On the Energy Transfer Performance of Mechanical Nanoresonators Coupled with Electromagnetic Fields:

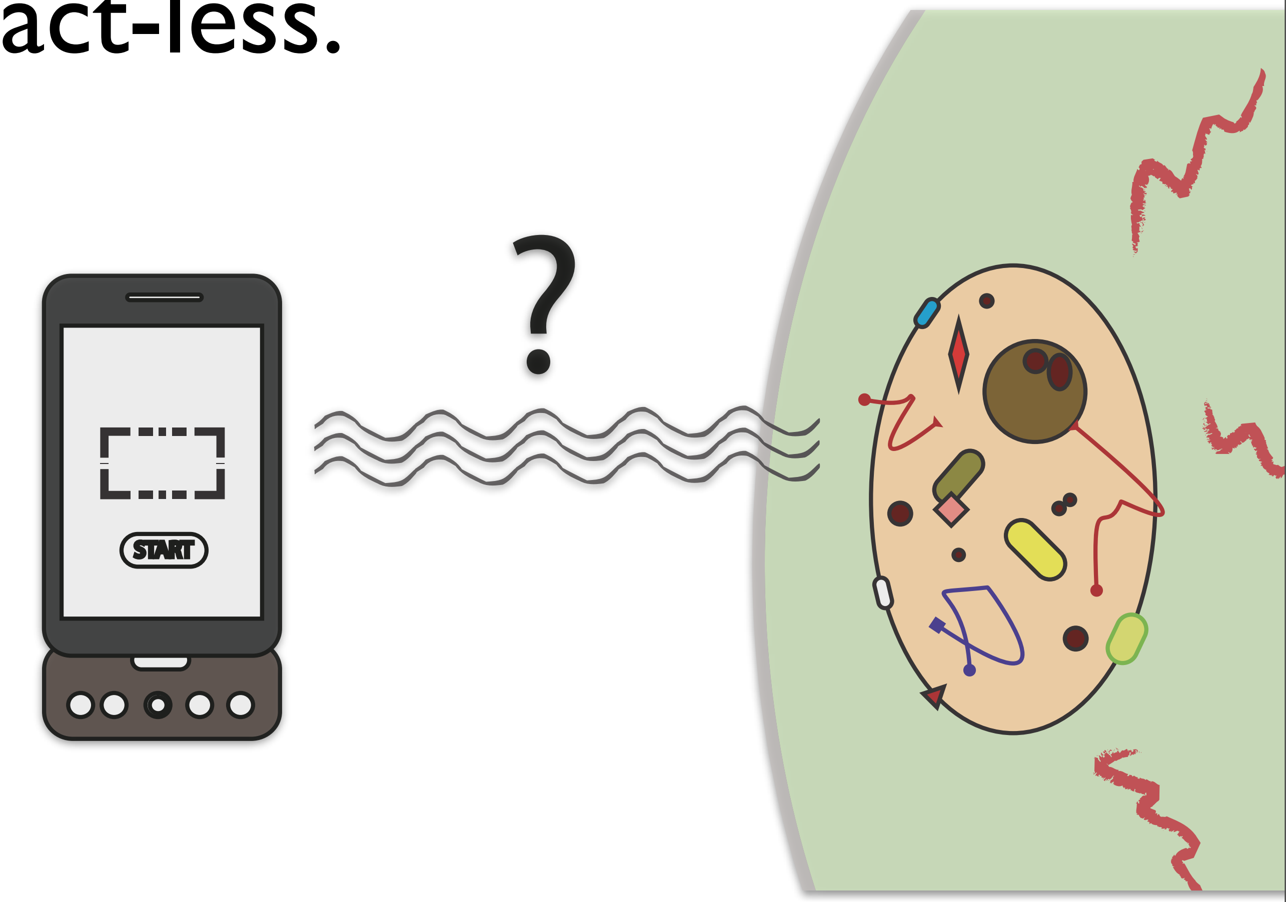
Applications with Magnetic Nanoparticles

Hooman Javaheri
Bernardo Barbiellini
Guevara Noubir

College of Computer and Information Science
Physics Department
Northeastern University

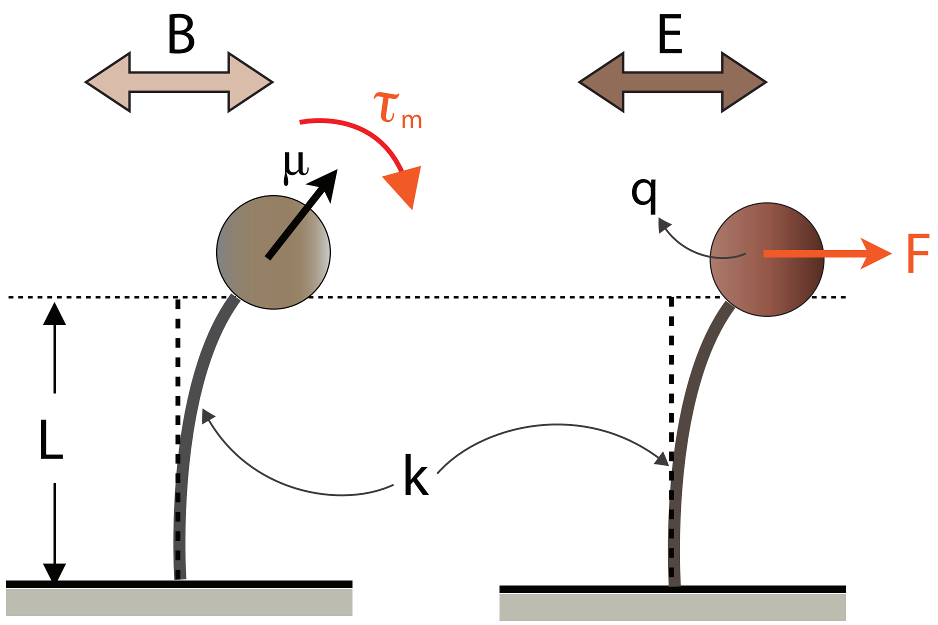
Wireless Delivery of Energy at Nano scale

- Wireless? Hmm.. Contact-less.
- Applications
  - Remote targeted biological actuation
  - Nanomedicine
  - Nanorobotics
  - Building block for nanoscale communication systems (Networks)
    - *Biologically-Enabled* wireless networks



- **We are looking for an efficient "Energy Channel" to send a message (meaningful and timely bundles of energy) to a nanodevice.**
  - No physical contact
  - *Localized* and *Selective* interaction
- **Electromagnetic coupling**
  - Static vs. High Frequency?
  - Magnetic vs. Electric?
- **EM coupled Mechanical Nanoresonators** to transduce EM energy via mechanical vibrations.
- **Resonance!**

- **We consider a *“purely classical”* model for electromagnetic coupling of mechanical nanoresonators.**



- We are interested in quantitative assessment of the energy transfer *at resonance*.
- We compare the performance of magnetic coupling with electric coupling.

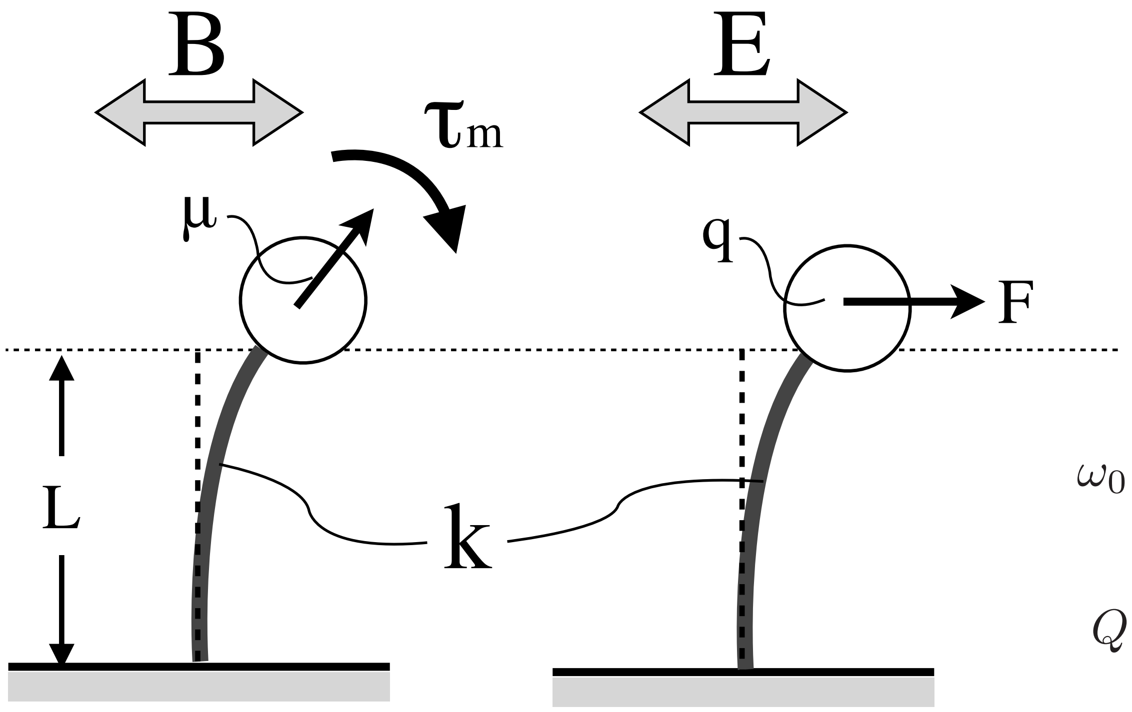
Methodology

- **Resonant scattering theory** (Coupled-mode theory)
  - ***Fluxes*** instead of ***Forces***.
- We consider the biological safe temperatures (RT)
- We assume that low viscosity conditions is synthetically achievable in the engineered system.

Mechanical Model

Cantilever Beam

Specialized Tip (Coupling)



$$\omega_0 = \sqrt{\frac{k}{m_f}}$$

$$Q = \frac{\sqrt{k m_f}}{D}.$$

Resonant Energy Transfer

Scattering Theory

Cross Section

Energy Deposit

$$\sigma_a(\omega) = 12\pi(\frac{c}{\omega})^2 \frac{\Gamma_a \Gamma_s}{(\omega - \omega_r)^2 + (\Gamma_a + \Gamma_s)^2/4}.$$

$$\Delta U(\omega) = P_a(\omega) \times \tau_a = \frac{\Phi \sigma_a(\omega)}{\Gamma}$$

$$\Delta U_r = \frac{48\Phi c^2}{\omega_r^2} \left(\frac{\Gamma_s}{\Gamma_a^2} \right) = \frac{48\Phi c^2}{\omega_r^4} \Gamma_s Q_a^2.$$

Electric Coupling

$$P_r^{\mathfrak{E}} = \frac{1}{4\pi\epsilon_0}\frac{p_0^2\omega^4}{3c^3}$$

$$U^{\mathfrak{E}} = \frac{1}{2}kx_m^2,$$

$$\Gamma_s^{\mathfrak{E}} = \frac{q^2}{4\pi\epsilon_0}\frac{2\omega^4}{3c^3k}.$$

$$\Delta U_r^{\mathfrak{E}} = \frac{q^2}{4\pi\epsilon_0}\boxed{\frac{32\Phi Q_a{}^2}{ck}}.$$

Magnetic Coupling

$$P_r^{\mathfrak{M}} = \frac{1}{4\pi\epsilon_0}\frac{\mu^2\omega^4\theta_m^2}{3c^5}$$

$$U^{\mathfrak{M}} = \frac{1}{2}\kappa\theta_m^2 = \frac{1}{2}kL^2\theta_m^2,$$

$$\Gamma_s^{\mathfrak{M}} = \frac{\mu^2}{4\pi\epsilon_0}\frac{2\omega^4}{3c^3k(Lc)^2}$$

$$\Delta U_r^{\mathfrak{M}} = \frac{\mu^2}{4\pi\epsilon_0}\left[\frac{1}{Lc}\right]^2\boxed{\frac{32\Phi Q_a^2}{ck}}.$$

does not depend on the coupling

$$\mu/Lc \approx q.$$

to achieve the same performance

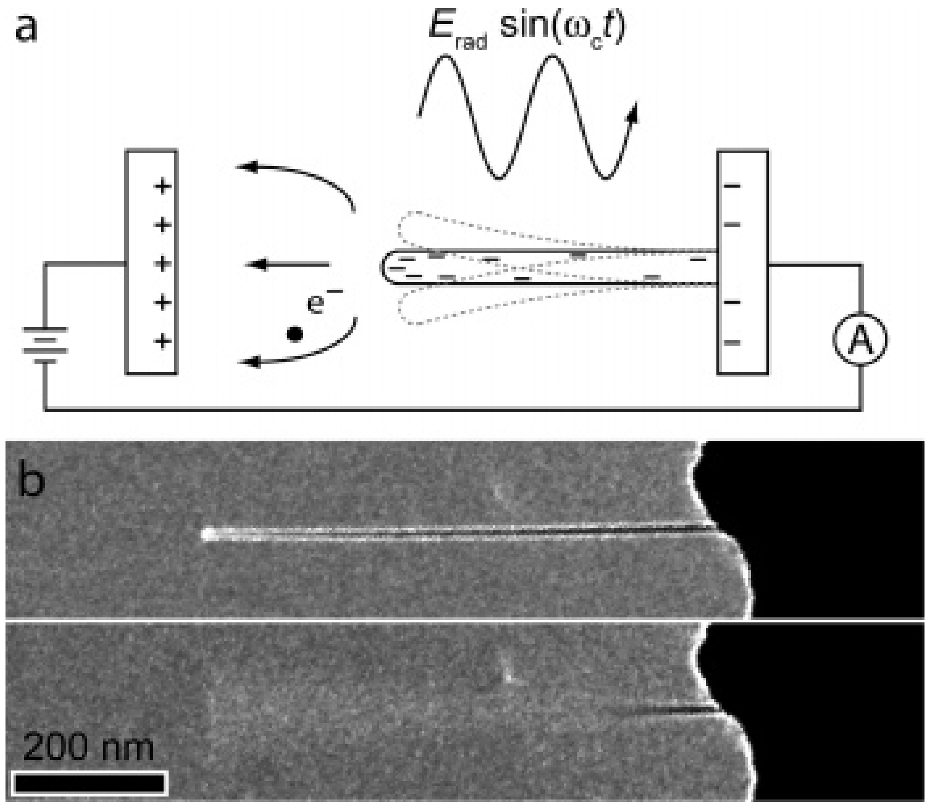
- We performed our analysis on few nanoresonators that are already demonstrated in the literature:

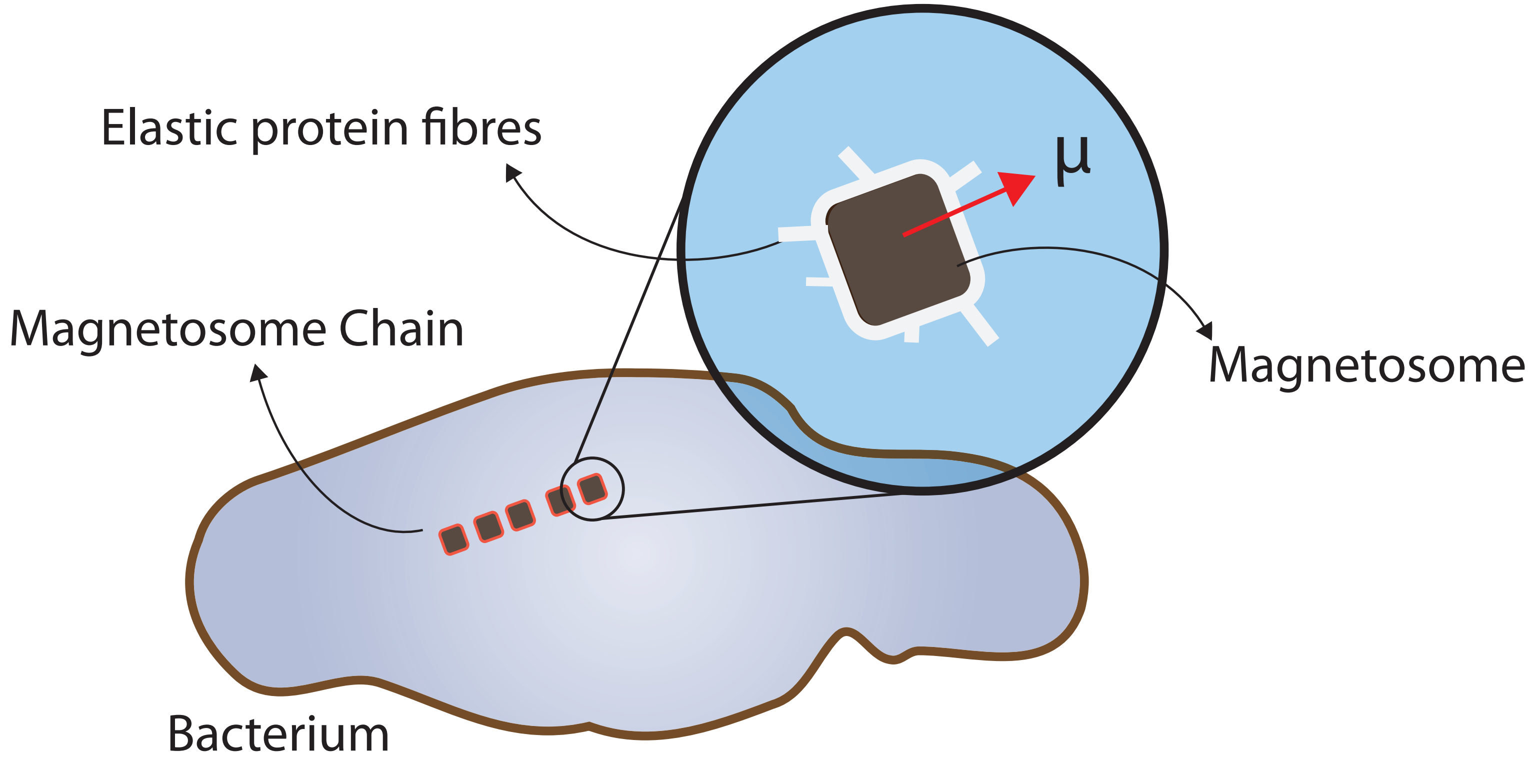
- Example: ***Nanotube Radio***

  K. Jensen, J. Weldon, H. Garcia, and A. Zettl, UC berkeley, 2007

- NR uses *electric* coupling

- We show that the same energy transfer performance is reached by replacing the electric dipole of the original nanotube prototype with a spherical Magnetite Nanoparticle of radius 160 nm.





- Natural Example: *Magnetosomes*

- We show that a significant amount of energy (~10^4 kT) can be deposited on magnetically coupled magnetosomes at resonance.

  This requires a synthetic encapsulation of the magnetic particle to reduce the viscosity.

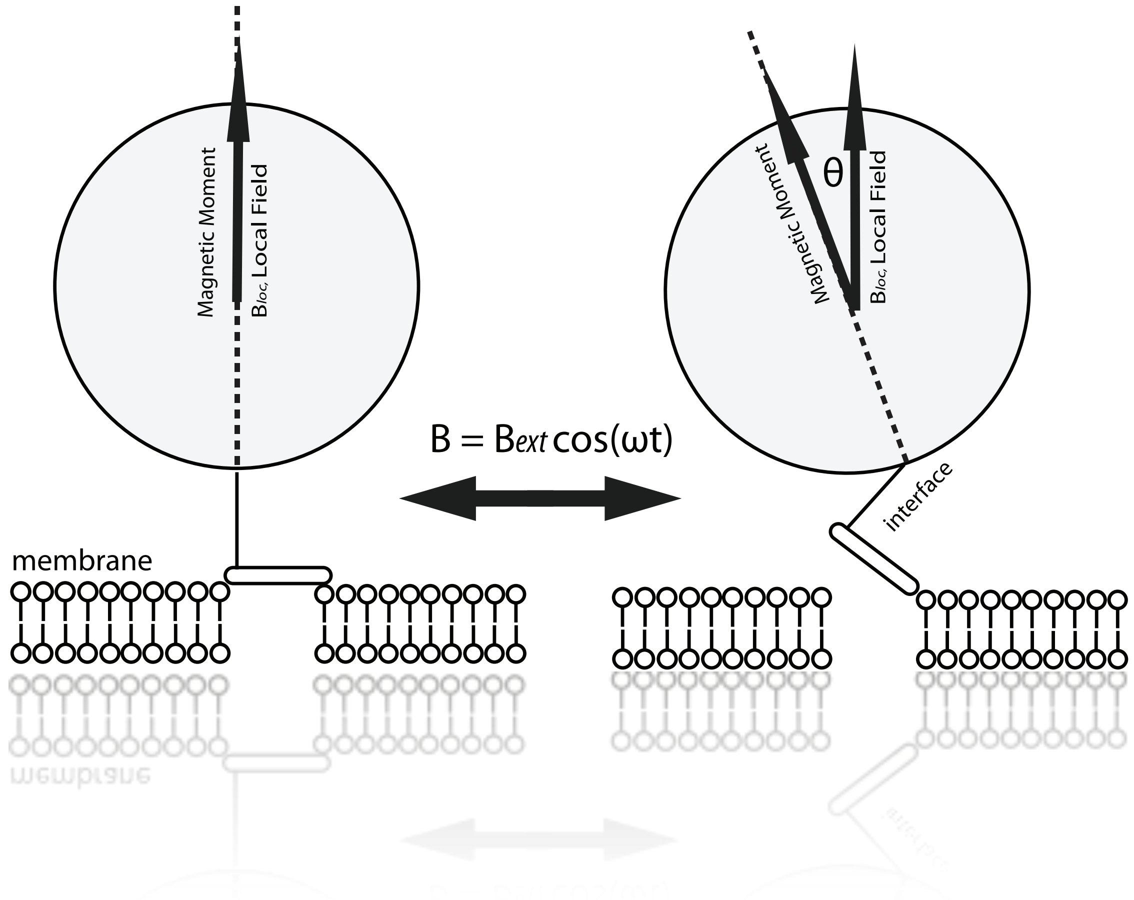
Ongoing and Future Work

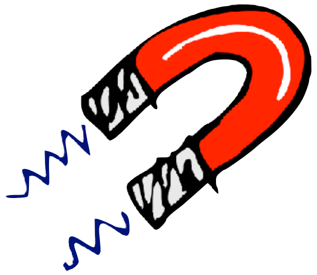
- Non-linear models
- Verification of the results by numerical methods such as Finite-element simulations
- Explore realistic mechanisms to demodulate the information from incoming energy bundles (messages).
- Manufacturing of a nano-receiver

Summary

- magnetically coupled mechanical nanoresonators are promising tools to deliver energy at nanoscale.
- The energy transfer performance of magnetically coupled systems is as good as their electrically coupled counterparts, if not better, within the scale of interest.
- Several applications exist in cellular biology (remote control and actuation), nanomedicine, nanorobotics.

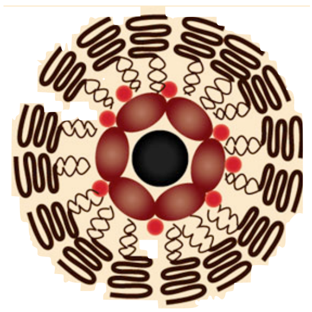
An example of existing models for Biological Actuations





Magnetic field

+



Magnetic Particle
(micro ~ nano)

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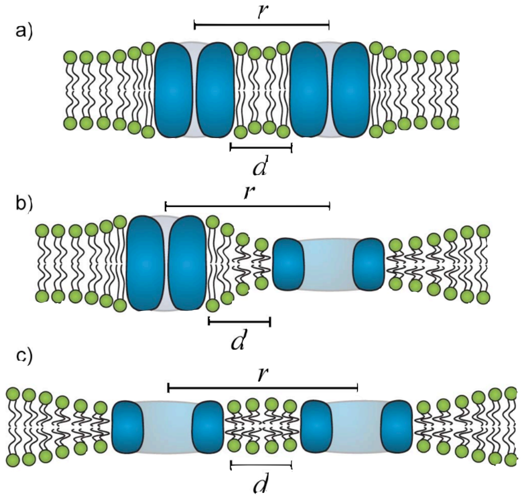

Mechanosensitive
ion channel