS, maintenance-free applications

- Marathon-like
- Constant, low Power
- Long periods of time

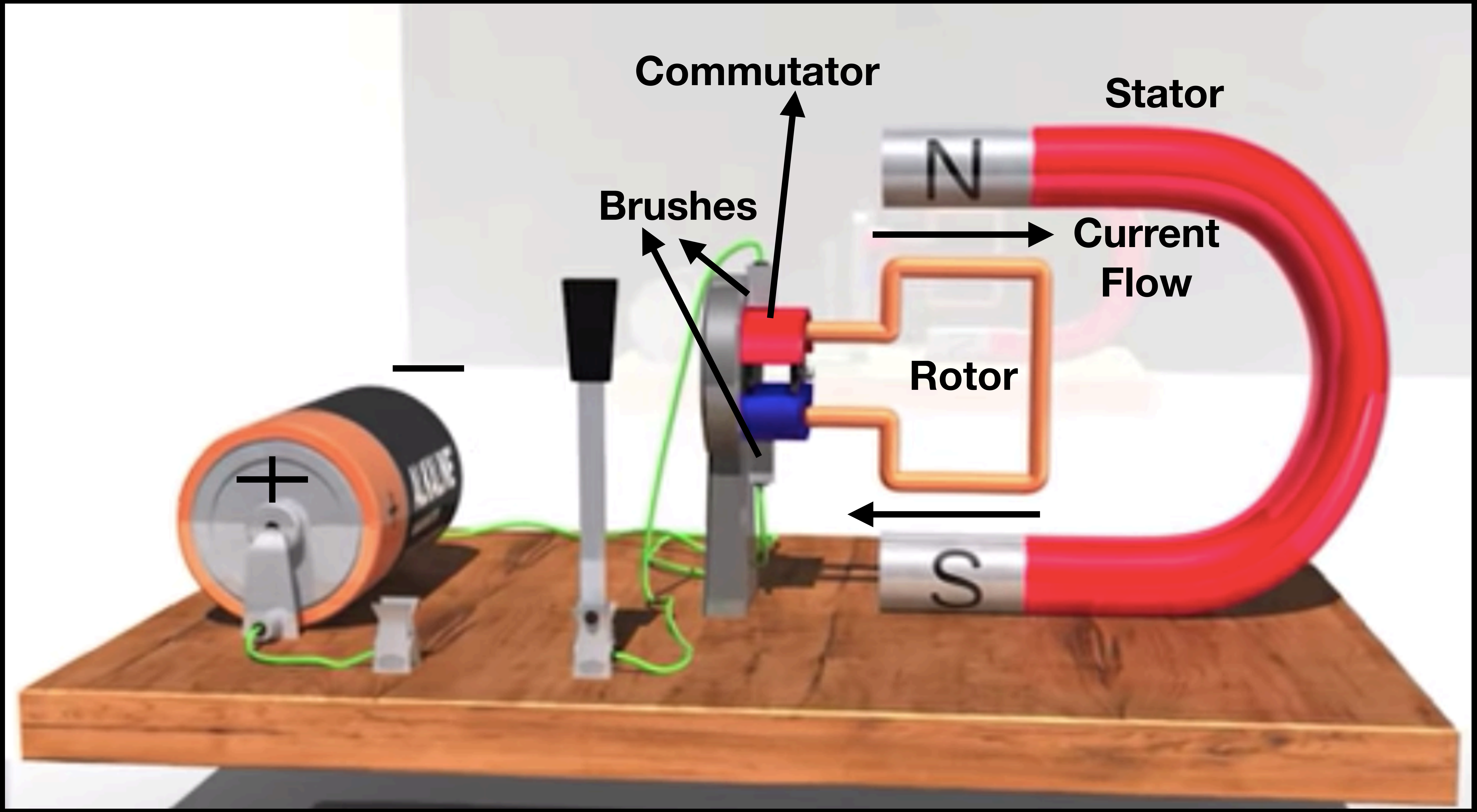
Metal-air batteries



- Bangalore-based nanotech startup Log9
- Aluminium plates in water, separated by graphene layers
- Aluminium corrodes and releases energy
- 8x energy density of Li-ion battery packs
- Not rechargeable
- Plates to be replaced every 1000km
    - Collected Al oxide can be recycled back

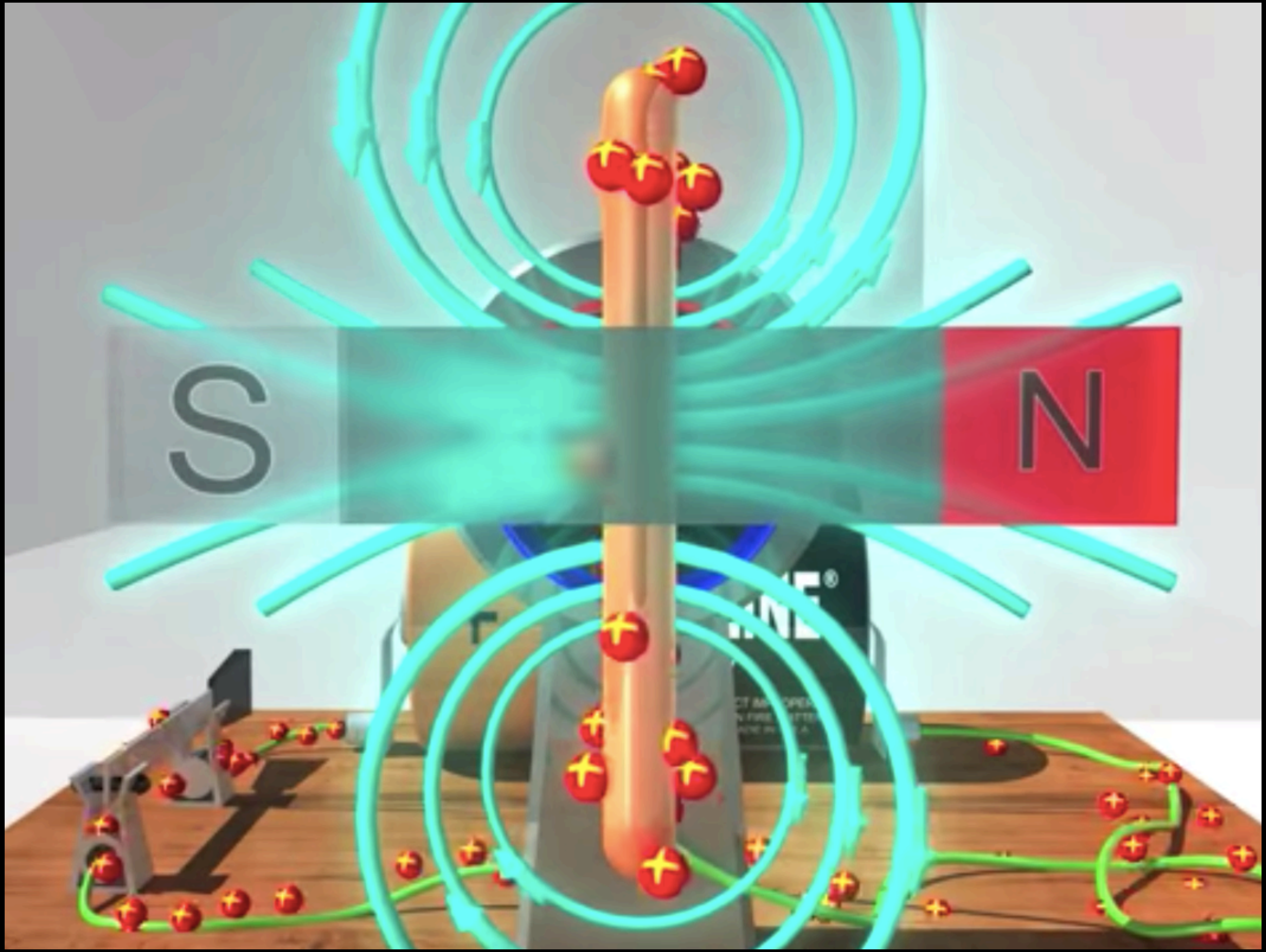
Motors

How a simple DC motor works



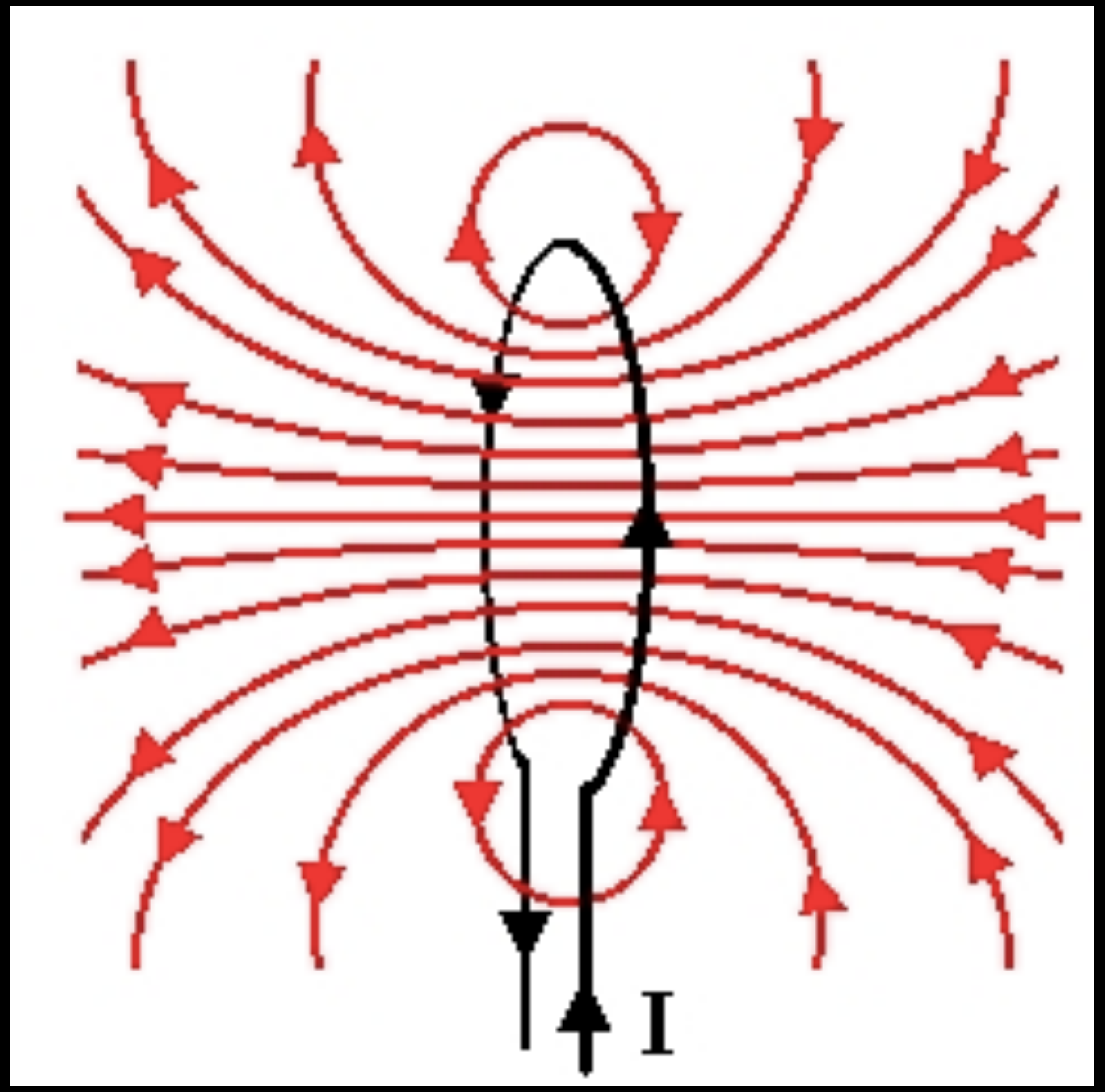
Source: https://m.youtube.com/watch?v=wxG3cwugXgs

Remove permanent magnet temporarily



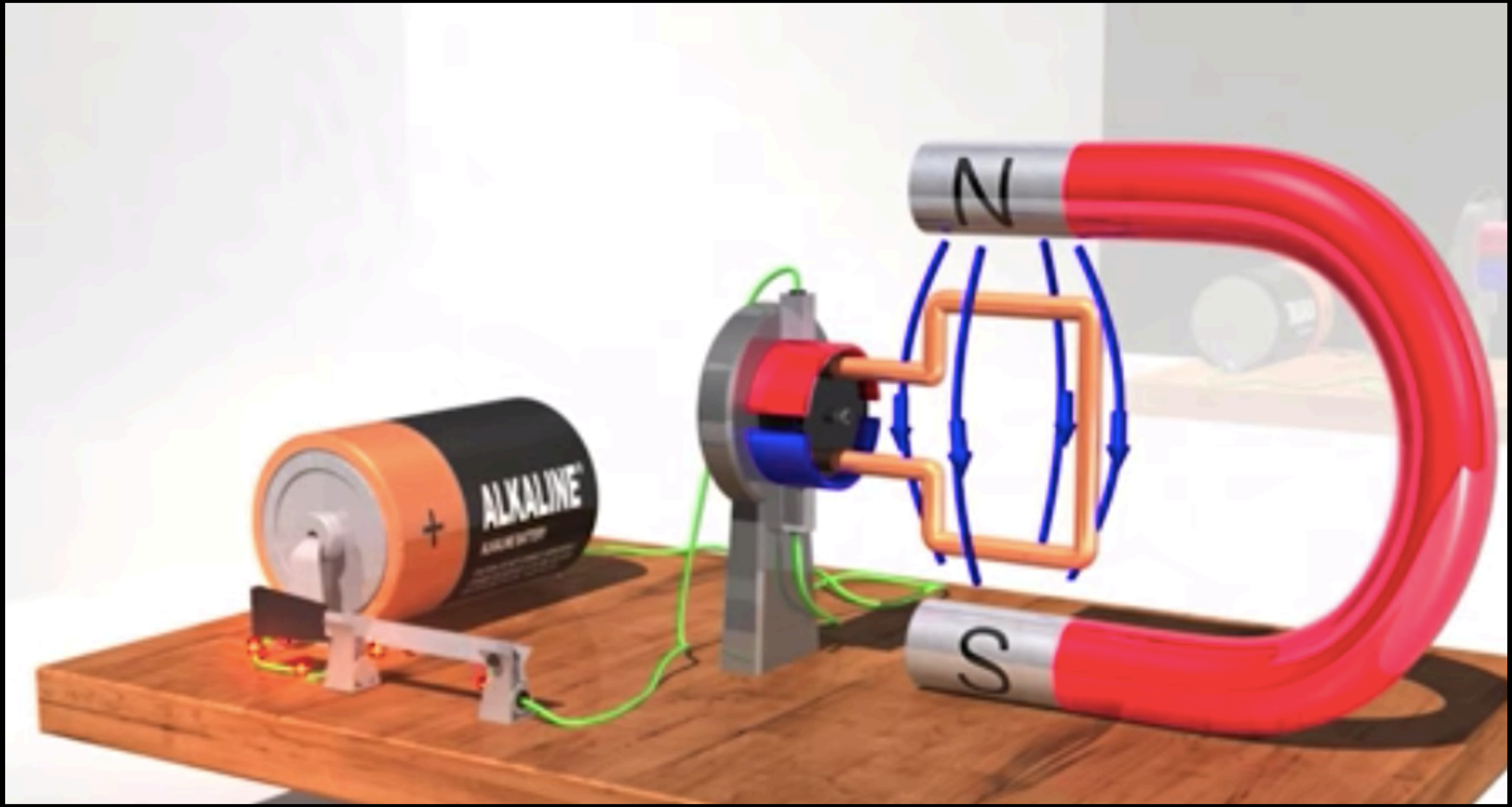
Ampere's law

Magnetic field around current carrying conductor

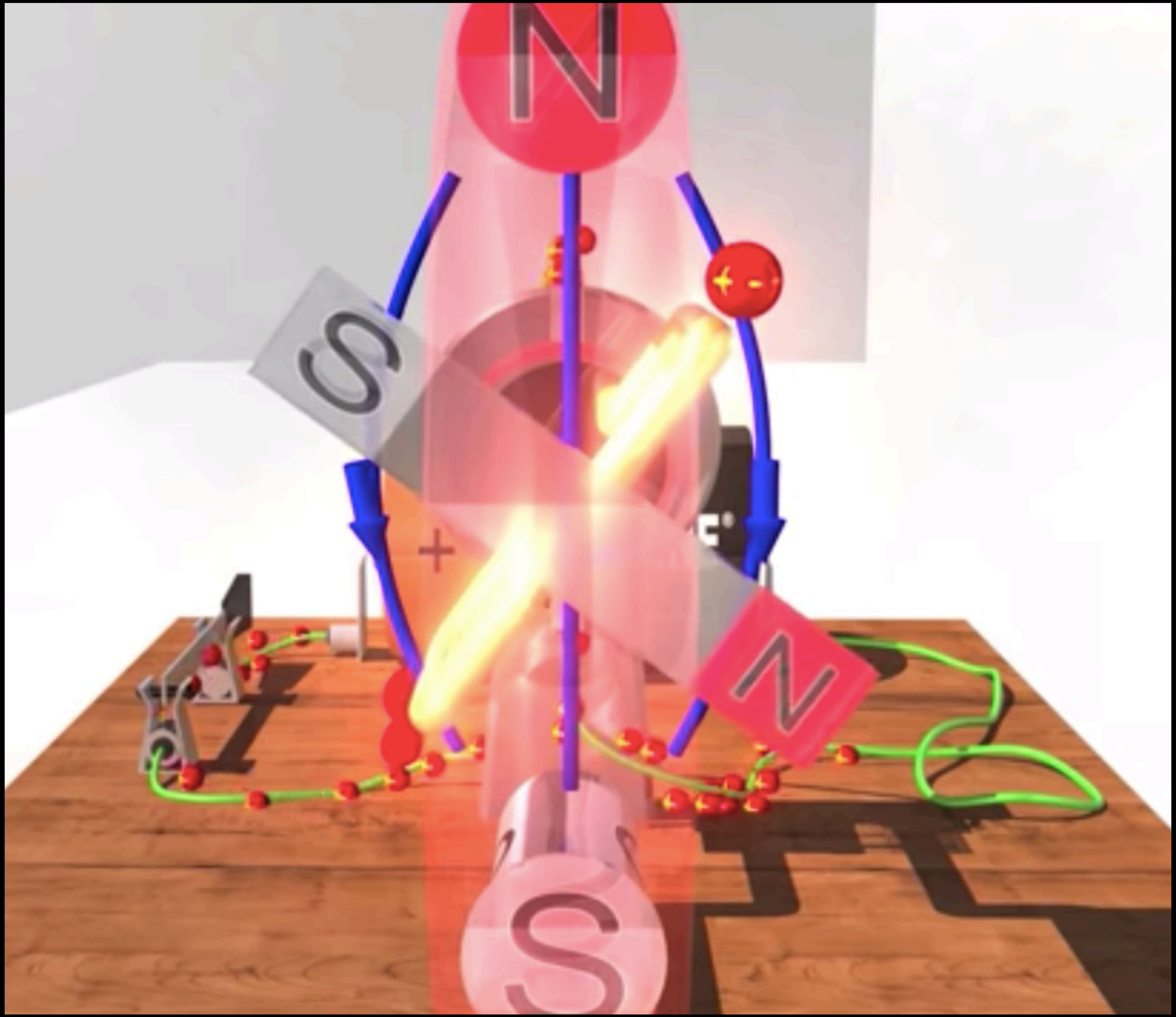


Right-hand grip rule gives direction of magnetic field

Re-introduce permanent magnet



Flux lines of permanent magnet shown in blue



Rotor starts to rotate

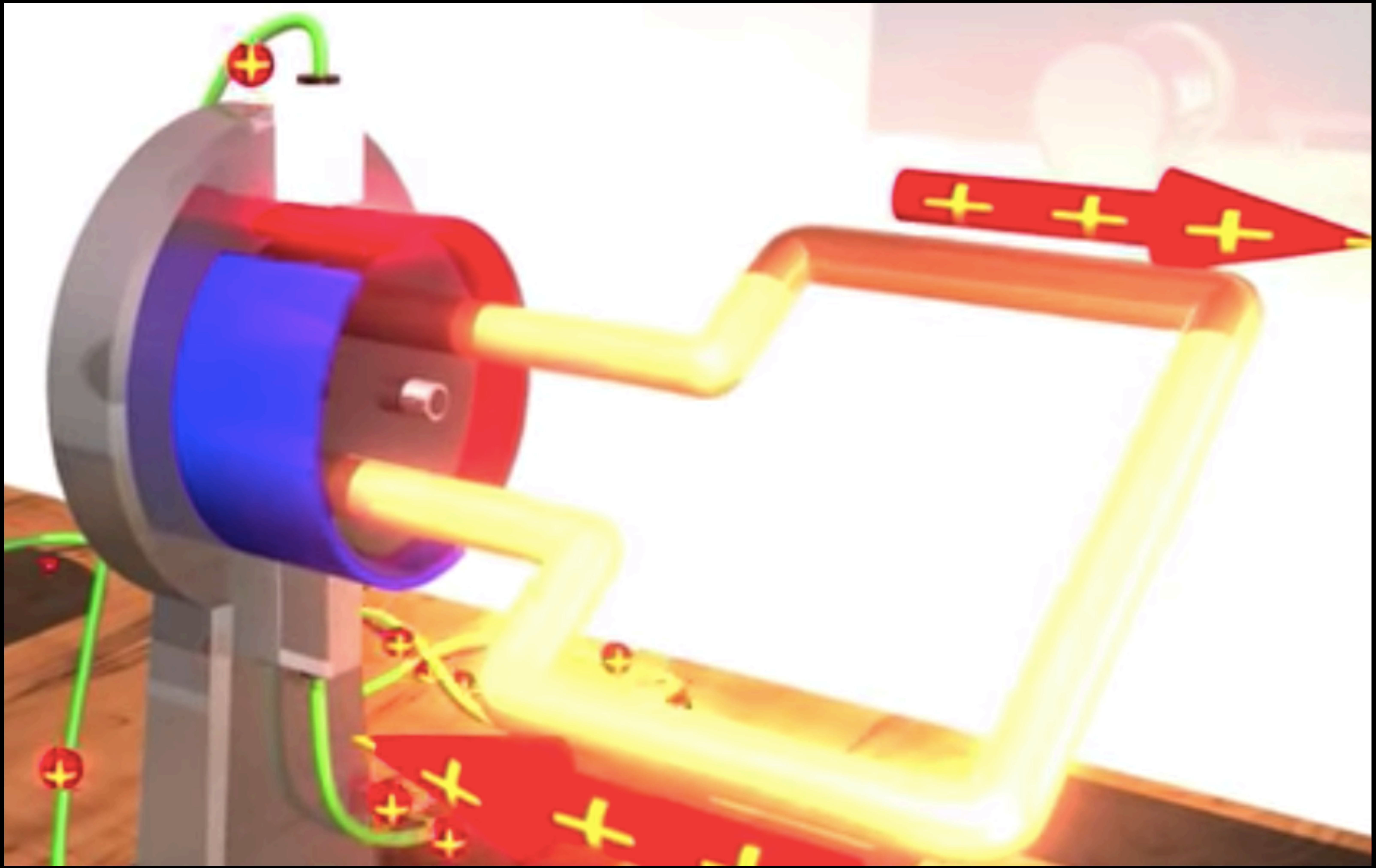
- Like-poles repel
- N-S will align

Formally -> Lorentz force

How to achieve continuous rotation?

Once N-S is aligned, no tendency to move

Brush and Commutator



Brush alternately touches the 2 rings of commutator

Current direction keeps reversing as does the electromagnetic field

Bridge electrical and mechanical

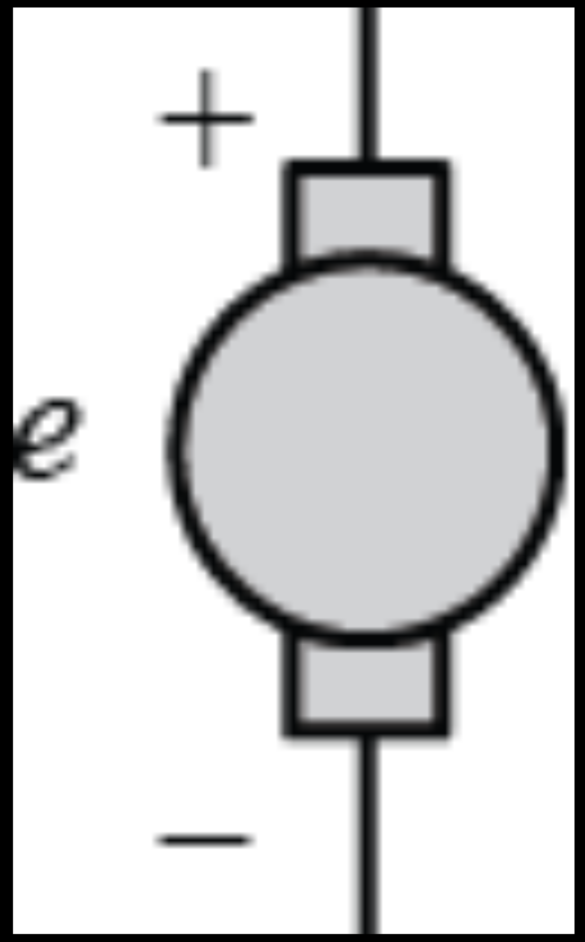
Wheel rotates when connected to motor
Relation between motor current to output speed?

Circuit Diagram for DC motor

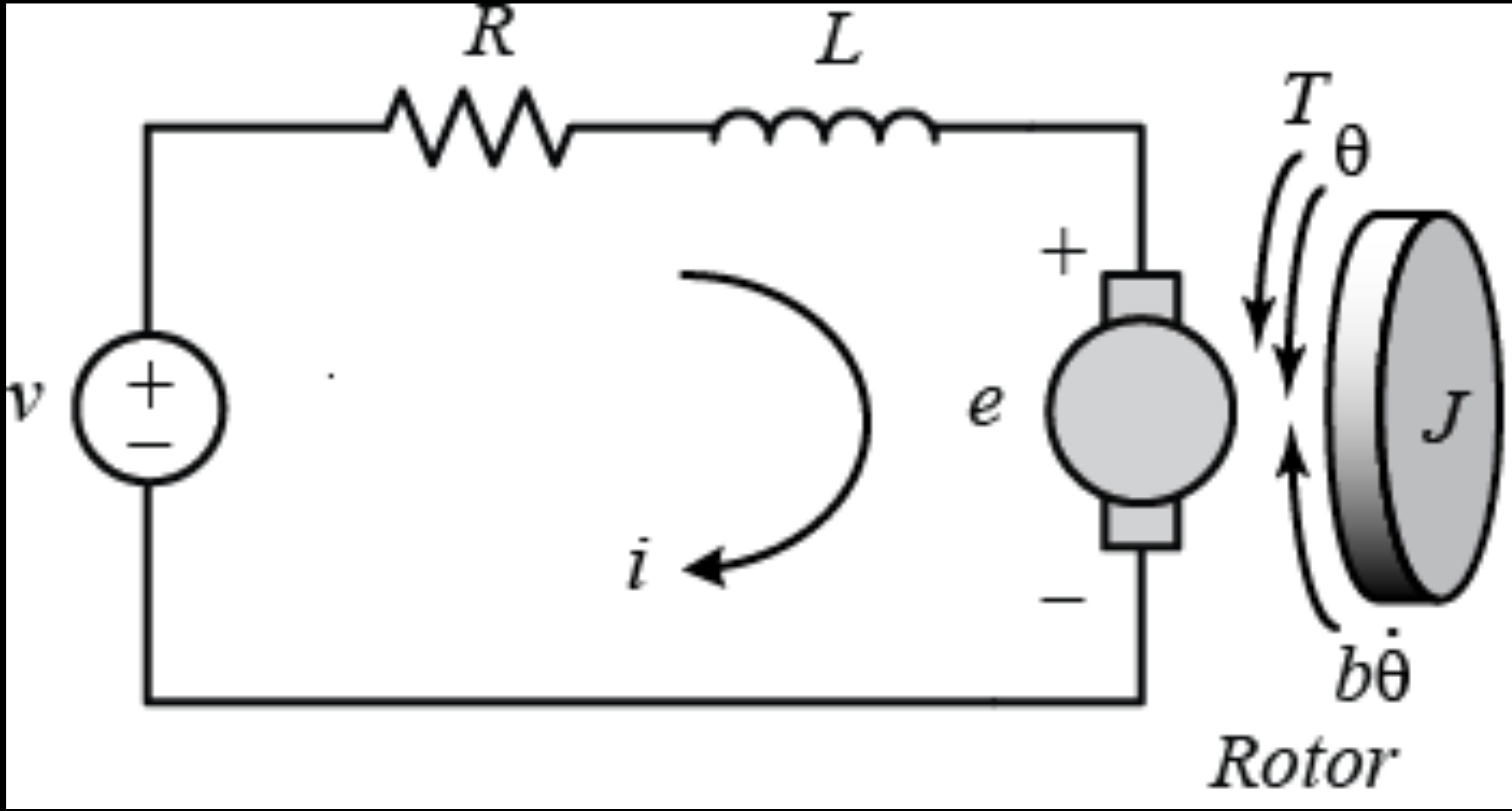
Two more concepts

Faraday's law = electromotive force (emf) developed as the rotor moves

Lenz's law = emf will oppose what causes the motion



DC motor equations



J = M.I ~ mass
ω ~ velocity
τ ~ Force

Kirchoff's voltage law

$$L\frac{di}{dt} + Ri = V - e_b$$

Newton's 2nd law

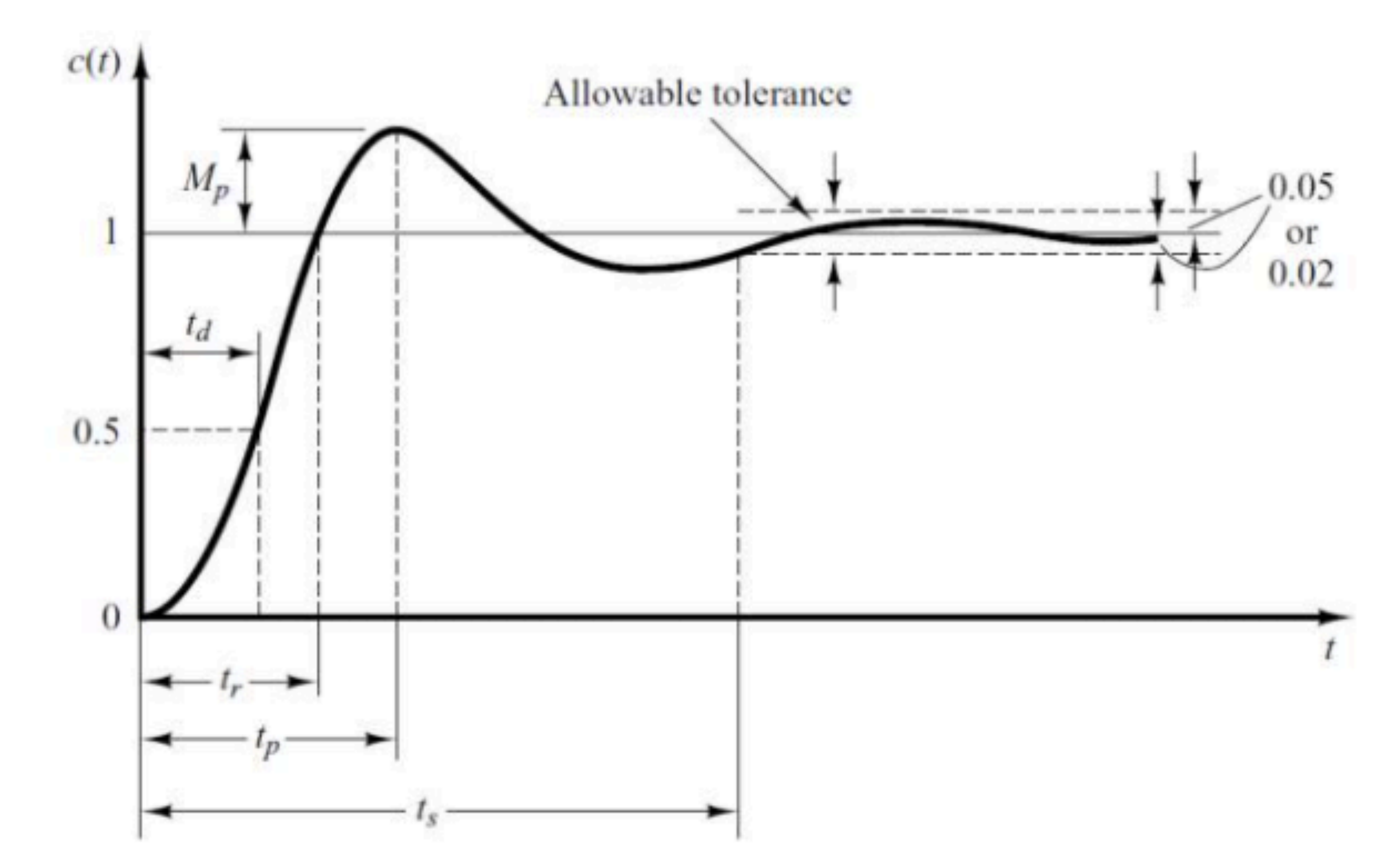
$$J\frac{d\omega}{dt} = \tau - \tau_{load} - B\omega$$

Electro-mechanical coupling

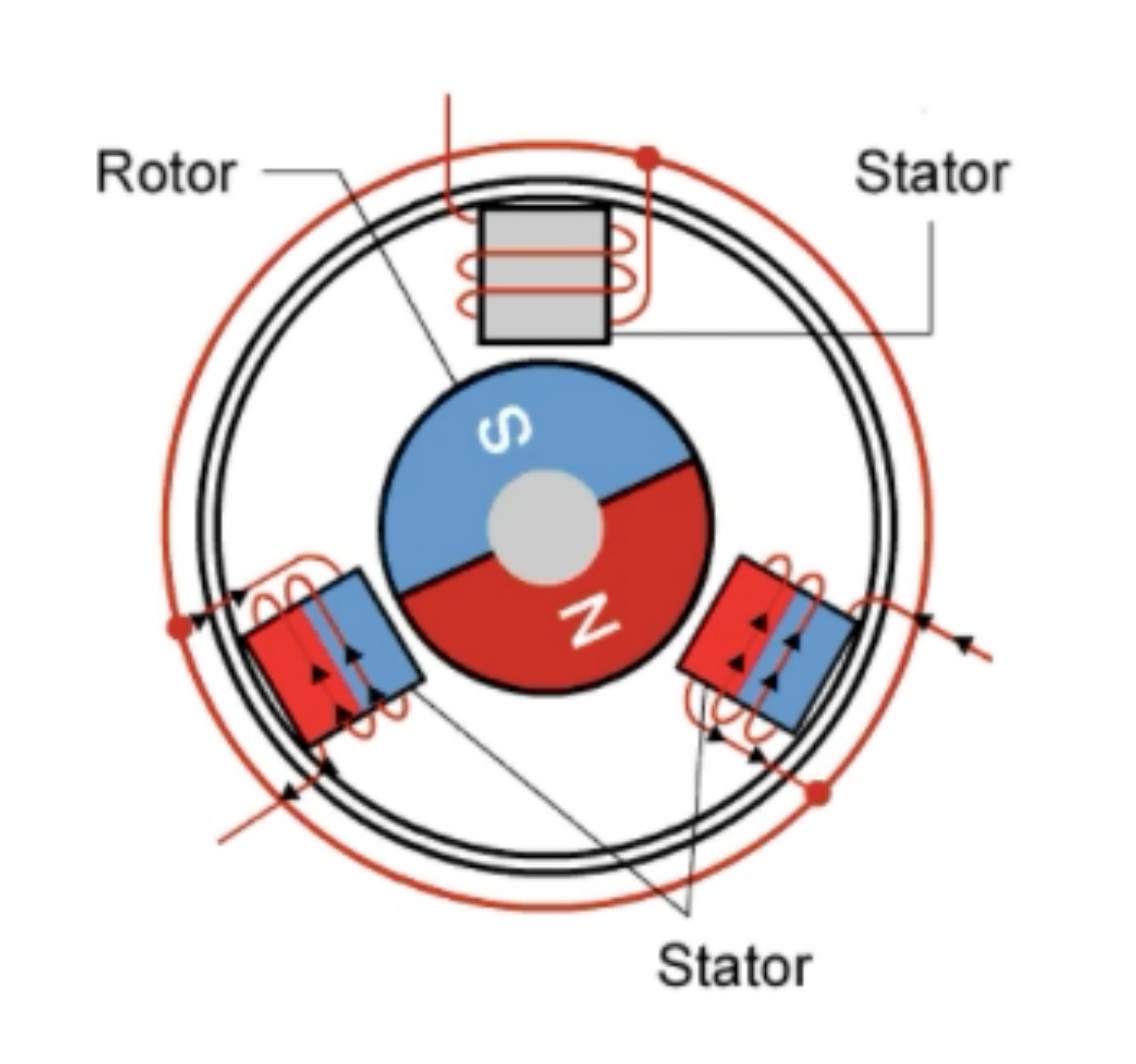
$$e_b = k \cdot \omega$$

$$\tau = k \cdot i$$

Second-order system response



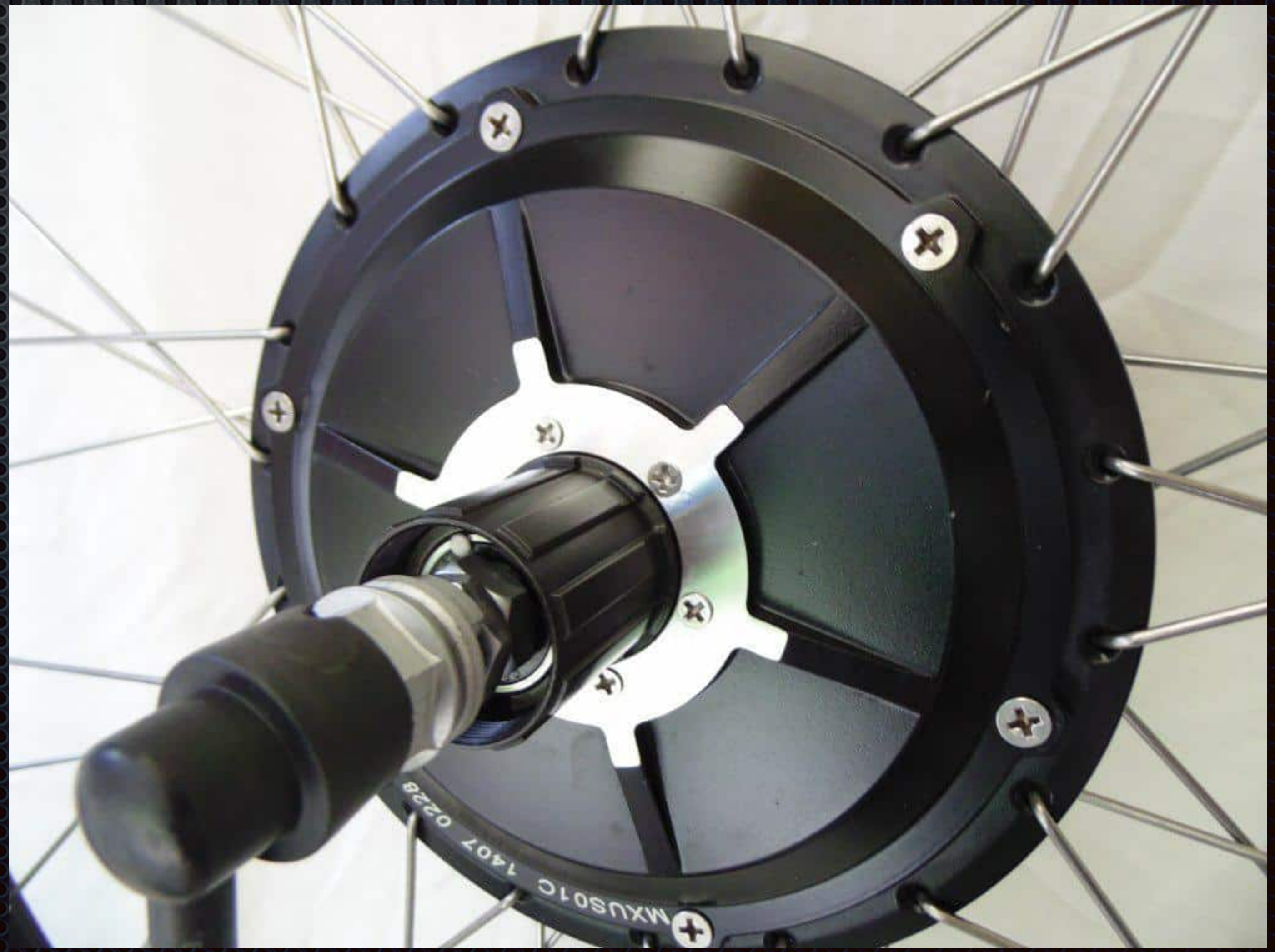
Brushless DC motor



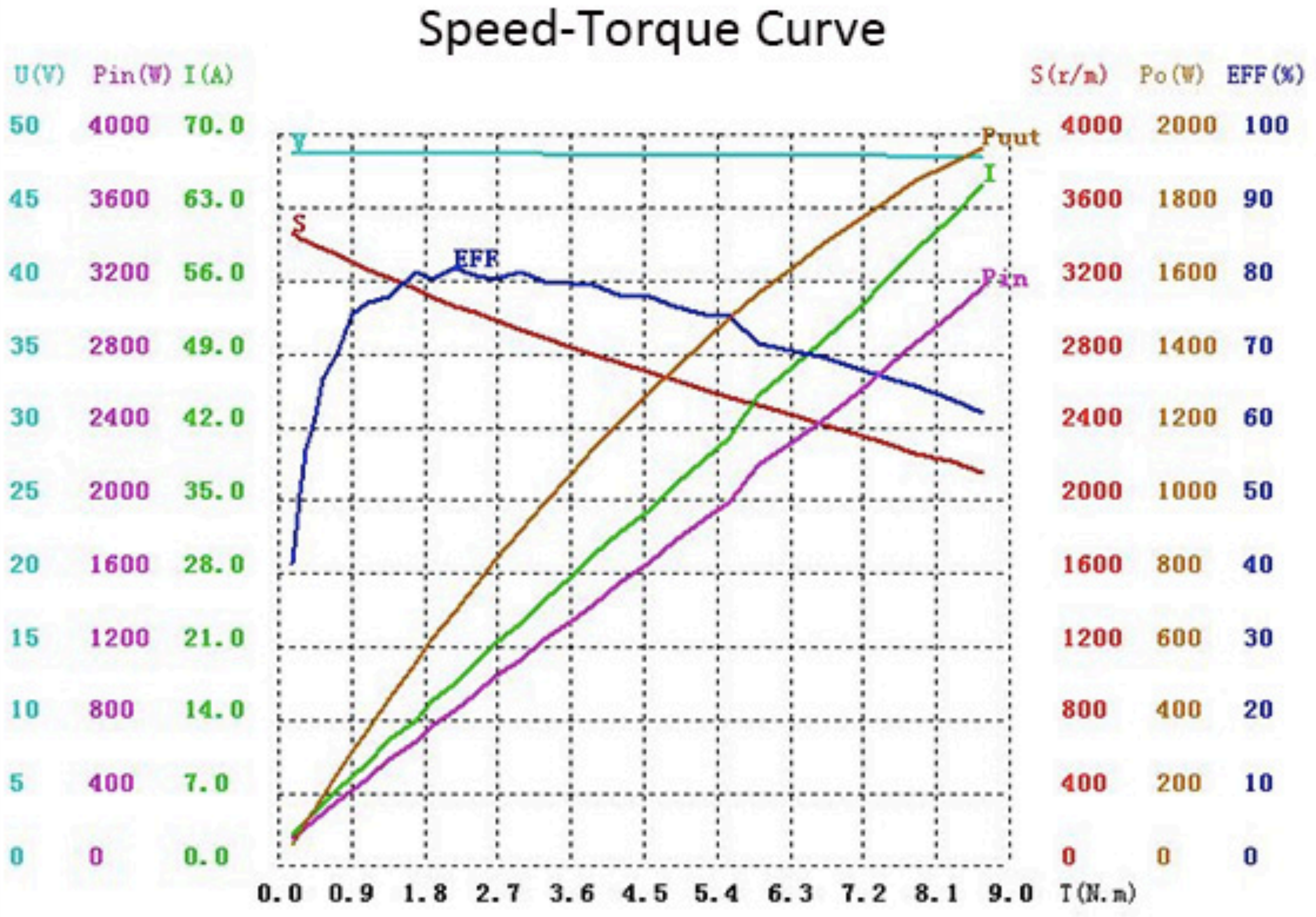
Advantages

1. Maintenance-free
2. Easier to control
3. Can get high torque at relatively low motor speeds

Hub BLDC motor



ATO-BLDC-750R3 750W BLDC Motor: datasheet



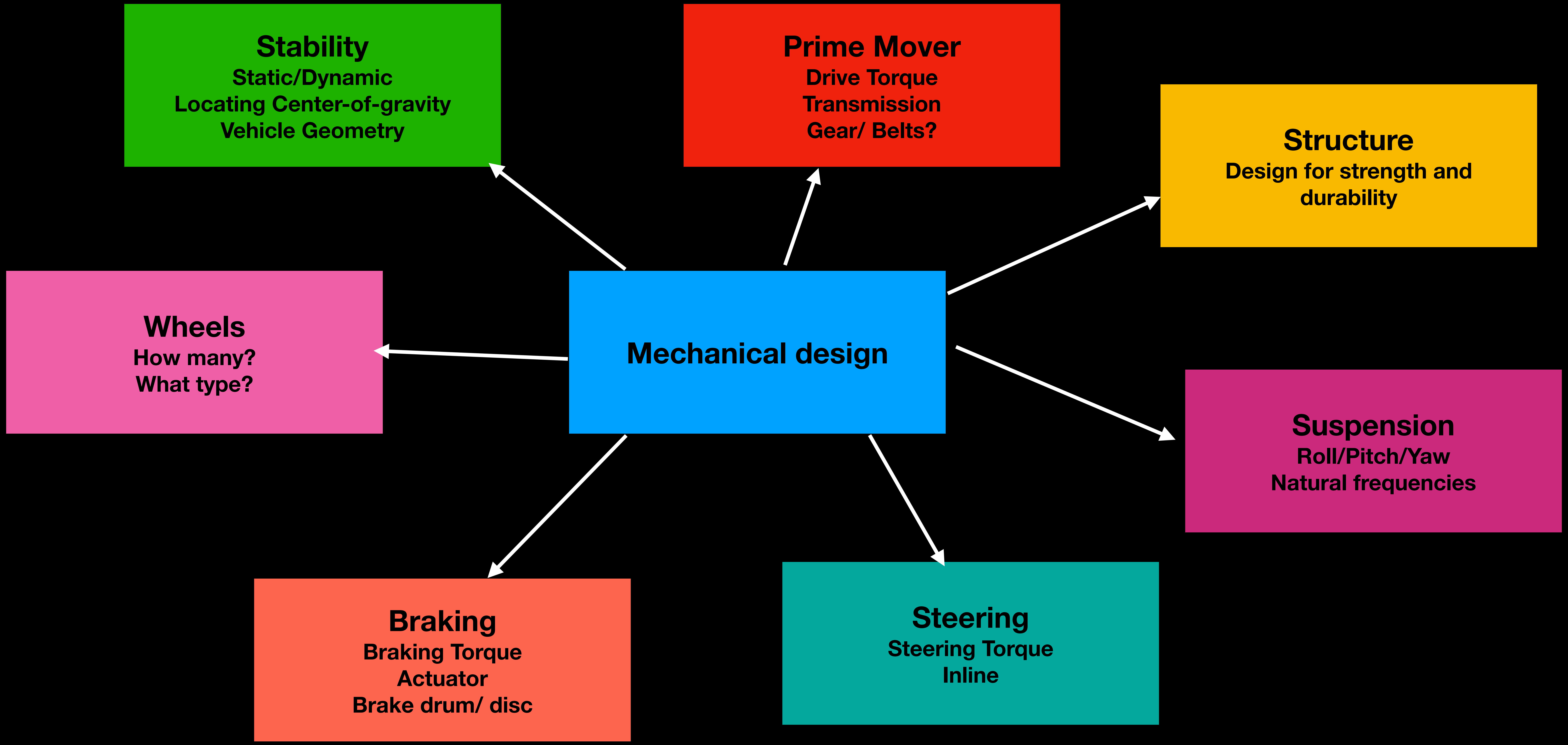
Starting point: 0.17 (N.m)
Speed = 3456 (r/m)
Current = 3.066 (A)

Max torque point: 8.66 (N.m)
Speed = 2158 (r/m)
Current = 65.32 (A)
Power Output = 1967 (W)
Efficiency: = 62.1 (%)

Power output point: 1967 (W)
Torque = 8.66 (N.m)
Speed = 2158 (r/m)
Current = 65.32 (A)
Efficiency: = 62.1 (%)

Max efficiency point: 81.8 (%)
Torque = 2.17 (N.m)
Speed = 3068 (r/m)
Current = 17.49 (A)
Power Output = 697.0 (W)

Mechanical sub-systems


Mechanical design
Stability
Static/Dynamic
Locating Center-of-gravity
Vehicle Geometry
Prime Mover
Drive Torque
Transmission
Gear/ Belts?
Structure
Design for strength and durability
Wheels
How many?
What type?
Suspension
Roll/Pitch/Yaw
Natural frequencies
Braking
Braking Torque
Actuator
Brake drum/ disc
Steering
Steering Torque
Inline

Rollover analysis for two wheeler

Point B just loses contact with ground

What is the max longitudinal acceleration?

Force-balance equation

$$N_a + N_b = mg$$

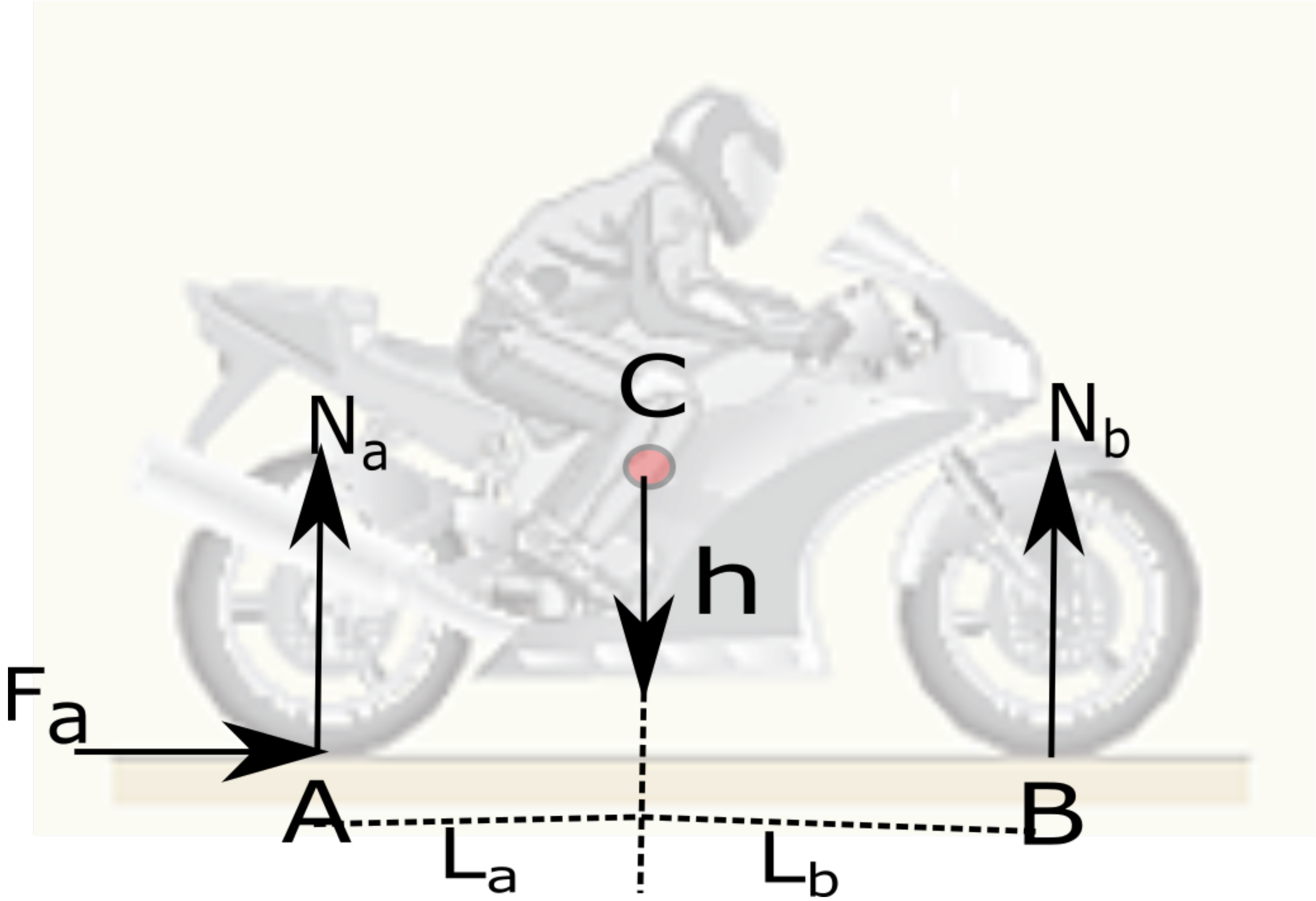
$$F_a - F_b = m\,a$$

Moment-balance equation at point B

$$N_b\,(L_a + L_b) - mg\,L_a + ma\,h - F_b\,(L_a + L_b) = 0$$

We know $N_b = F_b = 0$ and $F_a = \mu N_a$

$$a \leq \min(\mu, \frac{L_a}{h})g$$



Stability discussion

1. μ is typically 0.8 - 1.0 with a good tyre design on asphalt. What does it tell us about vehicle design?

2. Max acceleration does not seem to depend on the mass of the vehicle. Does that make sense? What did we simplify?

Problem to try

Can you find the max acceleration constraint for a 3 wheeler?

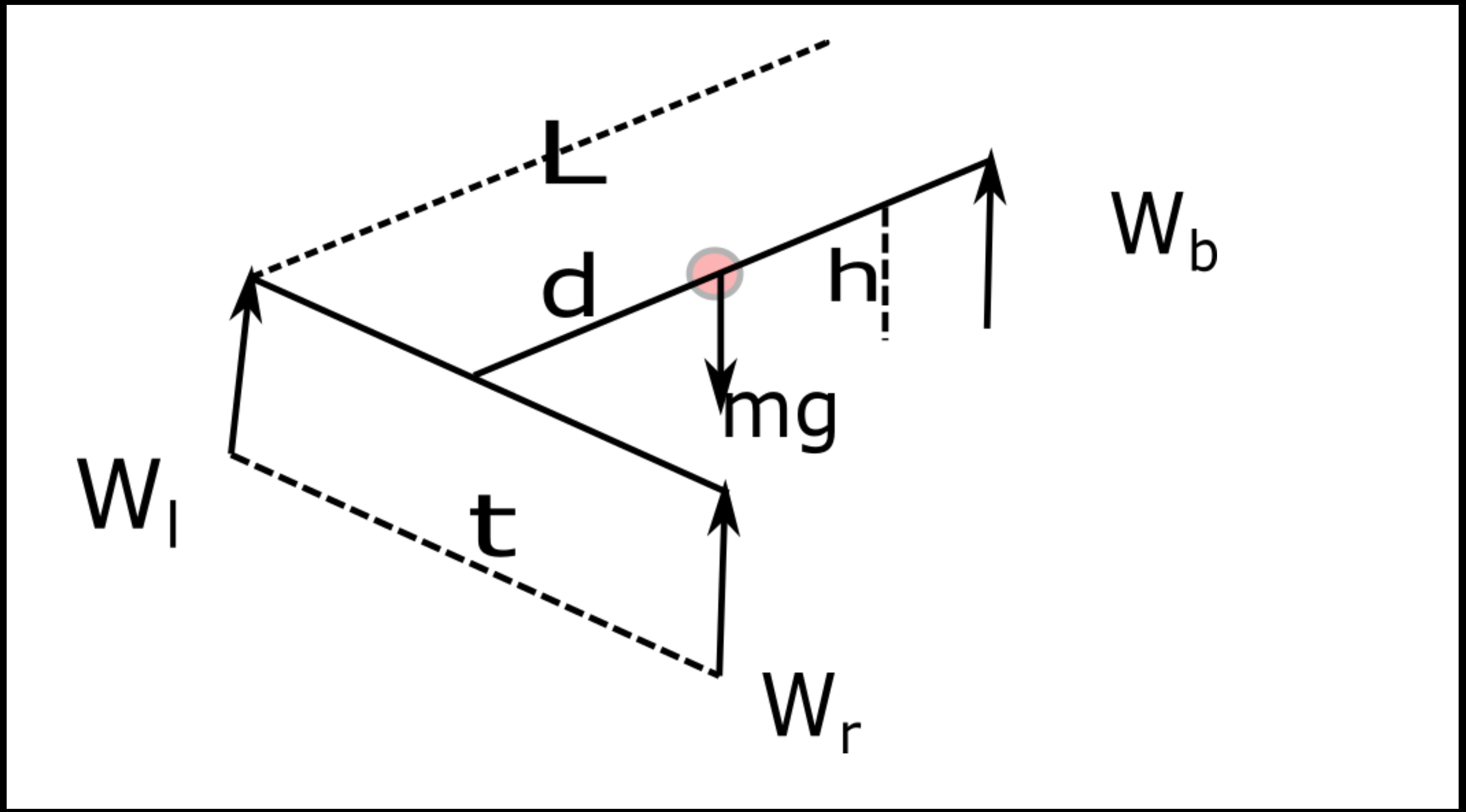
FBD is given

t = track-width

L = wheel-base

h = height of vehicle CG

d = CG location from axle mid-point



Suggestion

Assume left wheel lifts and take moments at the back wheel

Power requirements

Assumption: Stability is verified for given vehicle geometry and surface friction

How much power do we need to move a 1000 kg vehicle at v = 1 m/s up a 10% gradient?

$$P = F \cdot v$$

F = total pulling force ~ inertia, gravity and rolling resistance

$$F = ma + mg\sin\theta + \mu_r mg\cos\theta$$

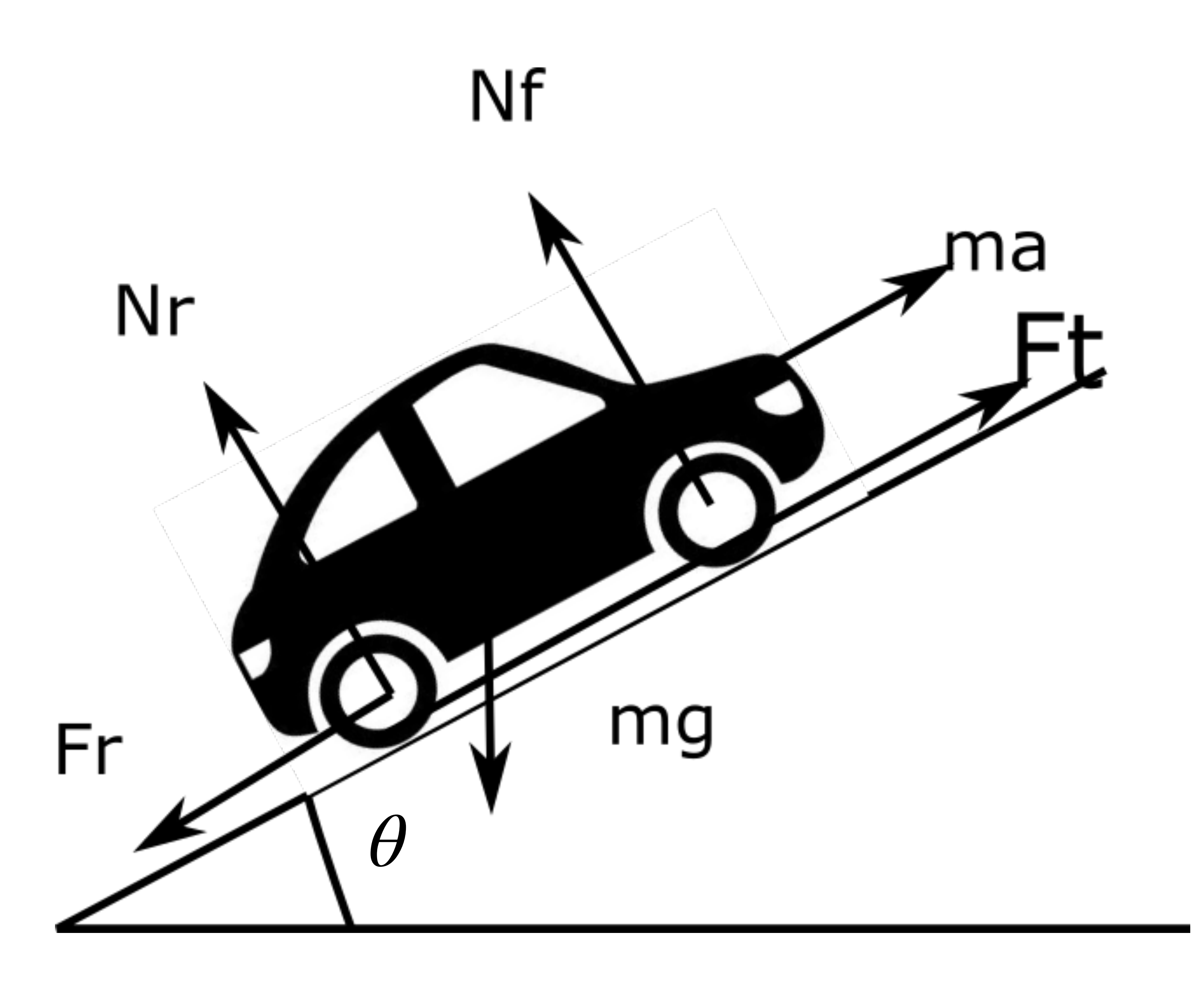
(a) Assume vehicle is already moving at 1 m/s

F = 1000 · 9.81 · sin(6) + 0.015 · 1000 · 9.81 · cos(6) = 1015 N

P = 1015 · 1 = 1.015 kW ~ 1 kW

(b) If we want to start from rest (assuming 0.5 m/s2), then power increases to

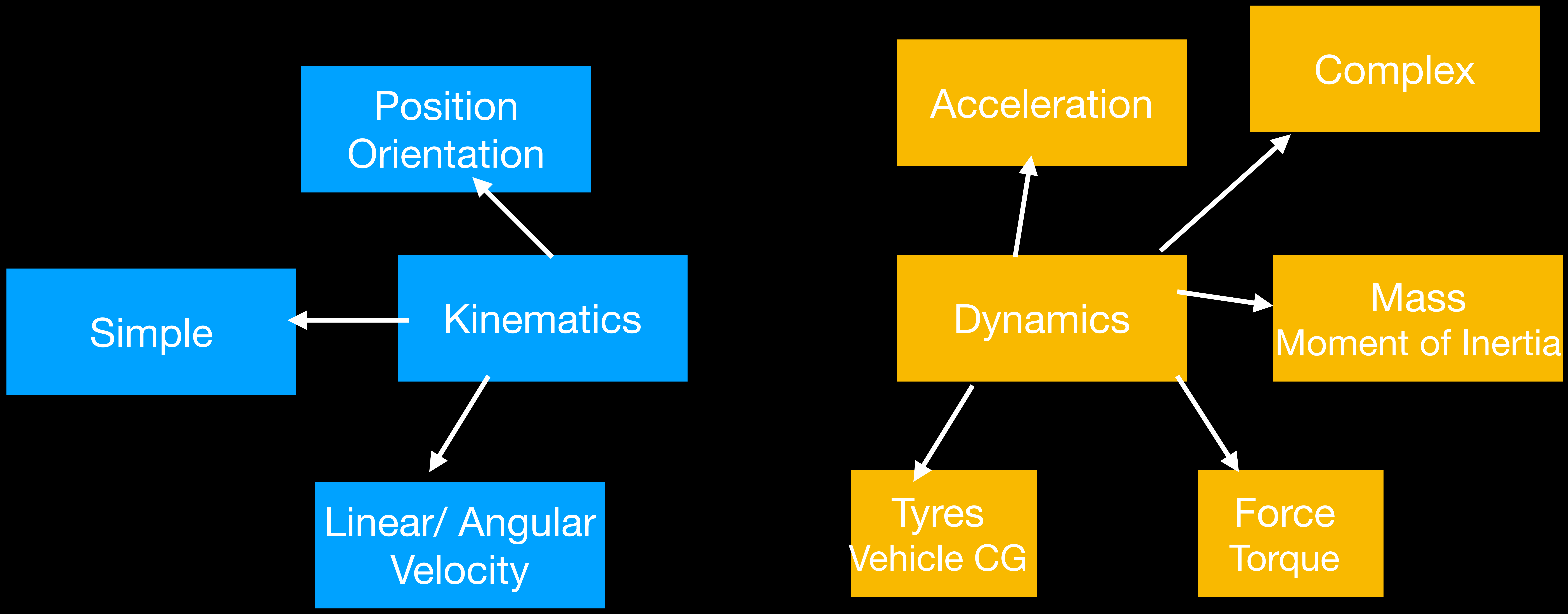
P = (500+1000+15) · 1 = 1.515 kW



Vehicle Modeling
(entry-point to Autonomy/ Control)

Kinematics and Dynamics

Models needed for simulation/ validation of control algorithms



Unicycle Model

Initially Robot is at A

In reference frame robot pose is (x, y, θ)

At velocity v, Robot moves to B in time dt

Pose is now (x', y', θ')

Relative motion in terms of v

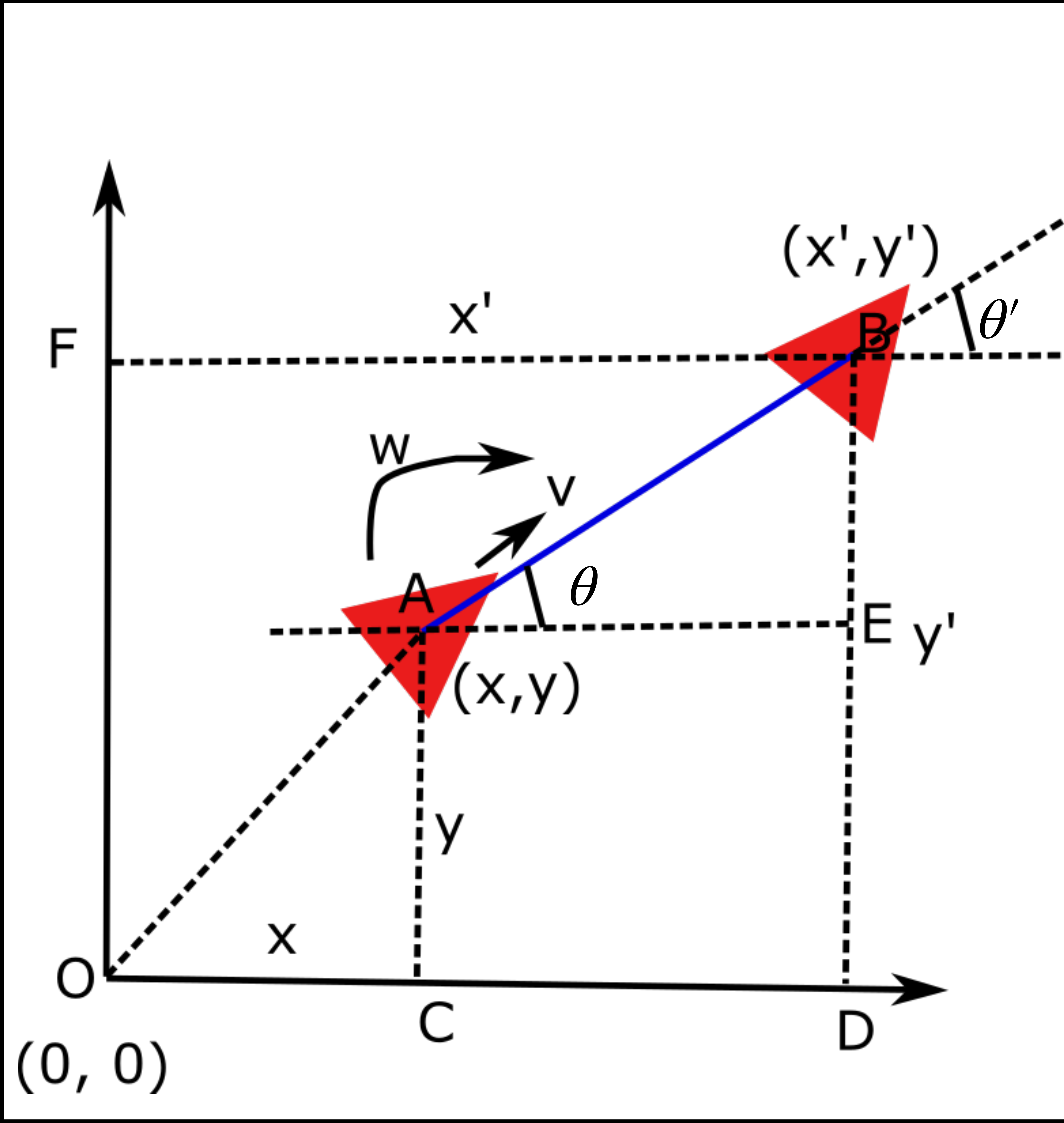
$$x' - x = v\cos\theta\, dt$$

$$y' - y = v\sin\theta\, dt$$

If robot also rotates at ω

$$\theta' - \theta = \omega\, dt$$

- **v and ω are commands**
- **Change in robot pose is effect**



Differential-drive model

Point of contact with ground has no net force

- Wheel will get "dragged" otherwise

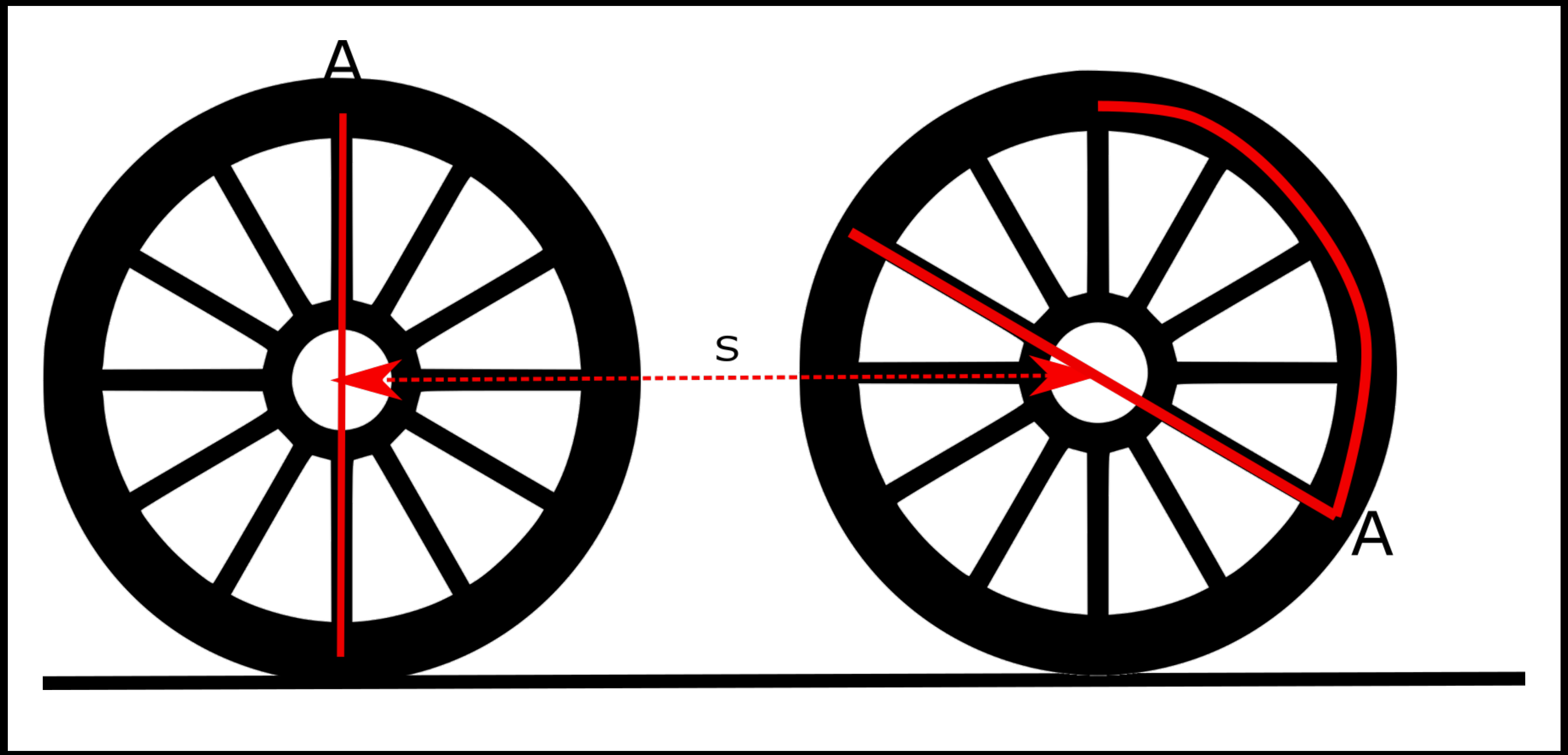
Wheel center moves same distance as any point in the rim (for ex: point A)

$$s = r\theta$$

Differentiating wrt time

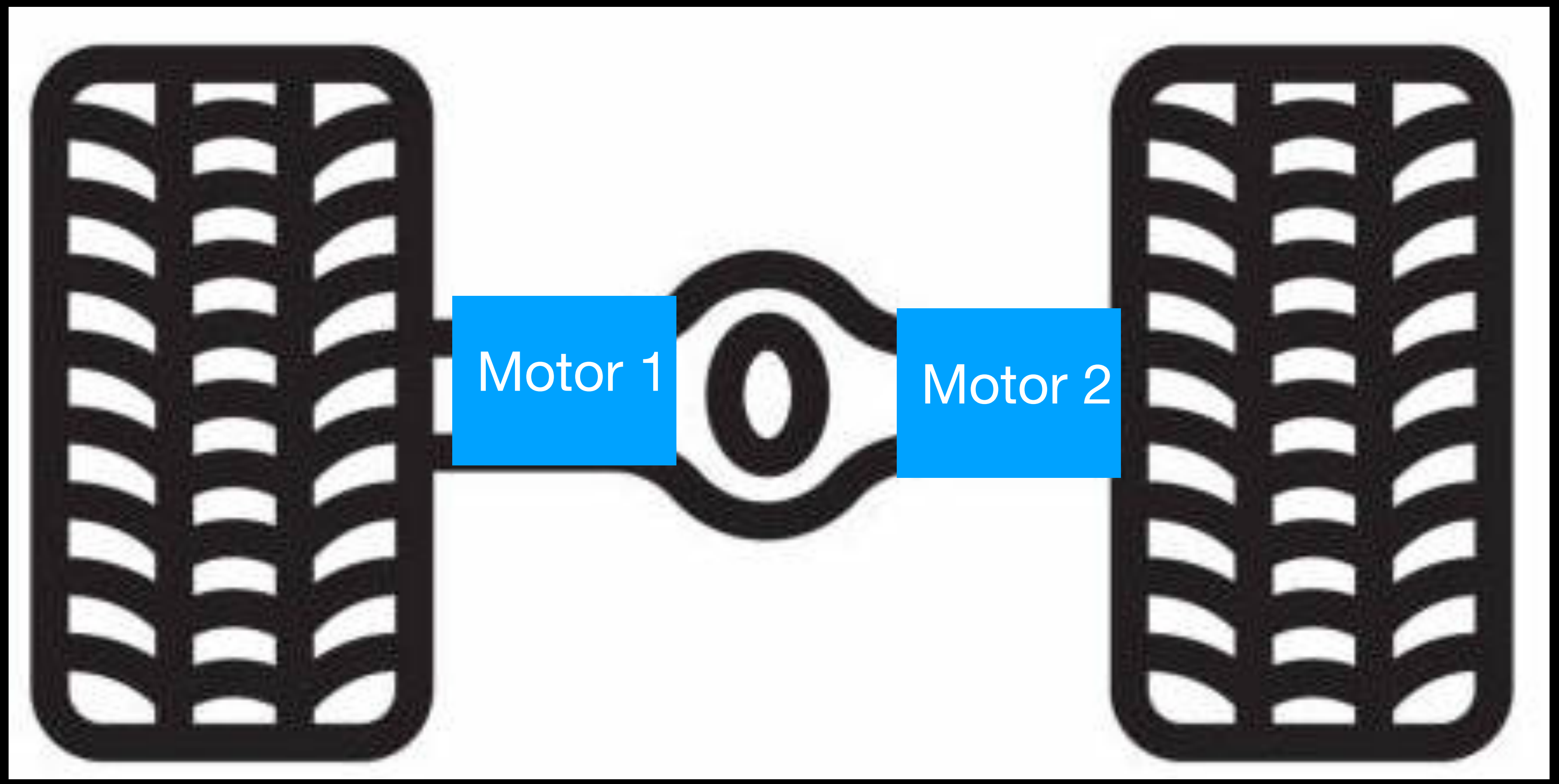
$$v = r\omega$$

Roll without slipping



Simple robot

- Connect 2 wheels through an axle
- Each wheel can be independently controlled with a motor



Differential Drive Model

Consider robot vehicle taking left turn

Two rotations happening

- 2 wheels are rotating
- Rigid body (2 wheels + axle) rotates around an imaginary point - ICC

How do they relate?

$$v_r = \omega\,(R + L/2)$$

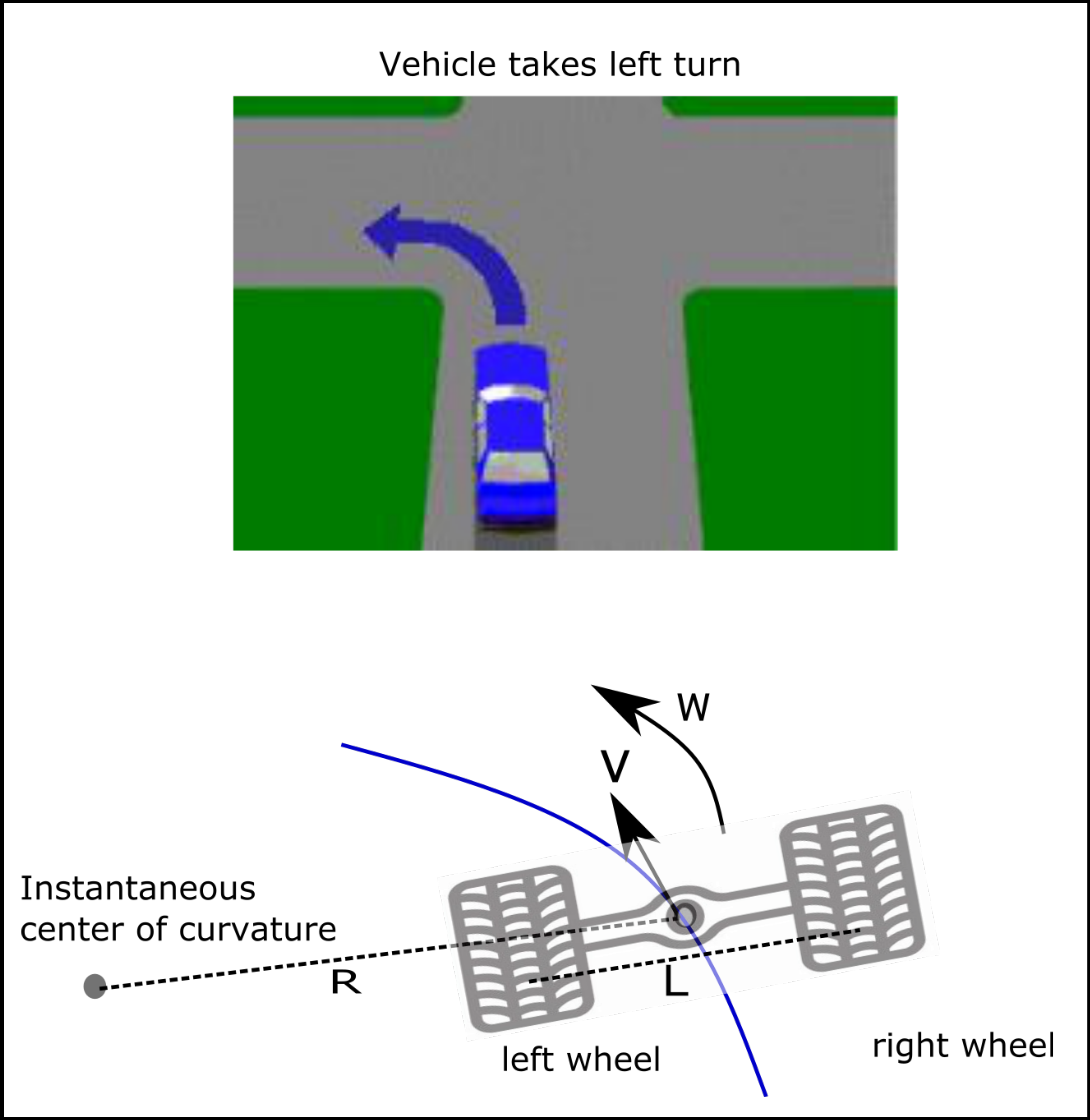
$$v_l = \omega\,(R - L/2)$$

Adding,

$(v_r + v_l)/2 = \omega\,R$ ~ avg velocity

Subtracting,

$$(v_r - v_l)/L = \omega$$



Differential drive

Each wheel has own angular velocities

$$\omega_r = v_r r \qquad \omega_l = v_l r$$

Rewriting, v and ω for the system is

$$v = \frac{r}{2}(w_r + w_l)$$

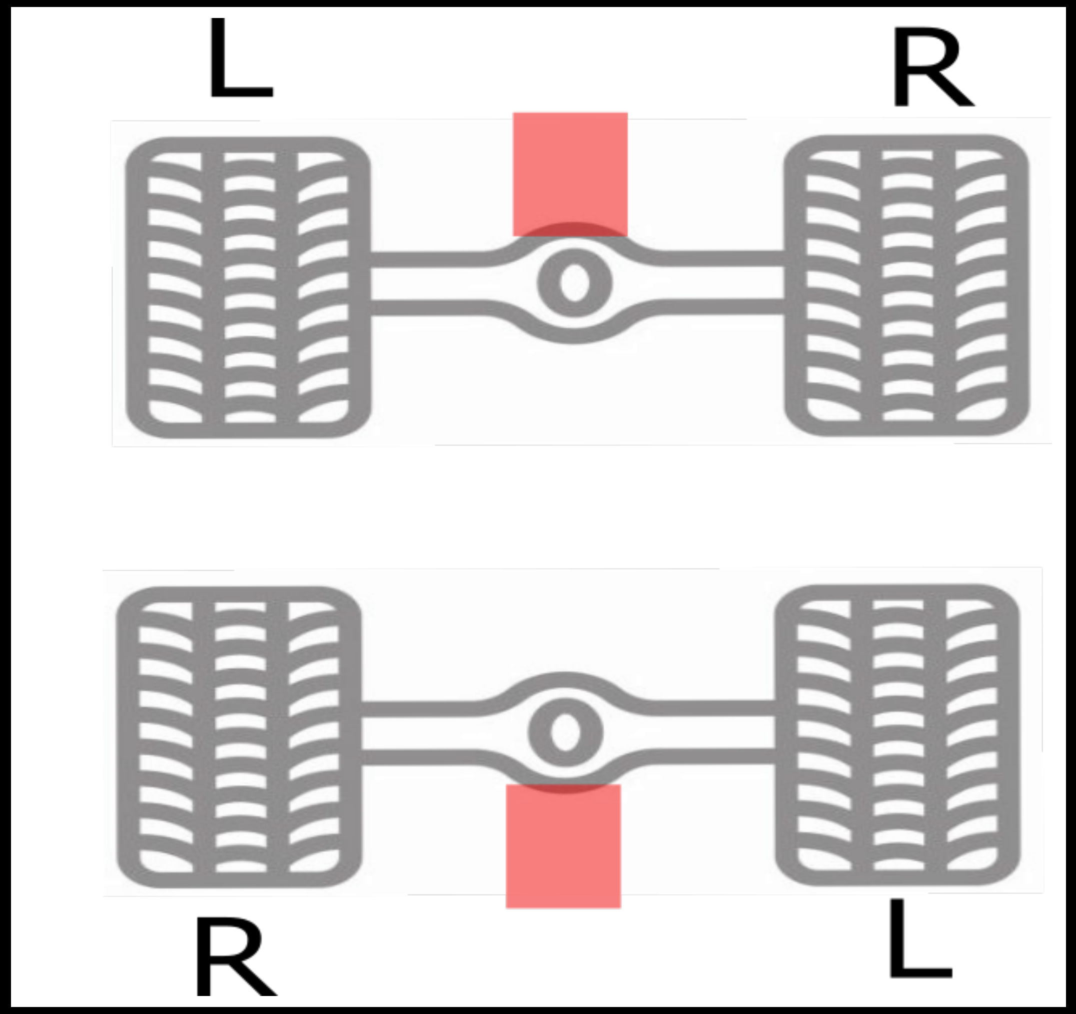
$$\omega = \frac{r}{L}(w_r - w_l)$$

Curvature

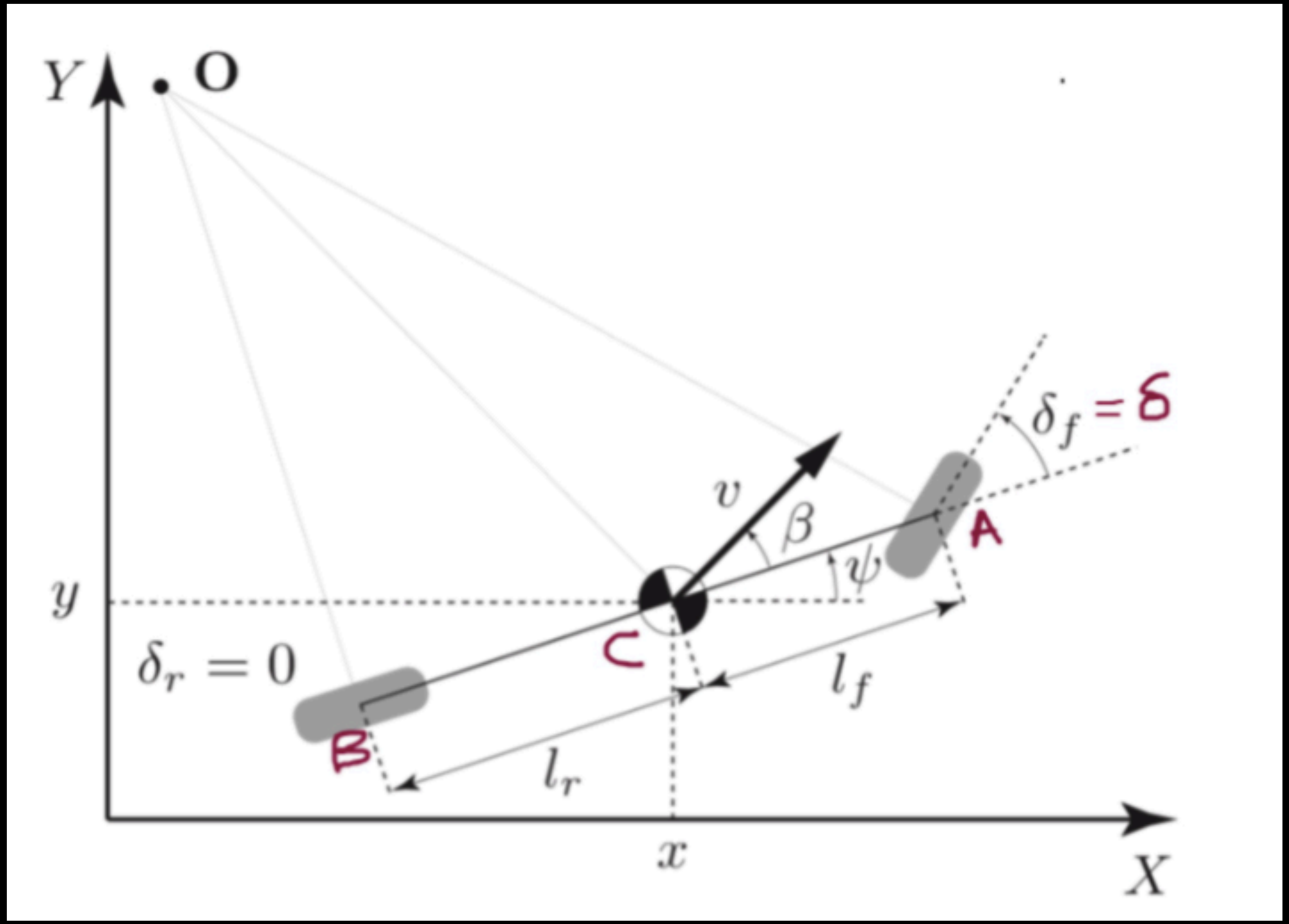
$$R = \frac{v_r + v_l}{v_r - v_l}$$

Interesting observations:

1. $\omega_r = \omega_l \implies$ Straight line
2. $\omega_r = -\omega_l \implies$ rotates about mid-point (Inplace)



Bicycle Model



Think of β as slip angle

Vehicle is being pushed sideways

Front wheels and Rear wheels separately lumped

Control inputs:

- Front wheel can be steered (δ)
- Rear wheel is powered (v)

C = location of vehicle center-of-gravity

$$\dot{x} = v\cos(\psi + \beta)$$

$$\dot{y} = v\sin(\psi + \beta)$$

$$\dot{\psi} = \frac{v}{l_f + l_r}\cos\beta\tan\delta$$

$$\tan\beta = \frac{l_r}{l_r + l_f}\tan\delta$$

Further readings

1. Vehicle Dynamics and Control by Prof. Georg Schildbach
2. https://youtu.be/FWh-enOdXM4 Walter Levin’s lecture on static friction
3. https://m.youtube.com/watch?v=eblPwXFb7TE interview with Eberhard and Tarpenning
4. Martin Engelhardt, Control of Mobile Robots course lectures, Georgia Tech
5. Prof. Krishnakumar, Vehicle Dynamics, IIT-Madras, NPTEL
6. Prof. Umanand, Basic Electrical technology, IISc, NPTEL


FROM THE DIRECTOR OF 'WHO KILLED THE ELECTRIC CAR?'
REVENGE OF THE ELECTRIC CAR
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