Welcome to

6.007 – Applied Electromagnetics
From Motors to Lasers

What is inside an iPhone ?

iPhone Technical Specifications

Operating System: OS X

Memory: 4gb or 8gb versions available

Processor: 32-bit, 620 MHz core

Muliti-Touch Display:
3.5 inch 480 x 320-pixel HVGA resolution,160 dpi

Wireless: Quad-band (850,900,1800,1900 MHz), WiFi (802.11b/g), EDGE, Bluetooth 2.0+EDR

Digital Camera:
2.0 mega pixels with 1200x1600 resolution

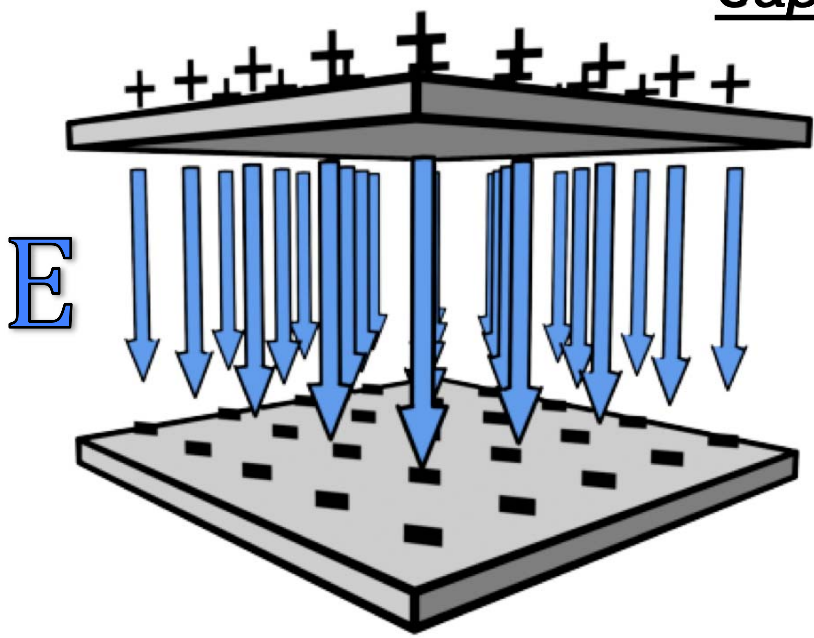
Battery: 1400 mAh, 3.7 V
Rechargeable lithium-ion,
Talk time: up to 8 hours,
Standby time: up to 250 hours,
Internet use: up to 6 hours,
Video playback: up to 7 hours,
Audio playback: up to 24 hours

Size: 4.5 x 2.4 x 0.46 in (115 x 61 x 11.6 mm)

Weight: 4.8 ounces (135 grams)

For more views of iPhone under the hood see
http://www.eetimes.eu/200001828
http://www.eetimes.eu/200001864

Capacitors



$+\sigma$

$q = Cv$

$-\sigma$

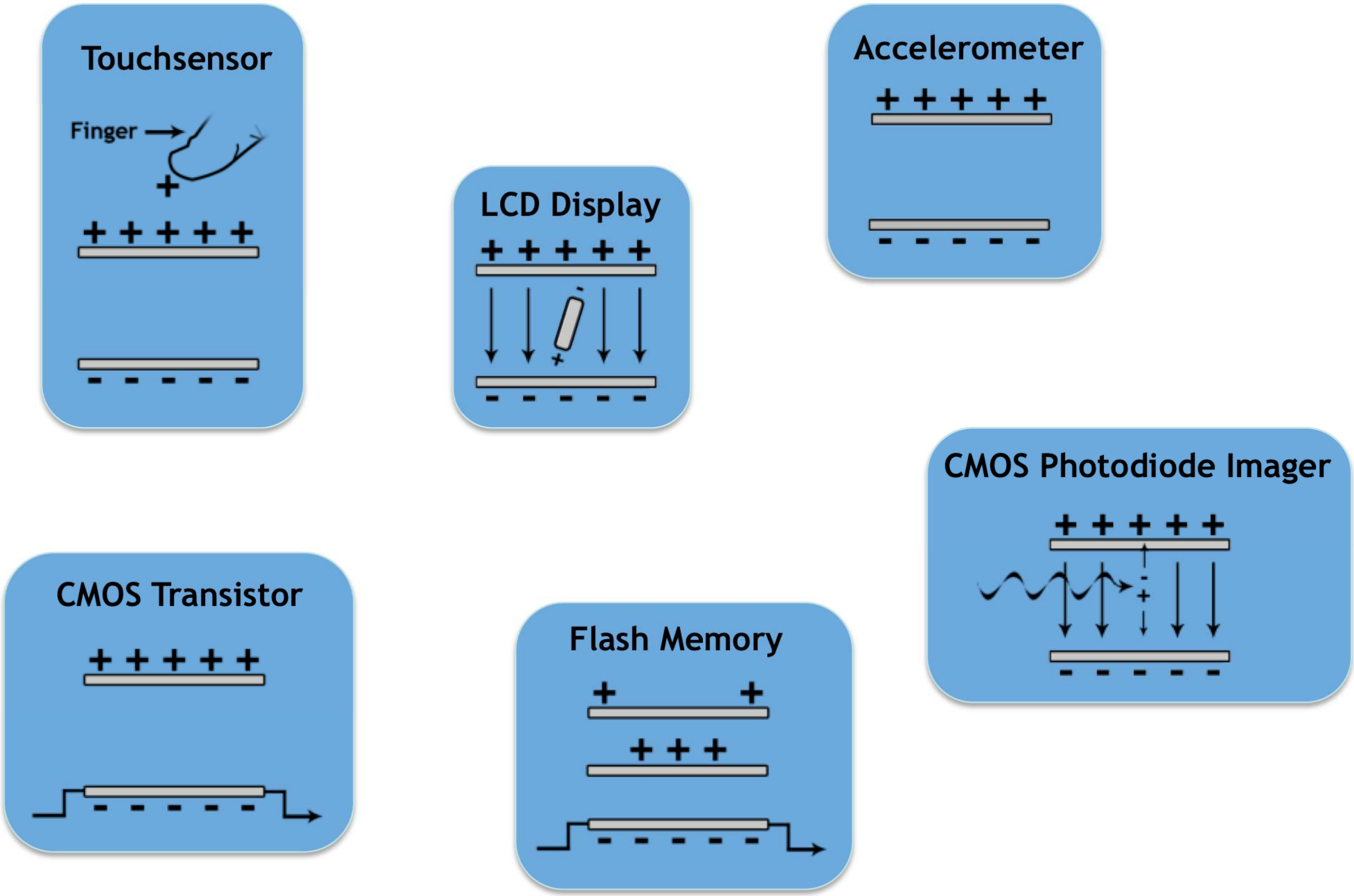
$$C = \epsilon_o \epsilon_r \frac{A}{d}$$

Maxwell's Equations

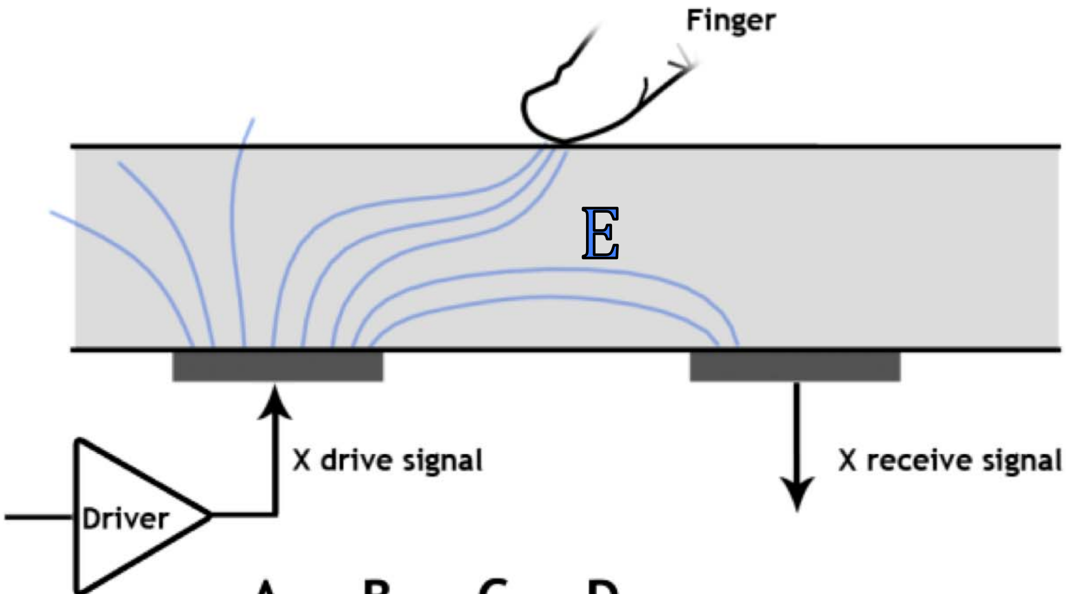
$$\oint_S \epsilon_o \overline{E} \cdot d\overline{A} = \int_V \rho dV \qquad \oint_S \overline{B} \cdot d\overline{A} = 0$$

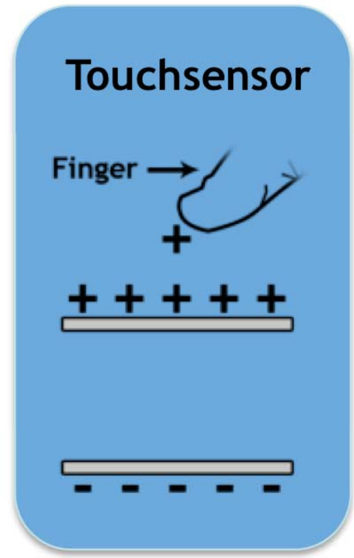
$$\oint_C \overline{E} \cdot d\bar{l} = -\frac{d}{dt}\left(\int_S \overline{B} \cdot d\overline{A}\right) \qquad \oint_C \overline{H} \cdot d\bar{l} = \int_S \overline{J} \cdot d\overline{A} + \frac{d}{dt}\int_S \epsilon E dA$$

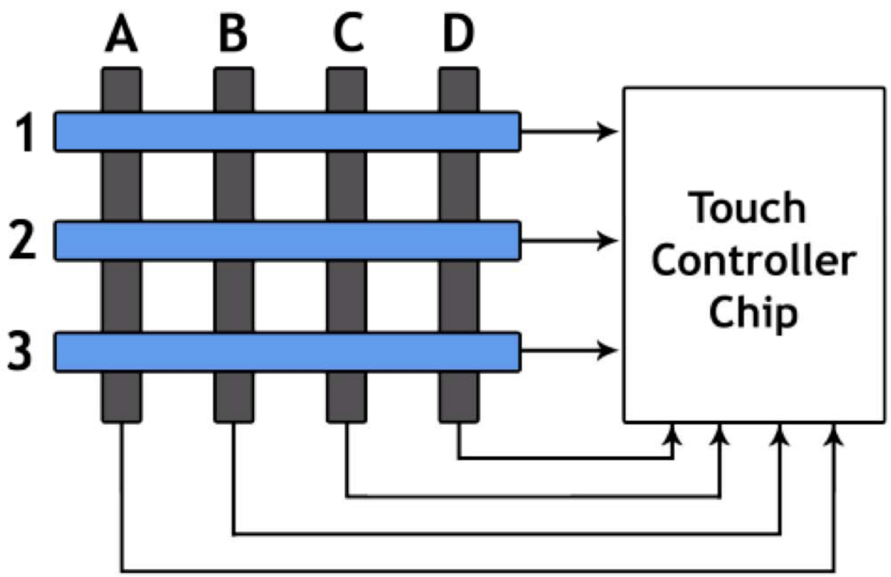
Capacitors in the iPhone



iPhone Capacitive Touch Sensor



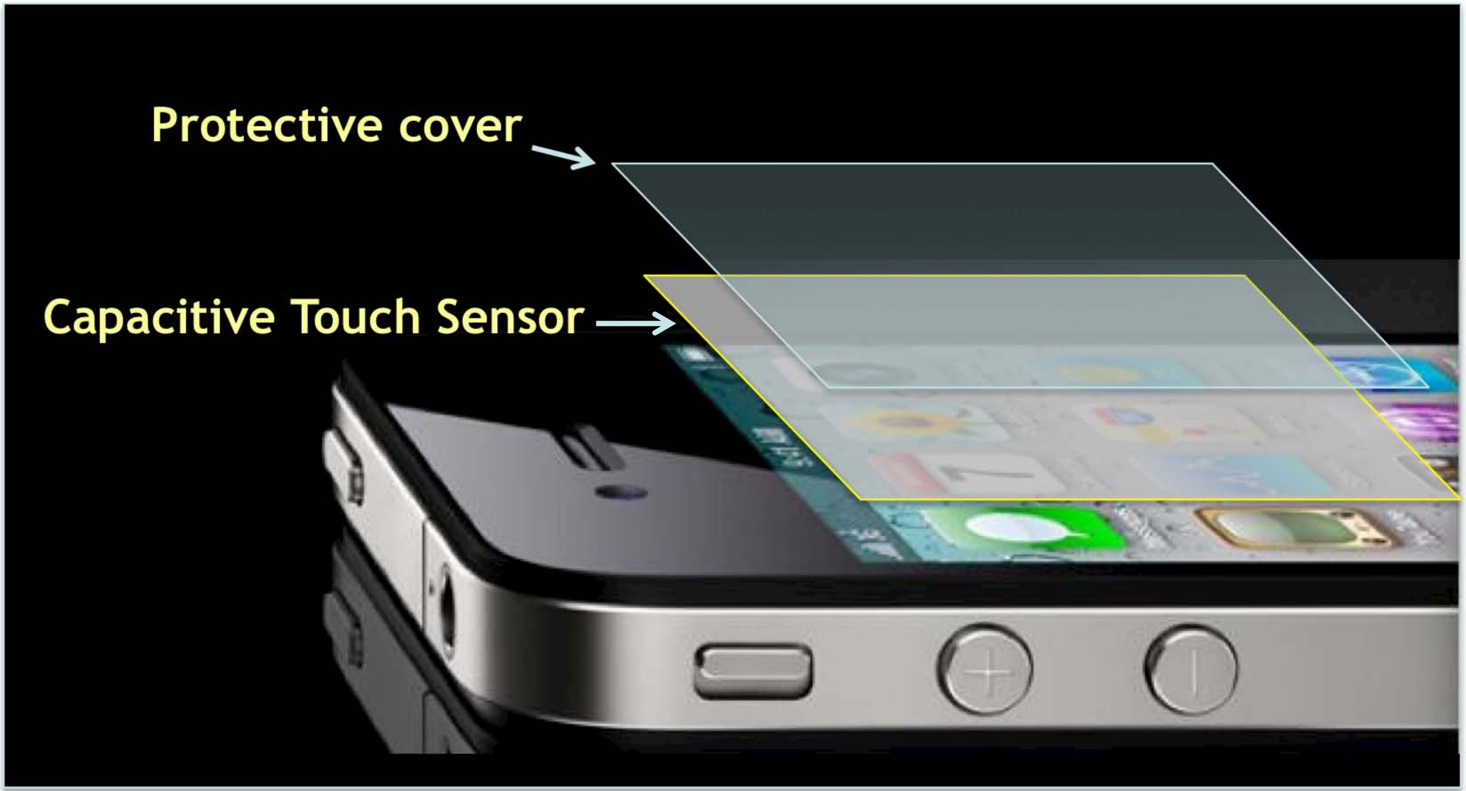




$$q = Cv$$

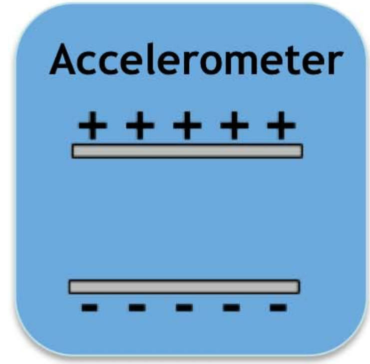
$$C = \epsilon_o \epsilon_r \frac{A}{d}$$

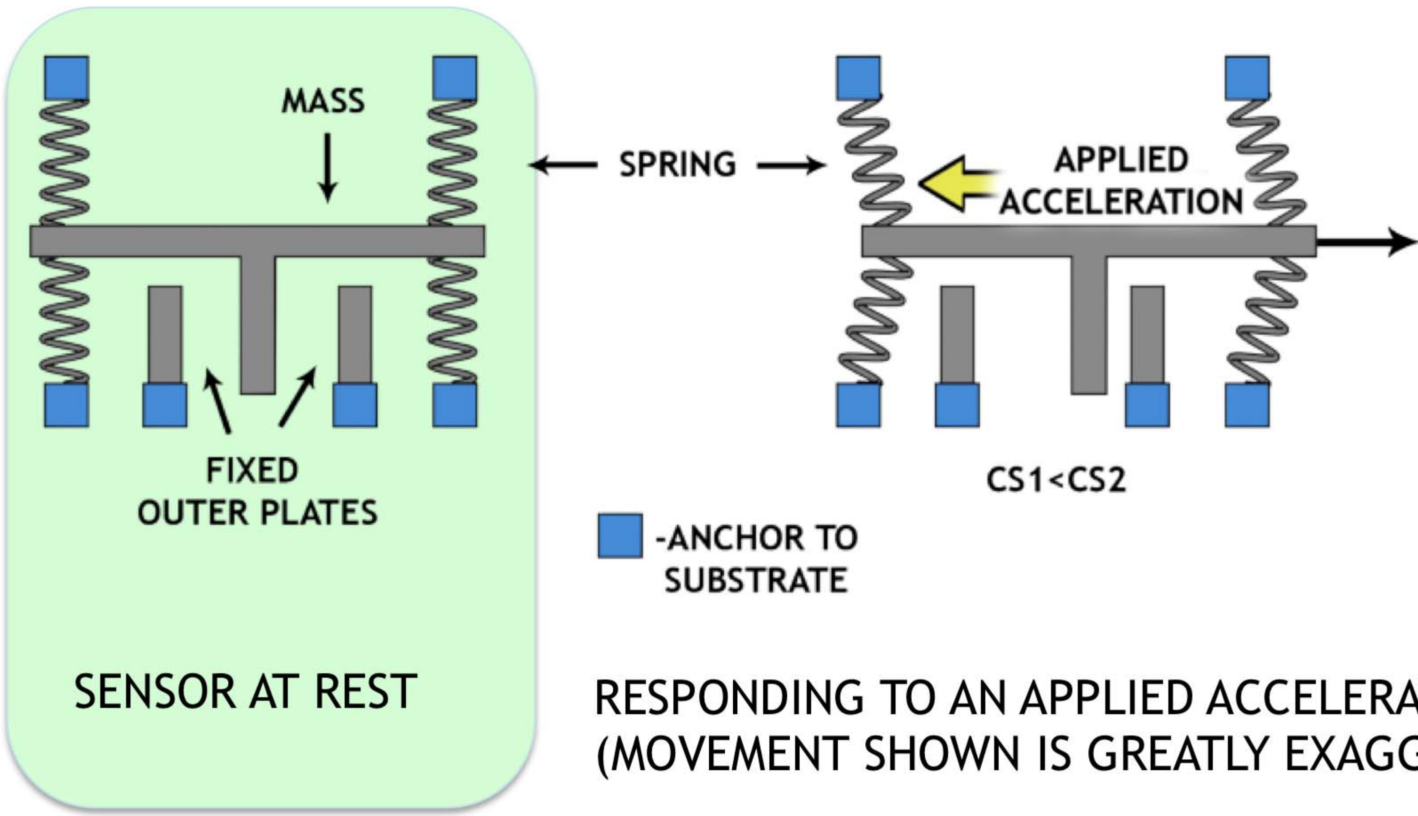
Liquid Crystal Display (LCD) and Touch Panel



Iphone image by Sean MacEntee
http://www.flickr.com/photos/smemon/4679667189/sizes/l/in/photostream/ on flickr

Accelerometers

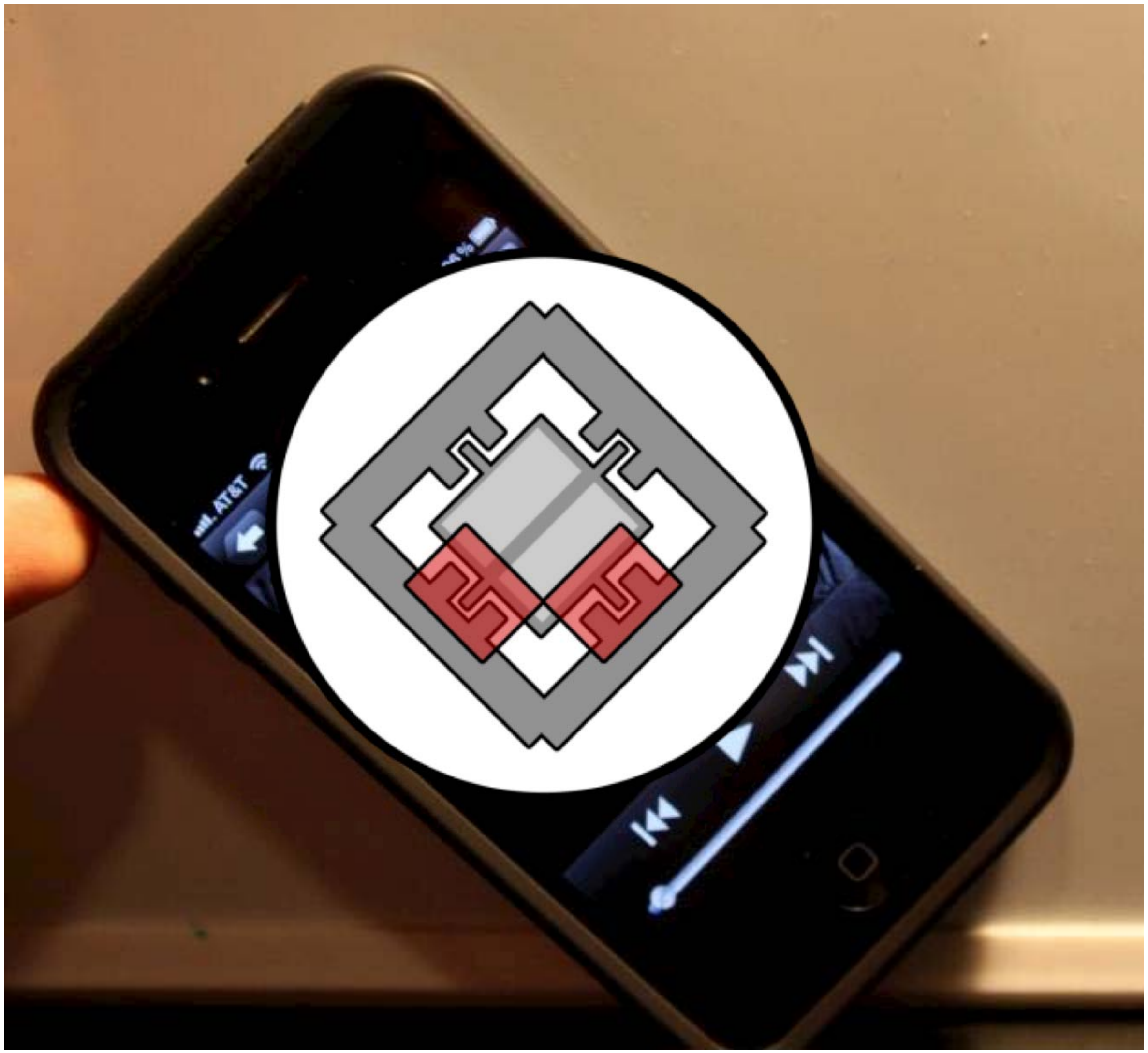


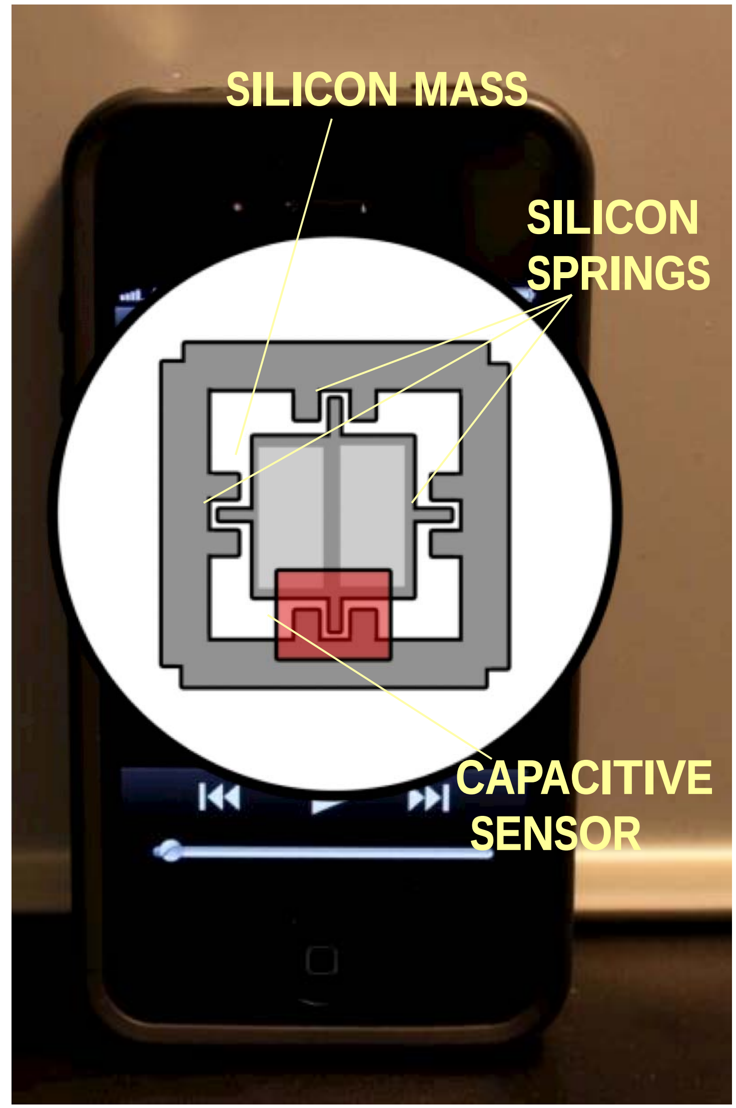


RESPONDING TO AN APPLIED ACCELERATION
(MOVEMENT SHOWN IS GREATLY EXAGGERATED)

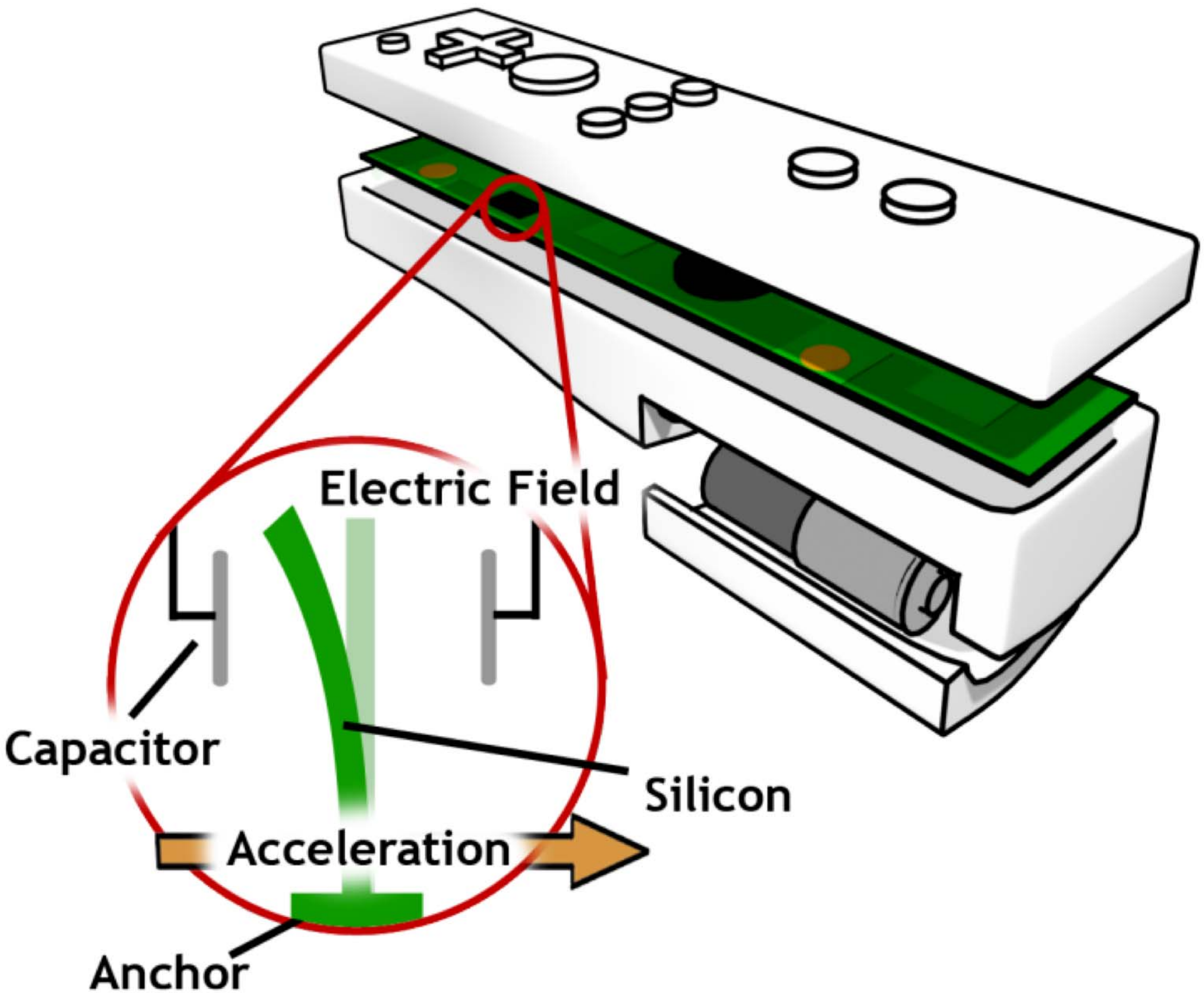
Accelerometer

... detects when you rotate the iPhone from Portrait to Landscape,
and automatically rotates the content of the display

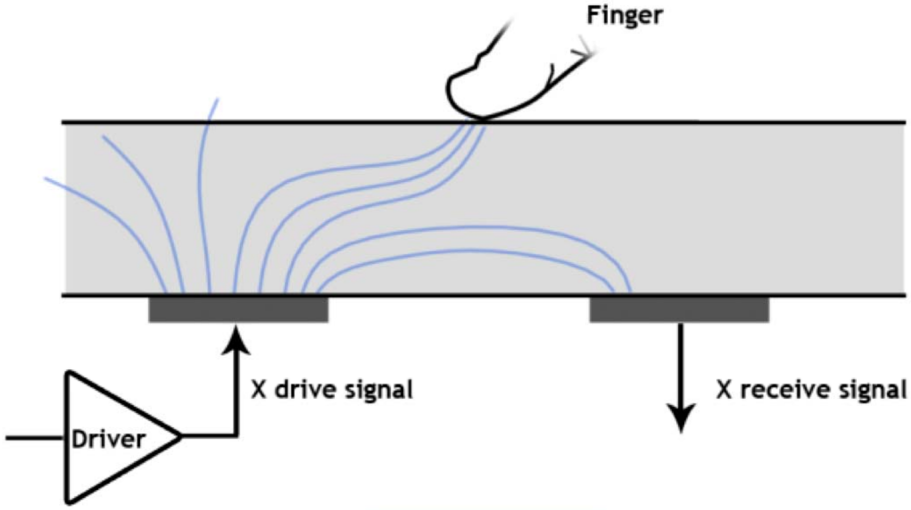


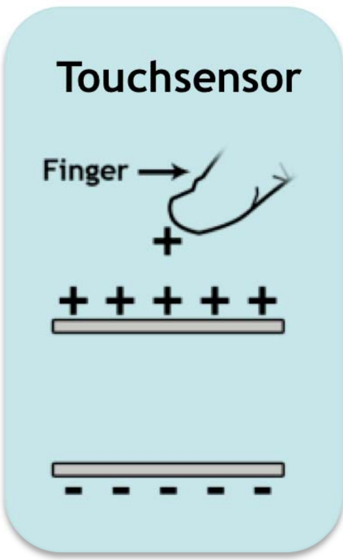


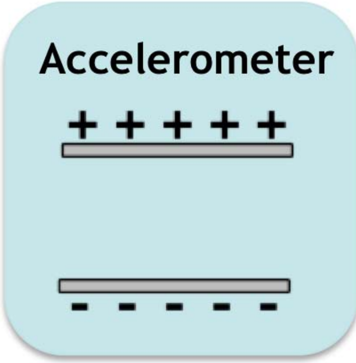
Accelerometers are Everywhere

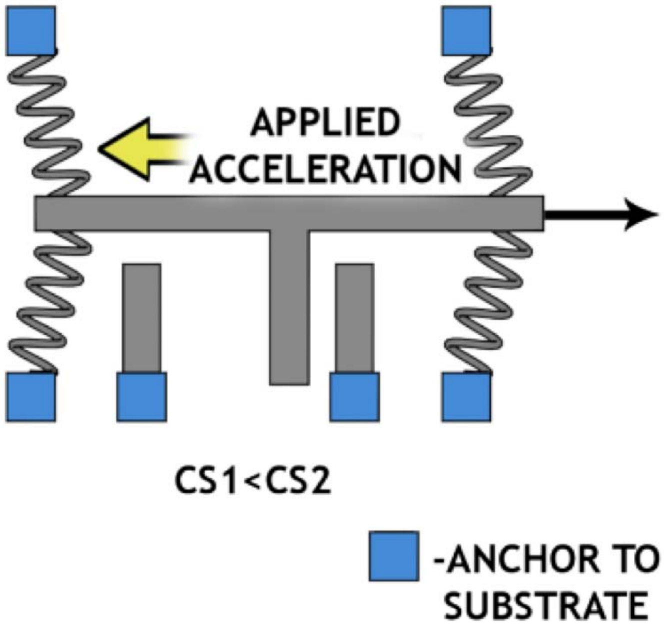


Capacitors in the iPhone

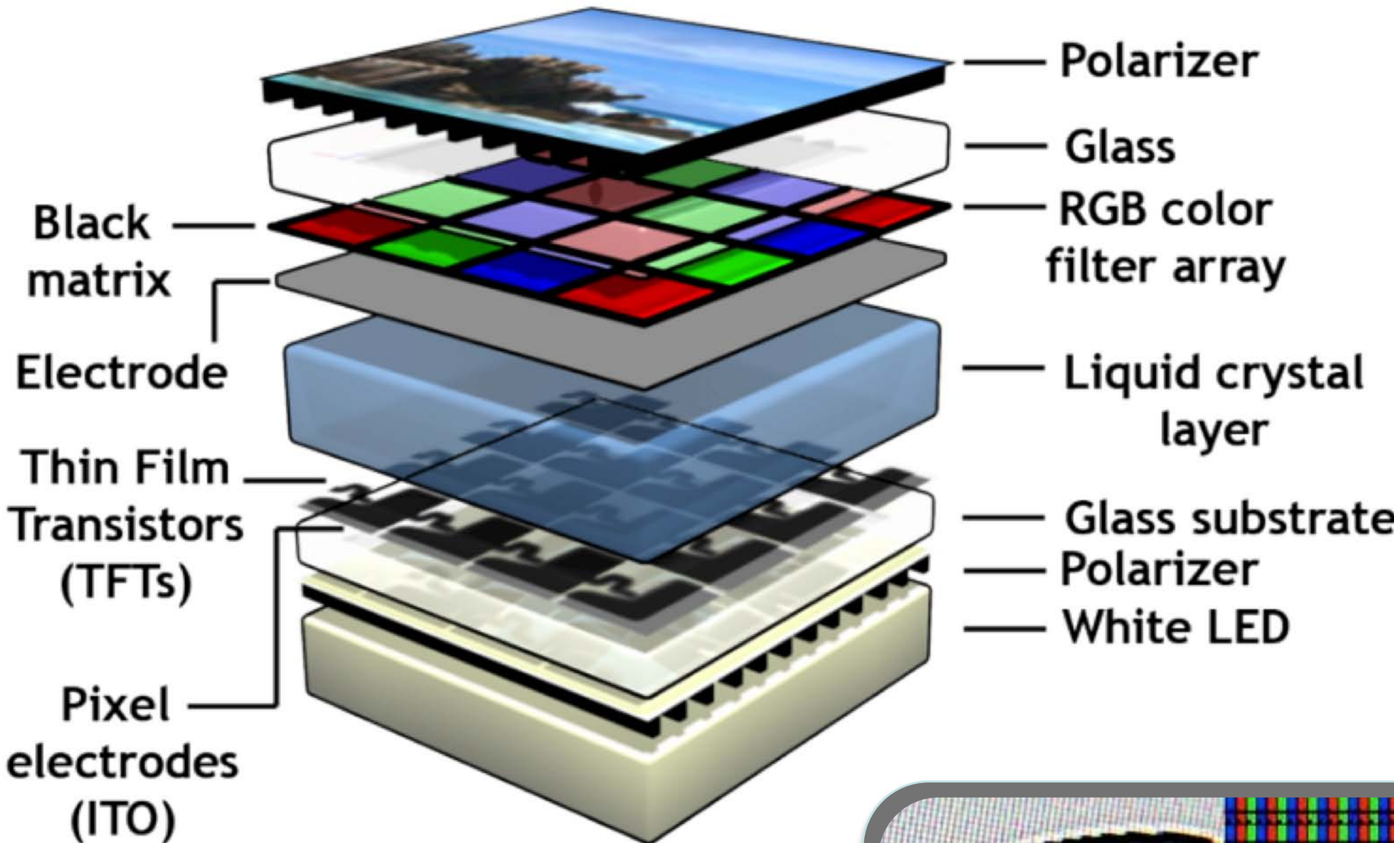




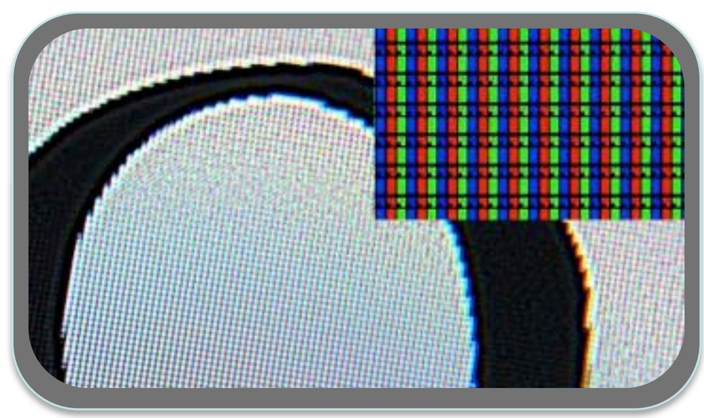




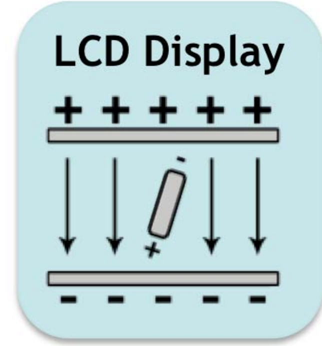
Liquid Crystal Displays

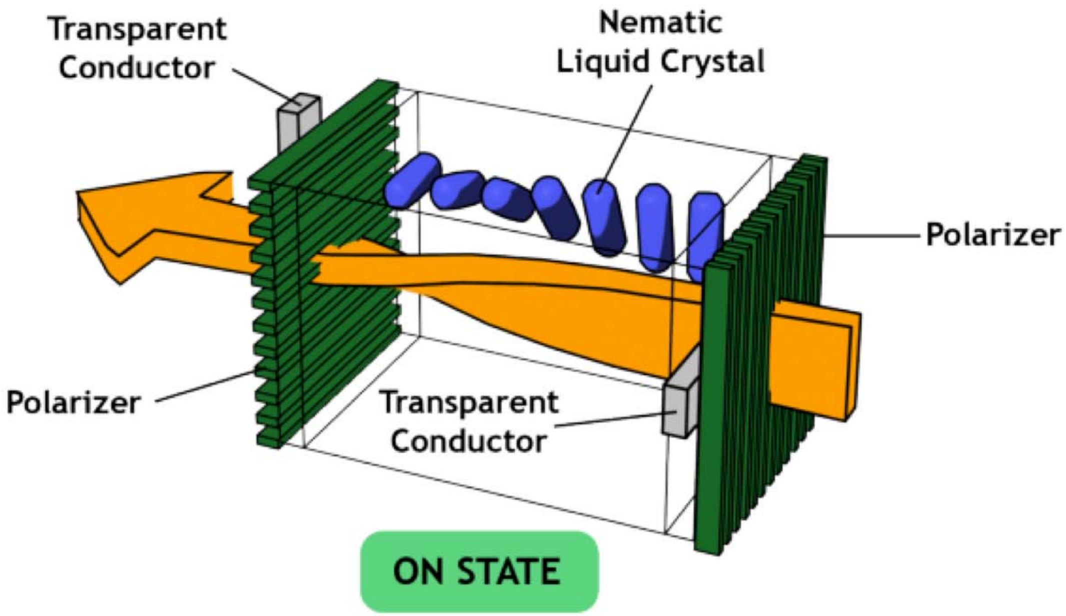


-Liquid crystals are electrically controlled light switches

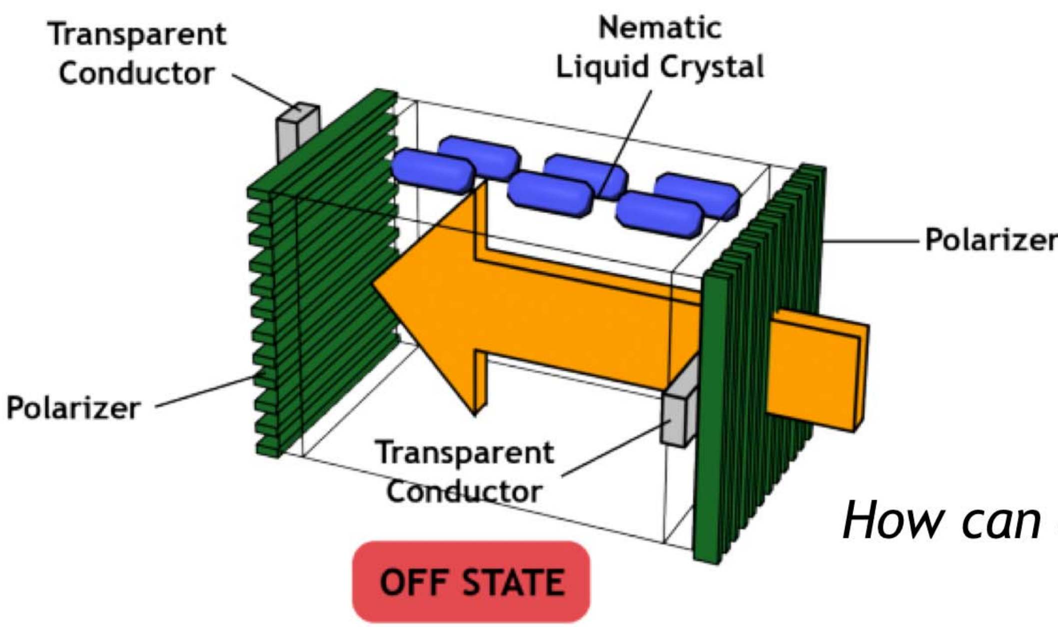


Liquid Crystal Displays





$$\mathbf{E} = 0$$



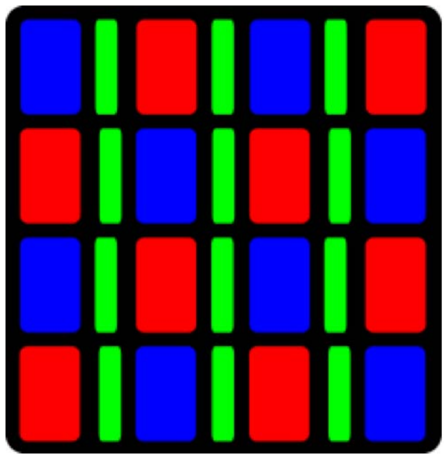
$$\mathbf{E} \neq 0$$

How can a material rotate polarization?

(ANSWER IN LAB 3)

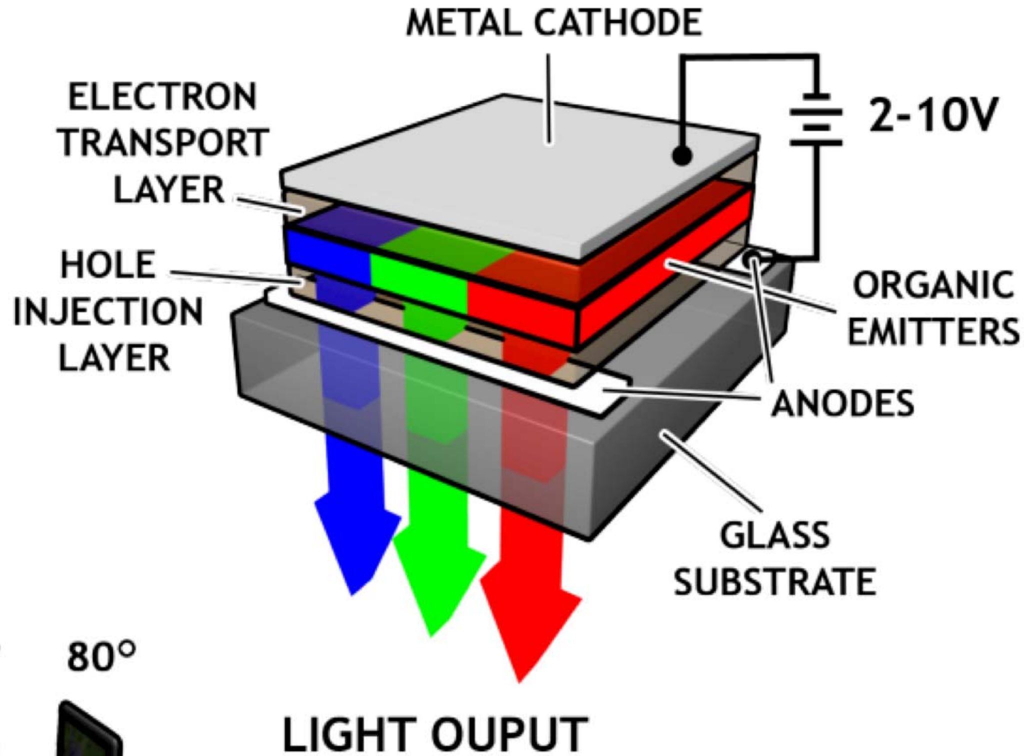
Nexus One: Organic LED Display

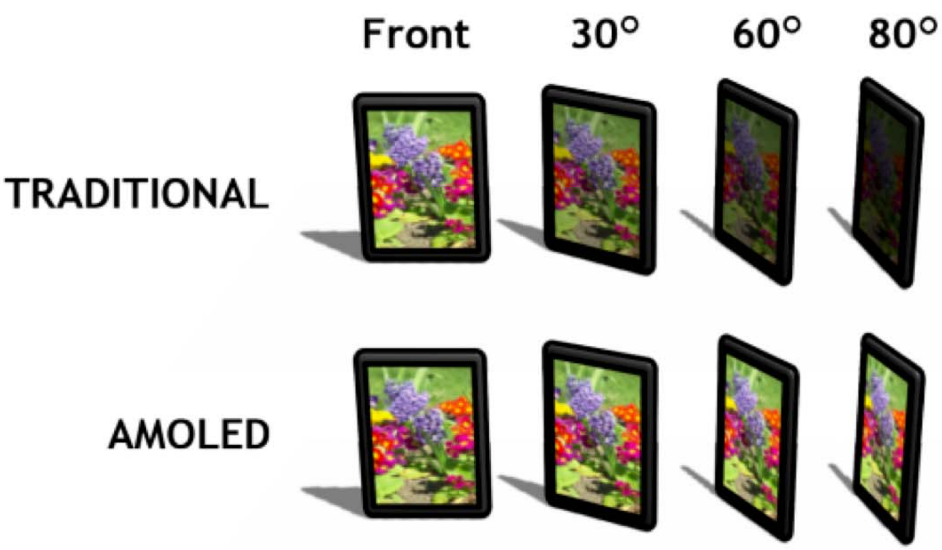
OLED pixels …

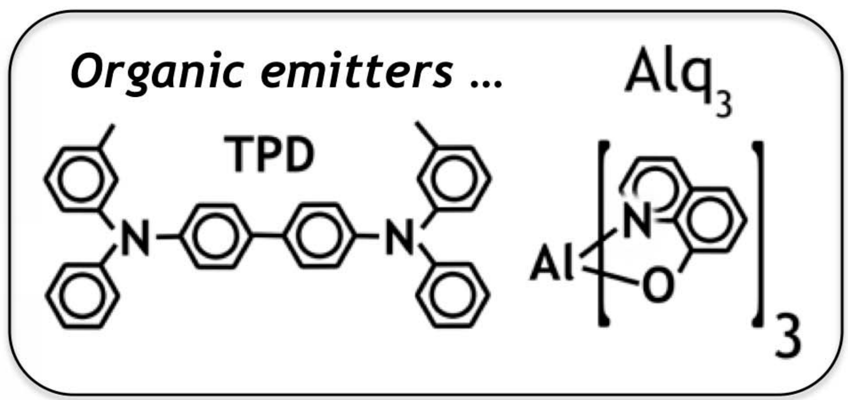


Nexus One picture in public domain

OLED subpixels …

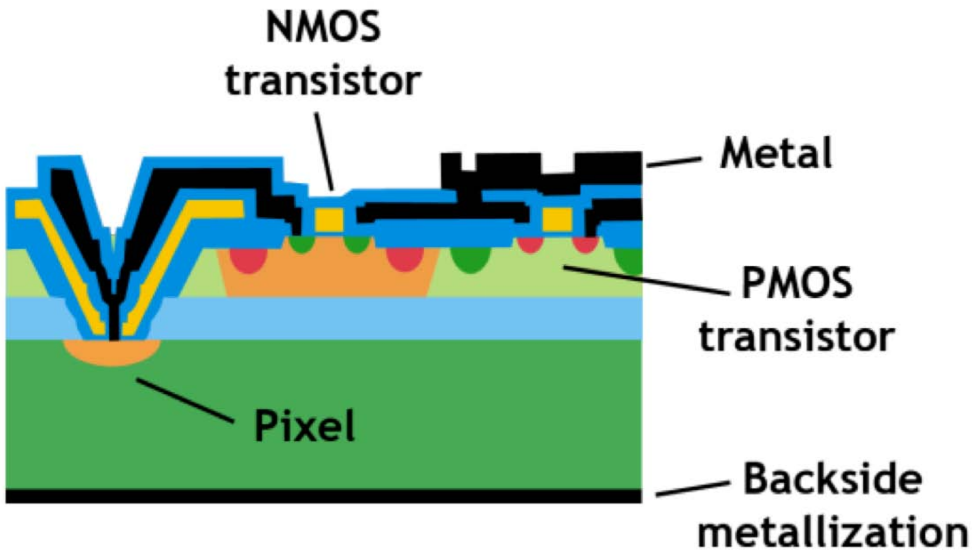


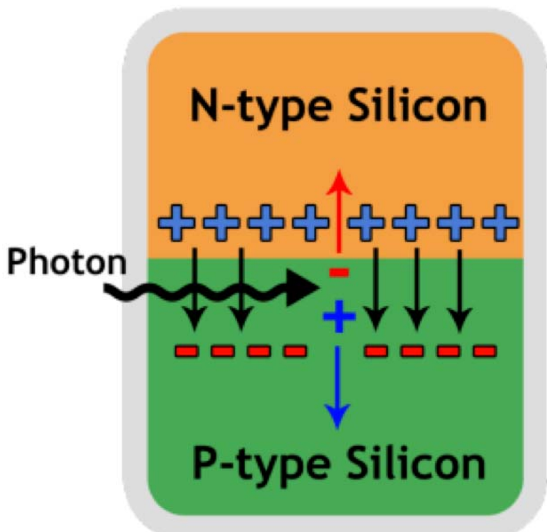


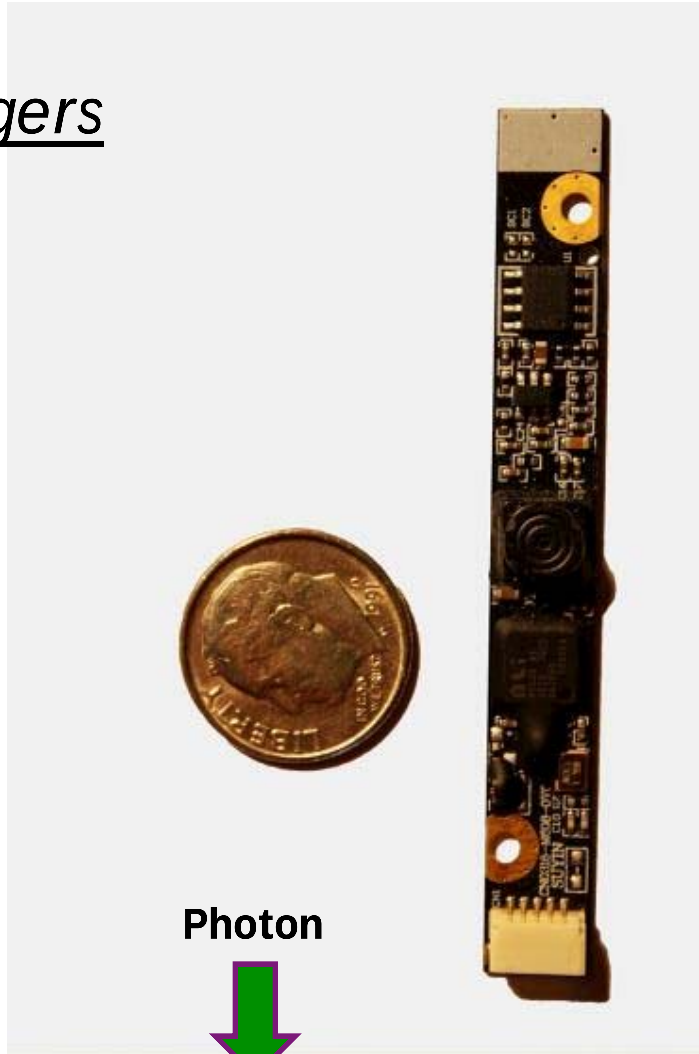


CMOS Photodiode Imagers

CMOS Imager Pixel





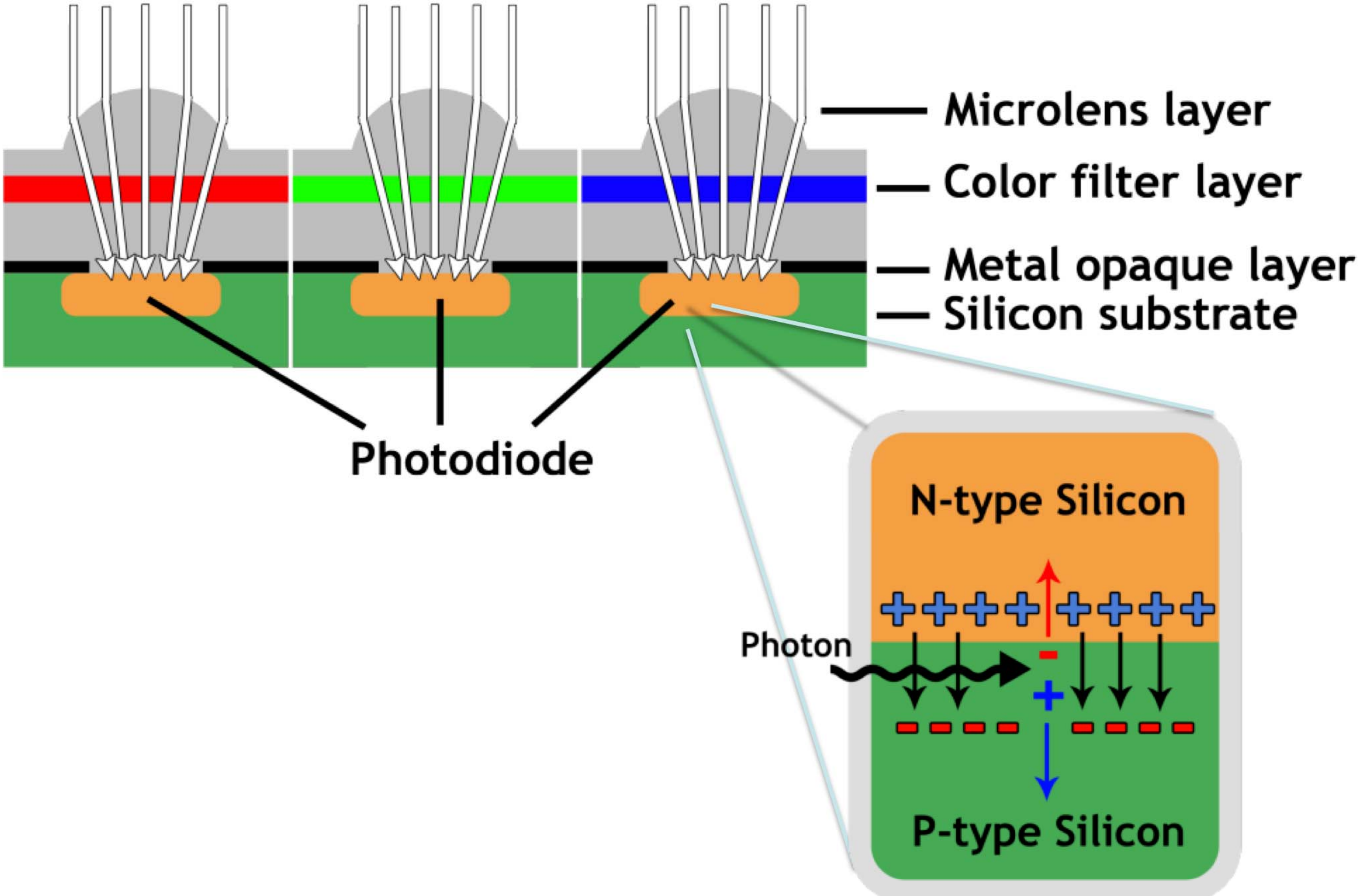


Photon

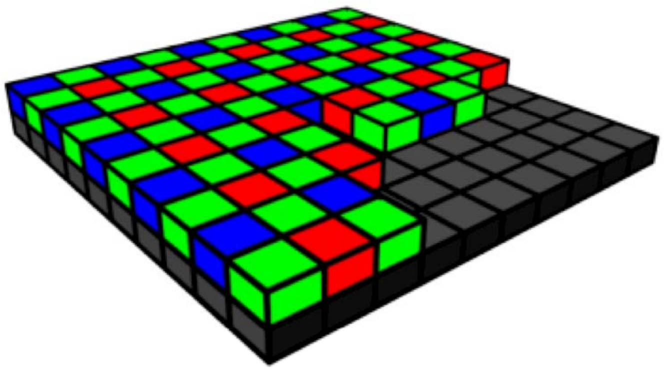
Charge (electron + hole)

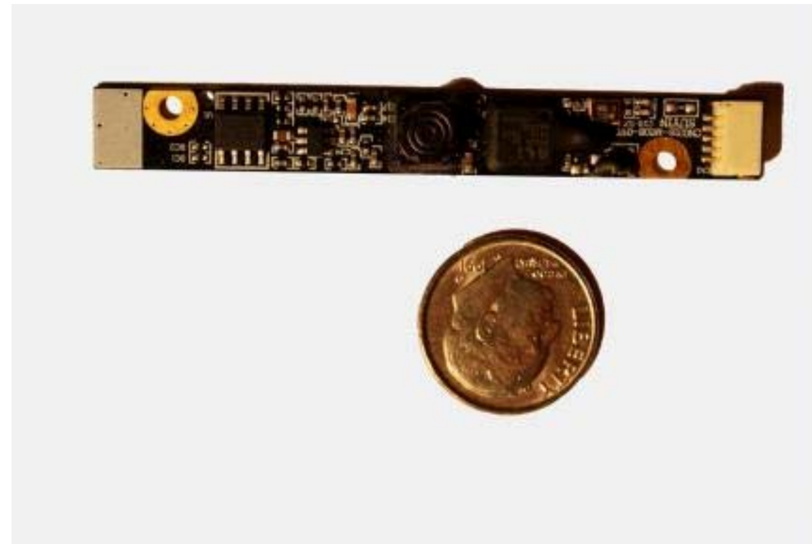
Current (E-field pulls charge apart)

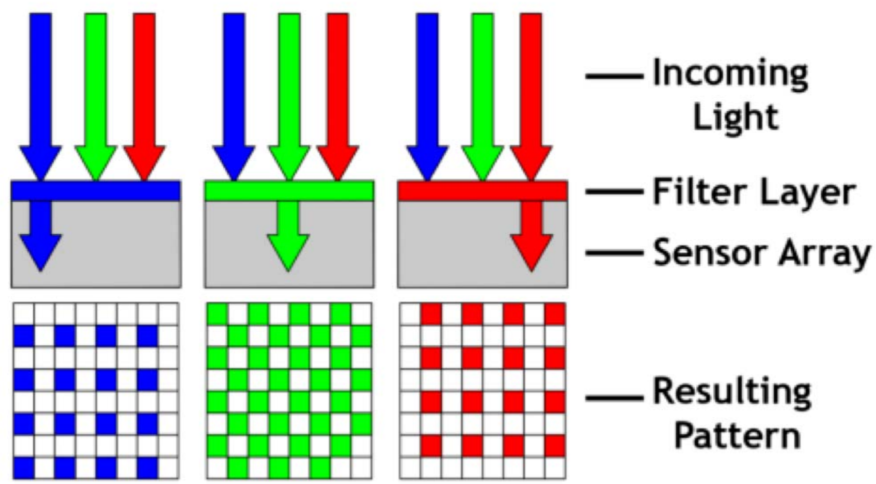
CMOS Photodiode Imagers



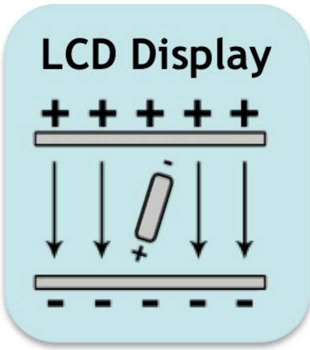
CMOS Imagers: Color Filters

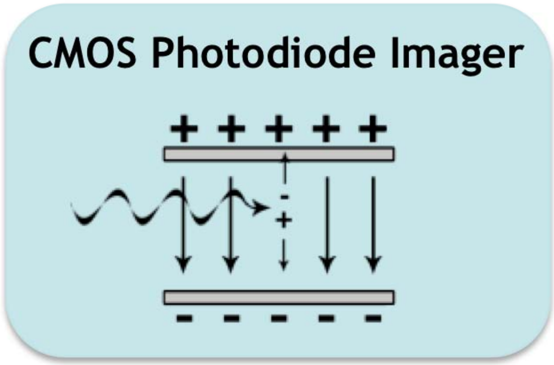


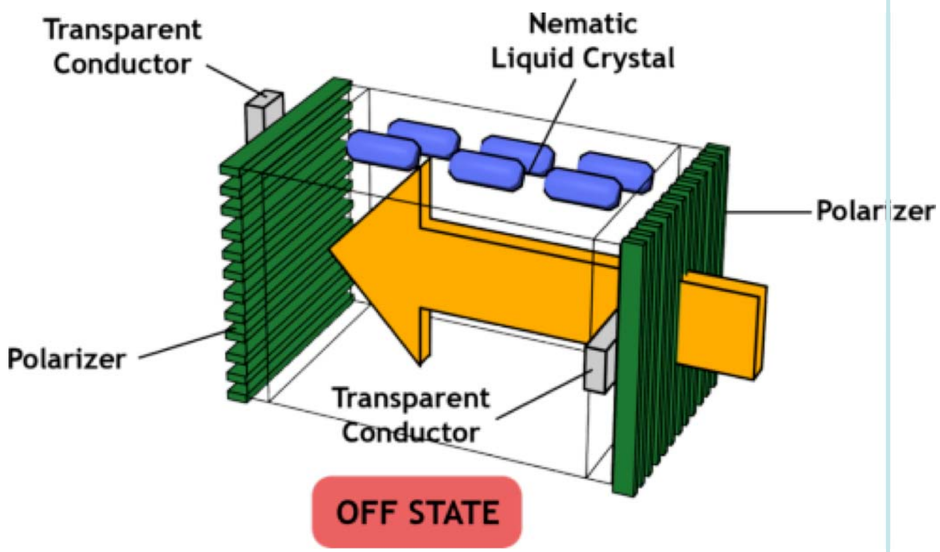


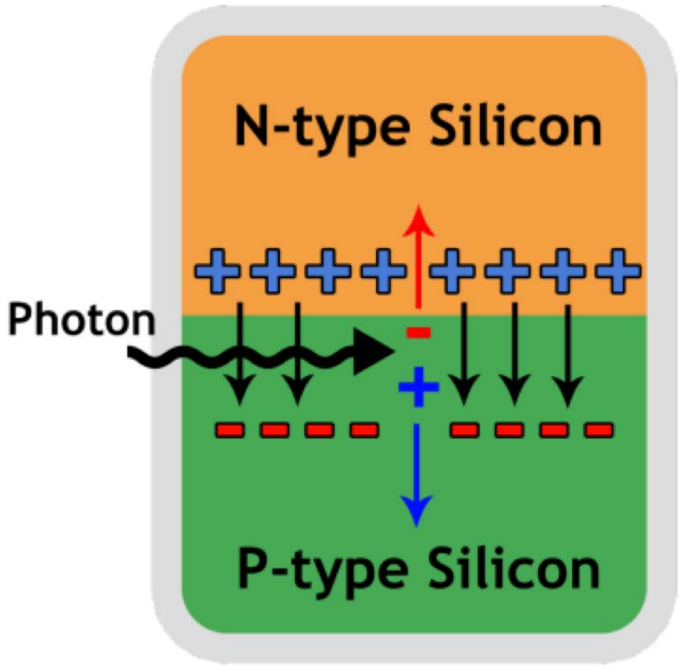


Capacitors in the iPhone









MOSFET: Transistor in a Nutshell

Conduction electron flow

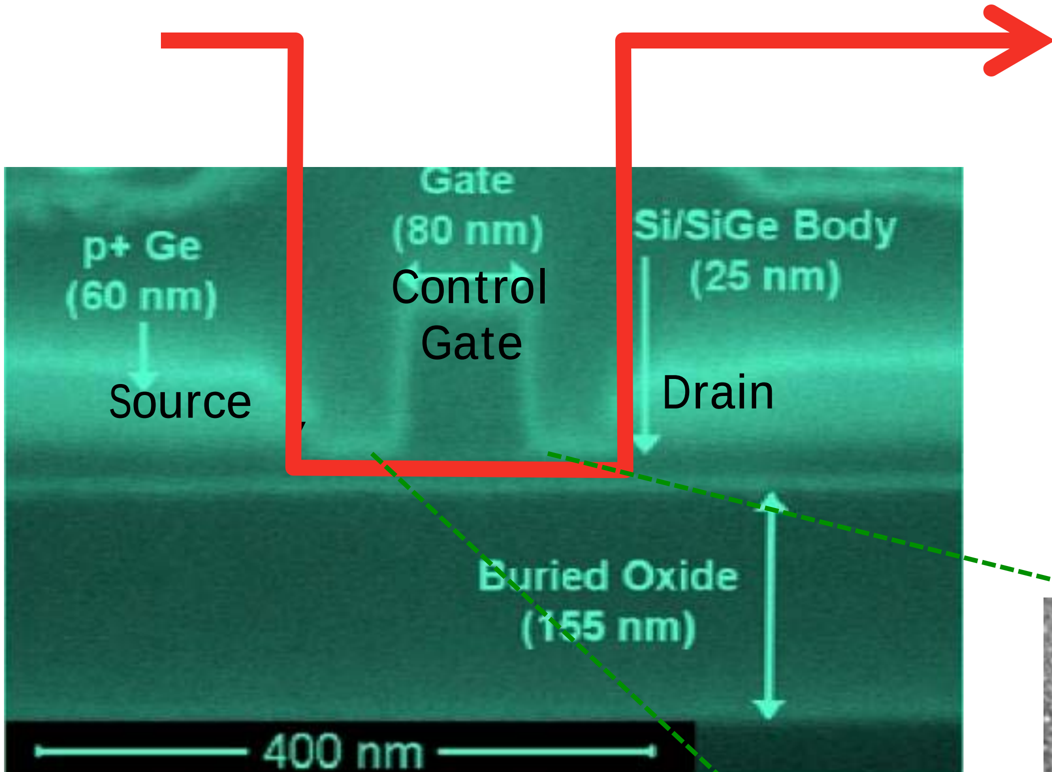


Image courtesy of J. Hoyt Group, EECS, MIT.
Photo by L. Gomez

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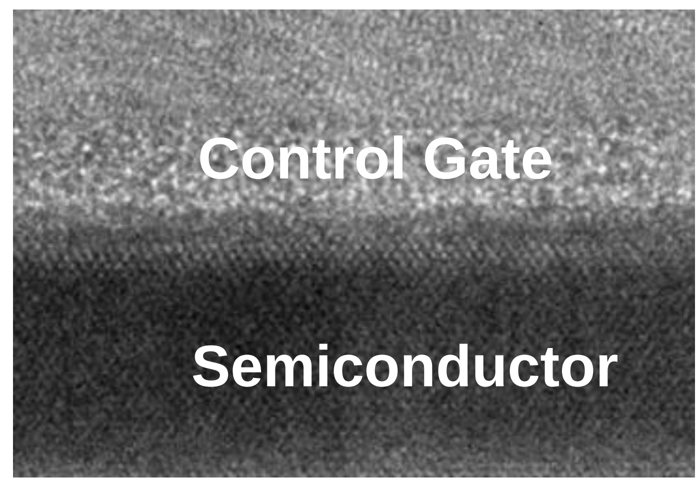
Photo by L. Gomez



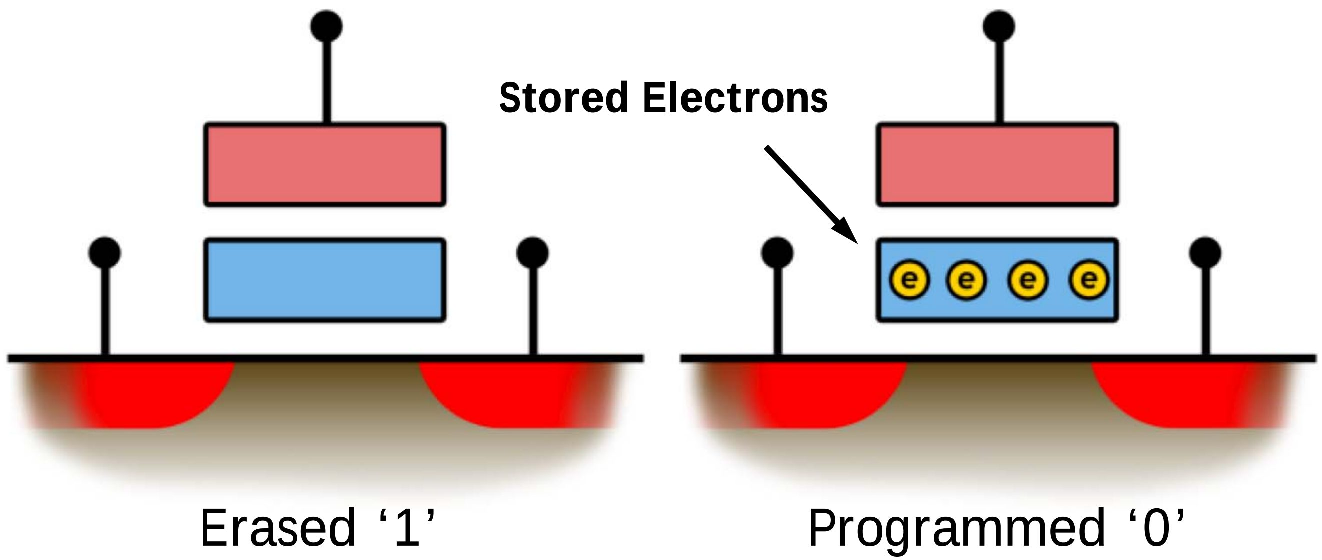
$$q_{channel} = Cv_{gate}$$

$$i_{sd} = v_{sd}/R = v_{sd} \times G$$

$$i_{sd} \propto v_{sd} \times q_{channel}$$

Transistor is an electrically (capacitively) controlled switch

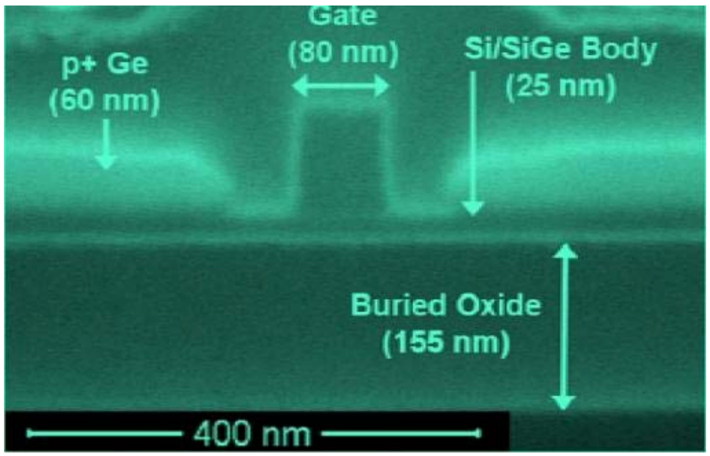
Card picture in public domain

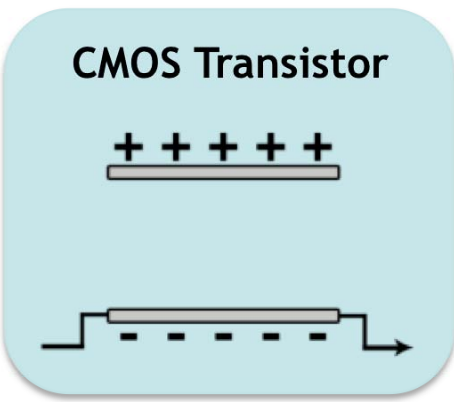


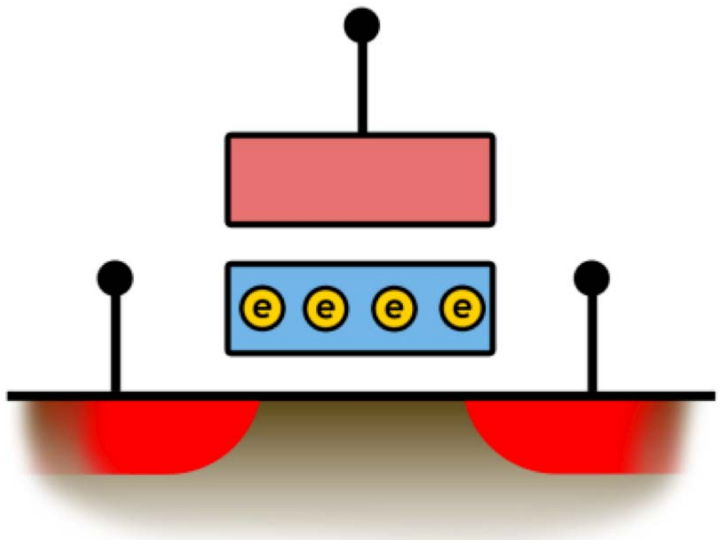
8GB iPhone employs Samsung's 65-nanometer 8-Gbyte MLC NAND flash

Capacitors in the iPhone

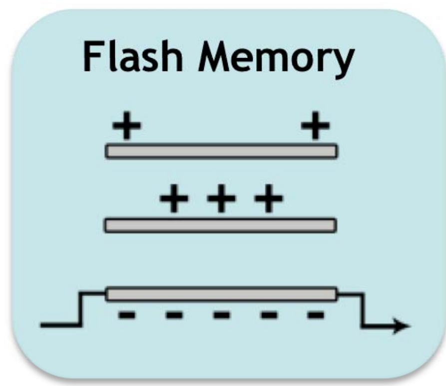
Image courtesy of Department of Electrical Engineering and Computer Science, MIT. Photo by L. Gomez, J. Hoyt







Programmed ‘0’

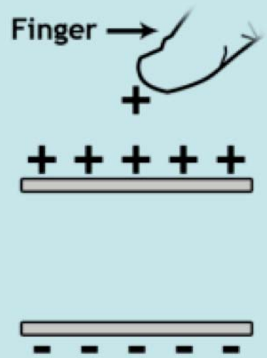


Capacitors in the iPhone

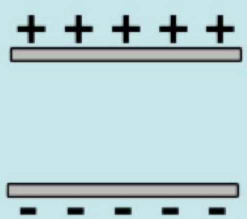
$$\int_S \epsilon_o \overline{E} \cdot d\overline{A} = \int_V \rho dV$$

$$q = \boxed{\mathrm{C}} v$$

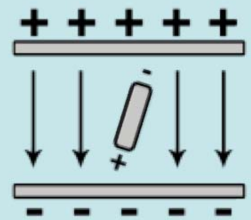
Touchsensor



Accelerometer

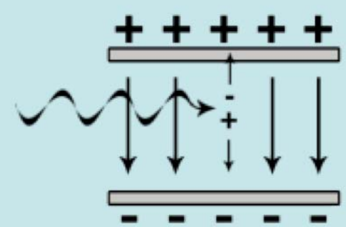


LCD Display

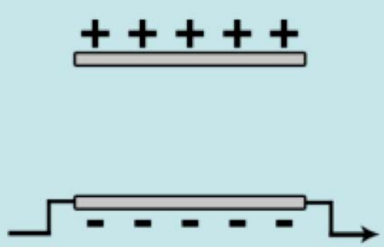


$$q = C \boxed{\mathrm{v}}$$

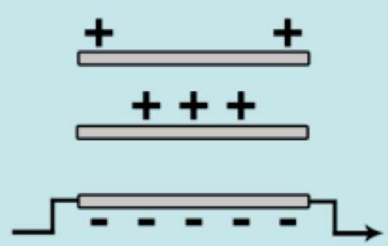
CMOS Photodiode Imager



CMOS Transistor



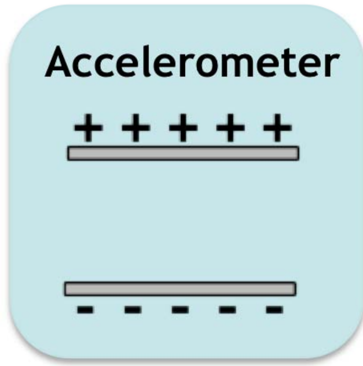
Flash Memory

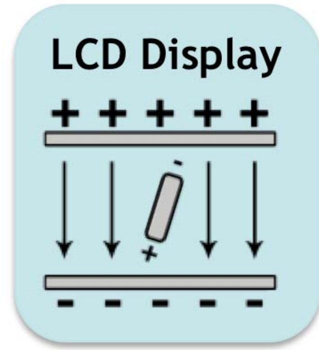


$$\boxed{\mathrm{q}} = Cv$$

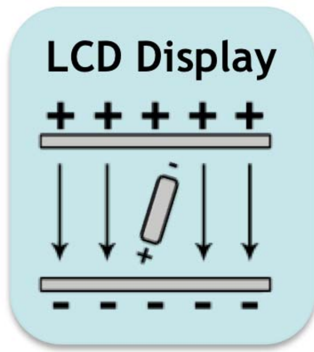
Three Big Ideas in 6.007

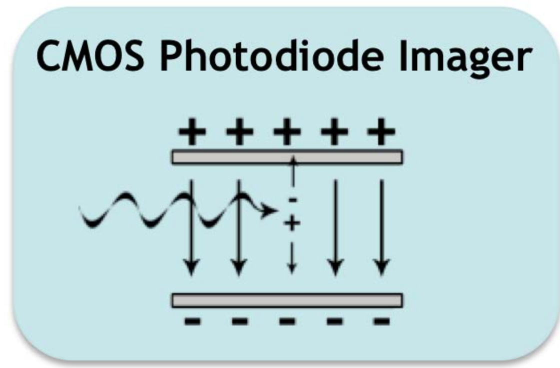
- ***MECHANICAL-TO-ELECTRICAL ENERGY CONVERSION***



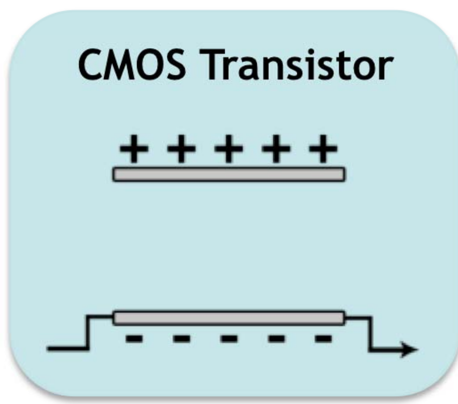


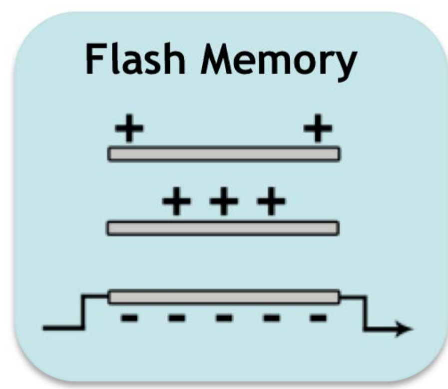
- ***INTERACTION OF LIGHT AND MATERIALS***





- ***QUANTUM MECHANICAL TUNNELING***



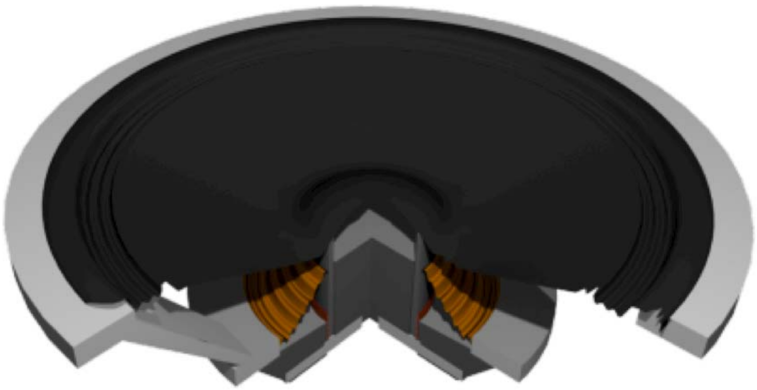


iPhone Components	6.007 Concepts
Touchpad	Capacitors
Display	Lights, Waveguides, Filters
Memory Card SIM	QM Tunneling Phenomena
Camera	Light Absorption, Photodetectors
Battery	Chemical Energy Conversion / Storage
Antennas	EM waves
Accelerometer, Speaker	Mechanical Energy Conversion, MEMS
LEDs	Solid State Lighting

iPhone Components	6.007 Concepts
Touchpad	Capacitors
Accelerometer, Speaker	Mechanical Energy Conversion, MEMS
Battery	Chemical Energy Conversion
Antennas	EM waves
Camera	Light Absorption, Photodetectors
Display	Lights, Waveguides, Filters, Eyes
Memory Card SIM	QM Tunneling Phenomena
LEDs	Solid State Lighting

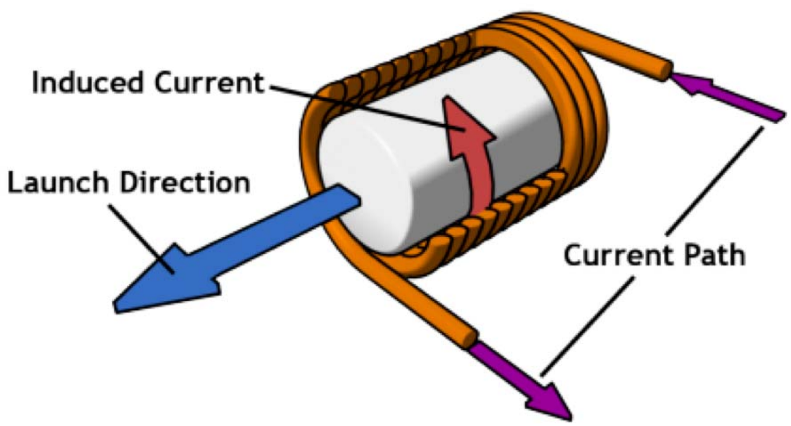
Lect	Subject
	Registration Day
1	Motors to Lasers Intro - iPhone Components
2	Energy and Power (Go Cart)
3	Electrical vs. Gas Engine
4	Energy in Electrical Systems
LAB	DC Motor+MatLab+Oscilloscope
T1	Tutorial
5	Electrostatics (Gauss's Law and Boundary Conditions)
6	Magnetostatics (Magnetic Fields and Forces)
7	Forces in Magnetostatics (Actuators)
8	Practical MQS Systems (Torroids, Solenoids, Magnets)
T2	Tutorial
9	Magnetic Materials
10	Faraday's Law (Induced emf)
11	Magnetic Circuits and Transformers
12	Forces via Energy Conservation (Energy Method)
	Presidents Day Holiday
T3	Monday Schedule of Classes (Tutorials Held)
13	Stored Energy and Magnetic Actuators
14	Energy Conversion Systems: Rail Guns
15	Dielectrics and Dipoles
LAB	Shooting Magnets
T4	Tutorial
16	Practical Dielectrics
17	Limits of Statics and Quasistatics
18	Linear Systems, Complex Numbers and Phasors
19	Electromagnetic Waves (Wave Equation)
T5	Tutorial
	Exam
20	Examples of Uniform EM Plane Waves (Poynting vector)
21	Generating EM Waves: Antennas
22	Interaction of Atoms and EM Waves (Lorentz Oscillator)
T6	Tutorial
23	Lossy EM Waves
24	Polarized Light and Polarizers
25	Birefringence
26	Liquid Crystal Display Technology
LAB	Liquid Crystal Displays
T7	Tutorial
27	Interference and Diffraction
28	Diffraction and Holography
29	Reflection and Transmission of EM Waves
30	EM Reflection and Transmision in Layered Media
T8	Tutorial
31	Optical Resonators
32	Refraction and Snell's Law
33	Fresnel Equations and EM Power Flow
34	Waveguides (optical systems)
LAB	Spectrometer
T9	Tutorial
35	Wavepackets
36	Photon - Quantum of Energy
37	Photon Momentum and Uncertainty
38	Examples of Heisenberg Uncertainty Principle
	Patriot's Day - Vacation
	Patriot's Day - Vacation
	Exam
39	Schrodinger Equation (drop date)
40	Particle in a Box
LAB	Quantum Mechanical Tunneling
T10	Tutorial
41	Reflection from a potential step
42	Tunneling
43	Tunneling Application (Flash Memory, STM)
44	From Atoms to Molecules
T11	Tutorial
45	Semiconductors
46	LEDs
47	Photodetectors, Solar Cells
48	Electron Wavepackets and Microscopic Ohm's Law
LAB	Extra Credit Lab
T12	Tutorial
49	Quantum Superposition and Optical Transitions
50	Lasers
51	Final Exam Review

Inductors in the iPhone



$$\oint_C \overline{H} \cdot d\bar{l} = \int_S \overline{J} \cdot d\overline{A} + \frac{d}{dt} \int_S \epsilon E dA$$

not a simple inductor (not magnetostatics)

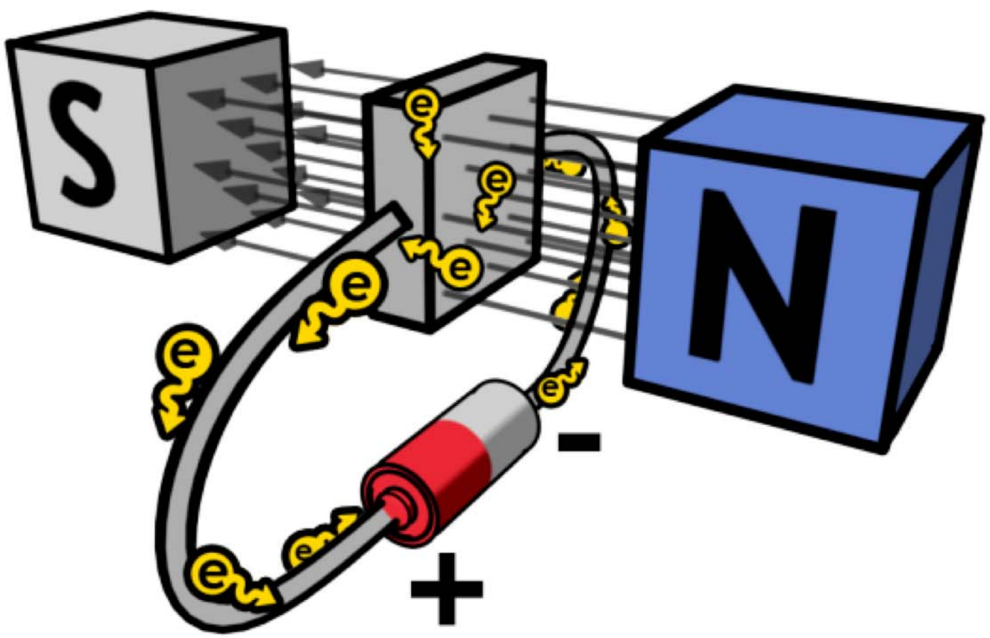


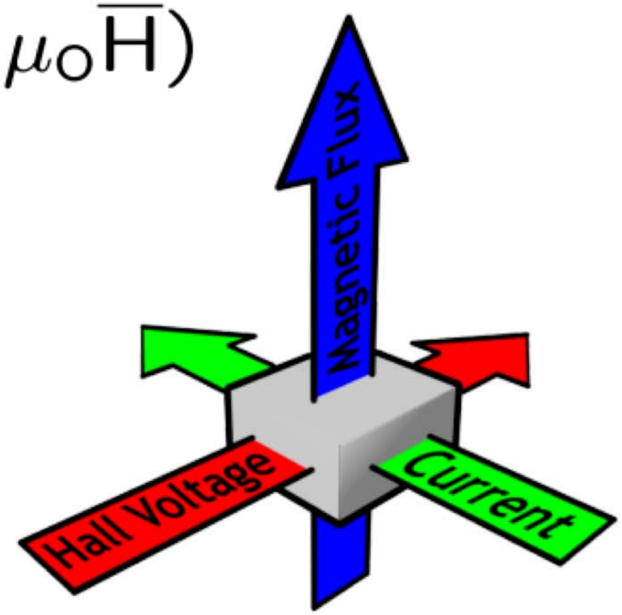
$$\oint_C \overline{E} \cdot d\bar{l} = -\frac{d}{dt}\left(\int_S \overline{B} \cdot d\overline{A} \right)$$

Magnetometers

Lorentz Force Law...

$$\overline{f} = q(\overline{E} + \overline{v} \times \mu_o \overline{\mathrm{H}})$$





Hall Effect

Magnetic field deflects electrons ...

... charge piles up on edges

& creates transverse potential difference

What is this doing in the iPhone 3G and Nexus One?

Nexus One picture in public domain

Course Details

Recommended Reading

Applied Electromagnetics
(Third edition)
L. C. Shen, J. A. Kong,
PWS publishing, 1995.

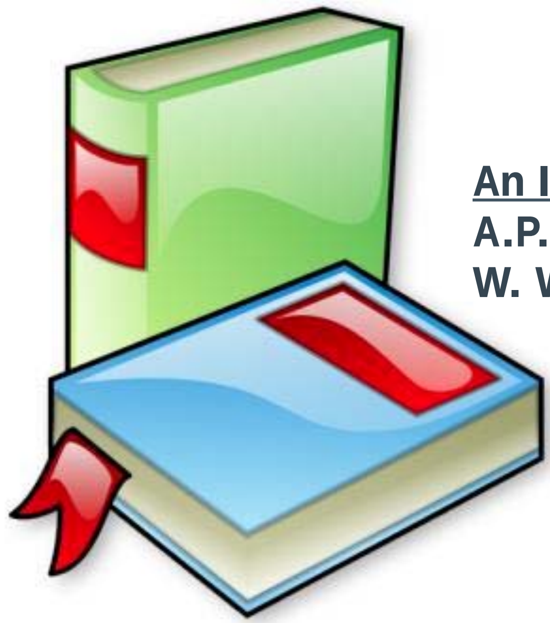


Image is in the public domain

An Introduction to Quantum Physics
A.P. French, E. F. Taylor
W. W. Norton & Co, 1978.

Grading

5	Labs	10%
10	Problem Sets	20%
2	Midterms	40%
1	Final Exam	30%

Energy Conversion in the iPhone

Energy Conversion in the iPhone

Heat: Charging and discharging transistors (capacitors)

Microprocessor energy consumption:

Variable speed microprocessor 620 MHz at 0.45 mW/MHz

Running 7 hours of video at ~280mW (620 MHz) = 1960 mWh

Running 8 hours of audio at <280mW (<620 MHz) < 2240 mWh

Visible Light: LED in Display:

$3 mW/cm^2$ for $\sim 40\ cm^2$ = 120 mW (40%) of processor power

7 hours of displaying = 840 mWh

Radio: Antenna radiation:

130mW of radiation (for 135g iPhone → 0.974 W/kg)

8 hours of operation = 1040 mWh

(Note: allowed FCC rating for portable appliances – 1.6 W of radiation per kg)

Total consumption over 7 hours of video (microprocessor+display) = 2800 mWh

Total consumption over 8 hours of talk (microprocessor+antenna) = 3280 mWh

Battery capacity 1400 mAh at 3.7V = 5180 mWh

Good Engineers ...

- Place *ethics* and *morals* above all else
- Are team players
- Follow a deterministic design process
- Follow a schedule
- Document their work
- Never stop learning

6.007 Electromagnetic Energy: From Motors to Lasers
Spring 2011