# Lecture 8
# Motors, Actuators, and Power Drives

**Forrest Brewer**

# Motors, Actuators, Servos

- Actuators are the means for embedded systems to modify the physical world
  - Macroscopic Currents and power levels
  - Thermal Management
  - Power Efficiency (often vs. Performance)
- Motor Types
  - DC Brush/Brushless
  - AC (shaded pole and induction)
  - Stepper Motors
  - Servo (variety of DC motor)
  - Peisio-electric (Kynar, Canon ultra-sonic)
  - Magnetic Solenoid
  - Electro-static (MEMS)

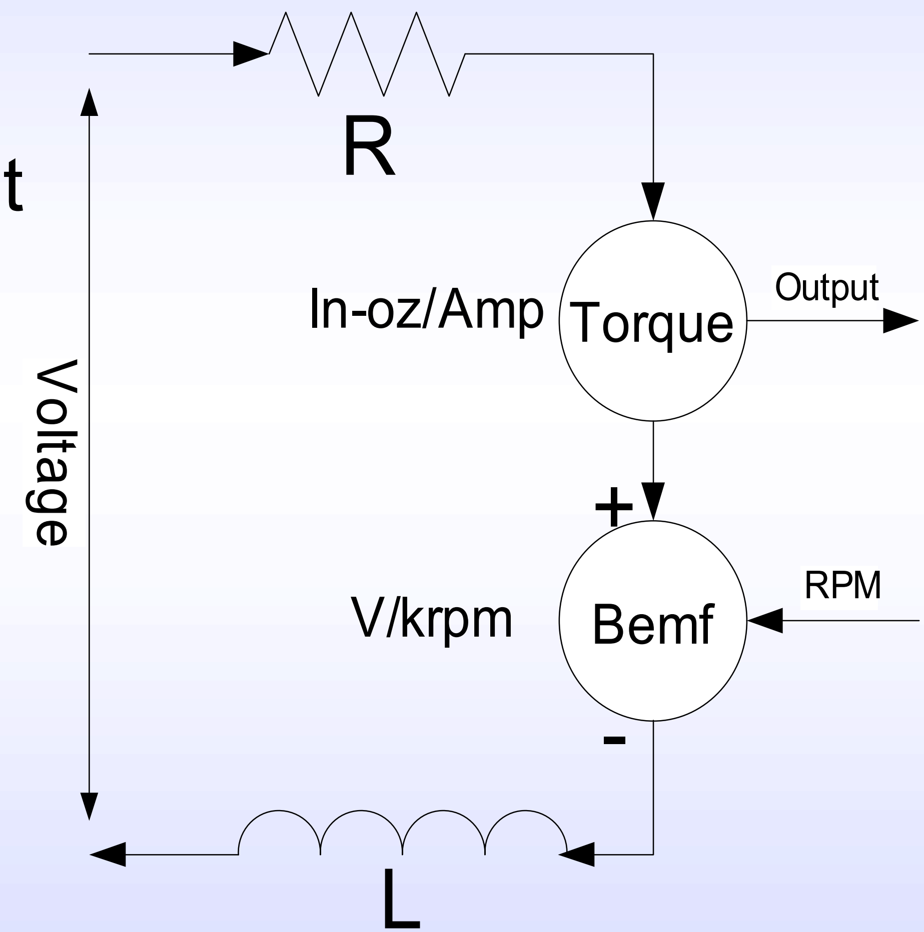
# DC Motor Model

- Torque (force) ~ Current
- Max Current = V/R
- Max RPM = $V/B_{emf}$

$B_{emf} = L\ dI/dt$

In general:

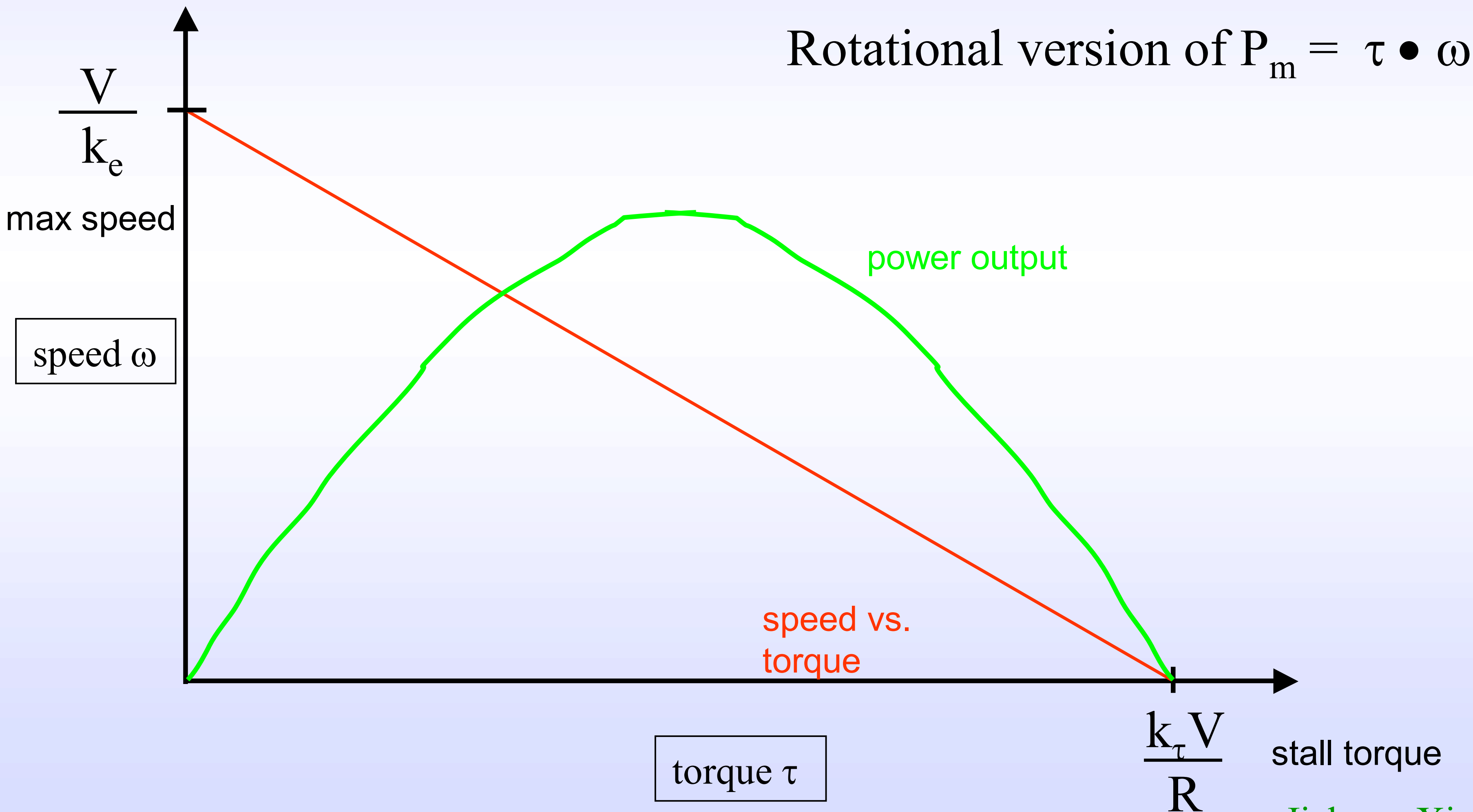
Torque ~ $(V - B_{emf})/R$



# speed vs. torque, fixed voltage

Linear mechanical power $P_m = F \bullet v$

Rotational version of $P_m = \tau \bullet \omega$




Jizhong Xiao

# Controlling speed with voltage

- The back emf depends only on the motor speed. $e = k_e \, \omega$
- The motor's torque depends only on the current, I. $\tau = k_\tau \, I$

$I_{stall} = V/R$
current when motor is stalled

speed = 0
torque = max

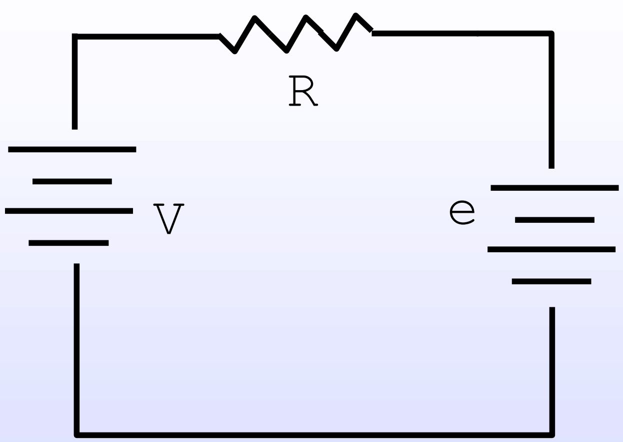
- Consider this circuit's V: $V = IR + e$

How is V related to ω ?

$$V = \frac{\tau R}{k_\tau} + k_e \, \omega$$

Speed is proportional to voltage.

$$\omega = -\frac{R}{k_\tau k_e} \tau + \frac{V}{k_e}$$

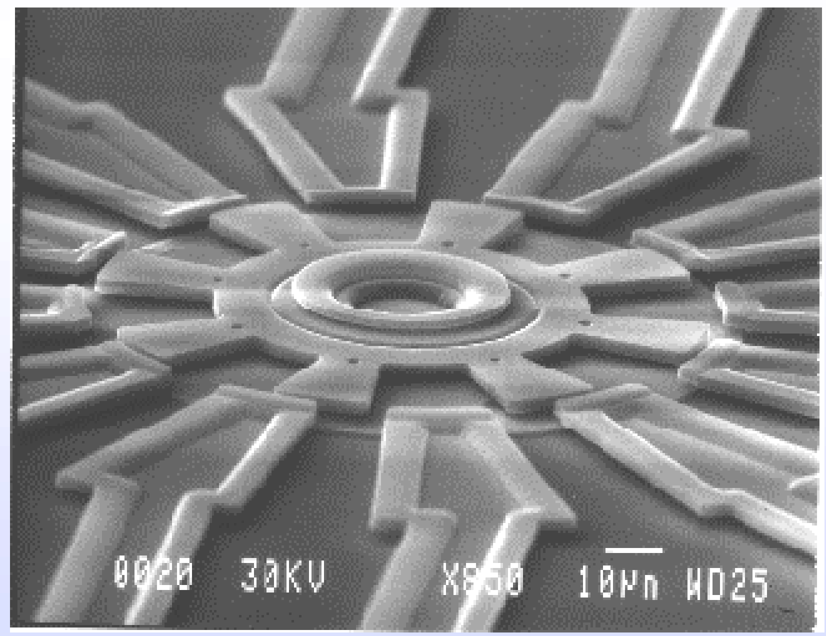



DC motor model

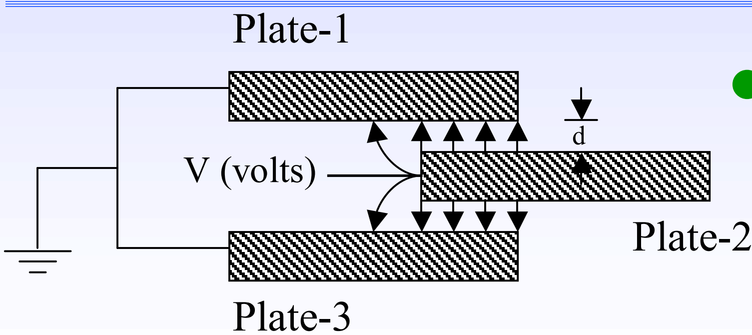
Jizhong Xiao

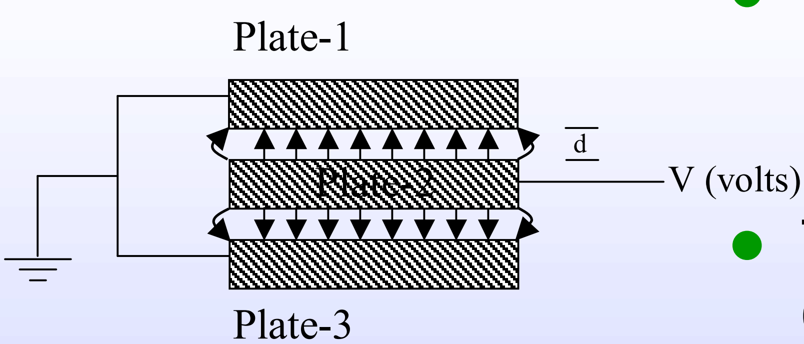
# Electrostatic MEMS Actuation

- Electrostatic Drives (MEMS)
  - Basic equations
  - Rotation Drive
  - Comb Drive



# Electrostatic Actuator Analysis



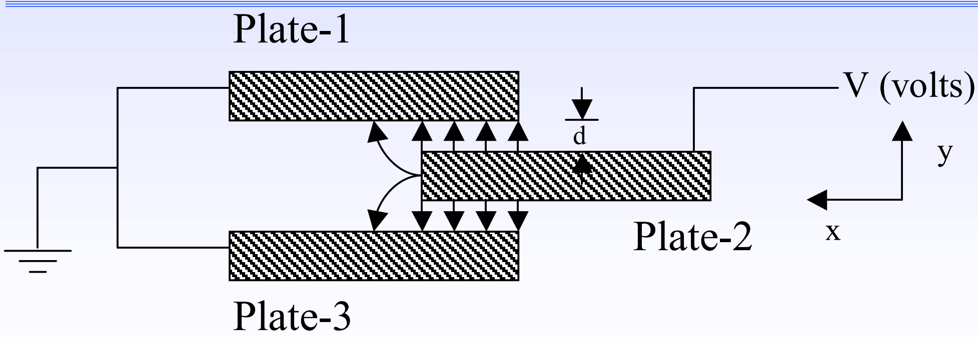

- Consider the capacitance of the two figures:
  - To good approximation, the capacitance is double in the second figure: $C_1 = C_2 / 2$
- Imagine that the charge is fixed in the top figure: $Q = C_1 V_1 = C_2 V_2$
- The stored energy is not the same!

$$E_1 = \frac{1}{2} C_1 V_1^2 = \frac{1}{2} (E_2 = \frac{1}{2} C_2 V_2^2)$$

- The difference must be the work done by the motion of the plate:

$$\Delta E = \int F dx \Rightarrow F = \frac{dE}{dx} \propto V^2$$

# Electrostatic Actuators




Consider parallel plate 1 & 2

Force of attraction (along y direction)

$$F_p = (\tfrac{1}{2}\,\varepsilon\,V^2)(A/g^2)$$

**1nN@15V**

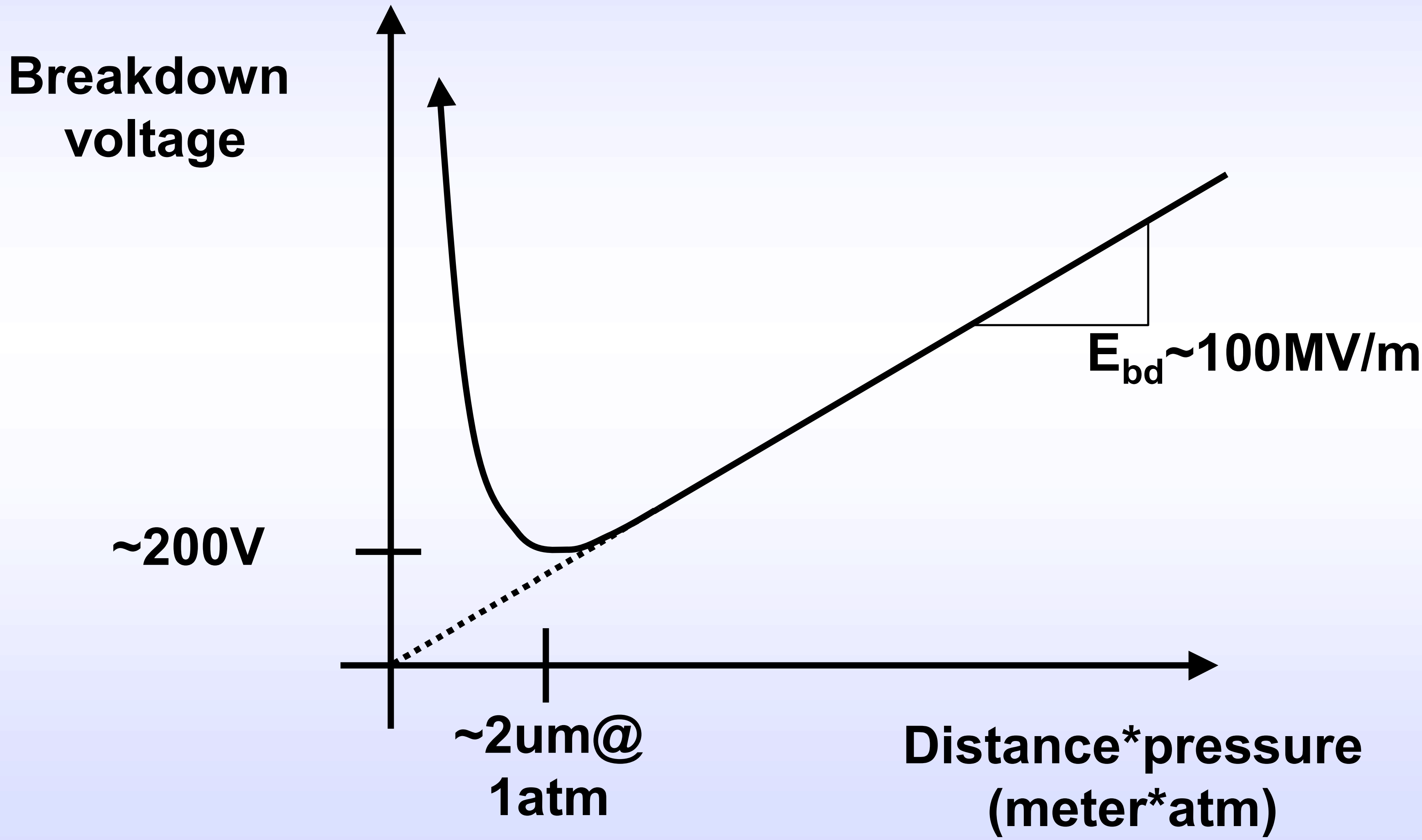
**dimensionless**

Consider plate 2 inserted between plate 1 and 3
(Popularly known as a COMB DRIVE)

Force of attraction (along x direction) $$F_c = (\tfrac{1}{2}\,\varepsilon\,V^2)(2t/g)$$

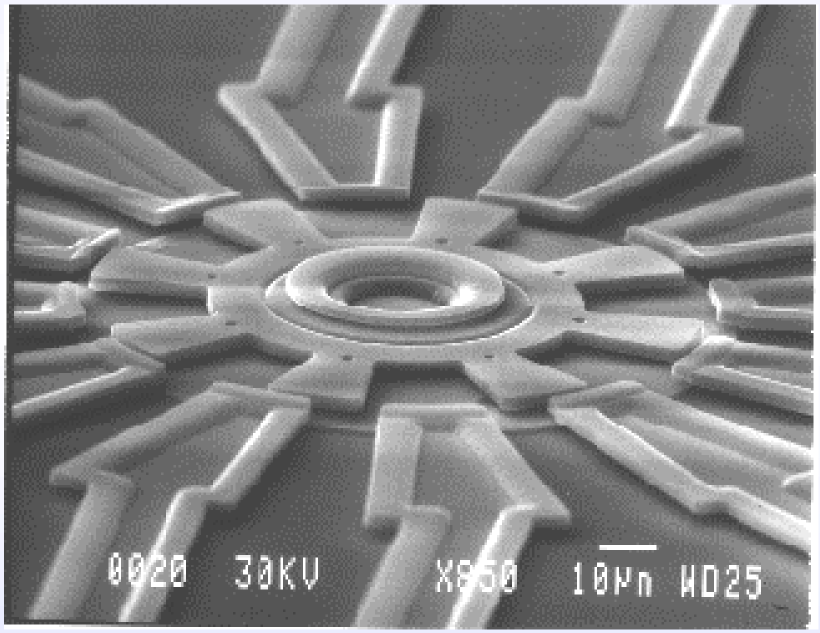
Constant with x-directional translation

# Paschen Curve

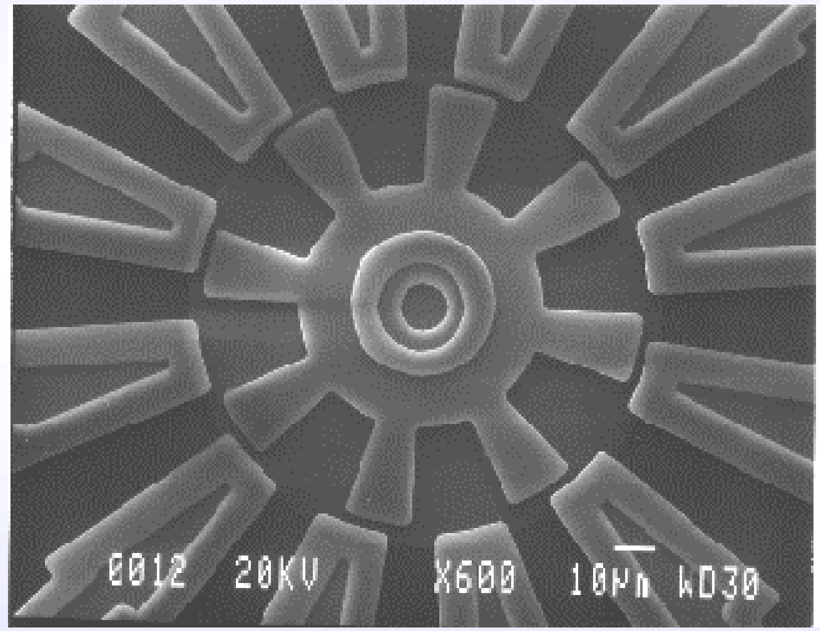


# Side Drive Motors

Side view of SDM




Top view of SDM




First polysilicon motors were made at UCB (Fan, Tai, Muller), MIT, ATT
Typical starting voltages were >100V, operating >50V

# A Rotary Electrostatic Micromotor 1×8 Optical Switch

A Rotary Electrostatic Micromotor 1×8 Optical Switch

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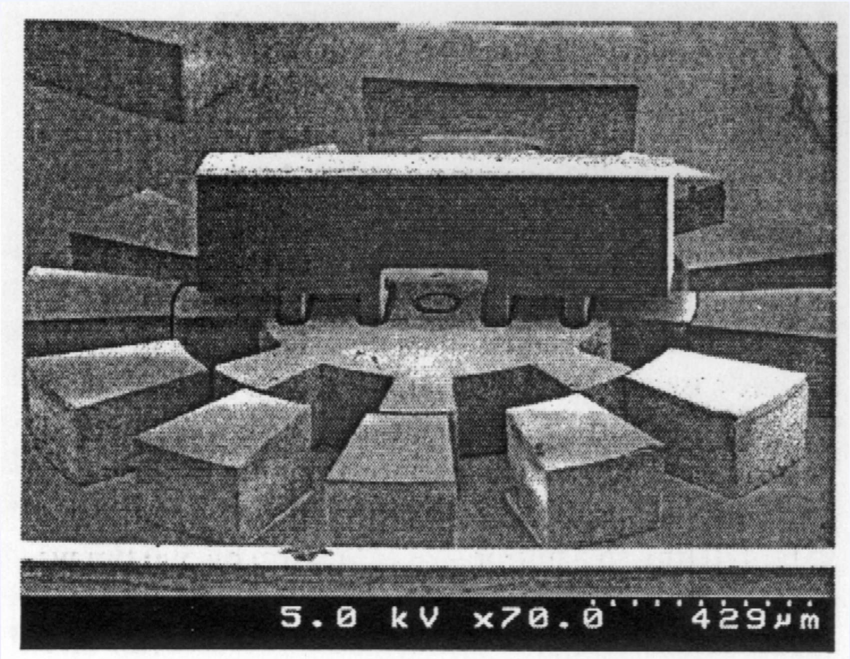



**Fig. 3 SEM photo of an assembled microswitch with vertical 200 μm-tall reflective mirror plate.**

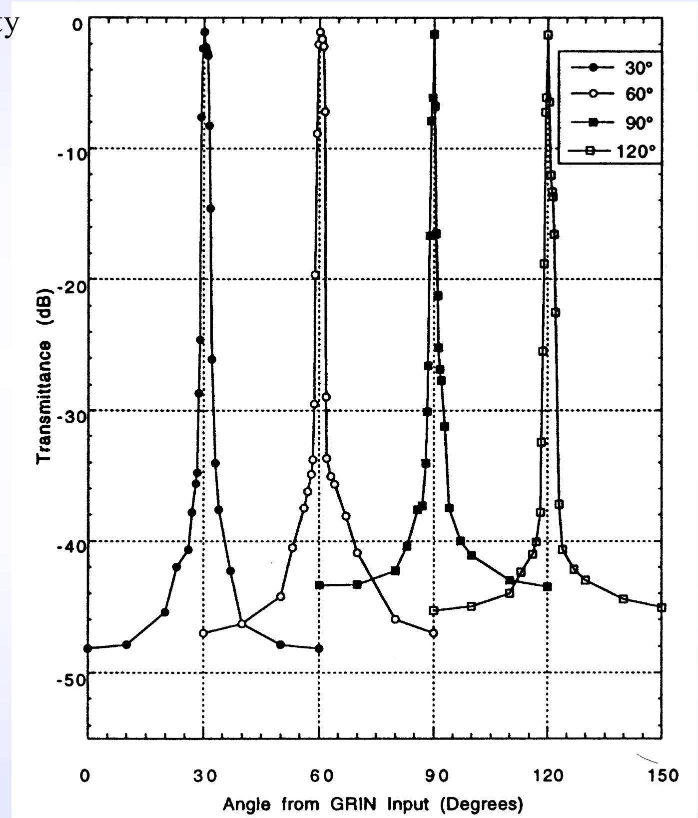
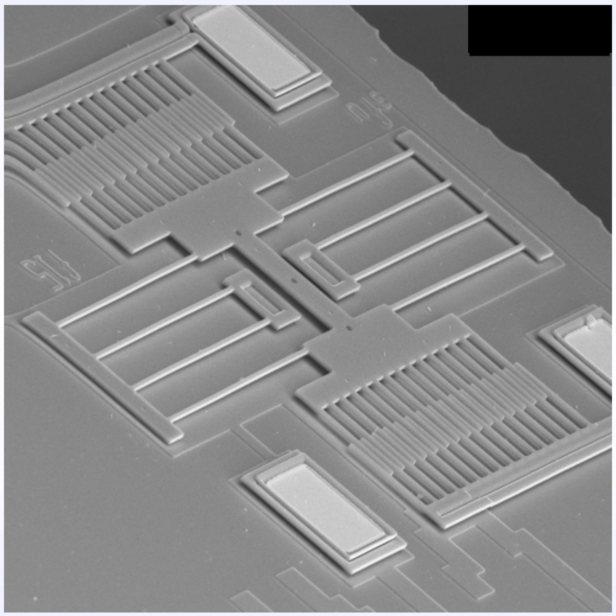


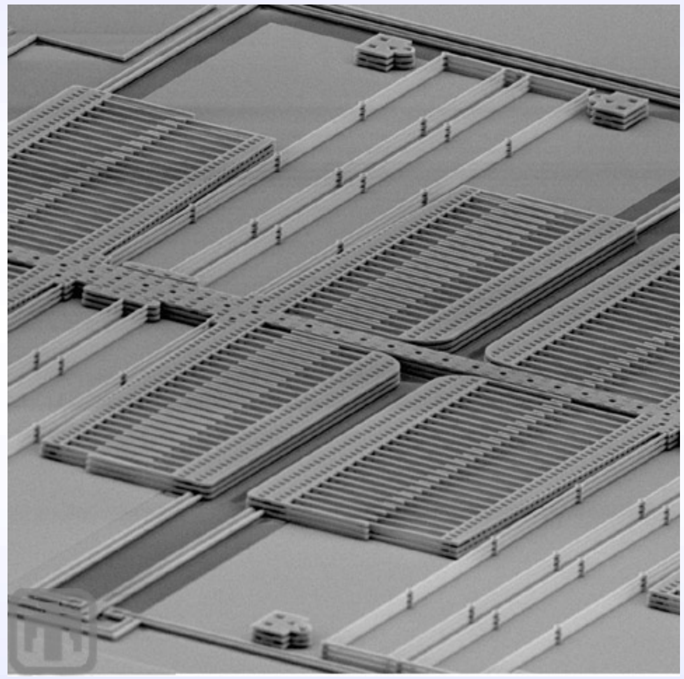

**Fig. 4 Insertion loss and crosstalk measurements for multi-mode optics at 850 μm.**

Micro Electro Mechanical Systems
Jan., 1998 Heidelberg, Germany

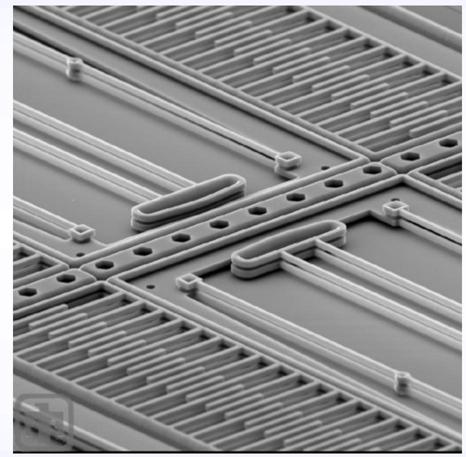
# Comb Drives



**Tang/Nguyen/Howe**

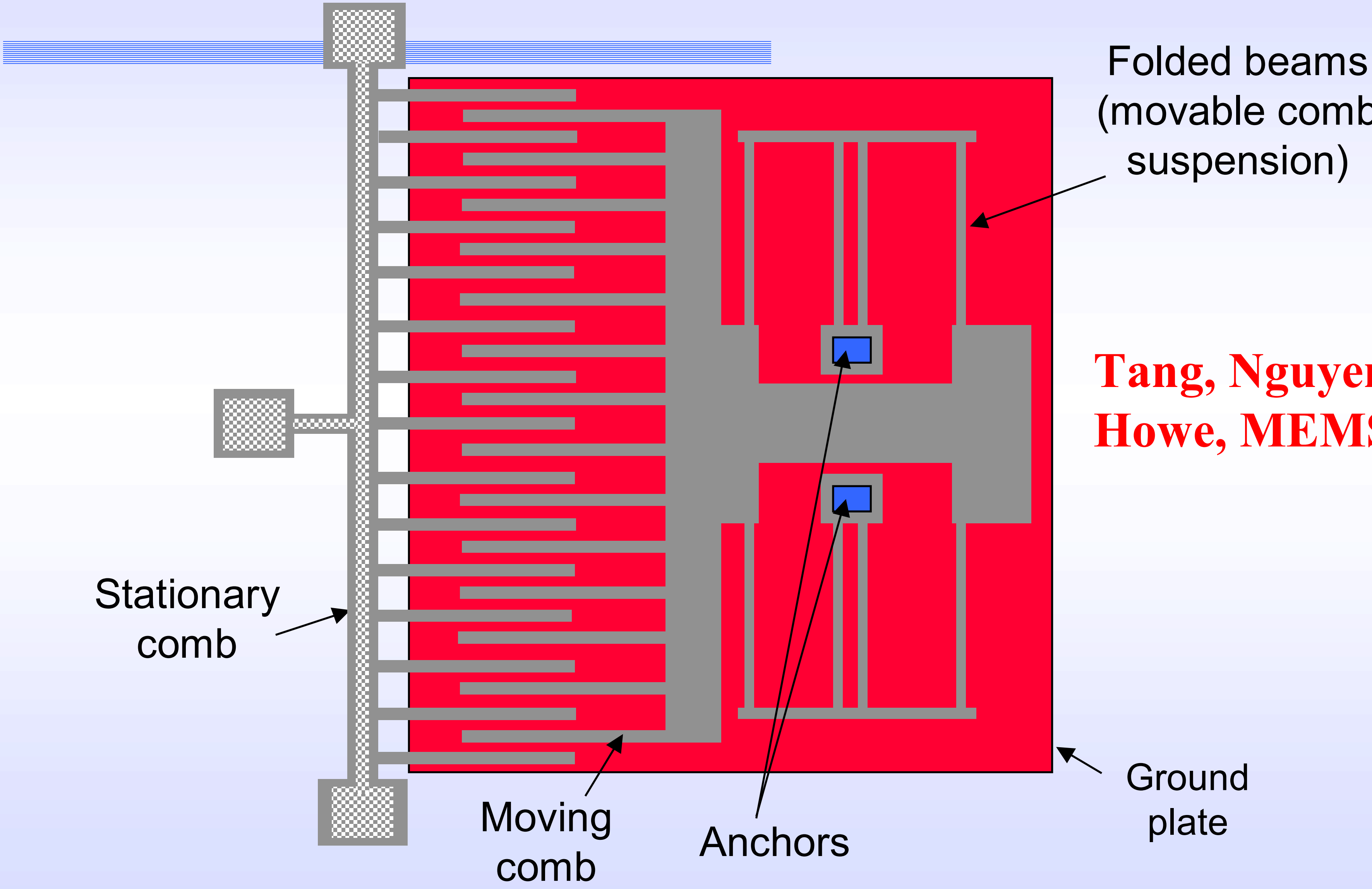


**Sandia cascaded comb drive (High force)**



**Close-up**

# Layout of electrostatic-combdrive




**Tang, Nguyen, Howe, MEMS89**

# Parallel-Plate Electrostatic Actuator Pull-in

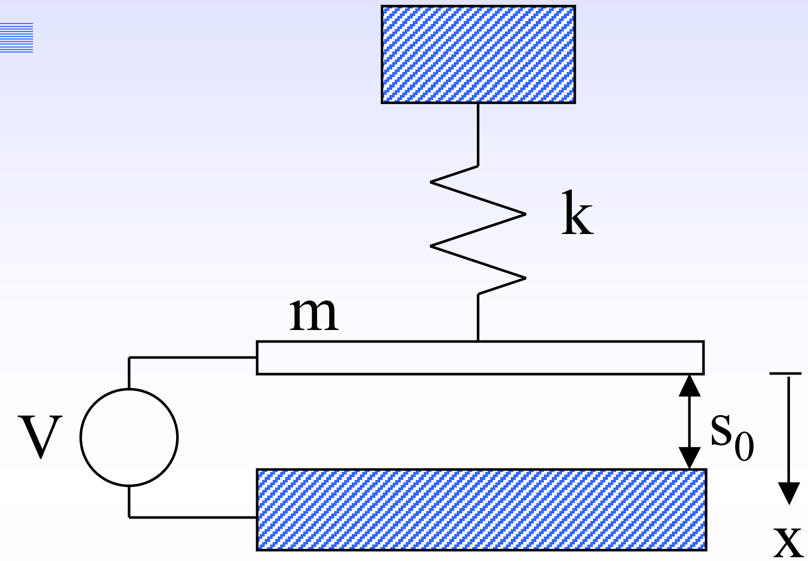
Electrostatic instability

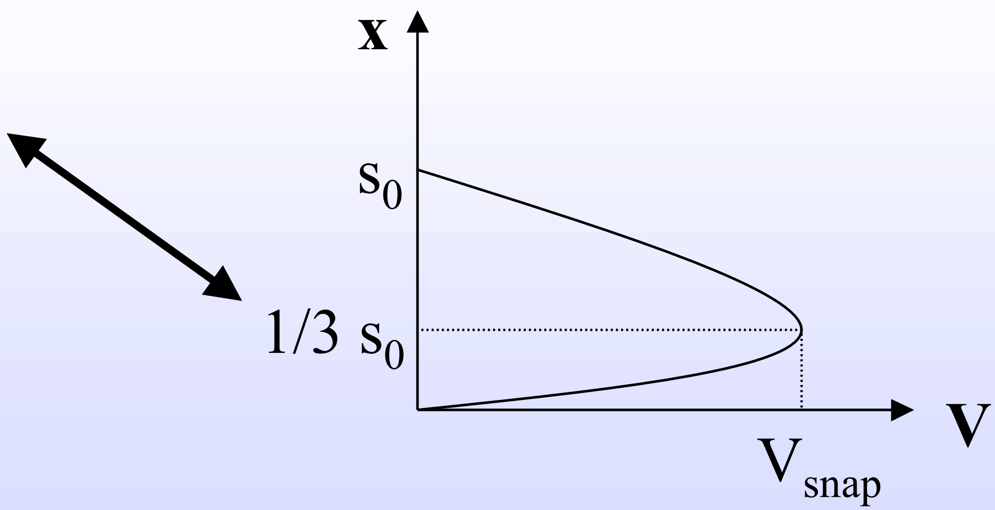
$$F = \frac{\varepsilon_0 V^2}{2(s_0 - x)^2} = kx \Rightarrow$$

$$V = \sqrt{\frac{2kx}{\varepsilon_0}}(s_0 - x)$$

$$\frac{\partial V}{\partial x} = 0 \Rightarrow x_{snap} = \frac{s_0}{3}$$

$$V_{snap} = \sqrt{\frac{8ks_0^3}{27A\varepsilon_0}}$$



# Electrostatic spring

$$F = \frac{\varepsilon_0 V^2}{2(s_0 - x)^2} \approx \frac{\varepsilon_0 V^2}{2(s_0 - x_0)^2}\left(1 + 2\frac{x - x_0}{s_0 - x_0}\right)$$

$$F = m\ddot{x} + kx \approx \frac{\varepsilon_0 V^2}{2(s_0 - x_0)^2}\left(1 + 2\frac{x - x_0}{s_0 - x_0}\right) \Rightarrow$$

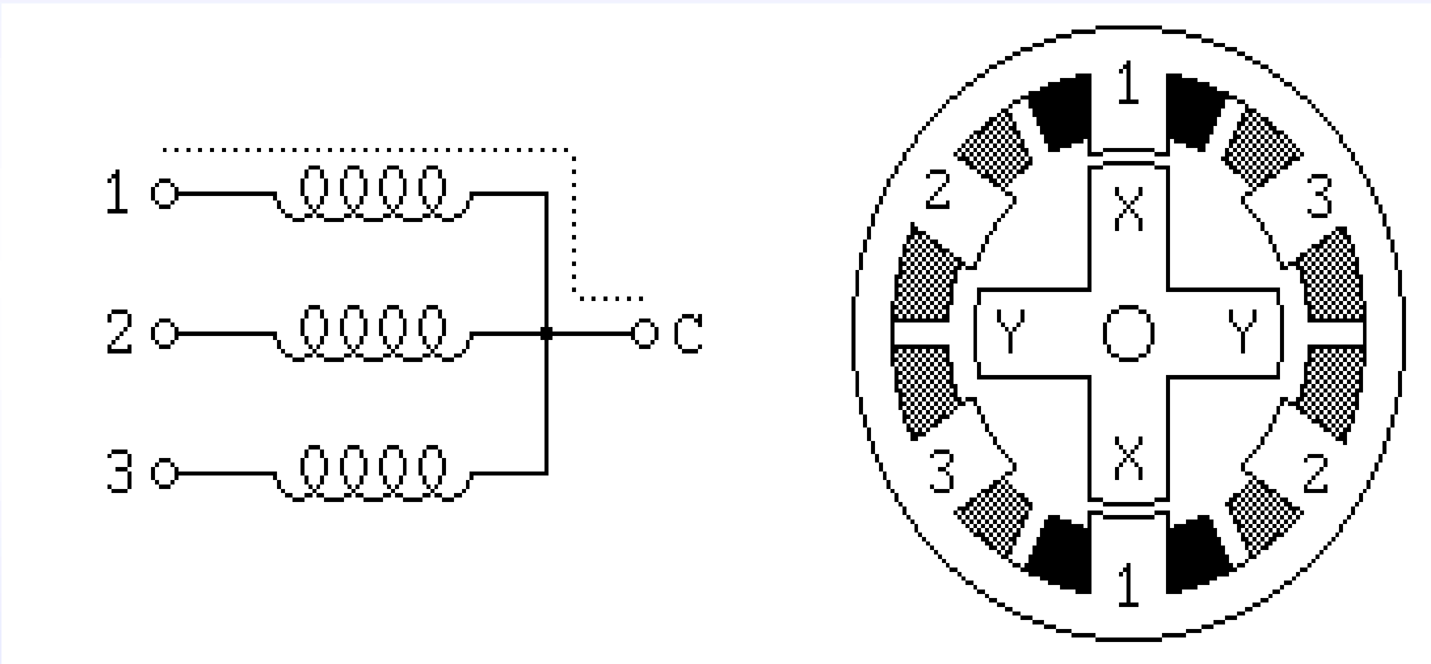
$$m\ddot{x} + \left(k - \frac{\varepsilon_0 V^2}{(s_0 - x_0)^3}\right)x = \frac{\varepsilon_0 V^2}{2(s_0 - x_0)^2}\left(1 - \frac{2x_0}{s_0 - x_0}\right)$$

- Adjustable stiffness (sensitivity) and resonance frequency

# Stepper Motors

- Overview
- Operation – full and half step
- Drive Characteristics

# VR Stepper Motor

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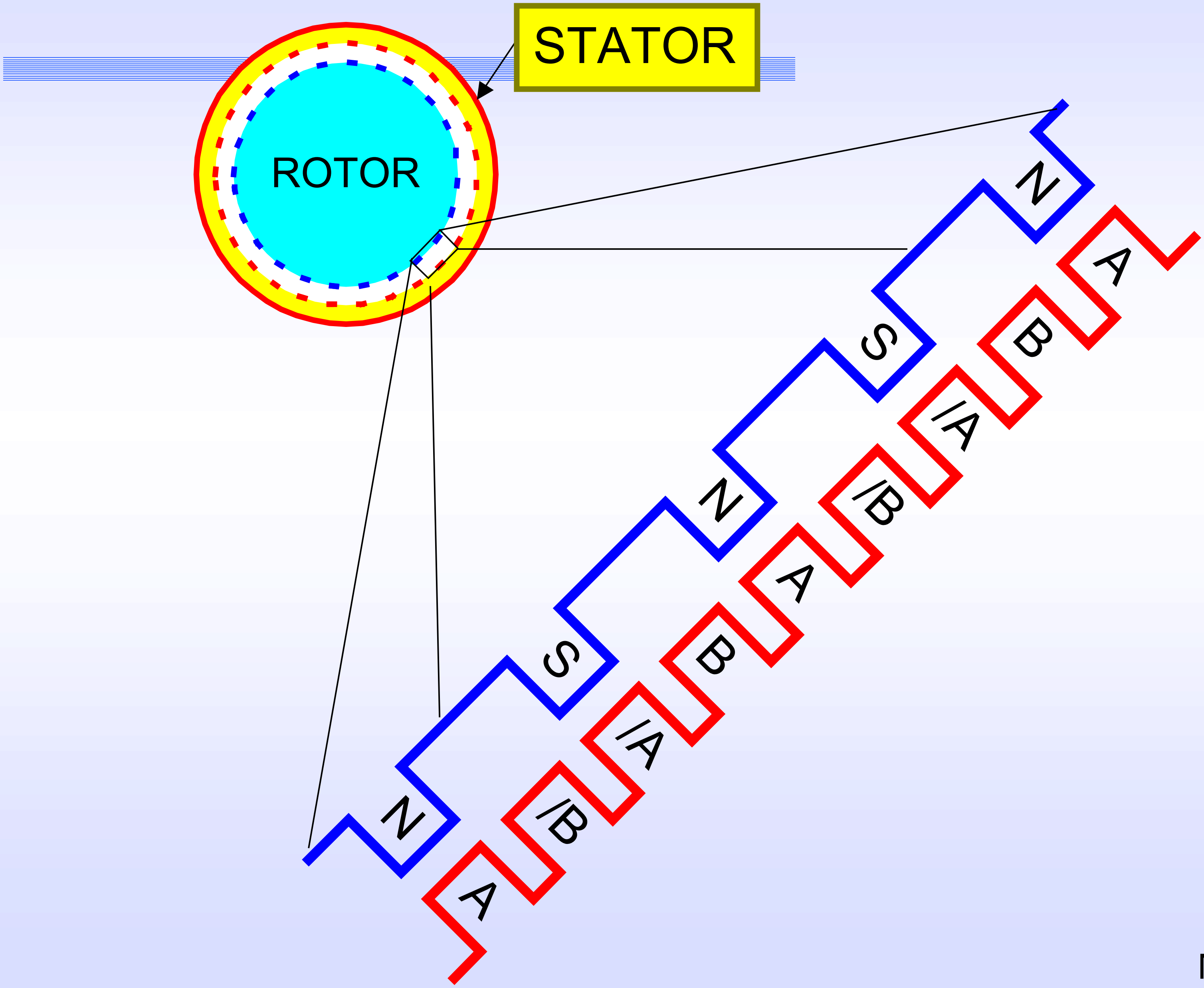
# Actual Motor Construction

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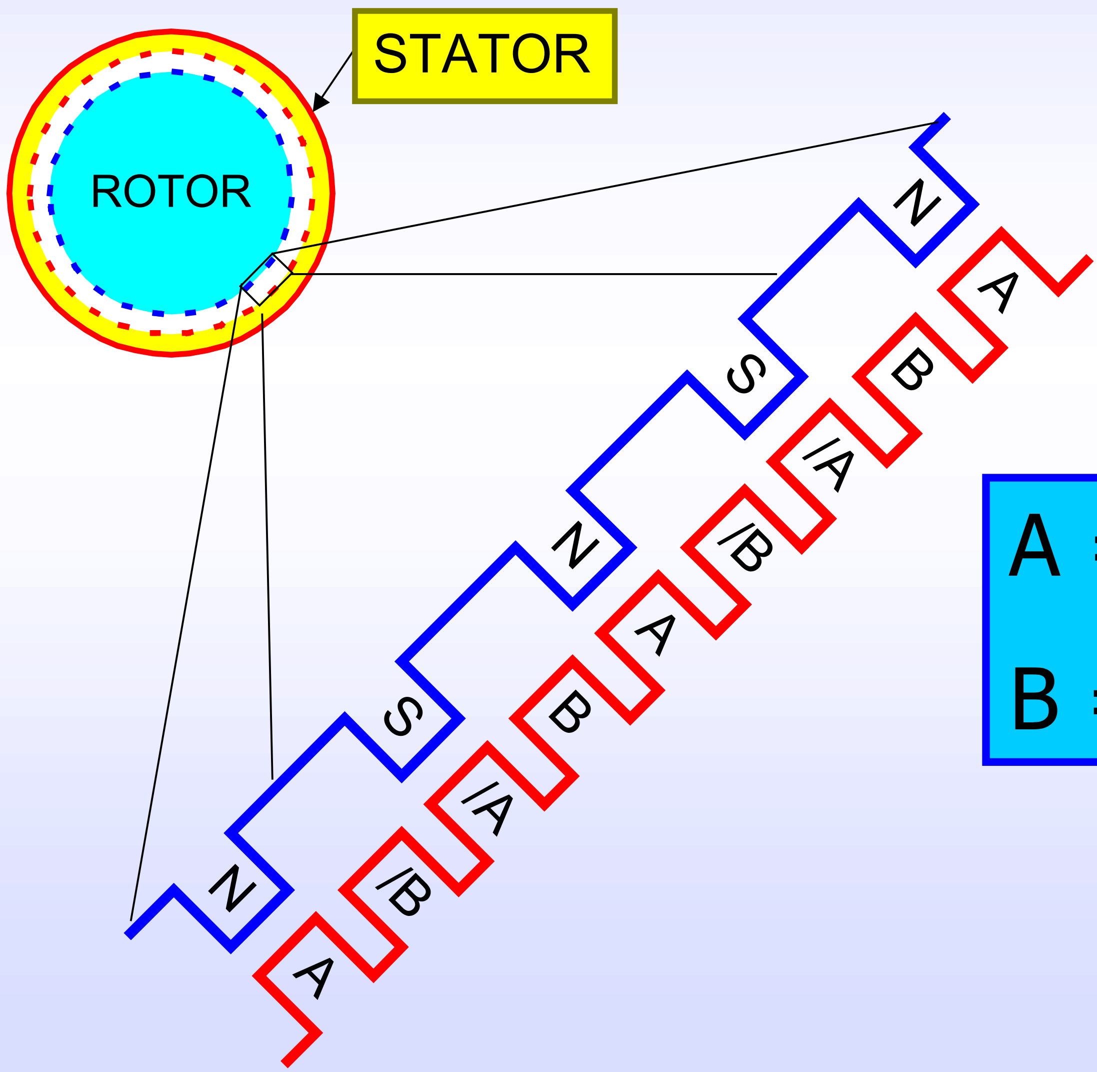
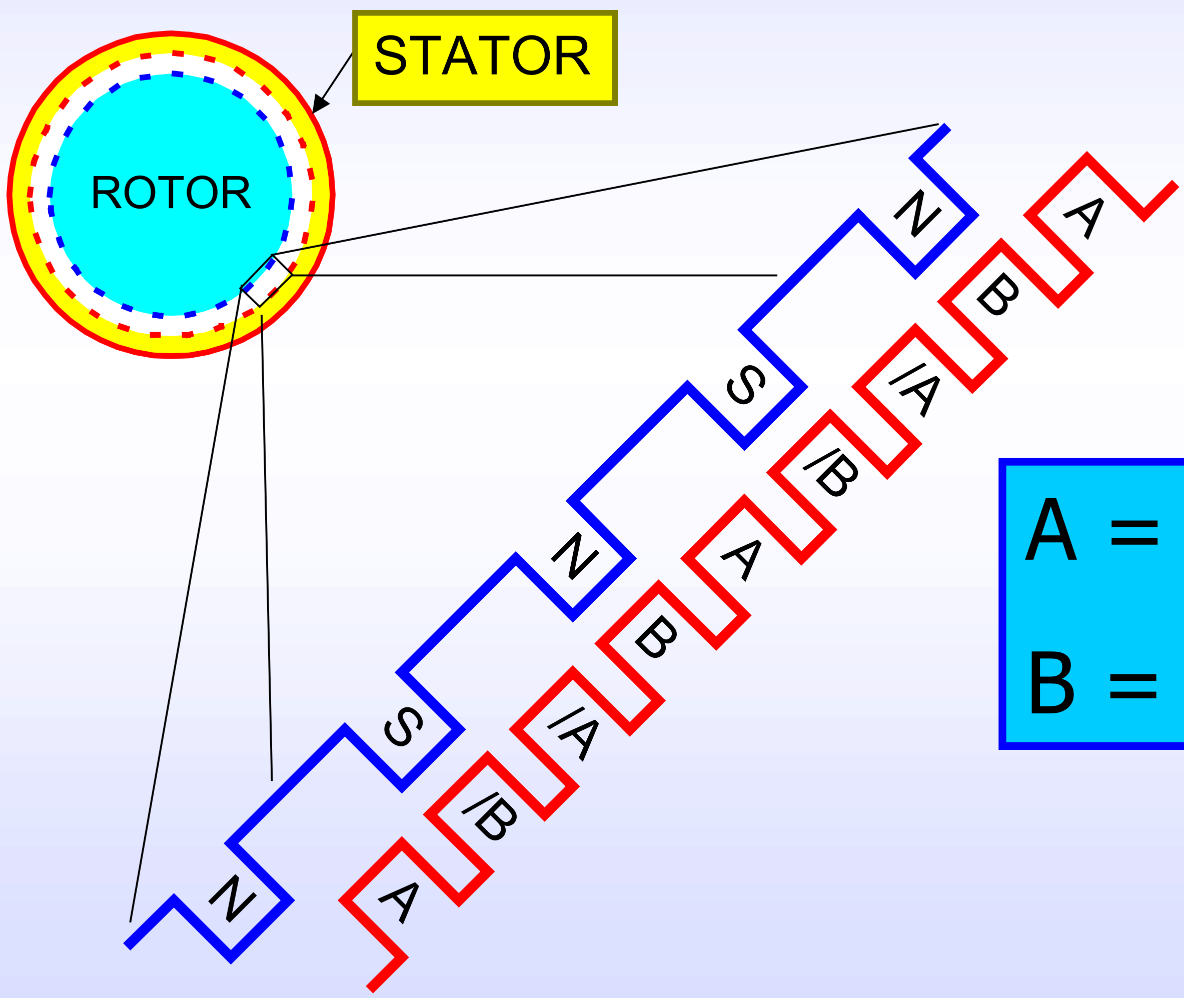
# Multi-pole Rotation, Full-Step




A = S

B = OFF

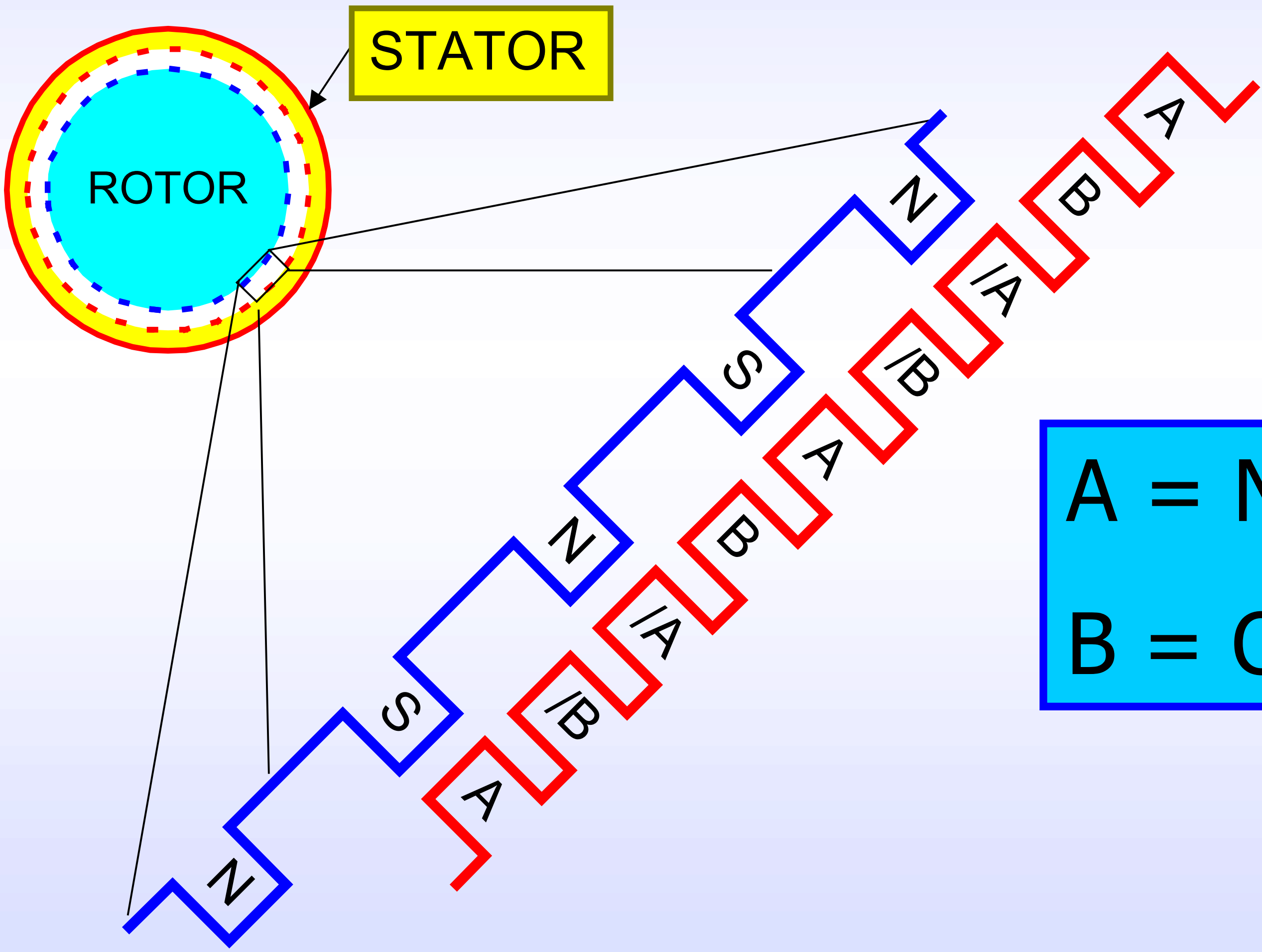
# Multi-pole Rotation, Full Step




A = OFF

B = S

# Multi-pole Rotation, Full Step




A = N

B = OFF

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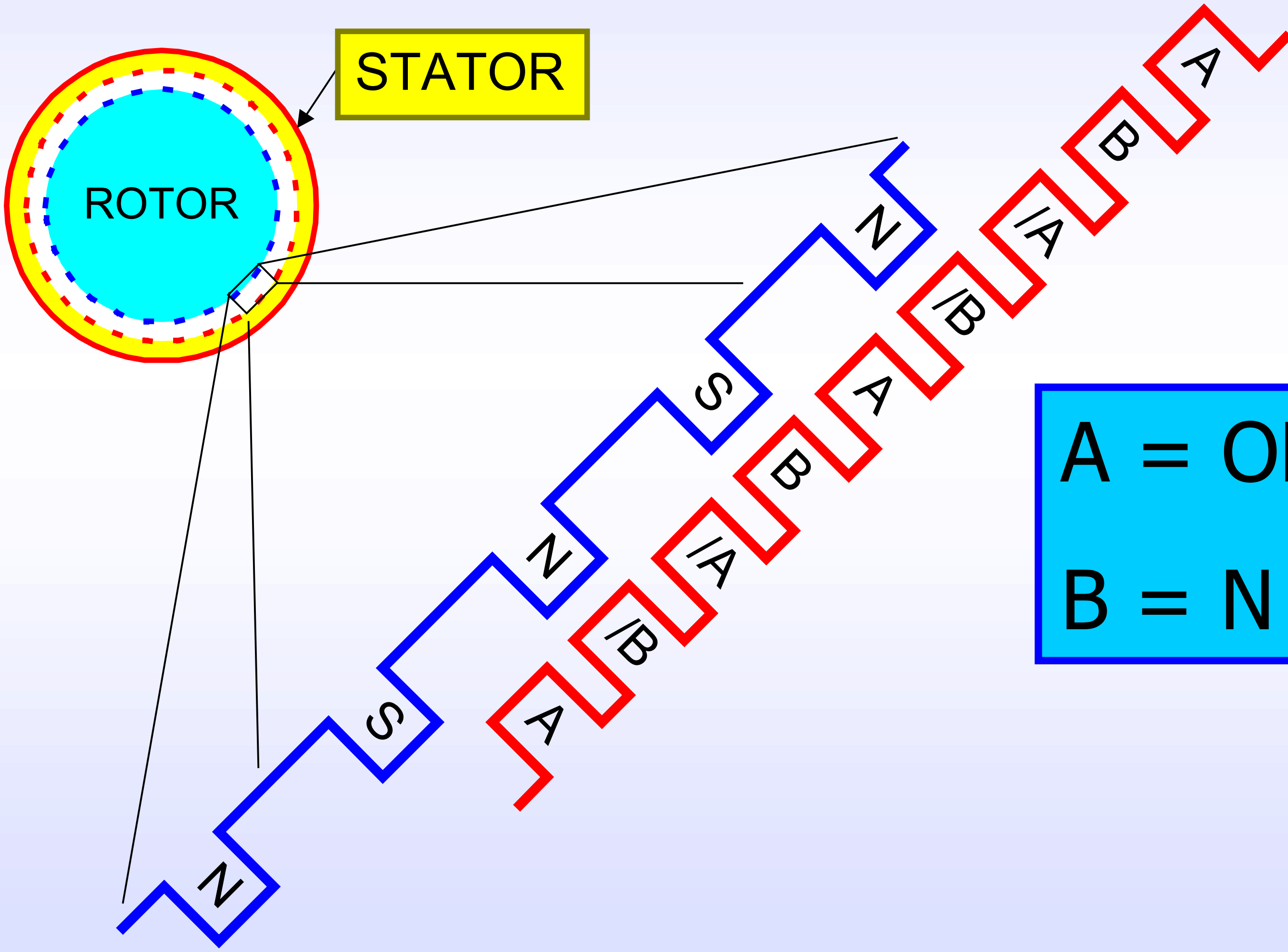
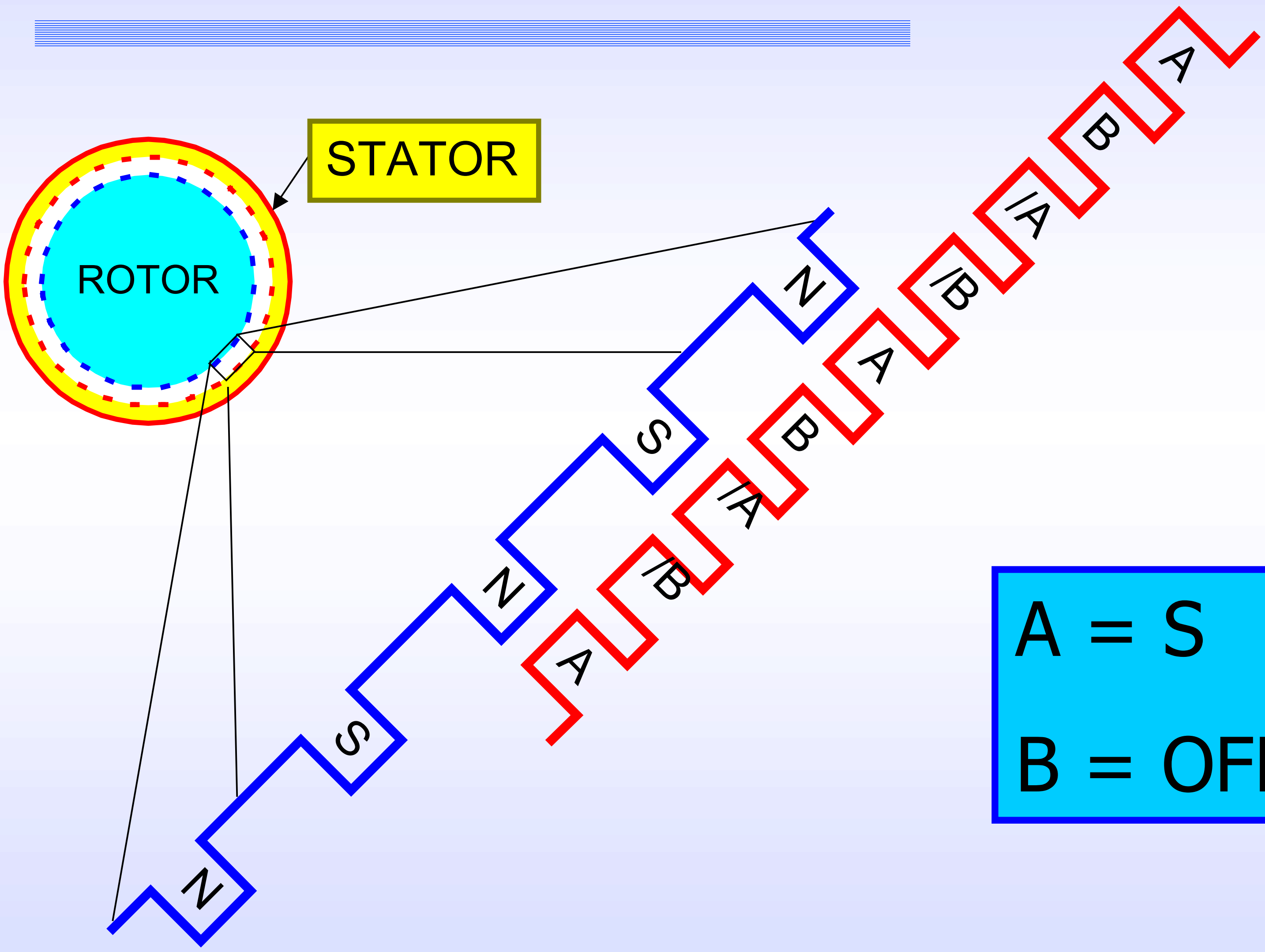
# Multi-pole Rotation, Full Step




A = OFF

B = N

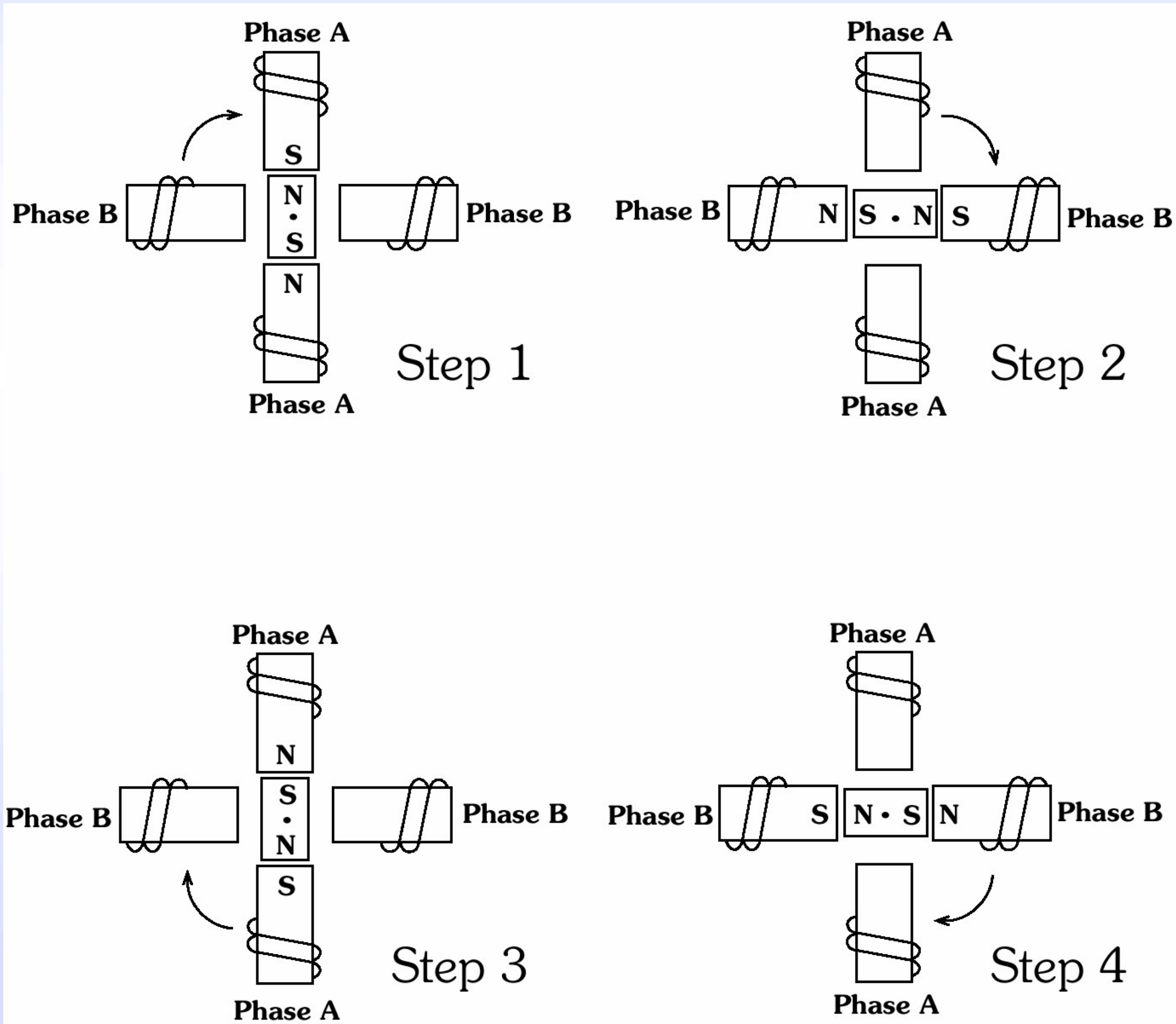
# Multi-pole Rotation, Full Step



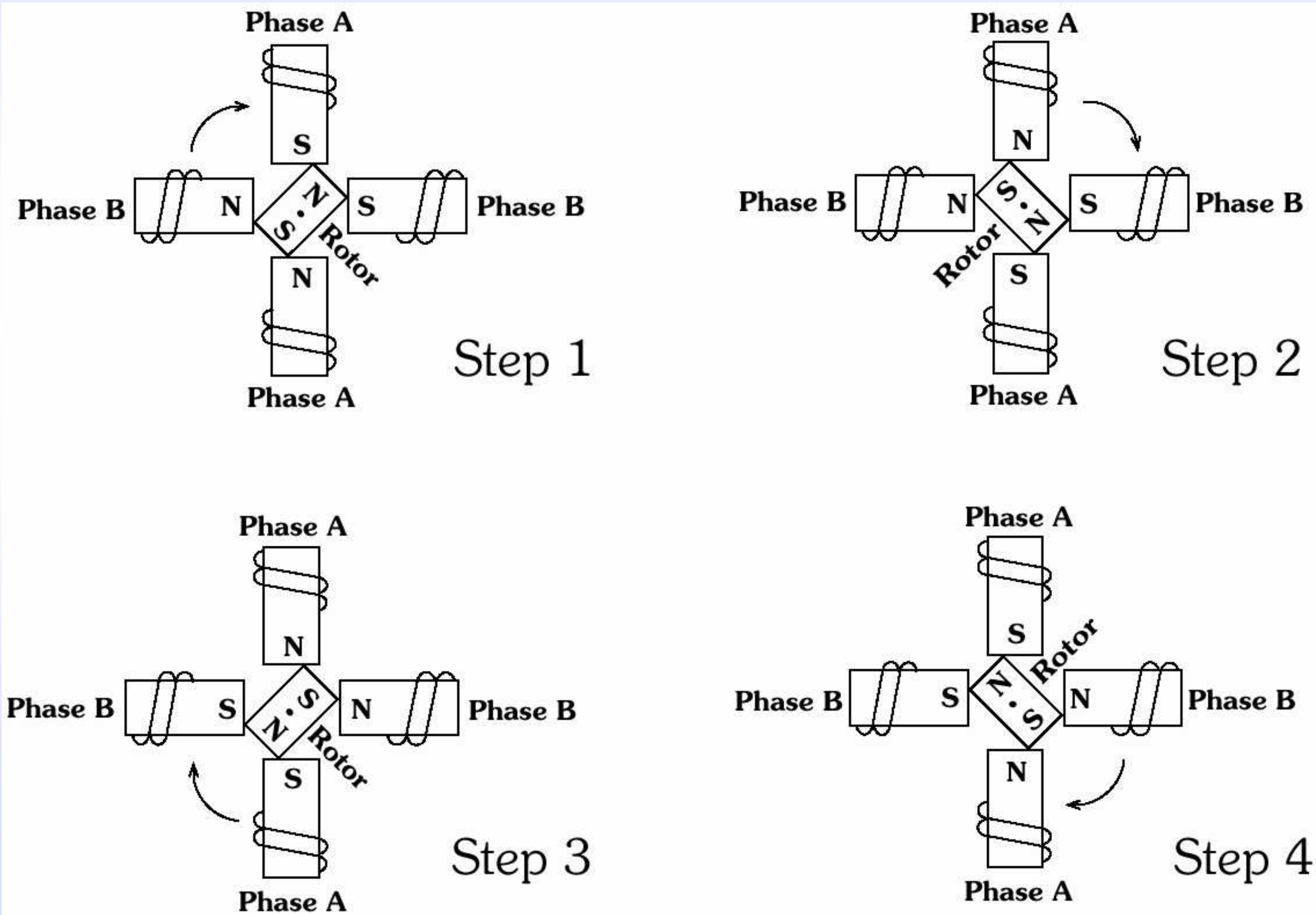

A = S

B = OFF

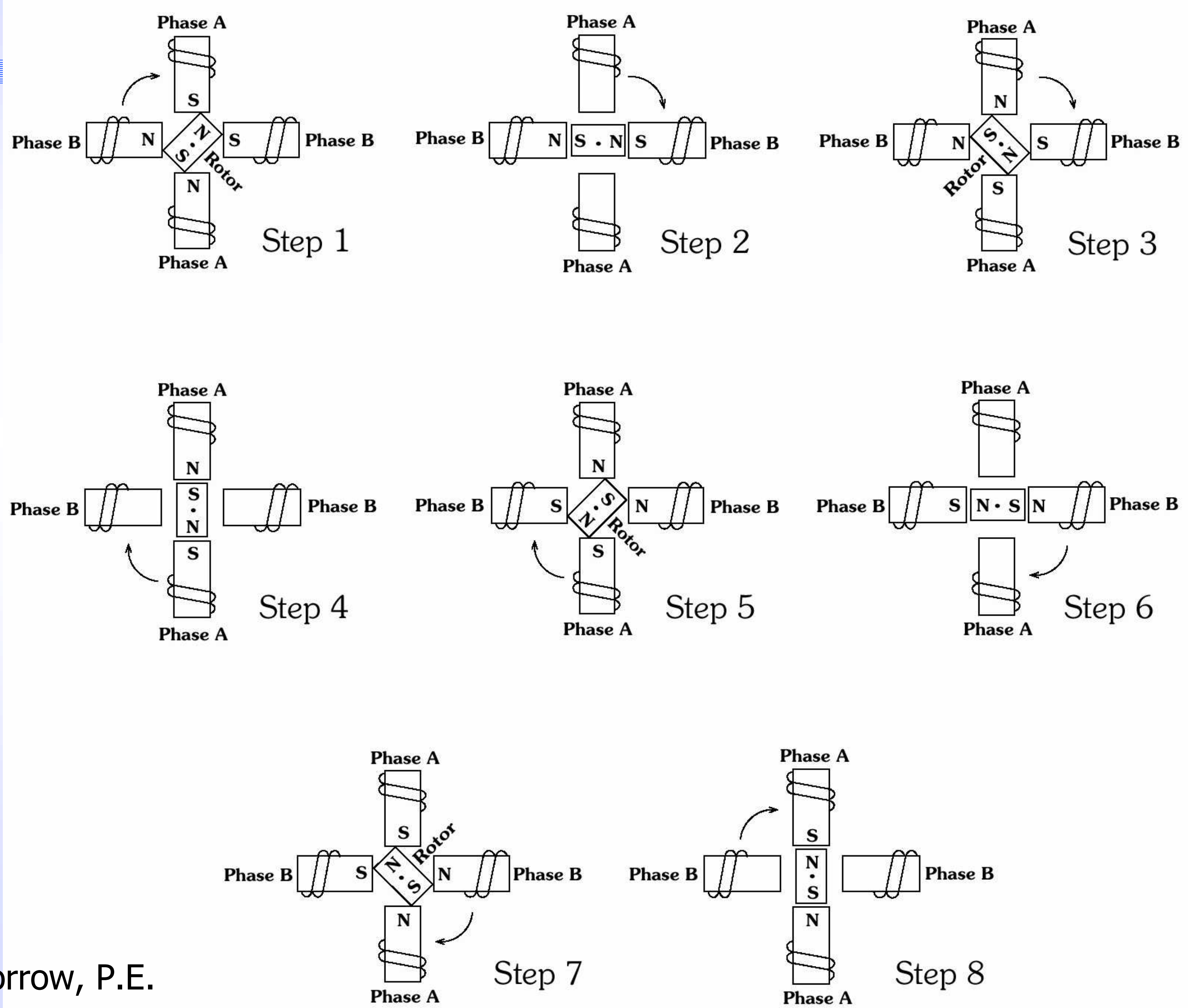
# "Full-Step" Stepping



# "Full-Step, 2-on" Stepping



# Half-stepping

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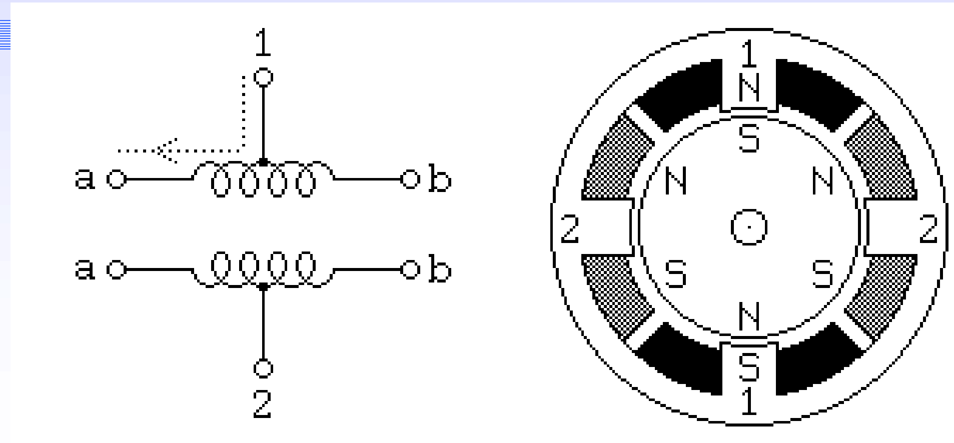
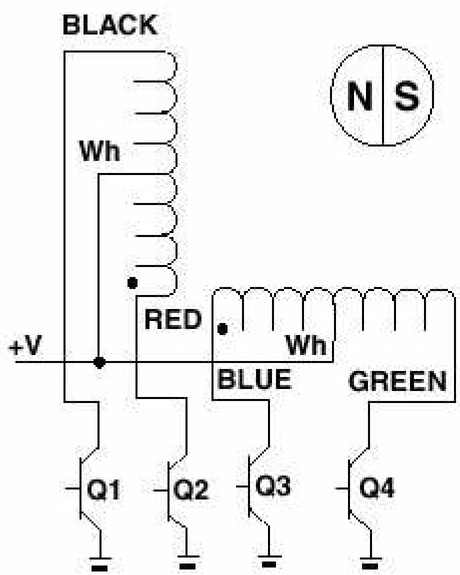
# Unipolar motor



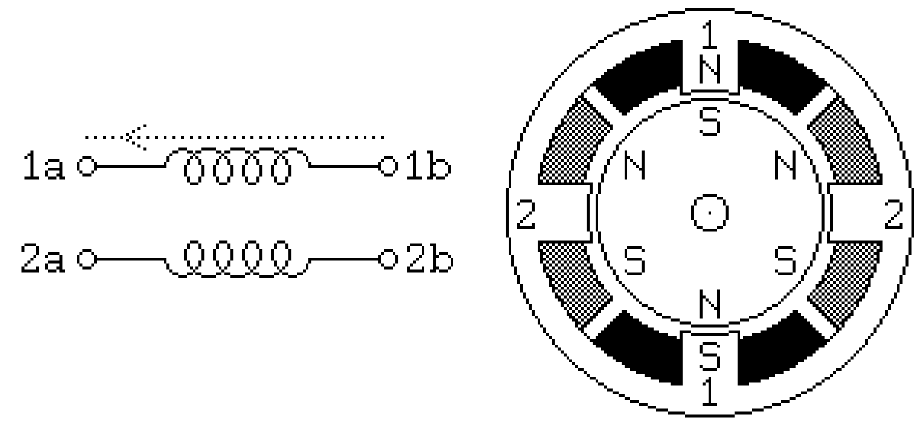



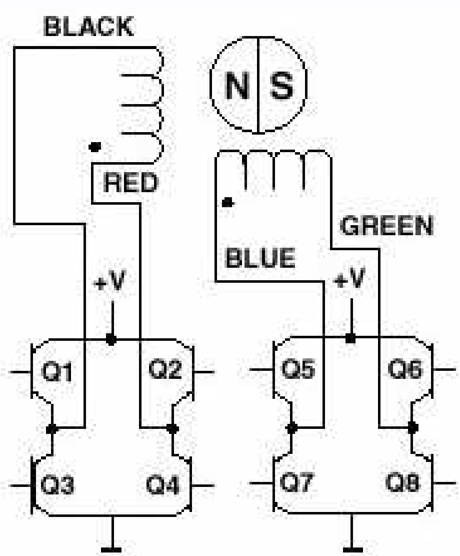

CW Rotation ↓

| Unipolar Step | Q1 | Q2 | Q3 | Q4 |
|---|---|---|---|---|
| 1 | ON | OFF | ON | OFF |
| 2 | OFF | ON | ON | OFF |
| 3 | OFF | ON | OFF | ON |
| 4 | ON | OFF | OFF | ON |
| 1 | ON | OFF | ON | OFF |

CCW Rotation ↑

# Bipolar motor



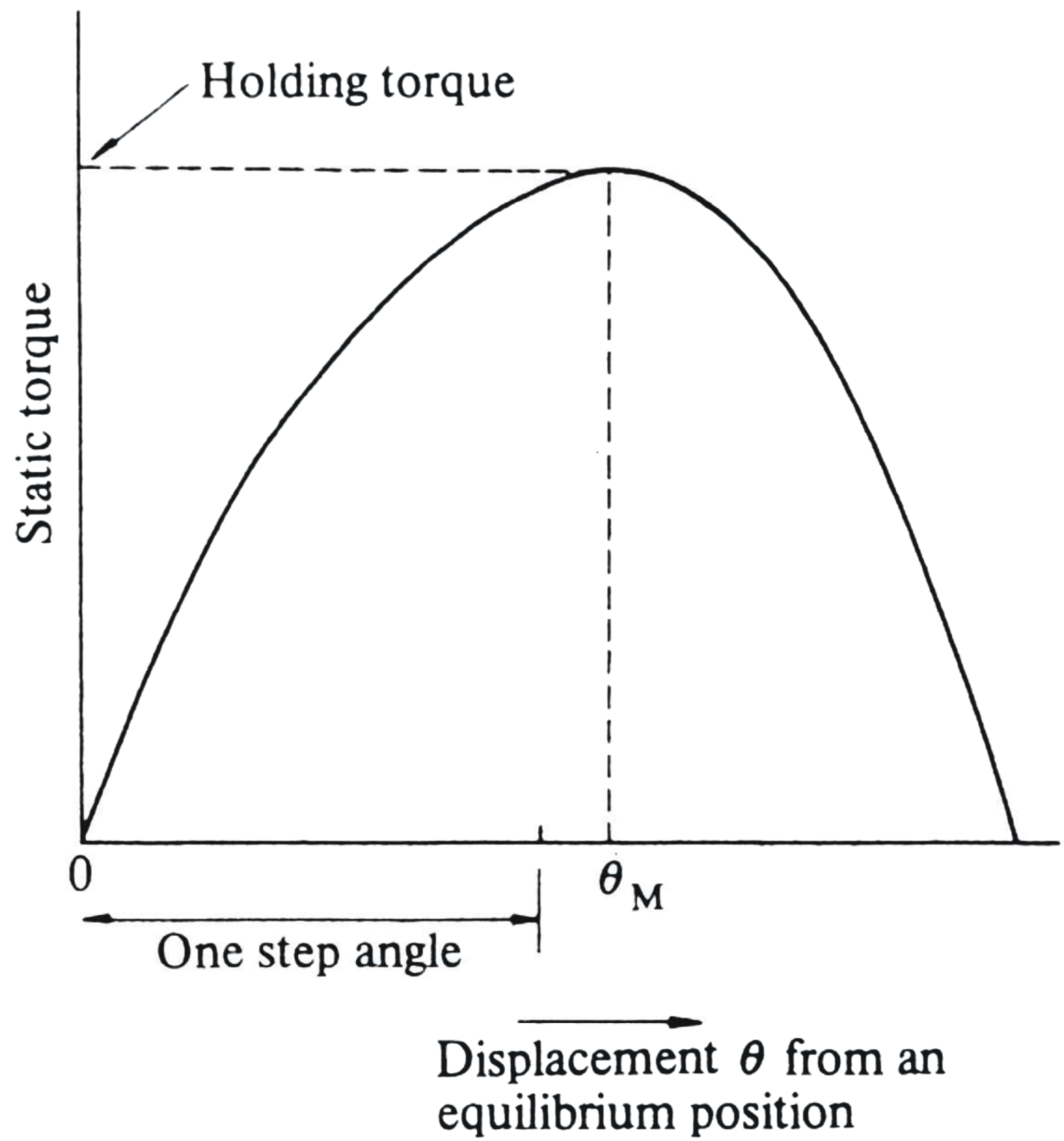




CW Rotation ↓

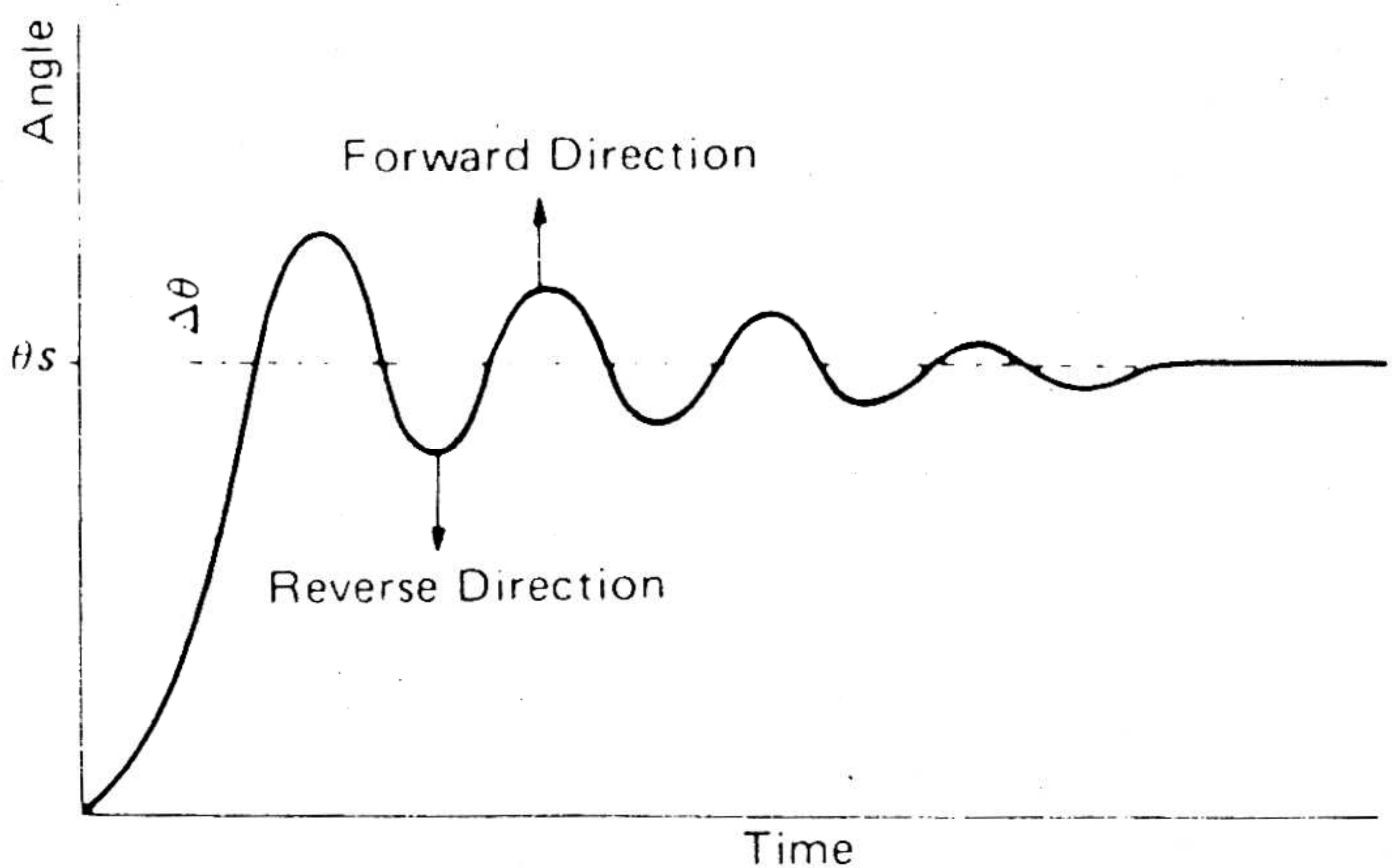
| Bipolar Step | Q2-Q3 | Q1-Q4 | Q6-Q7 | Q5-Q8 |
|---|---|---|---|---|
| 1 | ON | OFF | ON | OFF |
| 2 | OFF | ON | ON | OFF |
| 3 | OFF | ON | OFF | ON |
| 4 | ON | OFF | OFF | ON |
| 1 | ON | OFF | ON | OFF |

CCW Rotation ↑

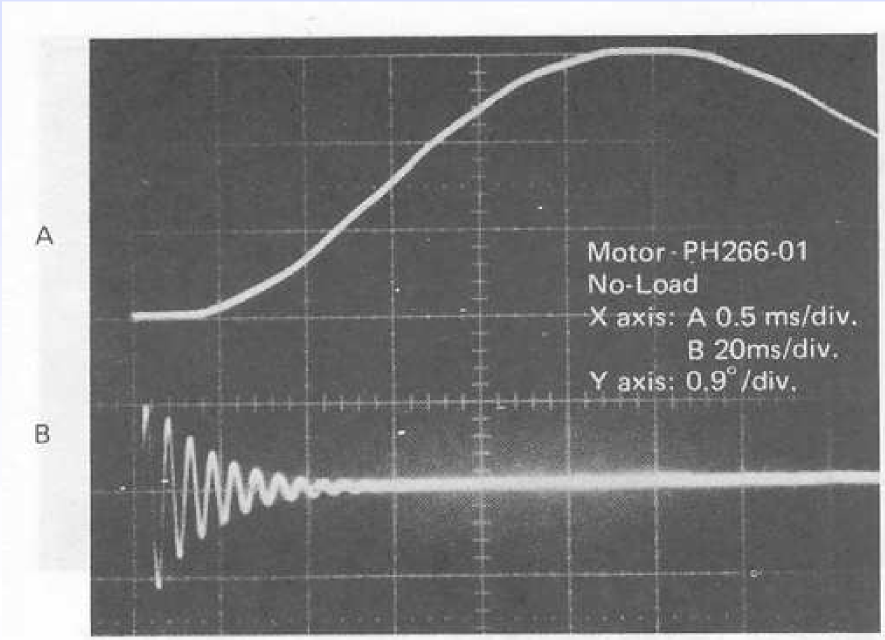
# Torque v.s. Angular Displacement

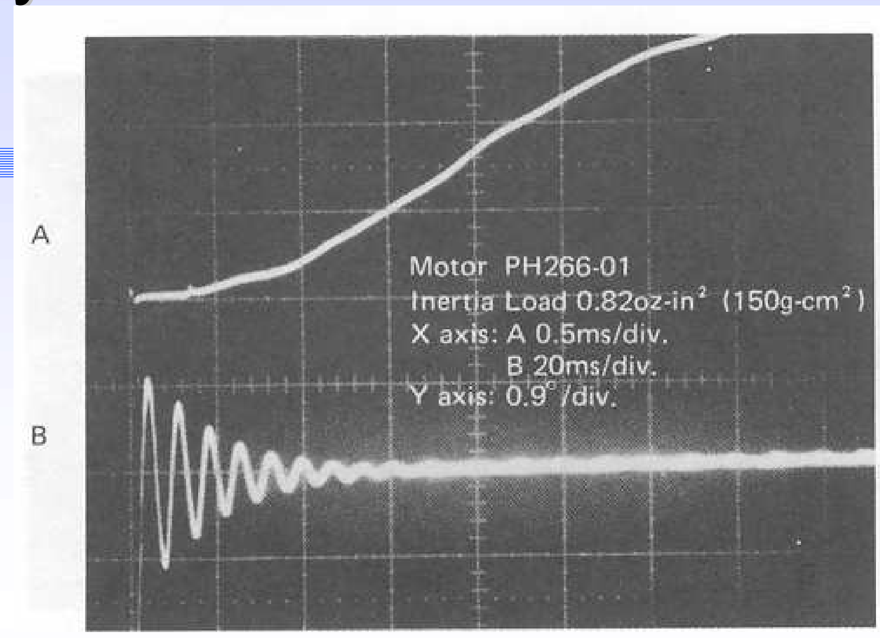


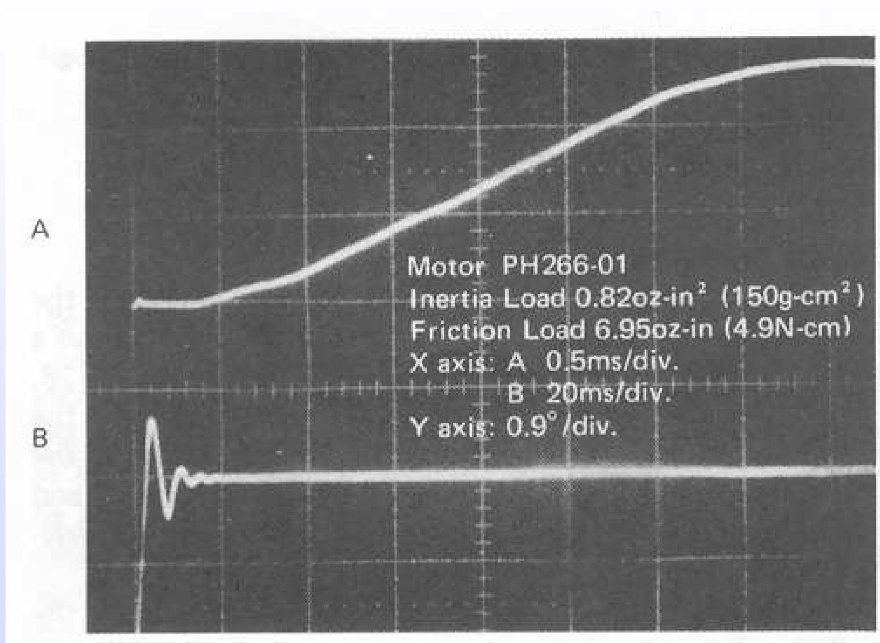
# Stepping Dynamics



# Load Affects the Step Dynamics



# Drive Affects the Step Dynamics

a

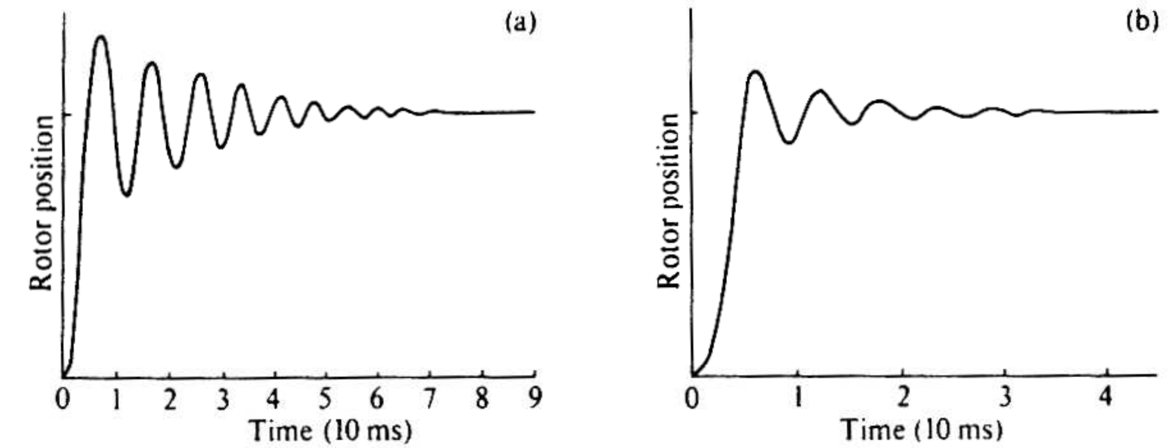
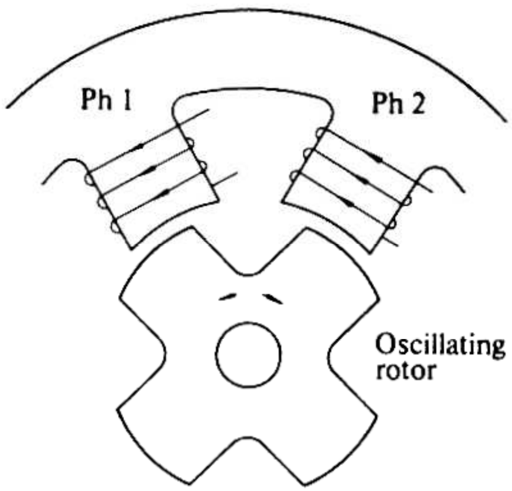
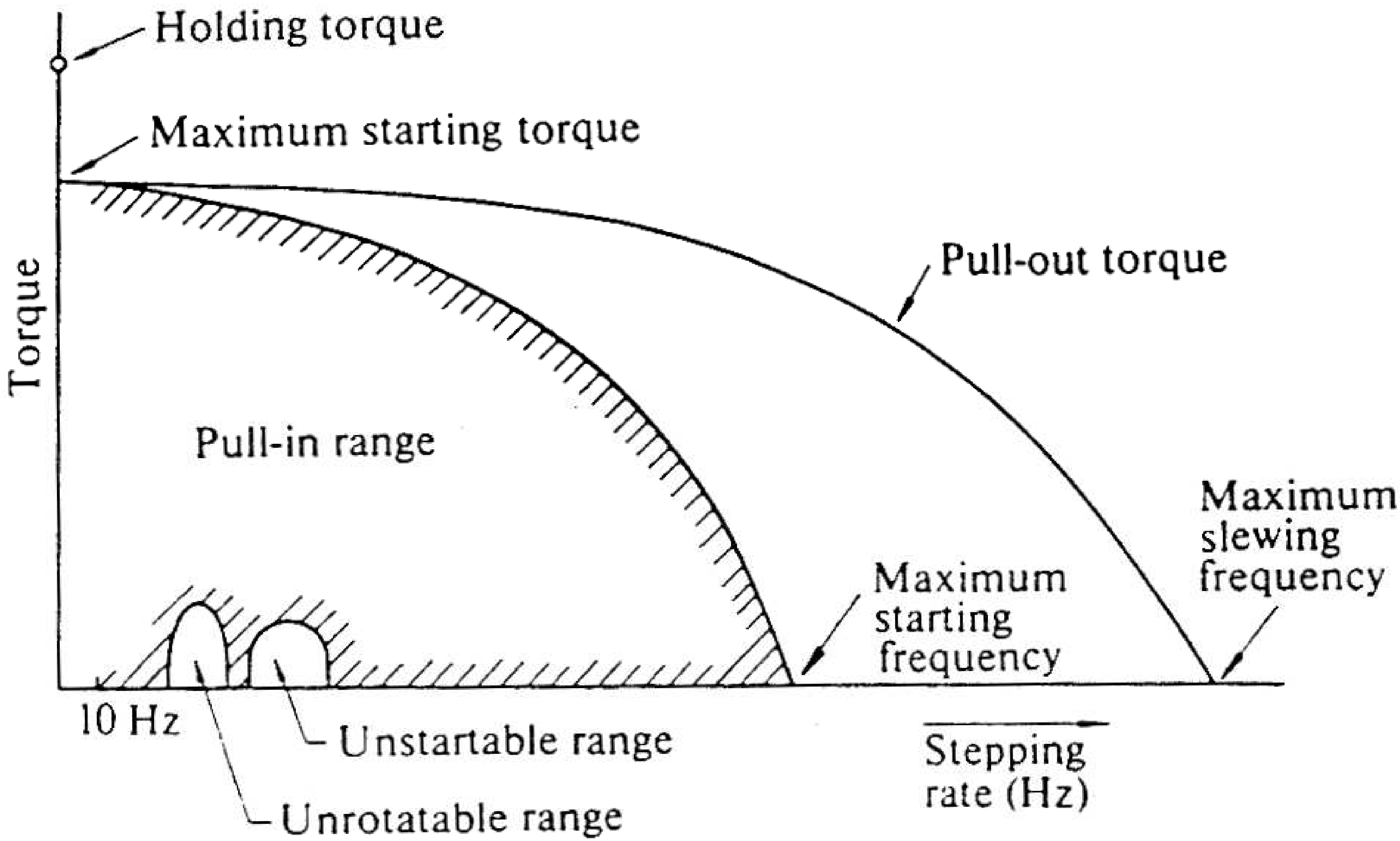


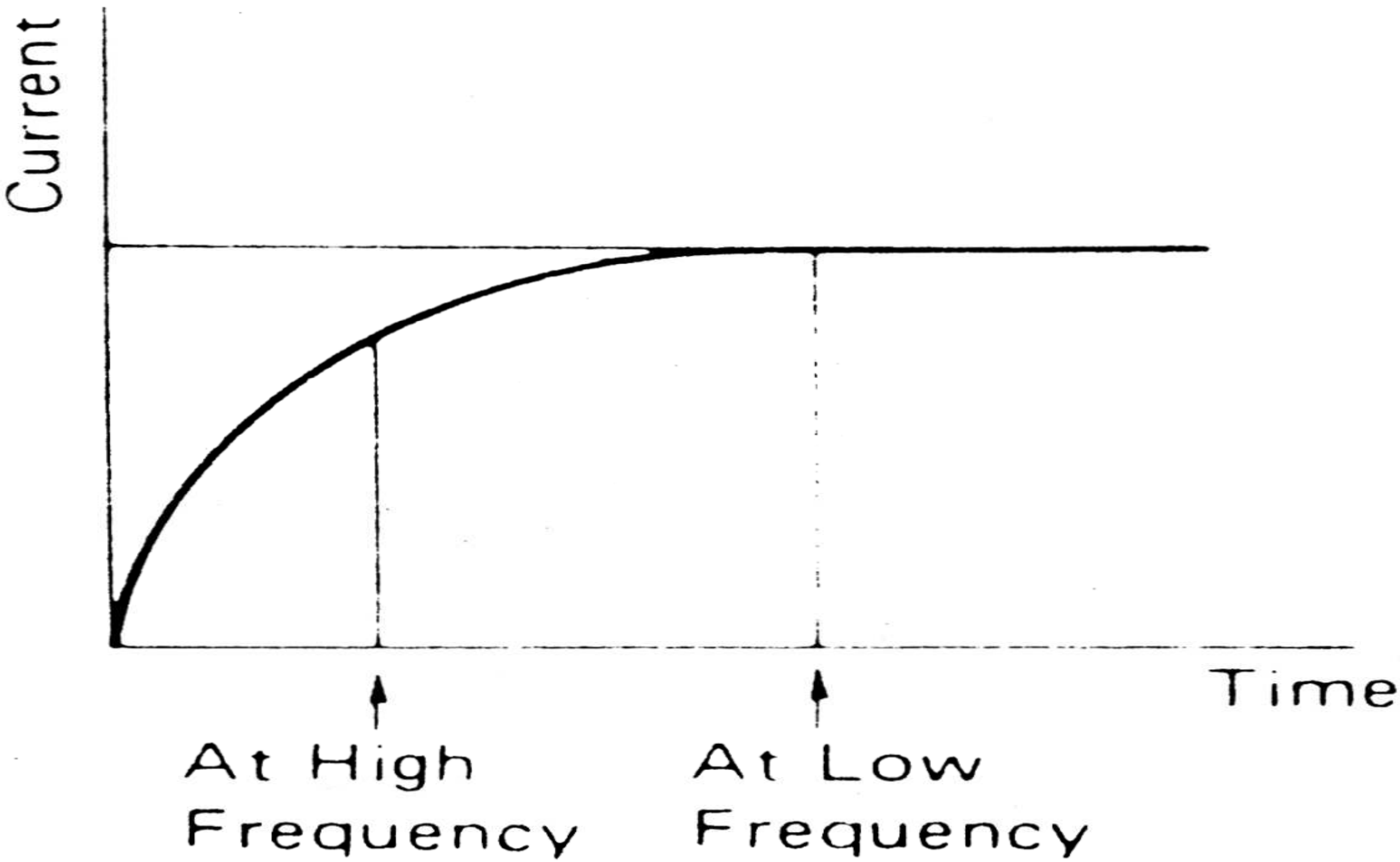

**Fig. 2.55.** Difference in single-step response between the single-phase (a) and two-phase (b) excitation.



# Stepper Motor Performance Curves



# Current Dynamics

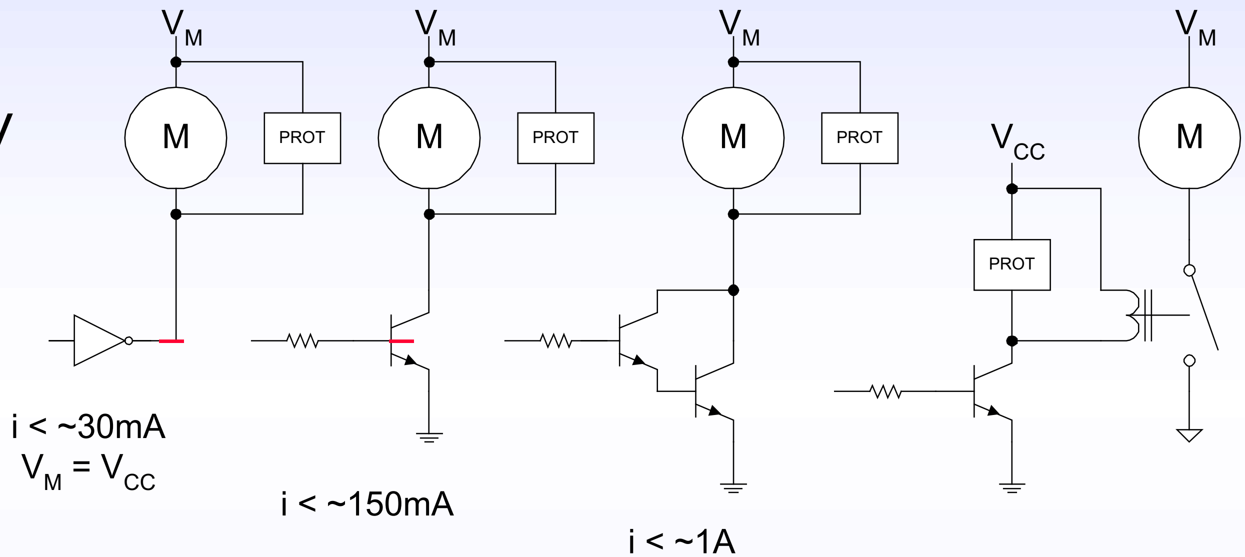


# Drive Circuits

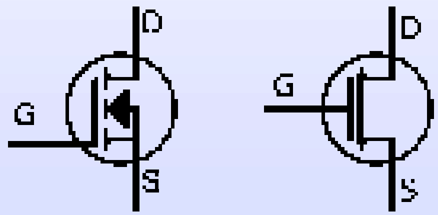
- Inductive Loads
- AC Motor Drive (Triac)
- H-bridge
- Snubbing and L/nR Stepper Drive
- PWM
- Micro-Stepping

# Inductive Load Drive Circuits

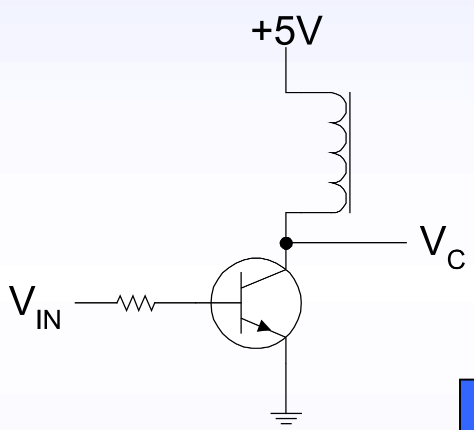
- BJTs
  - $V_{CEsat} \sim 0.4V$
  - $P_D = I_C * V_{CE}$

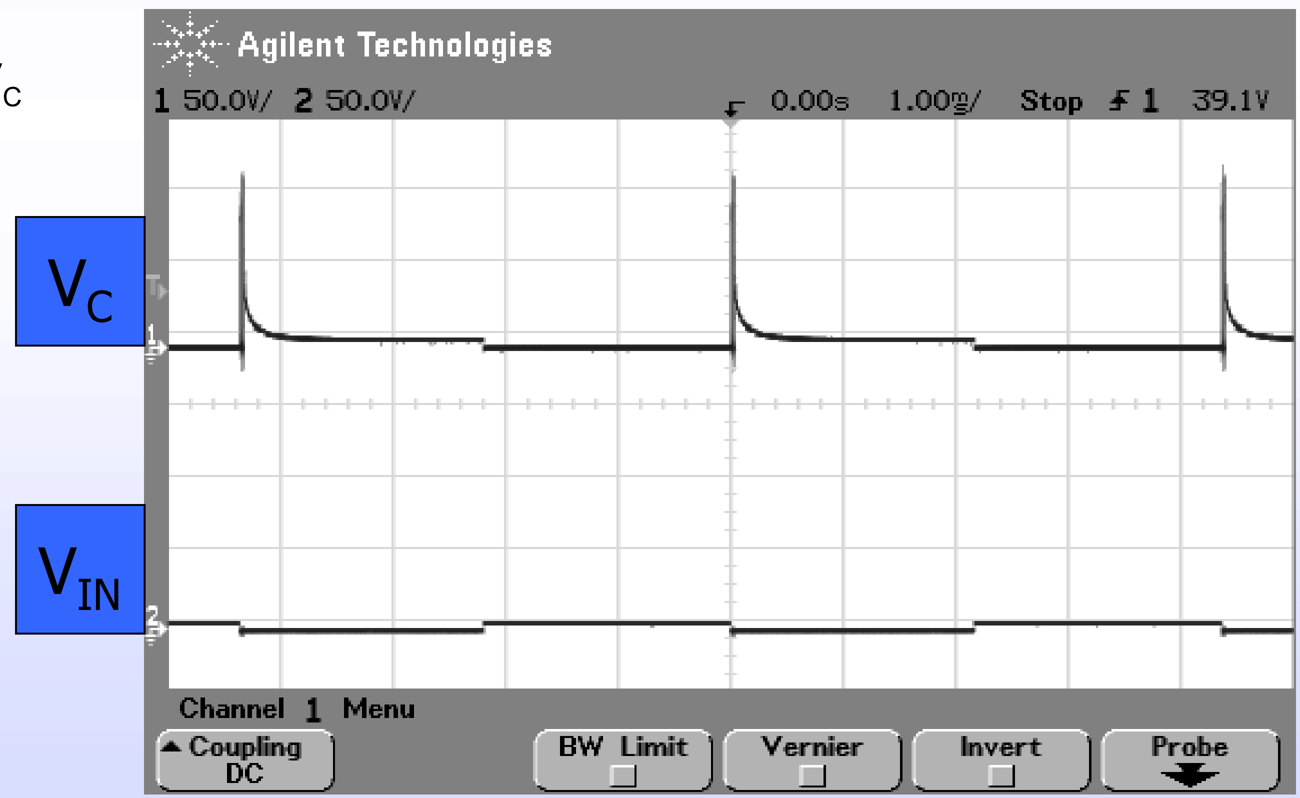



- MOSFETs
  - $V_{DS} = I_D * R_{DSon}$
  - $P_D = I_D * V_{DS}$



# Switching Characteristics

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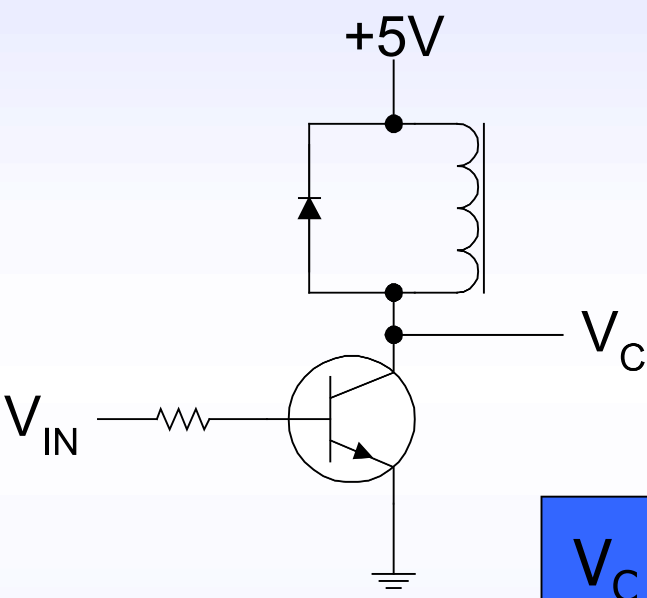
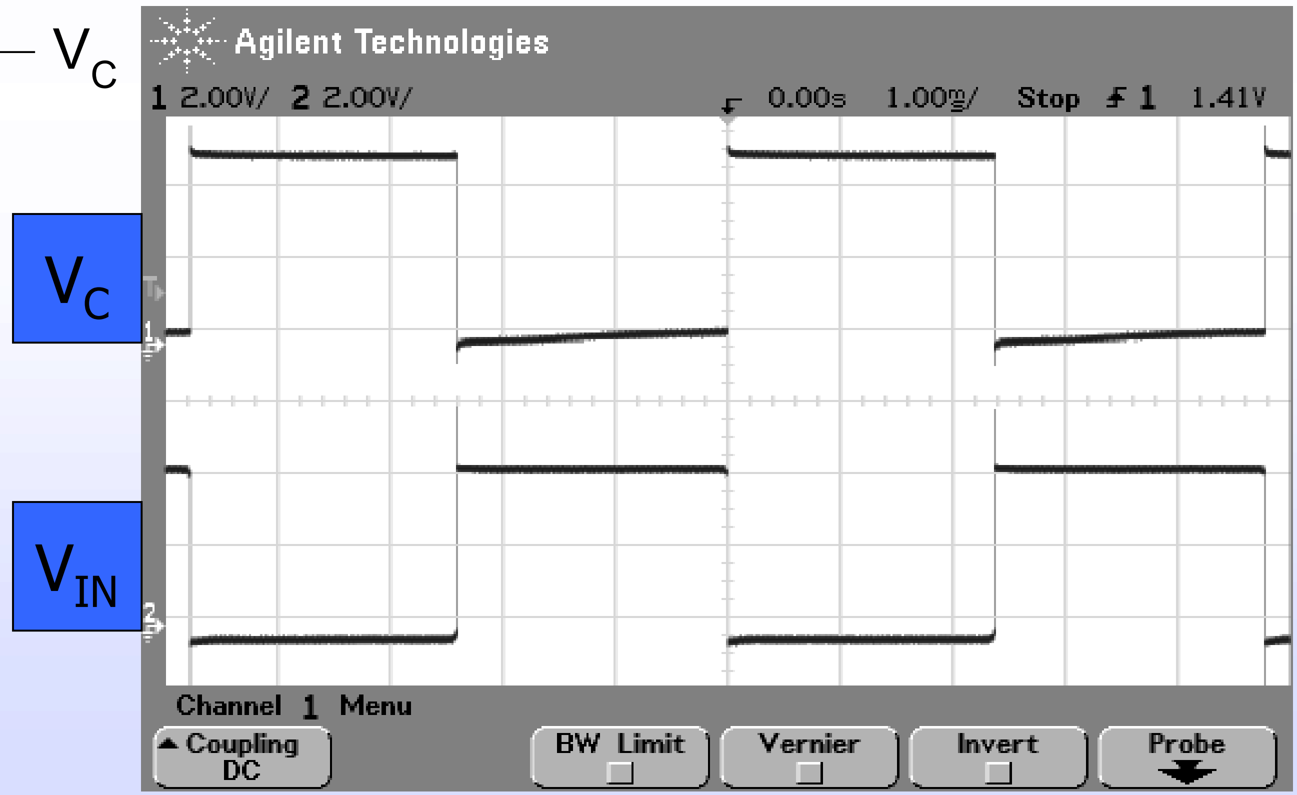
# Switching Characteristics

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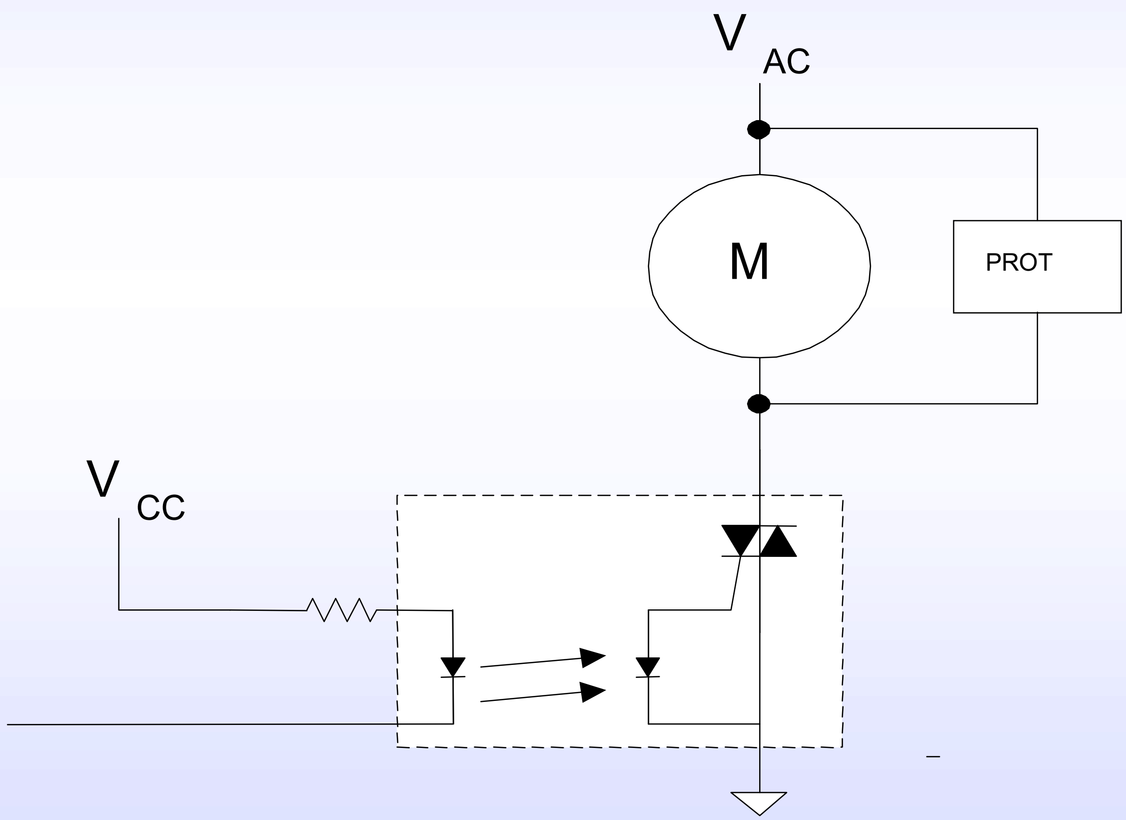
# AC Motor Drive

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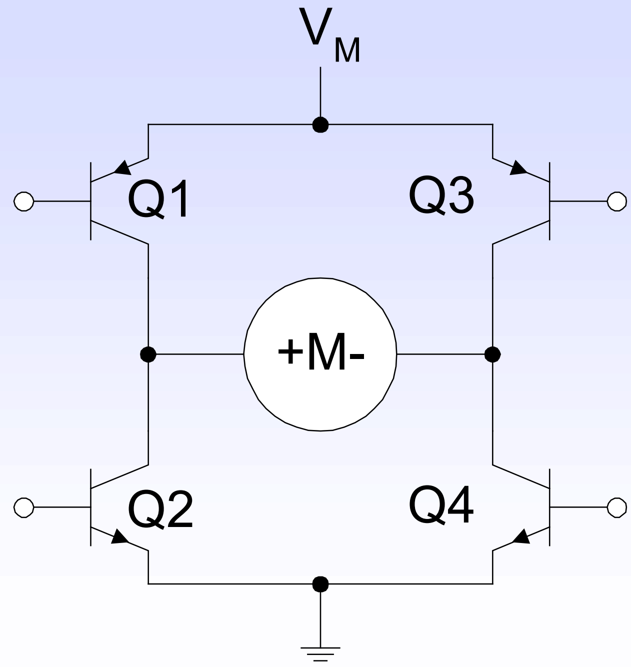
# H-bridge

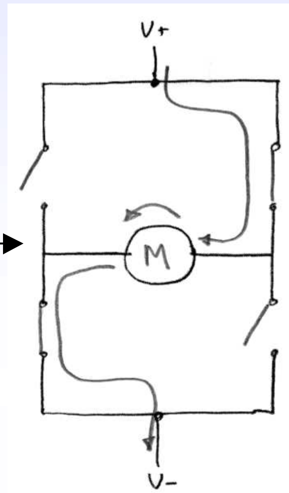
- An H-bridge consists of two high-side switches (Q1,Q3) and two low-side switches (Q2,Q4)
- BJTs or FETs




| Q1 | Q2 | Q3 | Q4 | |
|---|---|---|---|---|
| ON | ON | * | * | Don't use - short circuit |
| * | * | ON | ON | Don't use - short circuit |
| OFF | OFF | * | * | Motor off |
| * | * | OFF | OFF | Motor off |
| ON | OFF | OFF | ON | Forward |
| OFF | ON | ON | OFF | Reverse |
| ON | OFF | ON | OFF | Brake |
| OFF | ON | OFF | ON | Brake |

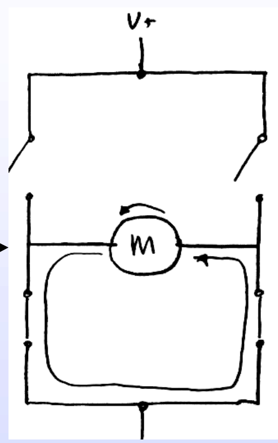
# H-Bridge/Inductor operation

V = IR →



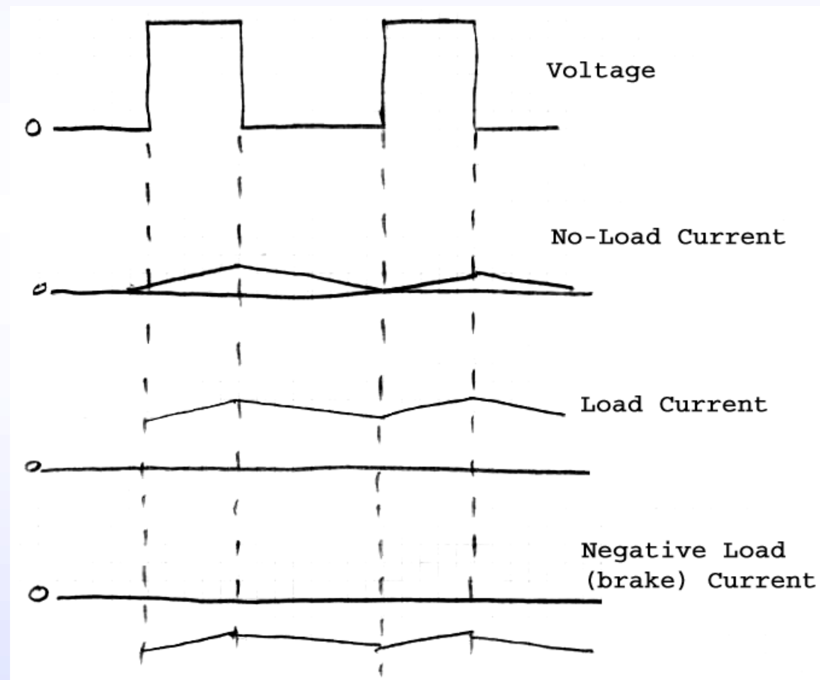

← V = V+

V = IR →

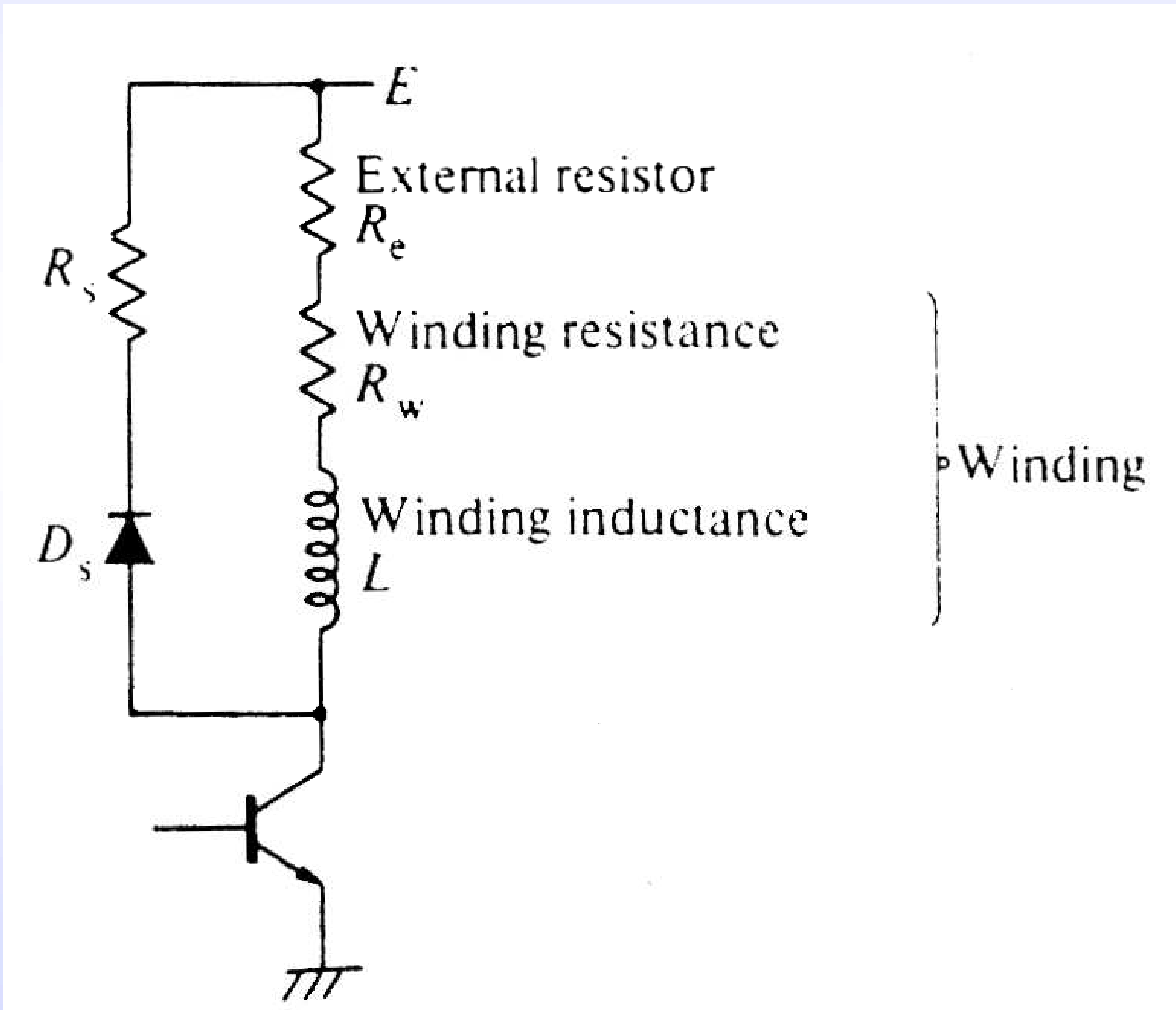



← V = 0

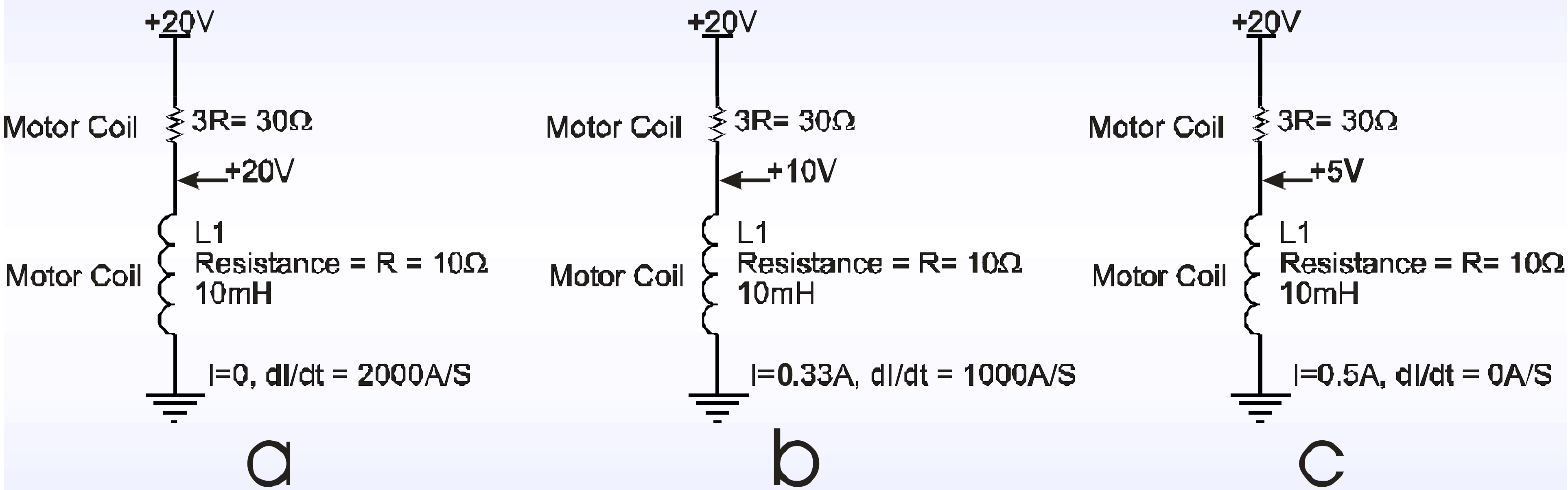
(V = -IR)



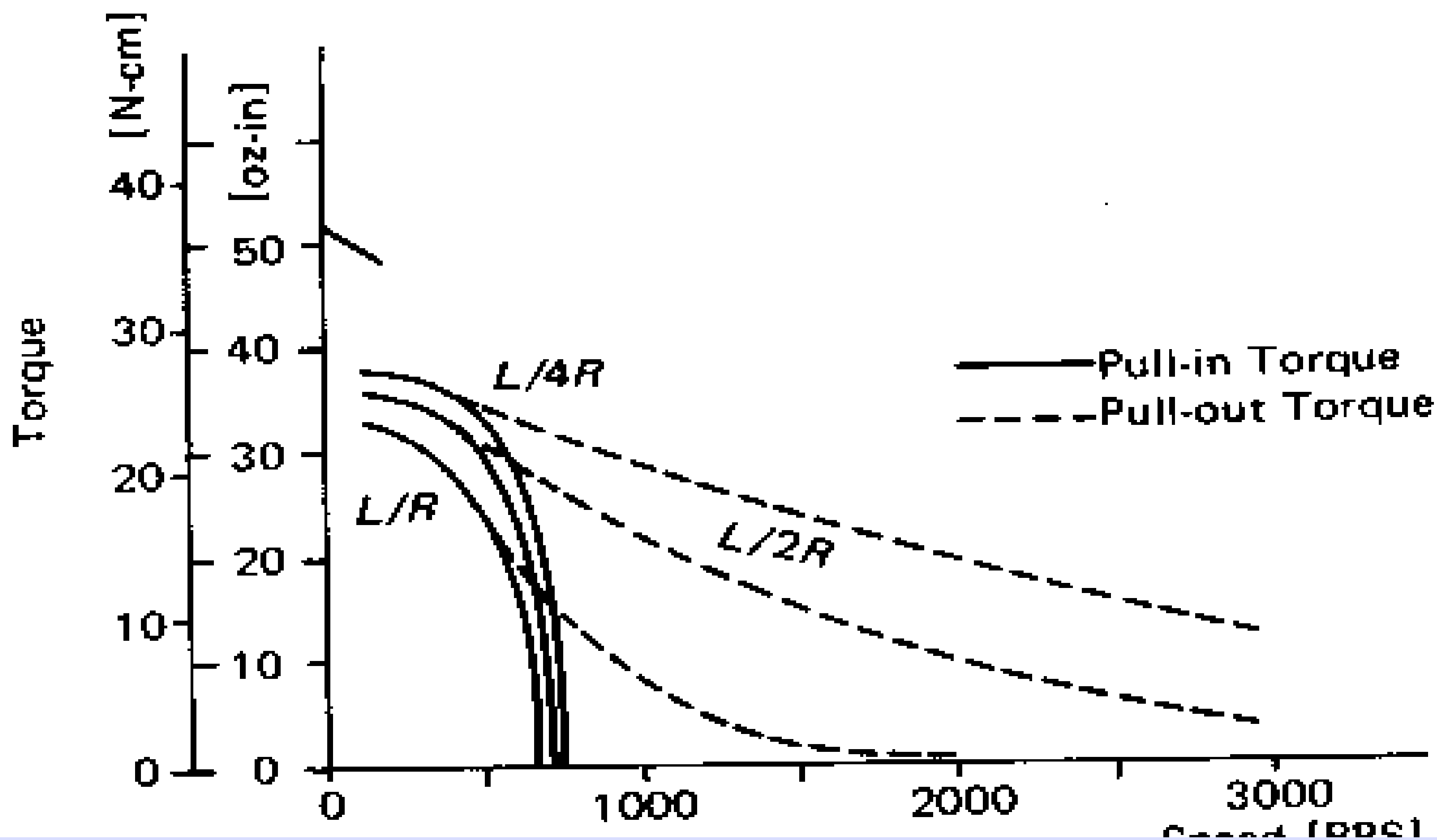
# L/nR Drive


E
External resistor
$R_e$
Winding resistance
$R_w$
Winding inductance
L
Winding
$R_s$
$D_s$

# Current Rise in Detail

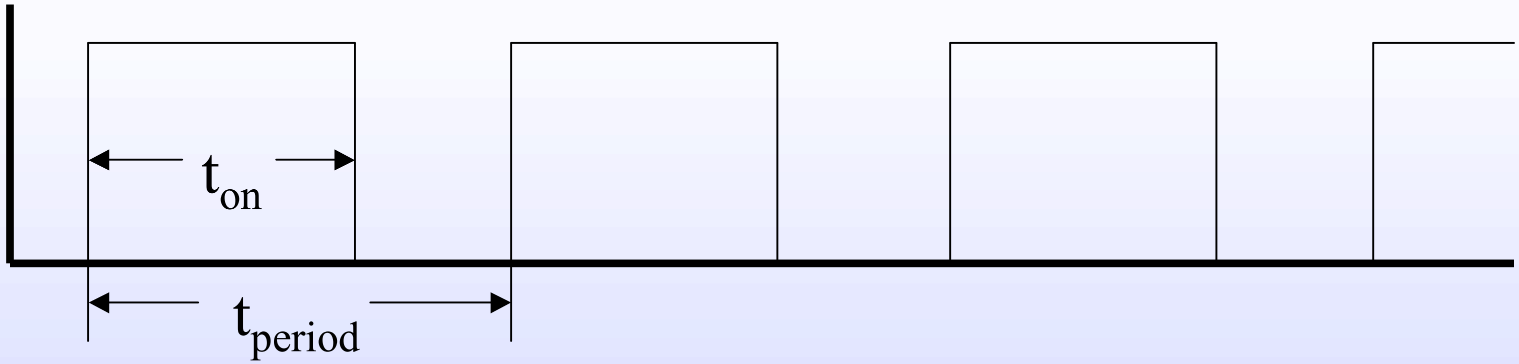


# Performance Improvement with L/nR Drive



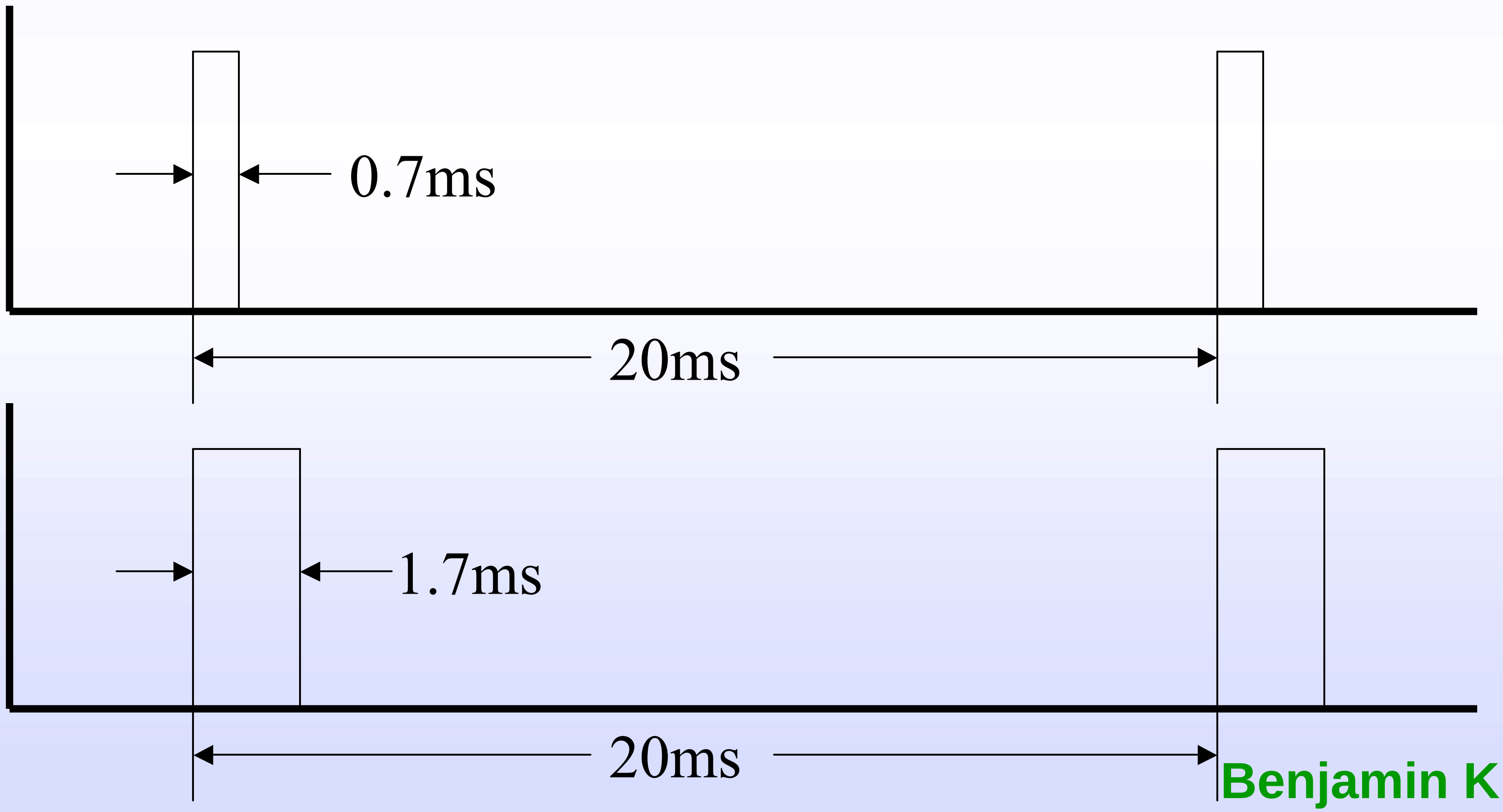
# Pulse-Width Modulation

- Pulse-width ratio = $t_{on}/t_{period}$
- Never in "linear mode"
  - Uses motor inductance to smooth out current
  - Saves power!
  - Noise from $T_{period}$



# Pulse-Code Modulated Signal

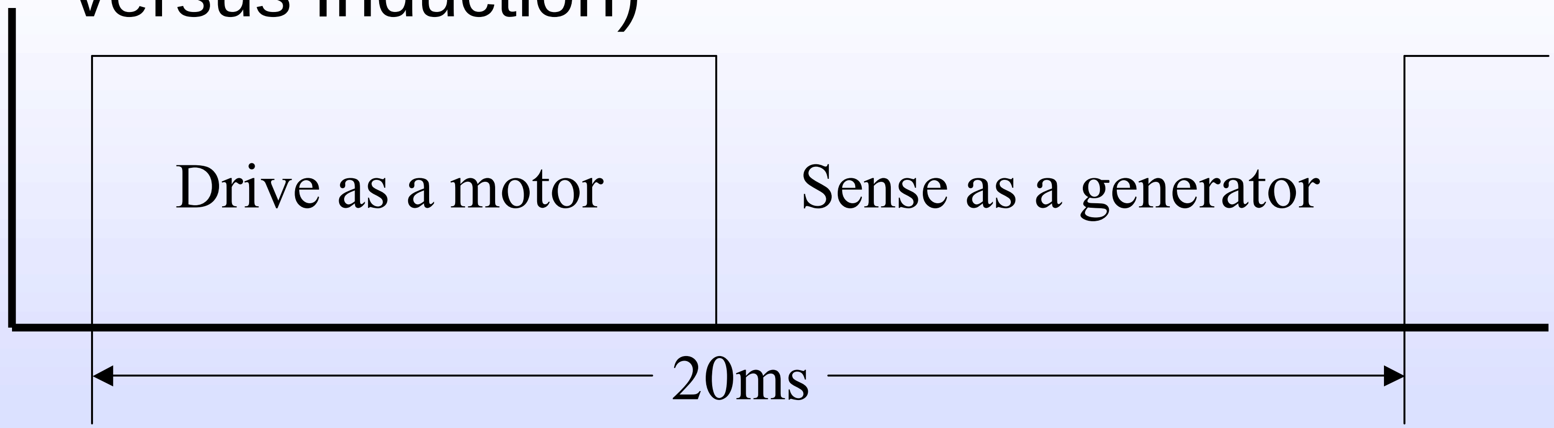
- Some devices are controlled by the length of a pulse-code signal.
  - Position servo-motors, for example.




**Benjamin Kuipers**

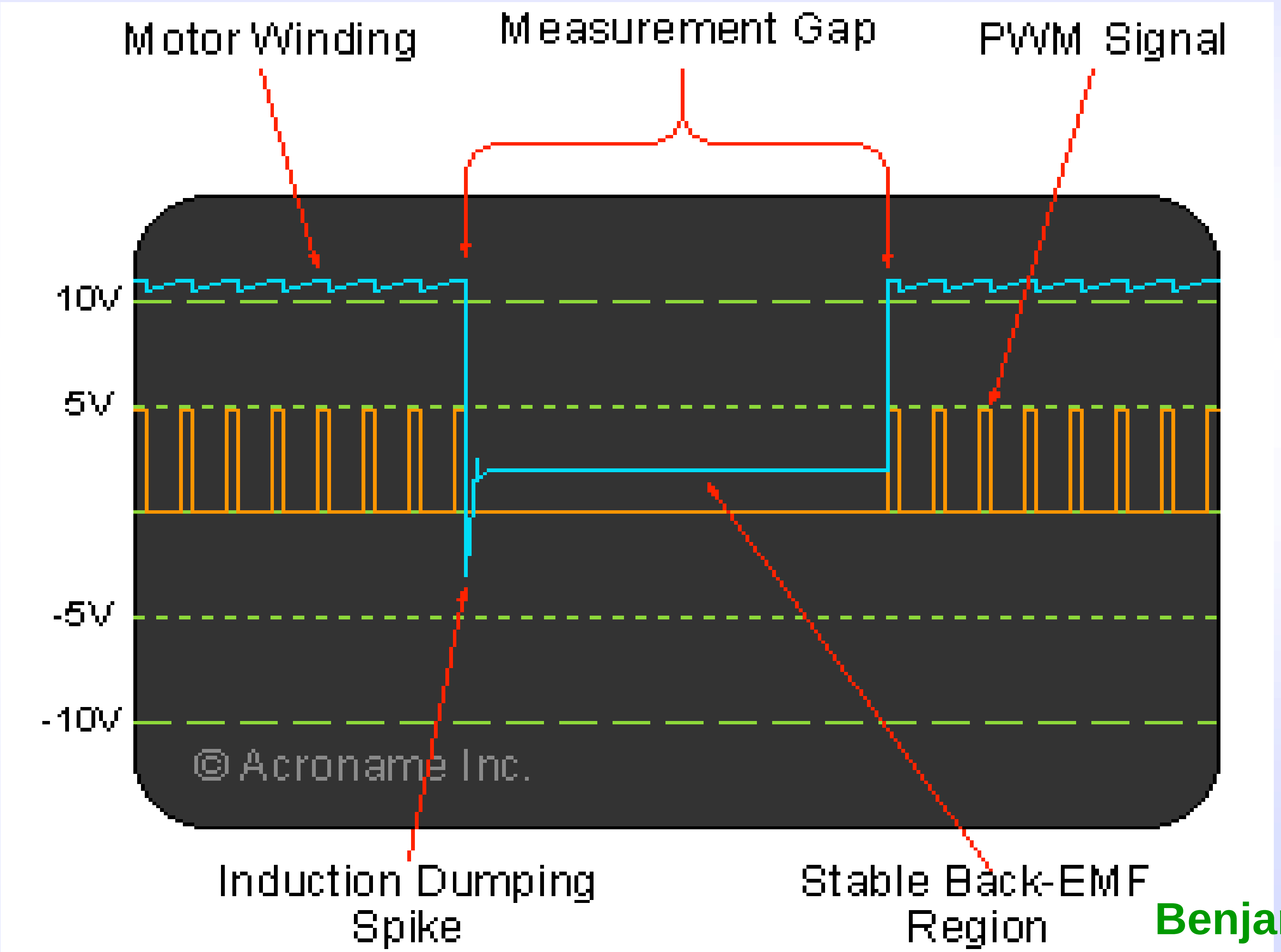
# Back EMF Motor Sensing

- Motor torque is proportional to current.
- Generator voltage is proportional to velocity.
- The same physical device can be either a motor or a generator.
- Alternate Drive and Sense (note issue of Coils versus Induction)




**Benjamin Kuipers**

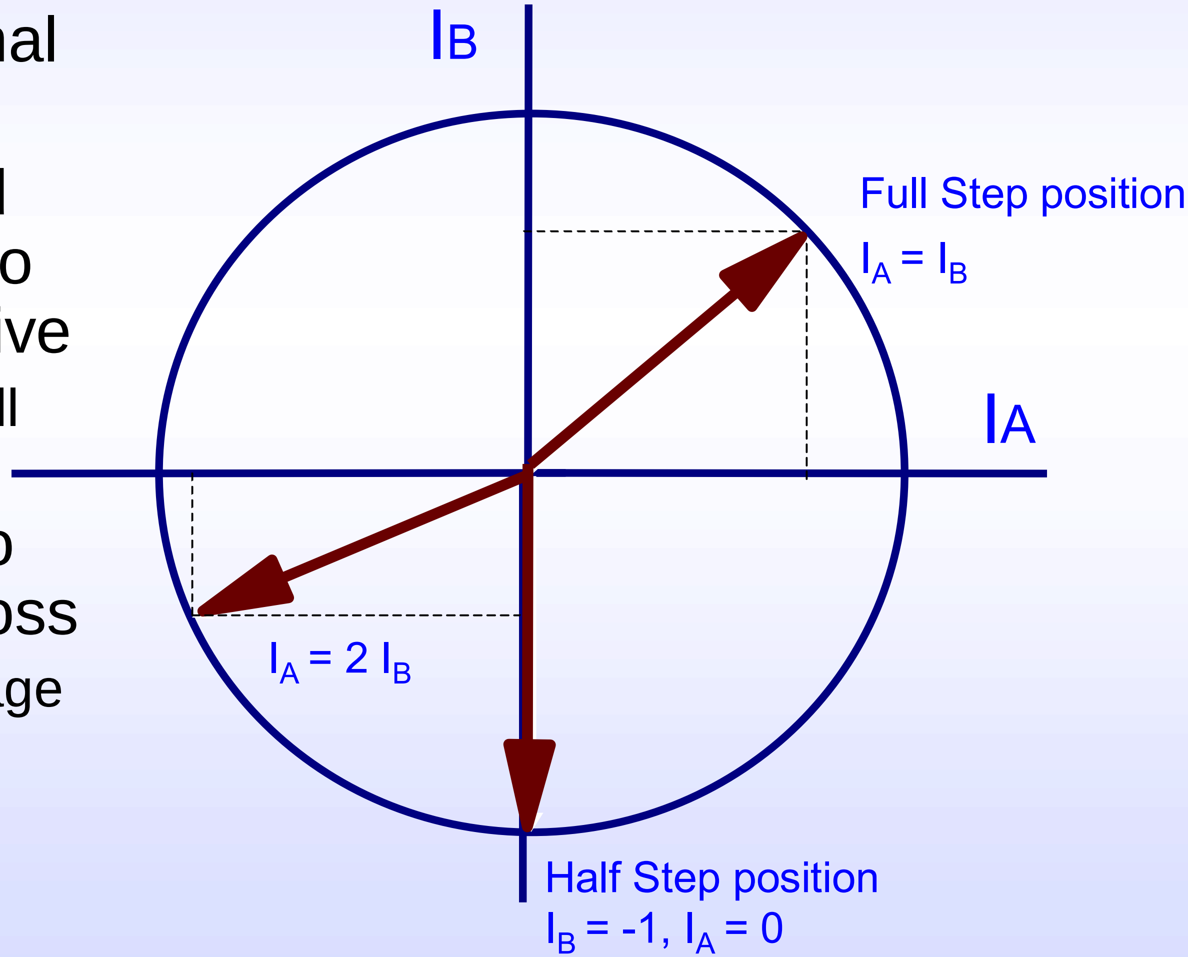
# Back EMF Motor Control




Benjamin Kuipers

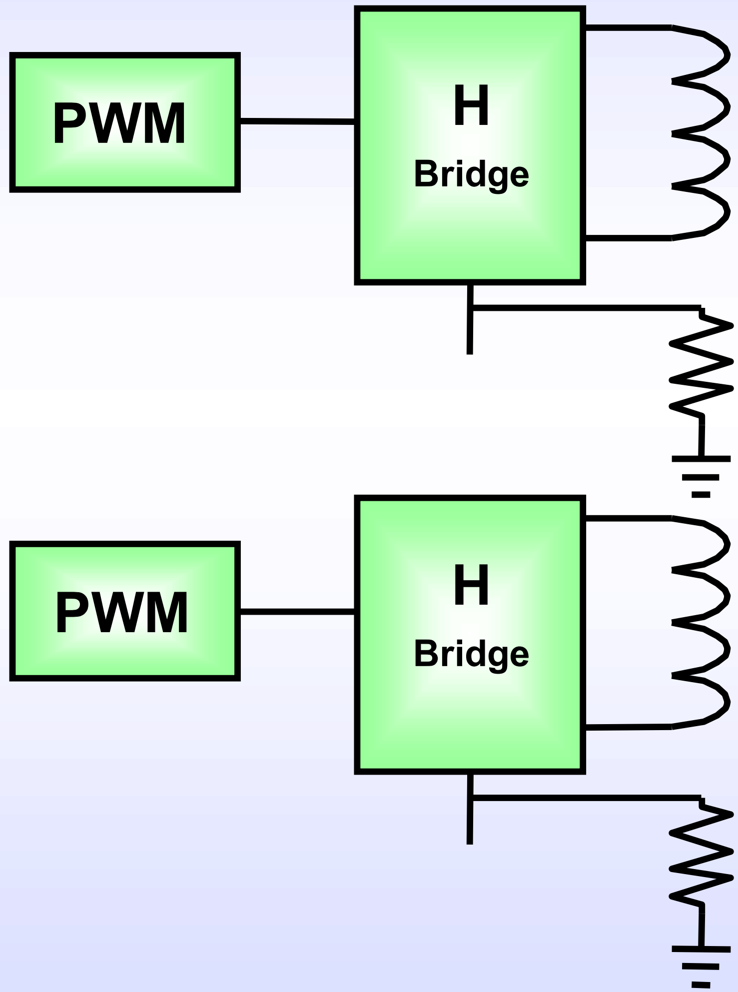
# Microstepping

- Use partial Drive to achieve fractional steps
- Stepper is good approximation to Sine/Cosine Drive
  - 2π cycle is 1 full step!
- Usually PWM to reduce power loss
  - Fractional voltage drop in driver electronics



# Microstepping Block Diagram

- Easy to synthesize the PWM from Microcontroller
  - Lookup table + interpolation
  - $\pi/2$ phase lag = table index offset
- Need to monitor winding current:
  - Winding L,R
  - Motor Back EMF
- PWM Frequency tradeoff
  - Low Freq: resonance (singing)
  - High Freq: Winding Inductance and switching loss



# PWM Issues

- Noise/Fundamental Period
  - Low Freq: Singing of motor and resonance
  - High Freq: Switching Loss
- Can we do better?
  - Not unless we add more transitions! (Switching Loss)
- If we bite bullet and use MOS drives can switch in 2-50nS…
- Then can choose code to optimize quantitization noise vs. switching efficiency
  - Modulated White Noise
  - Sigma-Delta D/A
- Requires higher performance Controller

# Motors and Actuators -- Software

- Embedded motor control is huge, growing application area
  - Need drive(sample) rates high enough to support quiet, efficient operation
  - Rates roughly inversely proportional to motor physical size
  - Stepper Motors are usually micro-stepped to avoid ‘humming’ and step bounce
  - Typical: 1kHz rate, 50kHz micro-step; slow HP motors 300Hz-1kHz
- Upshot- 1 channel “fast” or micro-stepped motor is substantial fraction of 8-bit processor throughput and latency
  - Common to run up to 3 “slow” motors from single uP
  - Common trend to control motor via single, cheap uP
  - Control multiple via commands send to control uPs