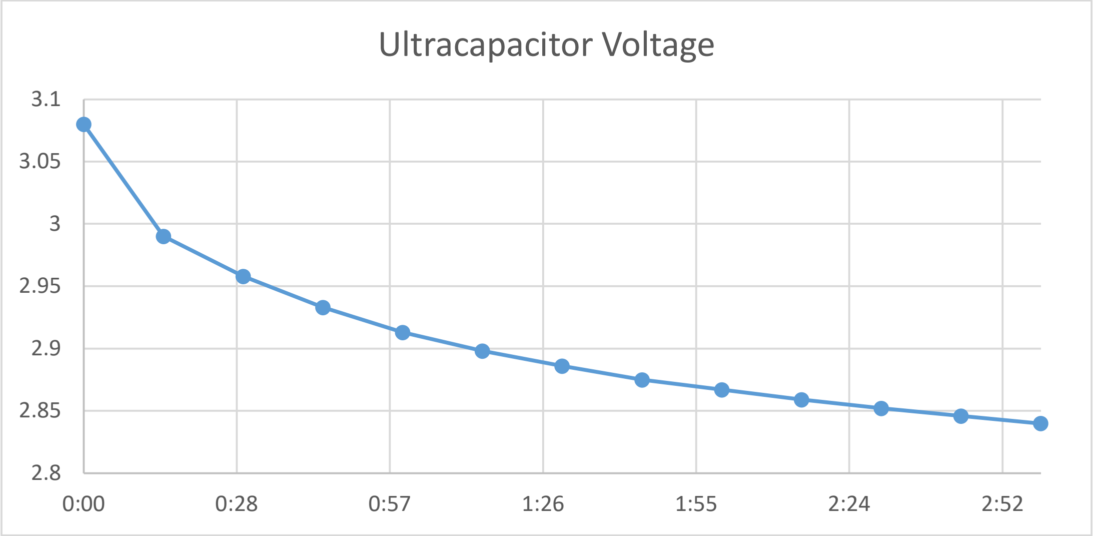
Question	Solution			
1	0.1	F		

2

Time (m:ss)	Ultracapacitor Voltage
0:00	3.08
0:15	2.99
0:30	2.958
0:45	2.933
1:00	2.913
1:15	2.898
1:30	2.886
1:45	2.875
2:00	2.867
2:15	2.859
2:30	2.852
2:45	2.846
3:00	2.84



Basic Energy Measurement Procedure

3	3.000	V		
4	7.500	s		
5	305.500	mJ	V2	1.700
6	40.733	mW		

Debug MCU Disabled

7	3.034	V		
8	15.000	s		
9	315.758	mJ	V2	1.700
10	21.051	mW		

MCU in Sleep/Wait Mode

11	3.030	V		
12	21.000	s		
13	314.545	mJ	V2	1.700
14	14.978	mW		

MCU in Deep Sleep/Stop Mode

15 AVLP, ALLS, and AVLLS are all set to one in the macro, so all three modes are allowed.
AVLP = Allow Very-Low-Power Modes (VLPR, VLPW, and VLPS are allowed)
ALLS = Allow Low-Leakage Stop Mode (LLS is allowed)
AVLLS = Allow Very-Low-Leakage Stop Mode (Any VLLSx mode is allowed)

16 The SMC->PMCTRL has reset values of all zeros, and any assignment would also result in all zeros, so the Normal Stop (STOP) mode is used. This register also tells us that the Normal Run mode (RUN) is used.

17	3.034	V		
18	241.000	s		
19	315.758	mJ	V2	1.700
20	1.310	mW		

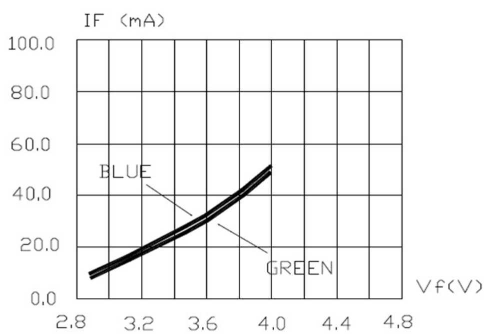
Detailed LED Analysis

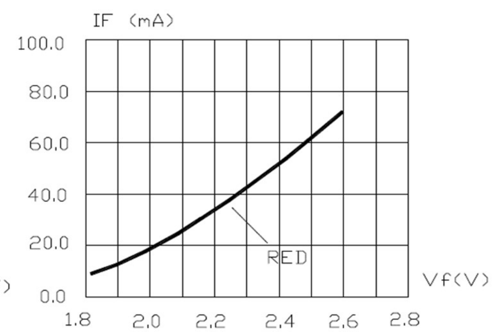
21	Color	Elapsed Time (since start)	Time in Voltage Range (s)	V_Upper	V_Lower	Energy Used (mJ)	Avg Power Used by System (mW)
	Blue	0:00:00	13.00	3.1	3	30.50	2.346
	Magenta	0:00:13	46.00	3	2.6	112.00	2.435
	Green	0:00:59	61.00	2.6	2.3	73.50	1.205
	Red	0:02:00	126.00	2.3	1.7	120.00	0.952
	(Off)	0:04:06		1.7			

22 The average power use in the Red range is about 21% lower that in the Green range. This is probably because higher voltages cause higher power consumption. The middle of the green range is 2.45 V, while the middle of the red range is 2.0V. If power is proportional to voltage squared and we look at the voltage in the middle of each range, we'd expect the green range to use (2.45V/2.00V)^2 = 150% the power of the red range. But green only takes about 21% more power. This results from the difference between the supply voltage and the forward voltage of the LEDs. The voltage difference divided by the current-limiting resistance determines how much current an LED will take. All three LEDs use 220 ohm current limiting resistors. The data sheet shows that the green LED has a much higher forward voltage than the red LED for the same current (e.g. 2.9 V vs. 1.8 V at 10 mA). Even though we're running the LEDs with much less current (e.g. at most 4 mA), the green LED will have a higher forward voltage than the red. As a result, it will draw less current. This reduces the impact of the higher operating voltage for the circuit in the green range.

Q22 Support

Color	V_Upper	V_Lower	V_mid	P_Upper	P_Lower	P_Mid	Normalized to Lower Red: Upper	Lower	Mid
Blue	3.1	3	3.05	9.61	9.00	9.30	2.40	2.25	2.33
Magenta	3	2.6	2.80	9.00	6.76	7.84	2.25	1.69	1.96
Green	2.6	2.3	2.45	6.76	5.29	6.00	1.69	1.32	1.50
Red	2.3	1.7	2.00	5.29	2.89	4.00	1.32	0.72	1.00





TYPICAL ELECTRICAL & OPTICAL CHARACTERISTICS (T_A = 25°C)

Characteristics	Condition	Symbol	Values			Unit
			R	G	B	
Dominant Wavelength	I_F = 20 mA	λ_{DOM}	619~624	520~540	460~480	nm
Spectral bandwidth at 50% I_{REL} max	I_F = 20 mA	$\Delta\lambda$	24	38	28	nm
Viewing Angle at 50% I_V	I_F = 20 mA	$2\theta½$	120	120	120	deg
Forward Voltage	I_F = 20 mA	$V_{F(avg)}$	2.0	3.2	3.2	V
		$V_{F(max)}$	2.6	4.0	4.0	V

Q23 Support		Red			Green			Blue				
Mode	P3V3	V_R (mV)	I_R (mA)	LED Power (mW)	V_R (mV)	I_R (mA)	LED Power (mW)	V_R (mV)	I_R (mA)	LED Power (mW)	Total LED Power (mW)	Ave Total LED Power (mW) (20% duty cycle)
Blue	3.3							590	2.68	7.268	7.268	0.363
	3.15							471	2.14	5.735	5.735	0.287
	3.1							430	1.95	5.219	5.219	0.261
	3.024							377	1.71	4.536	4.536	0.227
Magenta	2.99	1145	5.20	9.602				343	1.56	4.127	13.729	0.686
	2.8	965	4.39	8.049				202	0.92	2.385	10.434	0.522
	2.62	801	3.64	6.623				86	0.39	0.991	7.613	0.381
Green	2.6				96	0.44	1.093				1.093	0.055
	2.45				38	0.17	0.417				0.417	0.021
	2.32				13.5	0.06	0.142				0.142	0.007
Red	2.3	500	2.27	4.091							4.091	0.205
	2	240	1.09	1.920							1.920	0.096
	1.75	55	0.25	0.424							0.424	0.021

23

				Minimum % of Power used by LED	Maximum % of Power used by LED
Color	V_{upper}	V_{lower}	Average Power Used by System (mW) (from Q22)	Min (LED at V_Lower)	Max (LED at V_Upper)
Blue	3.15 V	3.0 V	2.346	9.67%	12.22%
Magenta	3.0 V	2.6 V	2.435	15.63%	28.19%
Green	2.6 V	2.3 V	1.205	0.59%	4.53%
Red	2.3 V	1.7 V	0.952	2.22%	21.48%

561: Reducing Oscillator Start-Up Delay

24

CLOCK_SETUP	Time Flashing Blue (s)	$V_{initial}$	V_{final}	Energy Used (mJ)	Average Power Used (mW)
0	24	3.16	3	49.280	2.053
0	38	3.275	3	86.281	2.271
0	38	3.29	3	91.205	2.400
0				**Average:**	**2.241**
1	25	3.25	3	78.125	3.125
1	28	3.28	3	87.920	3.140
1	21	3.212	3	65.847	3.136
1				**Average:**	**3.134**
2	11	3.16	3	49.280	4.480
2	26	3.28	3	87.920	3.382
2	12	3.169	3	52.128	4.344
2				**Average:**	**4.069**
3	25	3.267	3	83.664	3.347
3	29	3.295	3	92.851	3.202
3	14	3.162	3	49.912	3.565
3				**Average:**	**3.371**

25 CLOCK_SETUP 0 performs best. It uses the FLL (frequency-locked loop) driven by the slow internal reference clock to drive the CPU and bus at 20.9 MHz. a) The internal oscillator is used. It keeps running when asleep, which lets the system wake up much faster than the external oscillator, reducing the energy consumption for each wake-up. b) The code performs floating-point math, so running faster helps reduce the time the MCU is active. Timer interrupts happen about every 50 ms. Most times the ISR takes 1.57 us (33 cycles) while every 20th takes 36.95 us (772 cycles) Although this clock setup has the highest run mode current consumption (e.g. 6.3 mA), the high clock frequency makes the energy per clock cycle the second lowest (e.g. 90 nJ).

Ultracap on 5V Rail

26a By increasing the initial voltage on the capacitor, we increase the amount of energy stored in the capacitor. If the power requirements remain the same, we should be able to increase the run time since the capacitor would be able to supply that amount of power over a longer period of time.

26b The system won't actually last as long.The 5V supply rail drives the linear voltage regulator (U1), which drops the voltage to 3.3V. The regulator wastes power by dissipating Iout*(Vin-Vout) and Iquiescent*Vin as heat. This wasted power may be large enough to eliminate the benefit of having extra energy stored in the capacitor. Also, as other components in the system run at this higher voltage, it could lead to increased power and energy consumption compared to operating at a lower voltage leading to a lot of power being wasted.

27 (n/a)

28 Note: This is using CLOCK_SETUP 0, OpenSDA disconnected. As expected, the average power is much higher than when using the P3V3 rail (tens of mW v.s a few mW), so the system doesn't run very long at all. The average power used down to 1.7 V is 19.9 mW, while the average power used down to 3.0 V is 70.4 mW. Much more power is used at higher voltages since the linear voltage regulator dissipates it as heat.

	Elapsed Time (since start)	**Time in Voltage Range (s)**	**V_Upper**	**V_Lower**	**Energy Used (mJ)**	**Avg Power Used by System (mW)**
Total Time	0	53.00	4.9	1.7	1056.0	19.92

Blue Time	0.00	10.00	4.804	3	703.9	70.39