EE 43/100 Smart Dust Lab: Theory

1. Objectives

The purpose of this experiment is to introduce you to a new sophisticated wireless sensor system that can be used to make a wide variety of measurements. Along the way, you'll also experiment with individual sensors of temperature and illumination like those on the wireless "motes" -- so-called because they are only about an inch across now and can ultimately be made much smaller. The wireless sensor system that we'll explore, which communicates via high-frequency radio waves, was named Smart Dust by its inventor, Kris Pister, a Berkeley EECS prof.

2. Introducing Smart Dust

A Smart Dust mote is an electronic package composed of: an integrated-circuit radio transmitter and receiver (the combination is called a "transceiver"); a microcontroller that controls the operation of the mote; a random-access memory (RAM) like the one(s) in your computer; a "flash" memory like the one that stores pictures in a digital camera; some standard sensors – a resistive temperature sensor and a semiconductor illumination (light) sensor that produces a current when it is illuminated; an analog-to-digital converter (ADC) that converts the analog temperature and illumination sensor outputs to digital form for transmission elsewhere; a power source for the mote (typically a battery); and an antenna used both for transmitting and receiving signals.

The motes we'll use – called "Mica2dot" motes (don't ask) – also have three light-emitting diodes (LEDs) on them. The red LED indicates when the mote is turned on; the yellow and green LEDs flash when mote-to-mote communication is occurring. The Experiment Guide describes this more fully.

A computer software operating system – TinyOS – was developed in Berkeley's Computer Science Division to control mote operation. When wireless motes are first dispersed in an area – a room, a hallway, a building, or in a meadow – they autonomously attempt to set up a network along which they can send information from one mote to another. Somewhere, one mote is plugged into a special printed circuit board (PCB) that is connected to the serial port of a computer, such as a laptop. This board is known as a "base station"; its function is to collect the data provided to it by the assembly of motes. The topology of a typical Smart Dust mote network is shown in Fig. 1 below.

Fig. 2 shows a magnified view of one of the Smart Dust wireless sensor motes. Several of its components are identified; beneath the printed circuit board that you see is an integrated circuit like those used in portable telephones to drive an antenna connected to the mote for transmitting the mote identification and measured sensor data to the base station. These motes are made commercially by the Xbow Company ("cross-bow"), which you can reach at www.xbow.com .

Fig. 1. Topology of a typical Smart Dust mote network.

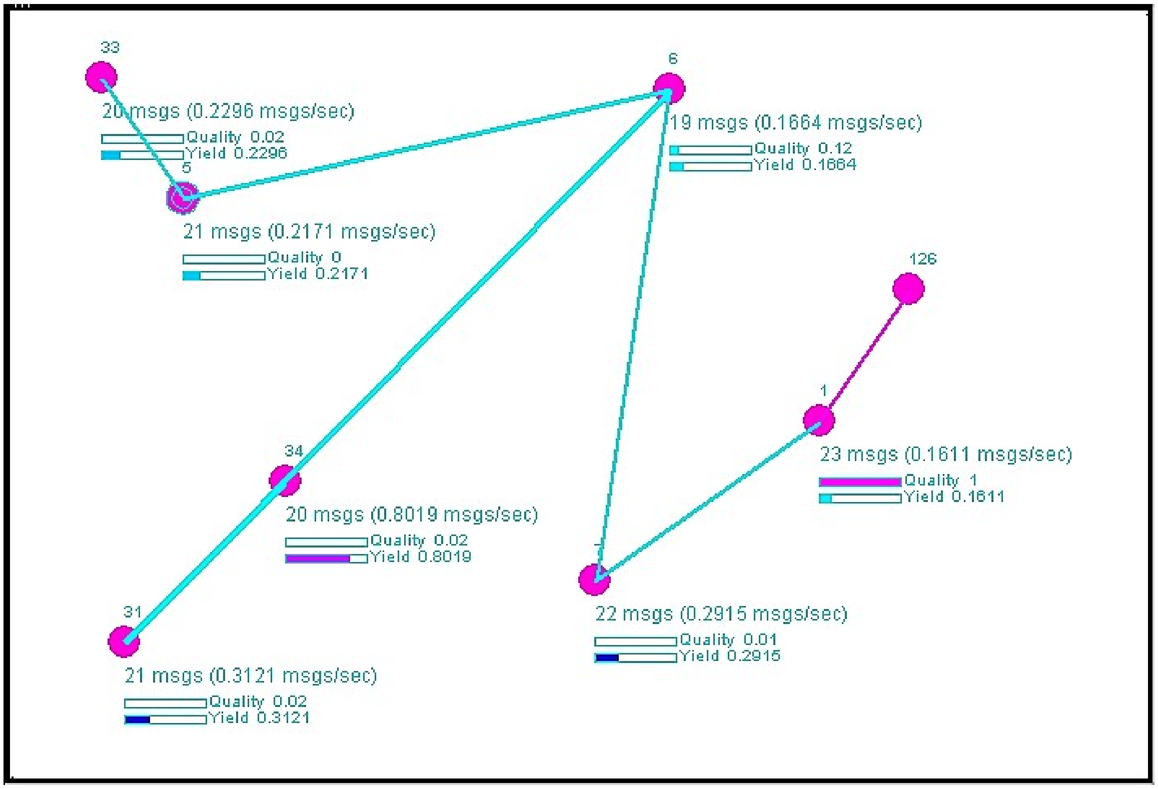
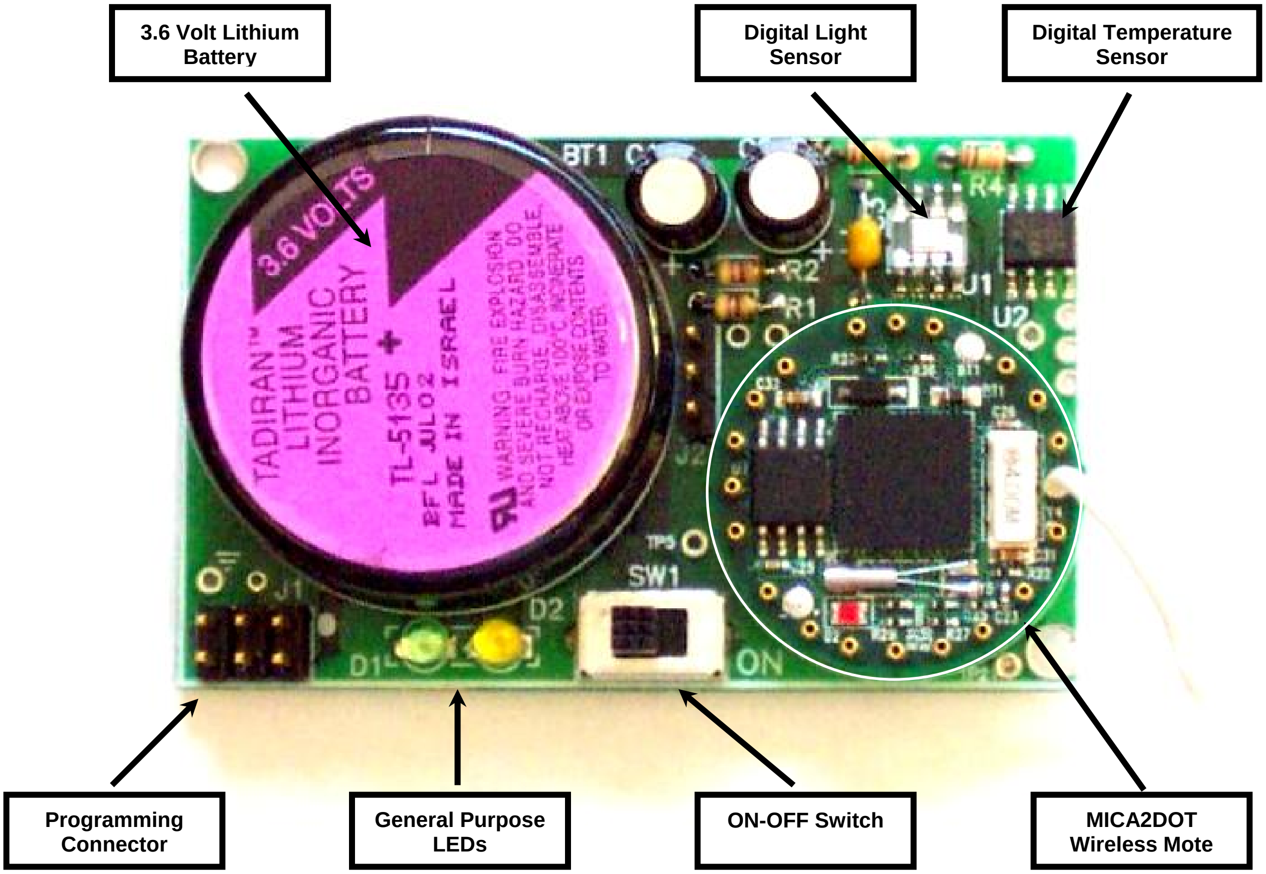


Fig. 2. Magnified view of the Smart Dust mote. The wireless telephone chip is beneath this printed circuit board. The mote connects to a short antenna for transmitting and receiving radio waves.



Each mote in the network has a unique identifier that it uses to preface each of its transmissions. Every mote transmits any sensor data that it has taken, along with information from other motes sent to it for passing along to the base station. If the proper software has been installed in the base station's computer, the network topology can be displayed on the base station's monitor. One should thus be able to observe when motes are added to the network, or when they leave it. The sensor data taken by each mote could also be displayed, processed and stored by that computer.

3. Uses

The possible uses are limited only by the available sensors and by the range that these motes can achieve – tens to hundreds of meters with radio communication, up to miles in certain circumstances when the motes are outfitted for optical communication using lasers.

The long list of sensed quantities that have been demonstrated includes: temperature, illumination, relative humidity, toxic gases, magnetic field, sound, acceleration, and rotation rate. As examples of some of their uses, motes bearing on-board accelerometers are being installed on the Golden Gate bridge to measure the accelerations produced by wind and traffic, and burrowing birds on an Eastern seaboard island are being monitored unobtrusively in their nests by motes that measure temperature and illumination, which are surrogate indications of burrow occupancy and activity.

A key feature of the motes is their low cost. The motes that you will use cost approximately $100 each in a quantity order of a few hundreds, and it is predicted that within a year or so the price might be as low as a few dollars. An important practical requirement is that the power required by any mote be kept low to prolong battery life; this means that the mote radios must be efficient, and that any sensors used must require very little power. Present motes require 10-20 mW for radio transmission and reception, and a number of sensors are available that are either passive (require no power source, an example being a photodiode for measuring illumination) or have low power requirements.

3. References

Here are two web sites you can check out:
robotics.eecs.berkeley.edu/~pister/SmartDust/
http://webs.cs.Berkeley.edu/tos/

EE 43 Smart Dust Lab: Experiment Guide

Smart Dust Motes

The motes that you'll use are contained in translucent plastic boxes that measure 1.5 x 2.5 x 0.6 cubic inches. There is an insulated antenna (inside the plastic tubing – a soda straw) attached to the box. You can turn on a mote by moving the black slide switch (visible through a hole in the box) with a small key or a pencil point; move the switch handle in the direction of the attachment point of the antenna to turn it on. **Be sure to turn the motes off when you're finished with them to prevent battery drain**.

Each pair of students will have available two motes in which stored TinyOS programs enable them to transmit and receive signals from similar motes, but be immune to transmissions from other motes. The boxes are marked S (send) or R (receive) to identify the transmitter and receiver, respectively. (The motes inside those boxes have identical hardware, but their software differs.) When a receiver is turned on, if there's no sending mote nearby that can communicate with it, nothing appears to happen. But when you turn on a transmitter, its red LED flashes periodically; a yellow and green LED also flash, acting as the readouts of a two-bit binary counter. The counts have no significance, but they serve to show you that the mote is working properly. If you now turn on a receiving mote while the associated sender is still on, you should see the receiver's lights flashing in synchrony with those of the transmitter.

When the motes are sensing real-world data – these motes can sense temperature and illumination – the measurements are transmitted over the wireless network to a base station that is plugged into a serial port on a computer, permitting data storage and display. Such a station should exist at one point in the lab.

Individual sensors

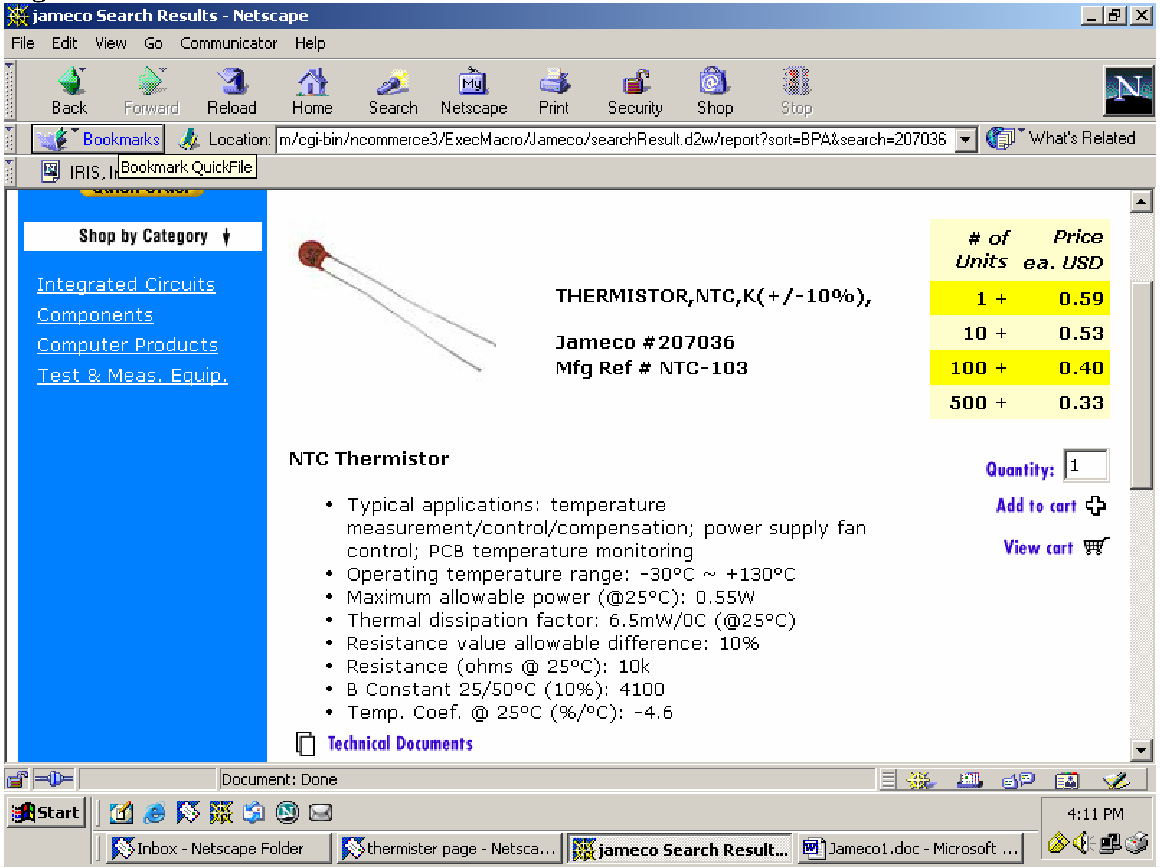
The original motes included analog sensors for temperature and illumination. We'll now describe how those sensors worked.

Temperature sensor – the thermistor

The analog temperature sensor on the mote is a black cube that is 1 mm on a side; it has silvery electrodes on two opposing faces. This is a two-terminal semiconductor device known as a thermistor because its resistance changes a lot when its temperature changes. When the temperature rises, the number of charge carriers in the thermistor increases, causing its electrical resistance to drop. (In common resistors, a temperature rise produces a resistance *rise* because at higher temperatures the vibrations of the atoms of the resistor are more intense, which impedes the flow of electric charges through the resistor.)

The thermistor you will test in the lab is not on the mote but rather is an individual Jameco Thermistor Model NTC-103 (NTC = negative temperature coefficient, meaning resistance goes *down* when temperature goes *up*). Several Jameco data sheets appear as Figs. 3A and 3B below. The characteristic curve for our thermistor in Fig. 3B should be the one that has the value of 10 kΩ resistance at 25^o C temperature (ask your GSI to be sure).

Fig. 3A Some data on the Jameco thermistors.



THERMISTOR,NTC,K(+/-10%),

Jameco #207036
Mfg Ref # NTC-103

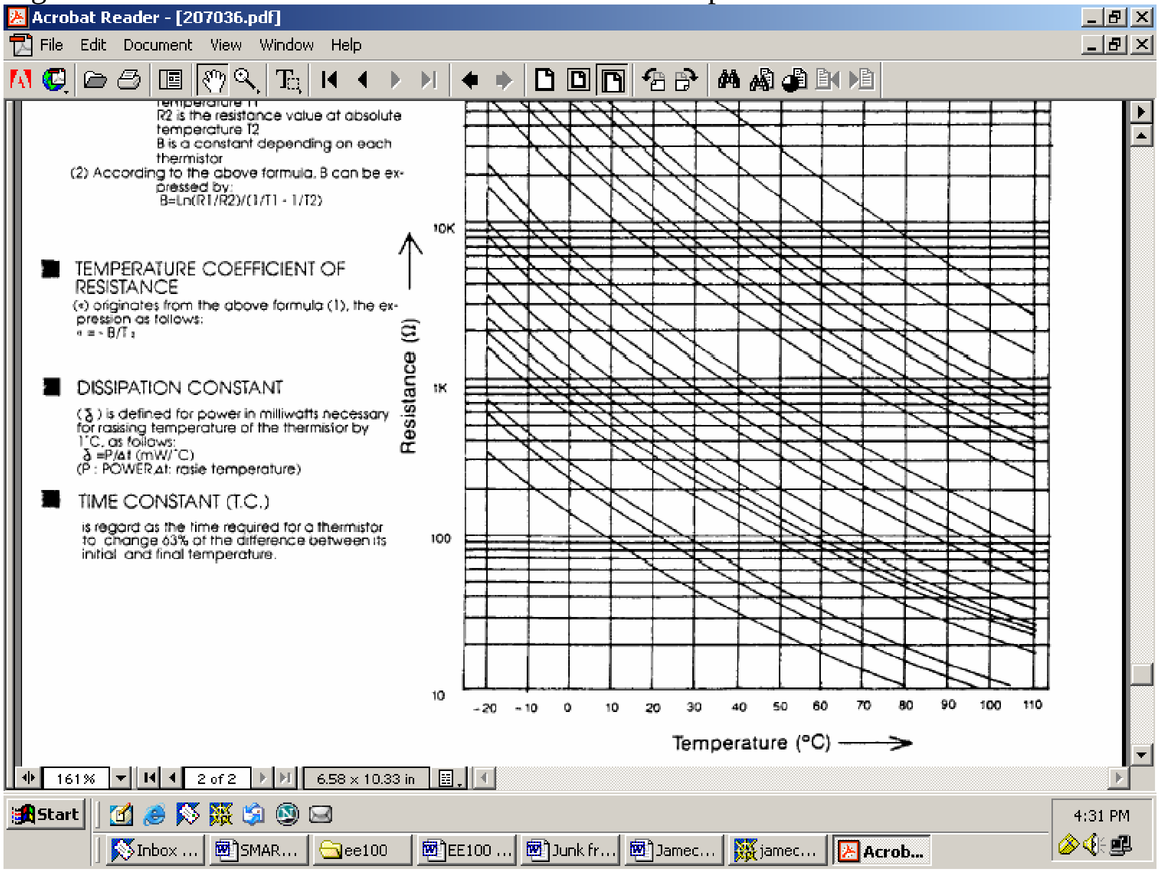
# of Units	Price ea. USD
1 +	0.59
10 +	0.53
100 +	0.40
500 +	0.33

NTC Thermistor

- Typical applications: temperature measurement/control/compensation; power supply fan control; PCB temperature monitoring
- Operating temperature range: -30°C ~ +130°C
- Maximum allowable power (@25°C): 0.55W
- Thermal dissipation factor: 6.5mW/0C (@25°C)
- Resistance value allowable difference: 10%
- Resistance (ohms @ 25°C): 10k
- B Constant 25/50°C (10%): 4100
- Temp. Coef. @ 25°C (%/°C): -4.6

Technical Documents

Fig. 3B. Thermistor characteristics – resistance vs temperature.



R2 is the resistance value at absolute temperature T2
B is a constant depending on each thermistor
(2) According to the above formula, B can be expressed by:
B=Ln(R1/R2)/(1/T1 - 1/T2)

TEMPERATURE COEFFICIENT OF RESISTANCE

(α) originates from the above formula (1), the expression as follows:
α = - B/T 2

DISSIPATION CONSTANT

(δ) is defined for power in milliwatts necessary for rasising temperature of the thermistor by 1°C, as follows:
δ =P/Δt (mW/°C)
(P : POWER Δt: rasie temperature)

TIME CONSTANT (T.C.)

is regard as the time required for a thermistor to change 63% of the difference between its initial and final temperature.

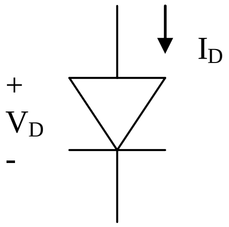
You should use an ohmmeter to measure the resistance of the thermistor as it is heated. You can heat it with your body by grasping the thermistor bulb between your thumb and forefinger. For heating over a larger temperature range, there are two options.

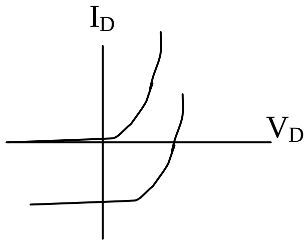
1. You can use the 22 Ω resistor and connecting it to the HP E3631A DC power supply. Set the supply voltage at 5.0 volts. Position the heating resistor over the white ceramic plate with rubber feet.
2. You can use a xenon light source to heat both the thermistor and an IC temperature sensor. The IC temperature sensor outputs a voltage that is linearly proportional to the temperature in degrees Centigrade. (Ask the GSI for the calibration information.)
3. You may also be able to observe the temperature dependence of resistance of a thin metal wire – the filament of a miniature light bulb. Connect the bulb to a DMM set to measure resistance. Heat the bulb with the xenon lamp or a nearby soldering iron and observe in what direction the resistance changes, as well as the magnitude of its change.

Illumination sensor – the photodiode or solar cell

The mote contains a photodiode – a semiconductor device that produces a current when a light shines on it, like a solar cell. In the lab you will be able to experiment with some

larger silicon solar cells that are not on the mote. Recall that the short-circuit current of a solar cell is proportional to the illumination incident upon the cell. The I-V characteristic of a typical solar cell is that shown in Figure 3.25 in Example 3.12 of the textbook by Schwarz and Oldham; the device isn't identified as a solar cell, but the characteristic is similar.
A rough approximation to such a characteristic was shown in class and is repeated below.





In the diode symbol, the arrowhead points in the direction of easy current flow, and the reference directions for current and voltage are shown. Recall also that a two-terminal device that has a positive current emerging from its positive terminal is *delivering* energy rather than dissipating it (think "battery"). In the lab, you will be able to measure the current and voltage to verify that this device can deliver energy. You can also see the effect of illumination on the short-circuit current as measured with an ammeter.

Light-Emitting Diodes

Since the motes include LEDs on them, we will take this opportunity to experiment a bit with them in this lab.

LEDs have I-V characteristics like those of ordinary silicon pn-diodes, but their turn-on voltages are higher than the 0.7V of the silicon diodes. The RadioShack book, "Getting Started in Electronics", which is at each lab station and also on 2-hour reserve in the Engineering Library, contains a table of LED turn-on voltages. As you go from red LEDs toward blue LEDs, the energy of the emitted photons increases, and so more electrical energy must be given to the electrons in the device. Hence, the turn-on voltage for a blue LED is higher than that for a red LED.

Because of their high efficiency and long life, LEDs are being used widely, one example being their appearance in traffic signals. They last at least 10,000 hours, and all their output is at the design wavelength. In contrast, incandescent traffic lights employ optical filters that absorb all but a narrow portion of the white light spectrum emitted by the bulb.

Here are the turn-on voltages measured on the variously colored LEDs that you can use in the lab:

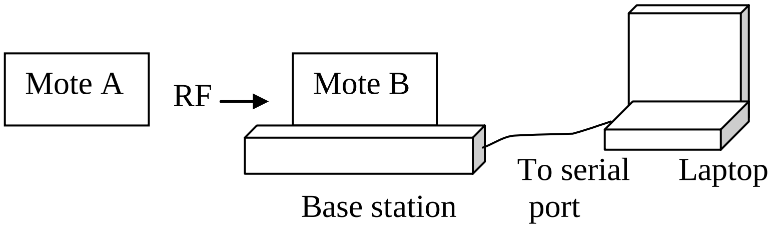
Diode color and size	Turn-on voltage (measured with a Fluke multimeter)	Safe maximum current (mA)
Red, small	1.60V	2mA
Red, large	1.50V	6mA
Yellow, small	1.70V	3mA
Green, small	1.790V	2mA
Green, large	1.793V	3mA

These measurements were made with the diode check feature of the Fluke or HP DMM, which you can verify in the lab.

IMPORTANT NOTE: The longer lead of an LED is the positive lead as indicated by the positive potential in the circuit symbol above.

Appendix: Smart Dust Laptop Display – Illumination Level (This display may not be available in your lab session – if it is you can see the structure of the packets sent by the motes)

Set-up: Smart Dust mote A sends wireless radio-frequency signal packet to mote B plugged in to “base station” that is connected to the serial port of the computer



Radio packet: Packet uses hexadecimal format; the packet contains a header that identifies the sending mote (Mote A), data from the light sensor, some unused time slots, and a cyclical redundancy check at the end:

```
7E 00 04 54 03 XX 01 00 00 … 00 01 00
[              ][↑ ][              ][    ]
 TinyOS header  |     Unused        CRC
                |
   Data from illumination
     sensor (TSL2550)
```

Hexadecimal number system:

The base is 16, just as decimal numbers have a base 10. The hexadecimal numbers represent the decimal numbers from 0 to 15, as follows:

Decimal number:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Hexadecimal equivalent:	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F

A hexadecimal number such as 7E means $7 \times 16^1 + 14 \times 16^0 = 7 \times 16 + 14 \times 1 = 126$

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RMW