Actuators

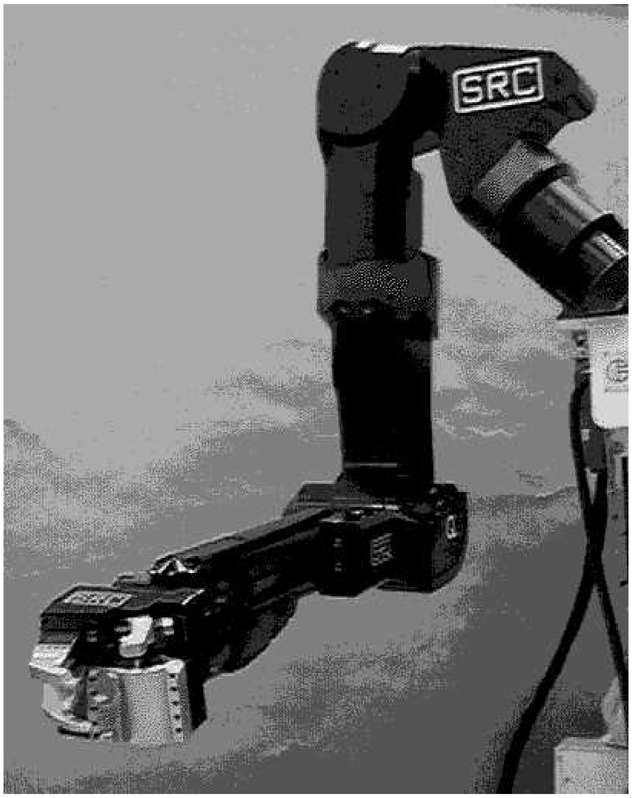
... physical devices that transform electrical, chemical, or thermal energy into mechanical energy...

challenges and opportunities with respect to power density, dynamic range, packaging, and passive properties.

- hydraulic
- pneumatic
- electric motors
  - stepper motors
  - permanent magnet DC motors
- artificial muscles
  - shape memory alloys
  - polymers
  - biological
  - Bucky tubes

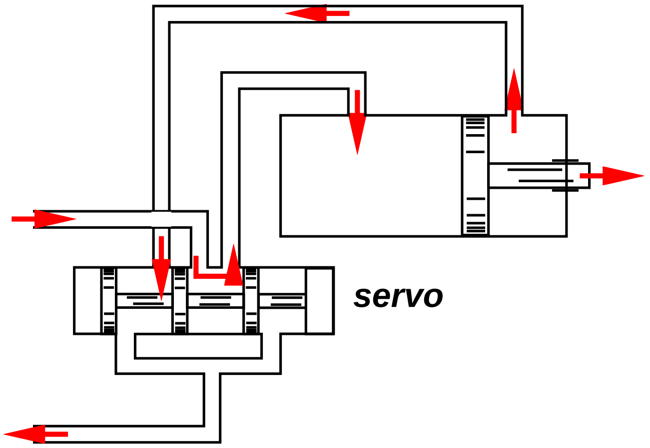
Actuators: Hydraulic

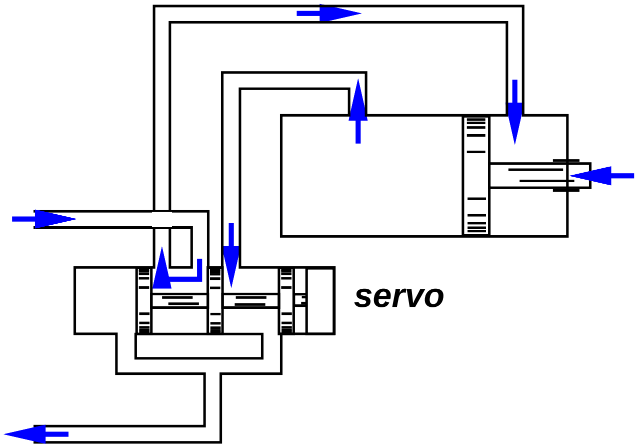
The Sarcos GRLA (General Large Robot Arm)



- 1.75 meters long from shoulder to wrist
- runs hydraulic actuators at up to 3000 psi
- driven by an exoskeletal master worn by a human teleoperator

Actuators: Hydraulic





- energy is stored in the high pressure fluid reservoir (1000-3000 psi)
- open-loop control - fork lifts, back hoes
- good bandwidth (5 KHz - fluid reverses direction 5 msec)

PROS

1. good power/weight
2. safe in explosive environments

CONS

1. expensive servos
2. messy
3. high maintenance

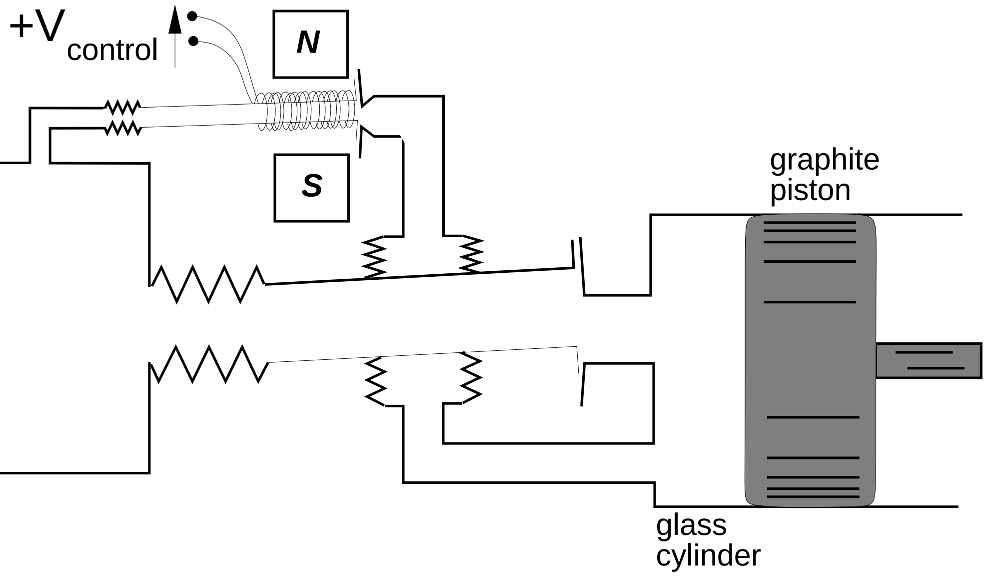
Hydraulics in Nature - Spiders

- spiders cannot extend their legs by activating muscles alone - they generally have no extensor musculature that is adequate
- they use their blood as hydraulic fluid
- blood pressure in spiders are typically very high compared to related animals.
- special valves and muscles that compress their forebodies act as actuators for their legs

Actuators: Pneumatic

(circa 300 BC) - theory of muscular movement - animal spirits, *pneuma*, flow down nerves to fill muscles and cause contraction...

- compressible fluid (air) $60 - 100$ psi
- jet-pipe servo control



PROS

1. light and cheap - pwer to weight approximately 16:1
2. passively backdrivable

CONS

1. stiction
2. delicate

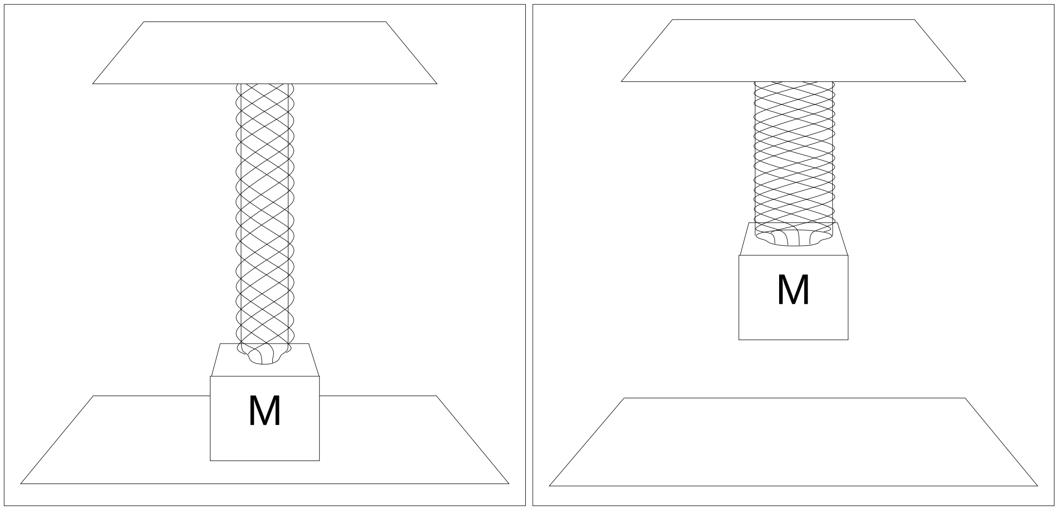
McKibben Air Muscles

PROS

1. preserve strength (proportional to bladder diameter) at the expense of speed, stroke about 40% of free length
2. $0-60$ psi reservoir, power-to-weight approximately 100:1
3. lightweight and passively backdrivable
4. greatest forces when fully elongated
5. very easy to package

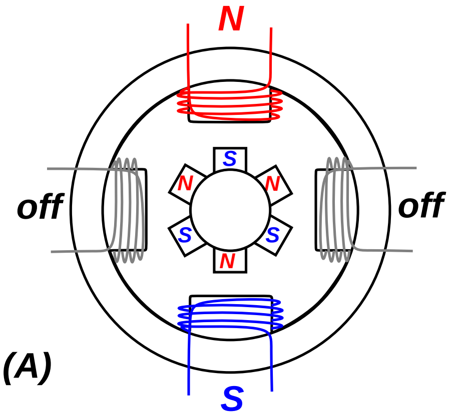
CONS

1. speed/bandwidth

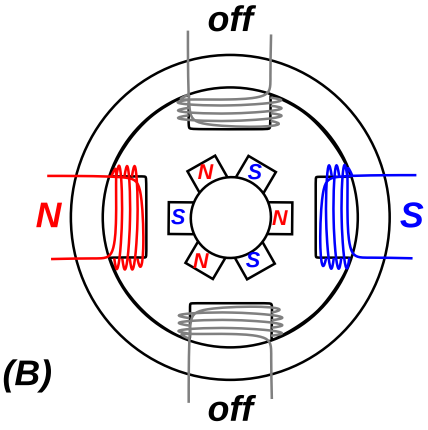


Actuators: Stepper Motors

- precise (low torque), open-loop position control
- *resonance* - typically between 50 and 150 $steps/sec$
- *cogging*



(A)



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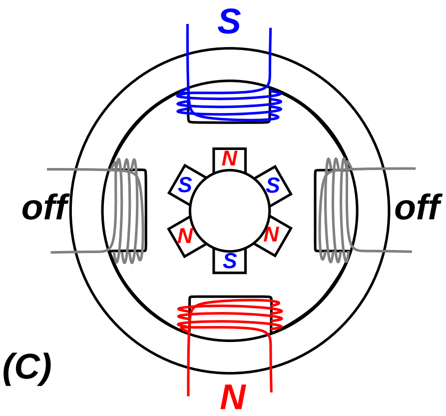

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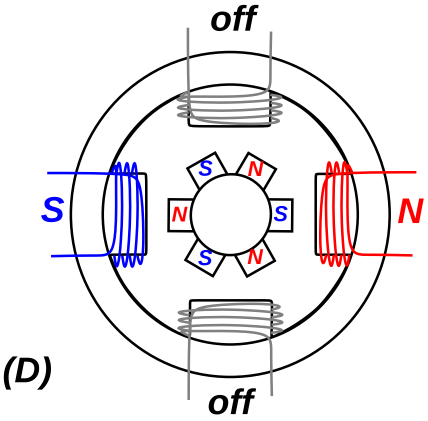


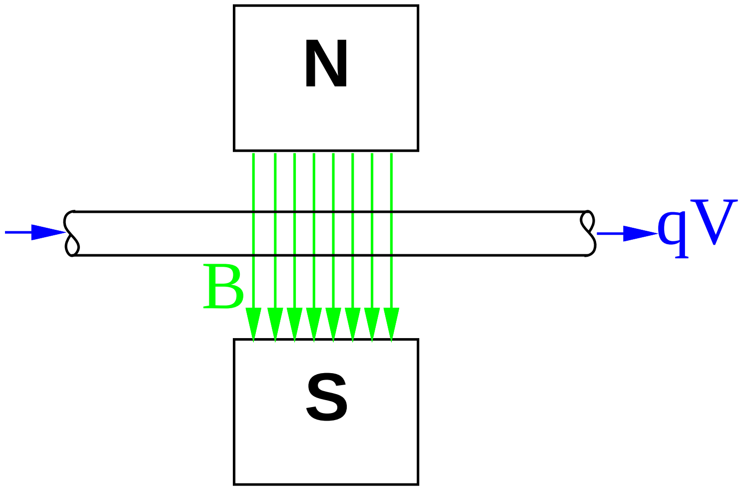
(D)

Actuators: Permanent Magnet DC Motors

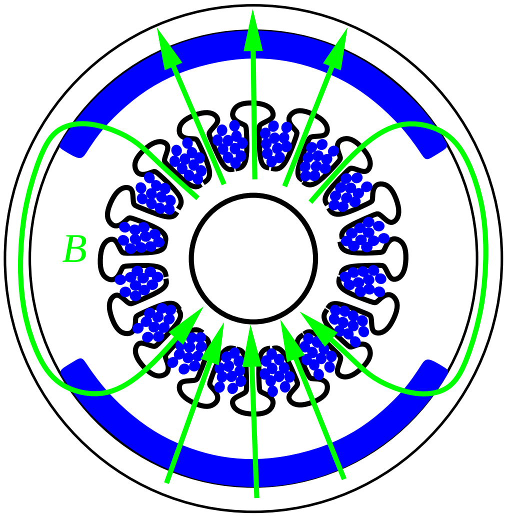
- run continuously in both directions
- closed-loop servo control w/position feedback
- relaible, good power/weight, high torques possible

Lorentz Force

$$F = qV \times B$$

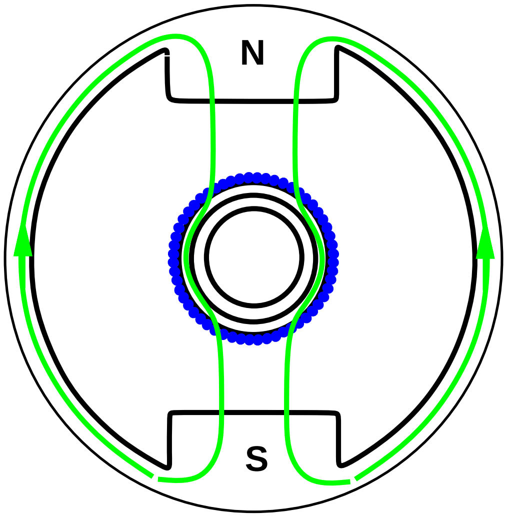


Actuators: Permanent Magnet DC Motors



Iron Core:

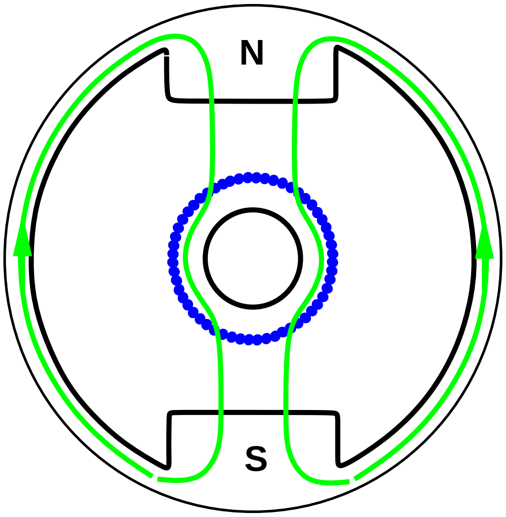
- high inertia, cogging
- very reliable
- cheap



Surface Wound:

- lower inertia
- no cogging
- higher cost
- rare earth magnets

Actuators: Permanent Magnet DC Motors (cont)



Moving Coil:

- coil *is* rotor
- rotor inertia extremely low
- high performance - big torque
- thin (0.02″), large diameter (12″)
- *printed-circuit motors*
- expensive

DC Motors - Electrodynamics

force: Newton $N = kg \cdot m/sec^2$

torque: the product of a force and a moment arm

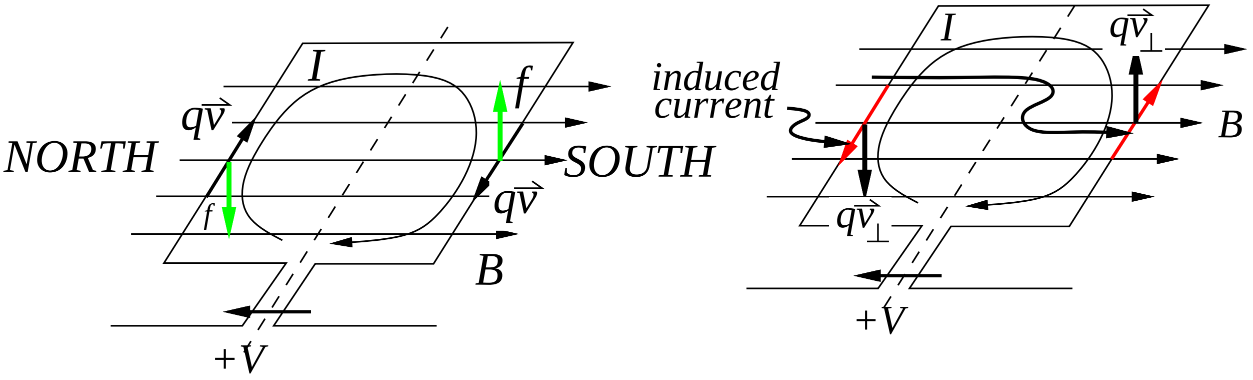
$$N \cdot m = \frac{kg \cdot m^2}{sec^2}$$

power: energy per unit time (Watts)

$$\begin{aligned} P &= VI(\text{electrical}) \\ &= \tau\omega(\text{mechanical}) \end{aligned}$$

$$Watt = \frac{volt \cdot coulomb}{sec} = \frac{Nm}{sec}$$

DC Motors - Electrodynamics



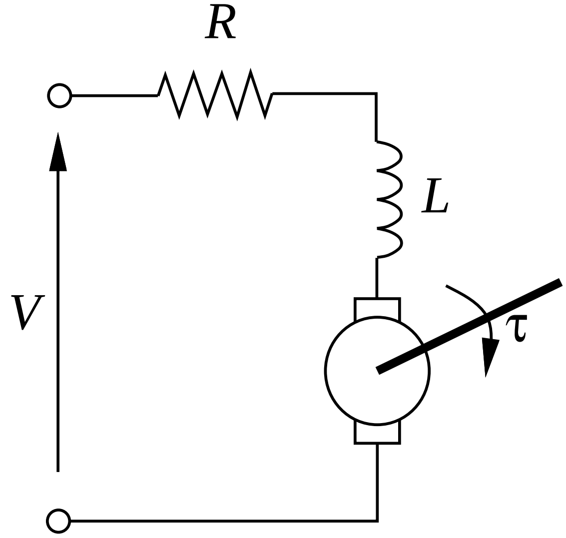
The Lorentz Force

Induced Backward Electromotive Force (Back EMF)

- K_t proportional to the number of loops
- commutation - the rotor runs out of torque when the current loop is perpendicular to B, reversing the current can continue to provide torque in the same direction.
- for a commutated motor, the rotor current alternates with frequency proportional to ω

$$\text{back emf} = L\frac{dI}{dt} = K_b\omega$$

Actuators: DC Motors Electrodynamics



$\tau = K_t I$ *motor torque*

$V_b = L\frac{dI}{dt} = K_b\dot{\theta}$ *back emf*

$$V = IR + K_b\dot{\theta}$$

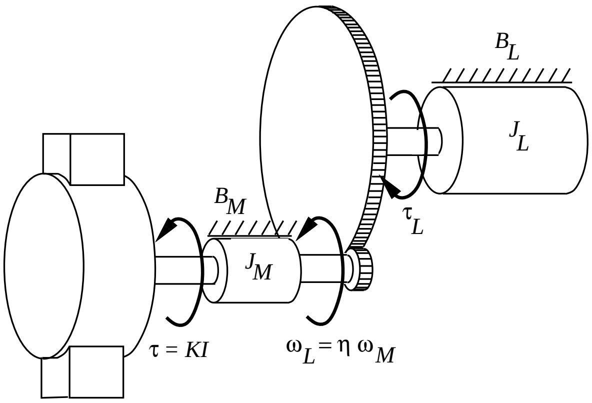
$$\begin{array}{ccccc}
\textit{mechanical} & & \textit{electrical} & & \\
\textit{power} & = & \textit{power} & - & \textit{losses} \\
\textit{out} & & \textit{in} & & \\
 & & & & \\
\tau\dot{\theta} & = & VI & - & I^2R \\
 & & & & \\
(K_t I)\dot{\theta} & = & (IR + K_b\dot{\theta})I & - & I^2R \\
 & = & K_b I\dot{\theta} & & \\
 & & & & \\
K_t & = & K_b & &
\end{array}$$

Actuators: DC Motors Electrodynamics (cont.)

$$\sum \tau = J\ddot{\theta} = KI = K\left[\frac{V}{R} - \frac{K\dot{\theta}}{R}\right]$$

$$\ddot{\theta} + \frac{K^2}{JR}\dot{\theta} + \frac{KV}{JR} = 0$$

Actuators: DC Motors/Gearhead Combinations



if the transmission is perfectly efficient:

$$
\begin{aligned}
\tau_{out}\omega_{out} &= \tau_{in}\omega_{in} \\
\tau_{out}(\eta\omega_{in}) &= \tau_{in}\omega_{in} \\
\tau_{out} &= (1/\eta)\tau_{in}
\end{aligned}
$$

if $\eta = 0.01$, the output shaft carries one hundred times the torque at one hundredth the velocity of the input shaft

Actuators: DC Motors/Gearhead Combinations — Compound Loads

dynamic equation of motion - equate the torque derived from Lorentz forces with the torques required to accelerate the load and to overcome viscous friction.

$$\tau = \left[J_M \ddot{\theta}_M + B_M \dot{\theta}_M \right] + \eta \left[J_L \ddot{\theta}_L + B_L \dot{\theta}_L \right]$$

but:

$$\begin{aligned} \theta_L &= \eta \theta_M, \\ \dot{\theta}_L &= \eta \dot{\theta}_M, \; and \\ \ddot{\theta}_L &= \eta \ddot{\theta}_M \end{aligned}$$

so:

$$\tau = \left[J_M + \eta^2 J_L \right] \ddot{\theta}_M + \left[B_M + \eta^2 B_L \right] \dot{\theta}_M$$

and:

$$\begin{aligned} J_{eff} &= J_M + \eta^2 J_L \\ B_{eff} &= B_M + \eta^2 B_L \end{aligned}$$

Artificial Muscles

- shape memory alloys have been used to steer endoscopes during minimally invasive surgery
- assist weakened scleral muscles and to help focus images in the eye
- time released medications are delivered from implantable capsules that dispenses drugs though microscopic *sphincters*
- considered for use as assistive devices for weakened or diseased heart muscles - a blanket of contracting artificial muscle could be wrapped around the heart ...

Issues

mechanical properties: elastic modulus, tensile strength, stress-strain relations, fatigue life, and thermal and electrical conductivity.

thermodynamic issues: efficiency, power and force densities, and power limits.

packaging: power supply and delivery, device construction, manufacturing, power transmission, dynamic modelling, control, and integration.

Shape Memory Alloys

...Nickel Titanium - Nitinol

when heated, crystalographic phase transformation from Martensite to Austenite results in strain in the new crystal structure that distorts the material into a preset shape.

1. Flexinol©- small diameter shape memory alloy actuator wires.
2. contract by 5-7% of their length when heated - opposite to the ordinary thermal expansion and one hundred times larger
3. exert comparatively high forces and are well suited to applications like endoscopes and *stents* that are inserted and positioned in one shape and then left behind in another.
4. can take a lot of current to heat electrically and contracts rather quickly although its cycle (heating-cooling-heating) time is quite slow (on the order of 1 Hz).

New Technologies - Not Ready for Prime Time

1. chemical polymers
    (a) gels - *intermediate between liquid and solid, consisting of a polymer lattice with an interstitial fluid*

    Jello - vitreous humor

    (b) abrupt volume changes up to 1000 fold in response to temperature, pH, and electric fields.
    (c) forces up to 100 N/cm^2 and contraction rates on the order of a second - approximately equal to human muscle
    (d) dynamics limited by the diffusion of molecules in the fluid through the polymer lattice
    25 um fibers → 1 second, 1 cm fibers → 2.5 days
    (e) challenge - actuator packages that bathe the gel in succession of chemical solutions (acid and base)
2. electroactive polymers
    (a) store electrons inside the large molecules, changing length of chemical bonds - used as batteries/capacitors
    (b) lot of voltage implies lot of EM noise issues
    (c) deform proportional the square of voltage - 10% of original length
    (d) dielectric constant - 1000 in new, elastic polymers (batteries 5).
3. polymer gel with electrorheological fluid (ERF)

   (a) stiffens and flexes within 100 msec in strong electric field (3000 V/cm) → noise
   (b) strength limited (0.001 N)
4. biological muscle proteins
   (a) "real" artificial muscle - actin and myosin extracted from shellfish, used to produce gels
   (b) immersed in ATP solution contraction rates of 0.001 mm/sec
   (c) implantable assistive technology for human muscle?
5. Fullerenes ("Bucky Balls") and nanotubes ("Bucky Tubes")
   (a) graphitic carbon - nanotubes the diameter of typical molecules, up to millimeters in length, very strong
   (b) increase length when electrons are pushed into the carbon structure.
   (c) relatively large length change, high elastic modulus → *very* large forces
   (d) polarizing ($\pm 1V$) a sandwiche can control flexion
   (e) macro-, micro-, and nano-scale actuators
   (f) extremely robust to thermal and chemical conditions
   (g) potentially achieve a greater mechanical stress than any other technology - *much more than muscle tissue*.