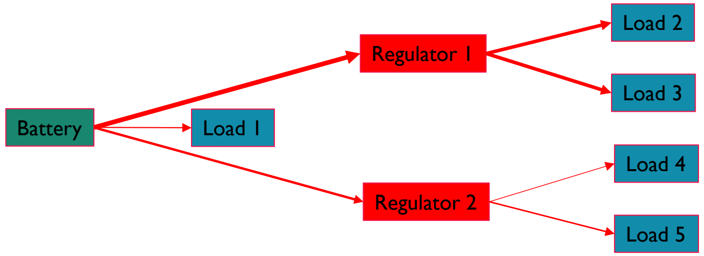
Power and Energy Analysis

The Big Picture

- Analyze: Read the mystery book and find the clues
  - Understand the roadmap (power system architecture)
  - Measure system and subsystem power consumption
  - Build power and energy model to perform "what if" experiments
    - (and re-validate often!)



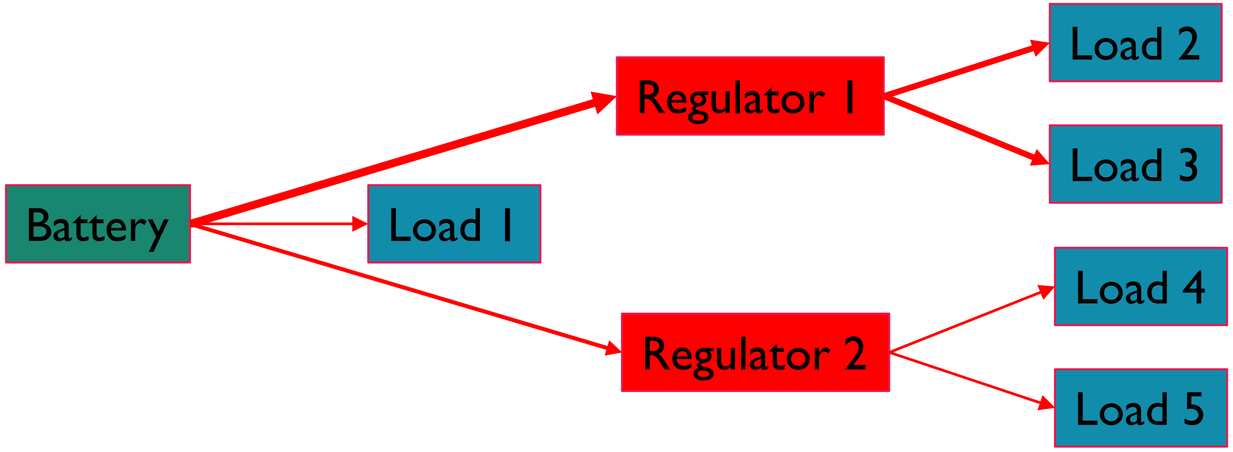
- Optimize: Use the right recipes from the cookbook
  - Apply methods based on dominant consumers

Basic Power and Energy Concepts

- Refresher
  - Power: How quickly am I using energy?
    - Power = current * voltage
    - 1 Watt = 1 Ampere * 1 Volt
    - Useful power: charging capacitors/inductors, emitting light or other EM energy, twisting liquid crystals, etc.
    - Other power dissipated as heat, raising system temperature
  - Energy
    - Energy = power * time = current * voltage * time
    - 1 Joule = 1 Watt * 1 second
- Save energy or power?
  - It depends on dominant limiting factors

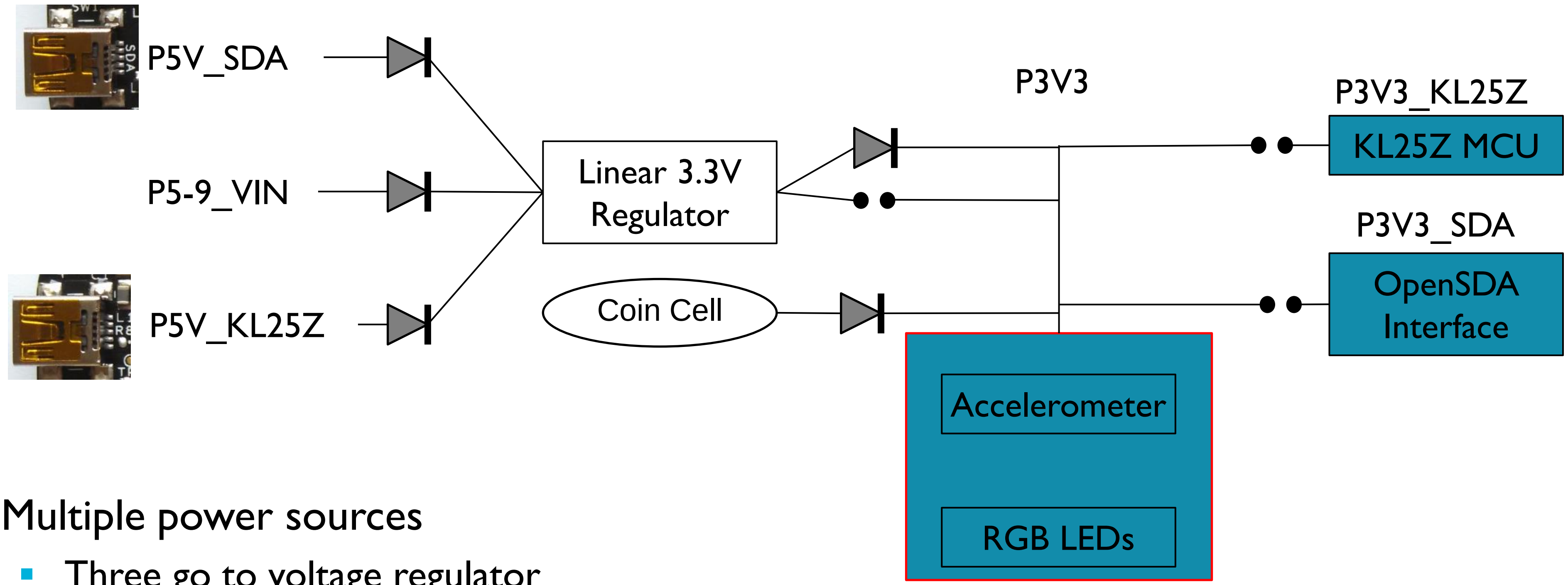
- Power-limited – can't pull energy out of supply quickly enough
  - Solar cell, other energy harvesting sources
  - Old batteries: zinc-carbon, coin cell, potato, lemon
- Energy-limited – not enough energy to pull out
  - Many capacitors, Li-ion or lead-acid battery
- Thermally-limited applications
  - Waste power is dissipated as heat => raises system temperature => reduces performance and reliability
  - High-temperature electronics (digital controller for aircraft turbofan engine)
- Applications with multiple constraints: Gamer's Extreme Cellphone
  - Supply with high power and high energy: large heavy battery
  - Support for high power dissipation: cooling fan

System Power Modeling



- Model the system
  - Can predict behavior without having to build it or make changes
  - Need to validate model to ensure it's accurate enough for the application
- Loads
  - MCU
  - Peripherals
- Power supply components
  - Voltage regulators and converters
  - Protection diodes

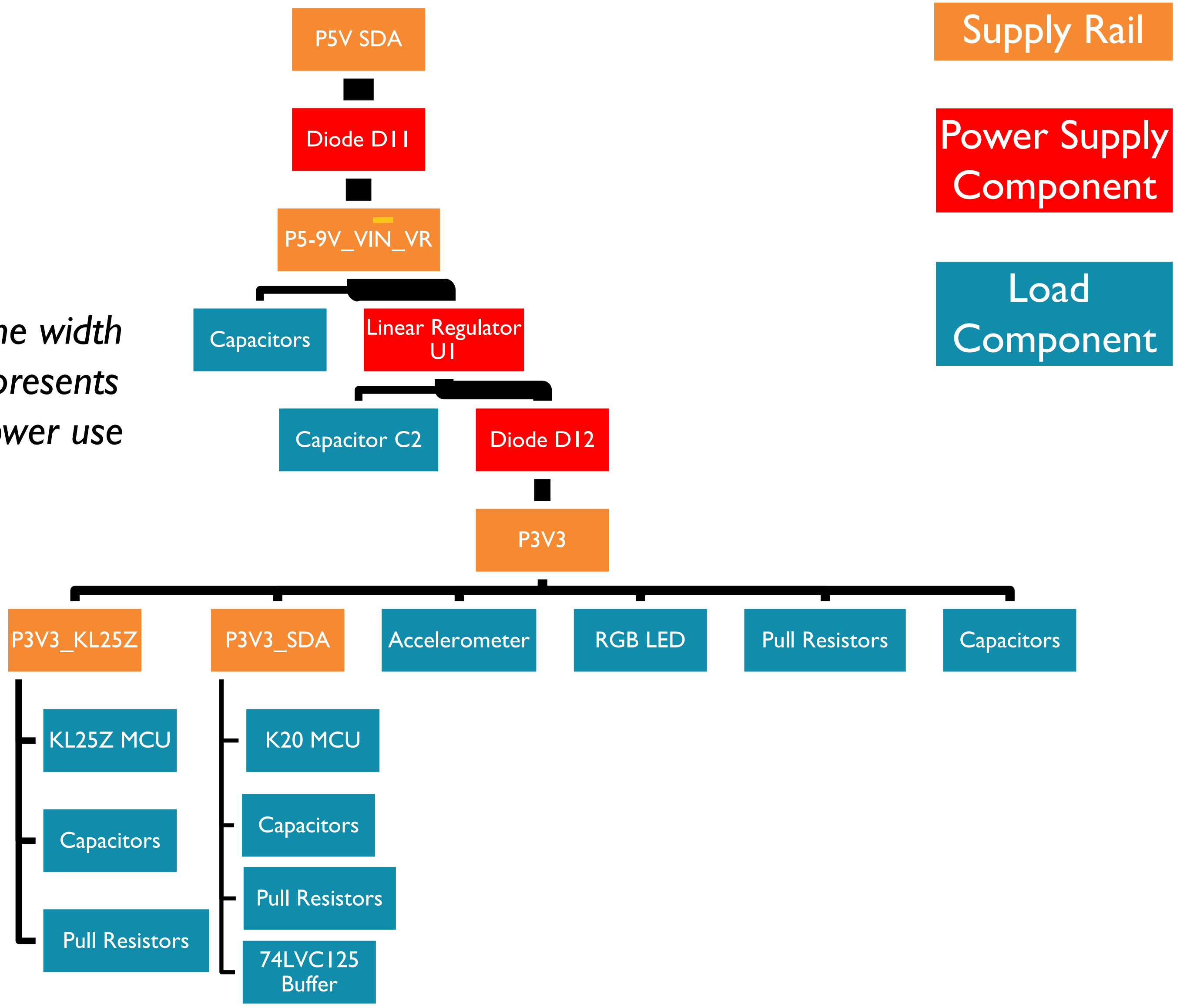
Freedom KL25Z Board Power Architecture



- Multiple power sources
  - Three go to voltage regulator
  - One (coin cell) is not regulated
- Diodes protect against damage if multiple power sources are connected simultaneously
- Multiple power domains (P3V3, P3V3_KL25Z, P3V3_SDA)

FRDM-KL25Z Power System Architecture Summary

Line width represents power use



- Modeling Approach
  - Build spreadsheet model for each component and supply rail
  - Initially ignore pull resistors and capacitors, add them later if needed

Component	Current (mA)	Voltage (V)	Power (mW)
Linear Regulator	20.14	1.7	34.23
Series Diode (D12)	14.14	0.22	3.11
KL25Z MCU	5.80	3.30	19.14
Red LED	2.75	3.30	9.08
Green LED	2.75	3.30	9.08
Blue LED	2.75	3.30	9.08
Accelerometer	0.09	3.30	0.28
SDA	8.85	3.30	29.21
Total Power			113.19

Spreadsheet Model

Item	Duty Cycle	Active Current (mA)	Average Current (mA)	Voltage (V)	Power (mW)
P5_SDA					
Series Diode (D11)	1				
P5-9V_VIN_VR Rail					
Linear Regulator (U1)	1	6.00	6.00	1.7	0.000
Series Diode (D12)	1	0.00	0.00	0.22	0.000
P3V3 Rail			32.08		105.867

Item	Duty Cycle	Active Current (mA)	Average Current (mA)	Voltage (V)	Power (mW)
P3V3 Rail			32.08		105.867
Accelerometer	1.000	0.09	0.09	3.30	0.281
Red LED	0.010	6.47	0.06	3.30	0.214
Green LED	0.010	2.43	0.02	3.30	0.080
Blue LED	0.010	2.86	0.03	3.30	0.094
Capacitors	1.000		0.00	3.30	0.000
LCD controller	1.000	6.00	6.00	3.30	19.800
LCD backlight	0.170	66.00	11.22	3.30	37.026
Touchscreen	0.001	8.25	0.01	3.30	0.027
uSD Card			0.00	3.30	0.000
SMPS			0.00	3.30	0.000
Audio Amp			0.00	3.30	0.000
P3V3_KL25Z			5.80		19.140
P3V3_SDA			8.85		29.205

Item	Duty Cycle	Active Current (mA)	Average Current (mA)	Voltage (V)	Power (mW)
P3V3_KL25Z			5.80		19.140
KL25Z MCU	1	5.80	5.80	3.30	19.140
Pull Resistors	1	0.00			0.000
Capacitors	1	0			0.000
P3V3_SDA			8.85		29.205
SDA	1	8.85	8.85	3.30	29.205
Pull Resistors	1				0.000
74LVC125 Buffer	1				0.000
Capacitors	1				0.000

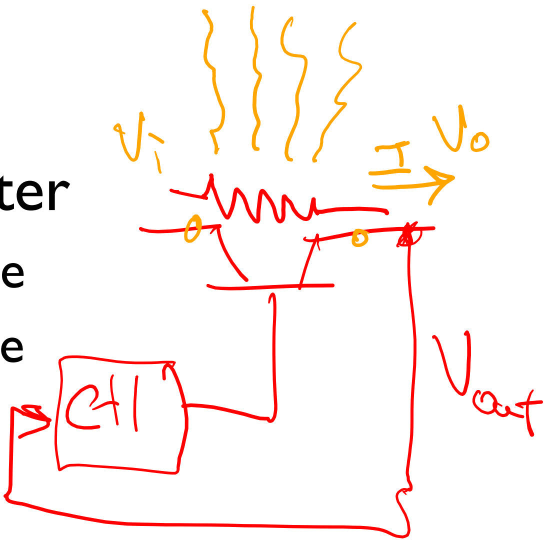
- Get initial estimates of current (at given V) from device datasheets, manuals
  - Look for "Electrical Characteristics" or similar
  - KL25Z MCU
  - SDA MCU (K20)
  - RGB LEDs
  - Accelerometer
- Add to spreadsheet
- Then refine model
  - **Validate** with measurements
  - **Improve accuracy** of device models (frequency dependence, duty cycle…)

Power Converter Modeling

$P = I \cdot (V_i - V_o)$

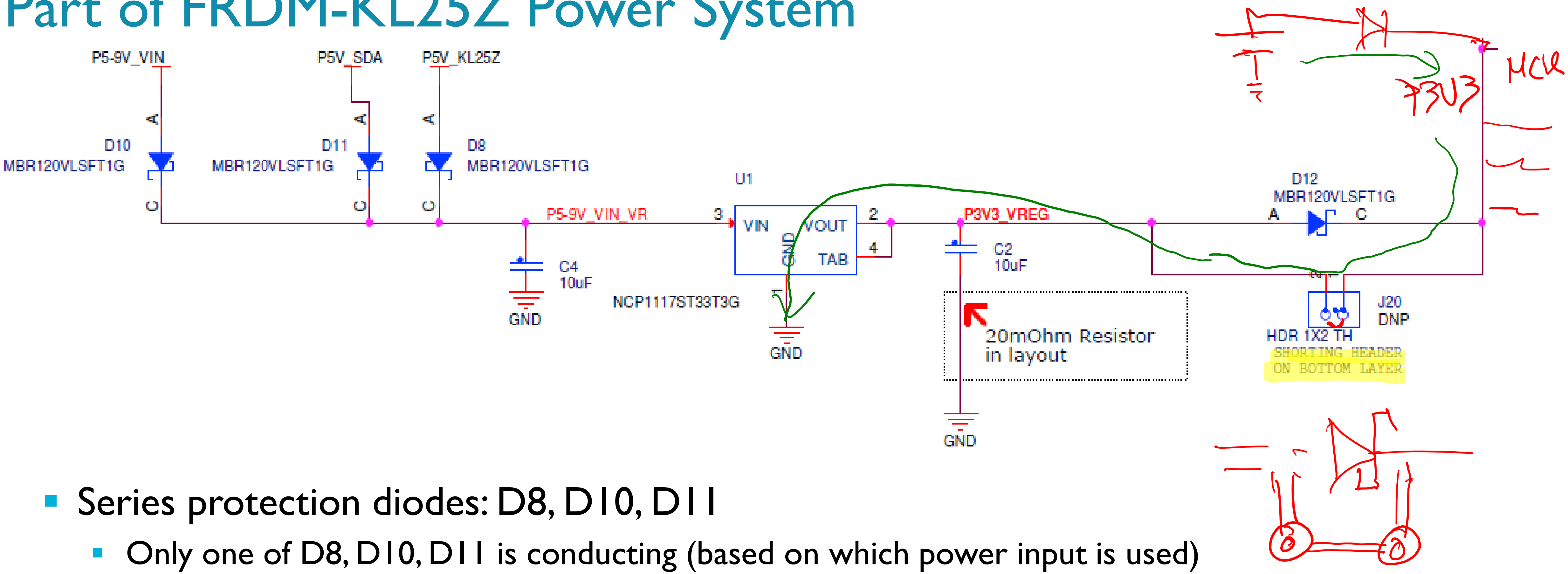
- Power system components
  - Power converters to change voltage
  - Diodes to ensure one-way power delivery
  - Switches to route power
- Power converter typically regulates its output voltage
  - Output voltage is ***constant*** regardless of changes in input voltage or output impedance (load)

- Linear power converter
  - Can only lower voltage
  - Simple and inexpensive
  - Generally inefficient



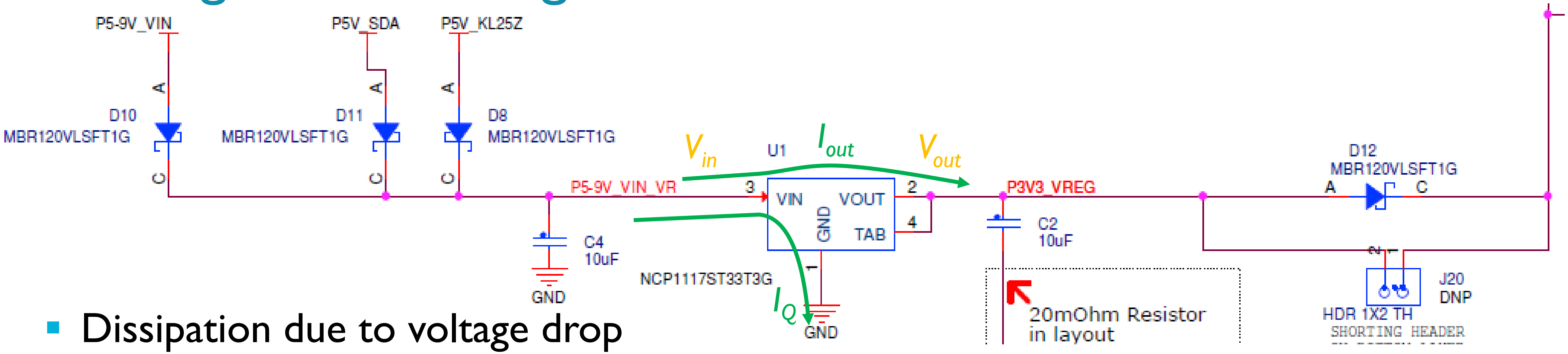
- Switching power converter
  - Can lower or raise voltage, depending on topology
  - More complicated and therefore more expensive
  - Can be very efficient

Part of FRDM-KL25Z Power System



- Series protection diodes: D8, D10, D11
  - Only one of D8, D10, D11 is conducting (based on which power input is used)
- Linear voltage regulator: U1
- Series protection diode: D12
  - Prevents coin cell (or other P3V3 source) from back-driving U1
  - Must cut shorting trace J20 so D12 will operate

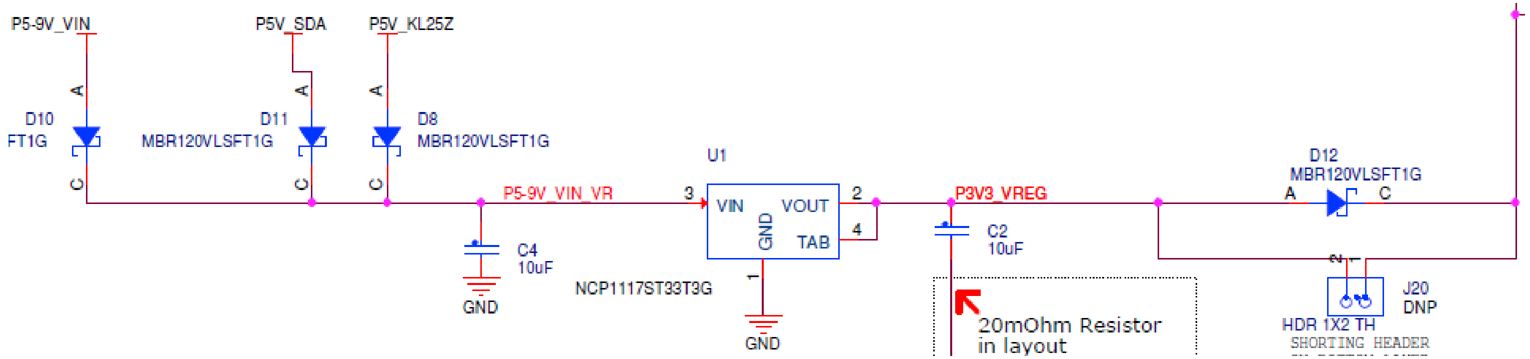
Modeling of Linear Regulator U1



- Dissipation due to voltage drop
  - $P_{drop} = I_{out} (V_{in} - V_{out})$
- Quiescent current: examine datasheet for NCP1117
  - $P_Q = I_Q V_{in}$
  - Have data for V_{in} =15 V
  - What is I_Q for V_{in} = 5 V? Should measure it.

	Symbol	Min	Typ	Max	Unit
Quiescent Current	I_Q				mA
1.5 V (V_{in} = 11.5 V)		–	3.6	10	
1.8 V (V_{in} = 11.8 V)		–	4.2	10	
1.9 V (V_{in} = 11.9 V)		–	4.3	10	
2.0 V (V_{in} = 12 V)		–	4.5	10	
2.5 V (V_{in} = 10 V)		–	5.2	10	
2.85 V (V_{in} = 10 V)		–	5.5	10	
3.3 V (V_{in} = 15 V)		–	6.0	10	
5.0 V (V_{in} = 15 V)		–	6.0	10	
12 V (V_{in} = 20 V)		–	6.0	10	

Modeling of Diodes D8, D10, D11, D12



- Series protection diodes: $P = IV$
- Only one (or two) will be active and dissipating power
- Examine datasheet for MBR120VLS I/V curves
  - About 0.25 V at 0.1 A (100 mA)
  - What about at 25 mA? Could measure, extrapolate or use diode model (https://en.wikipedia.org/wiki/Diode_modelling)

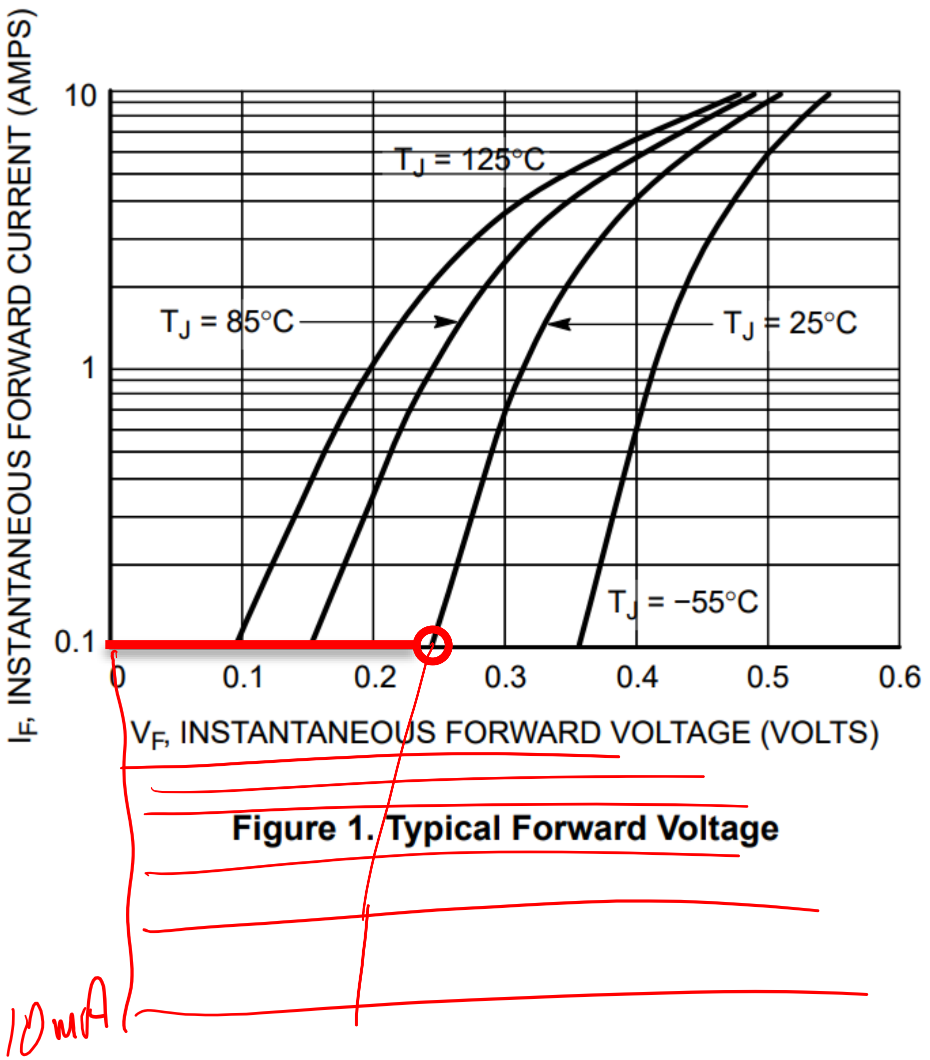
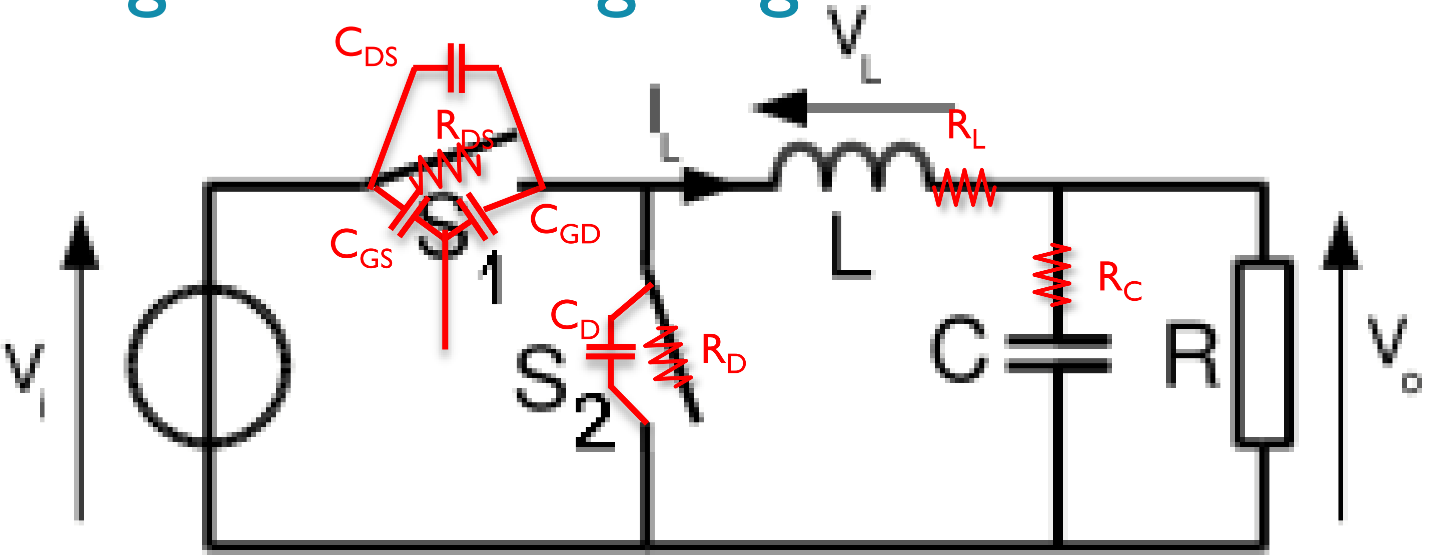


Figure 1. Typical Forward Voltage

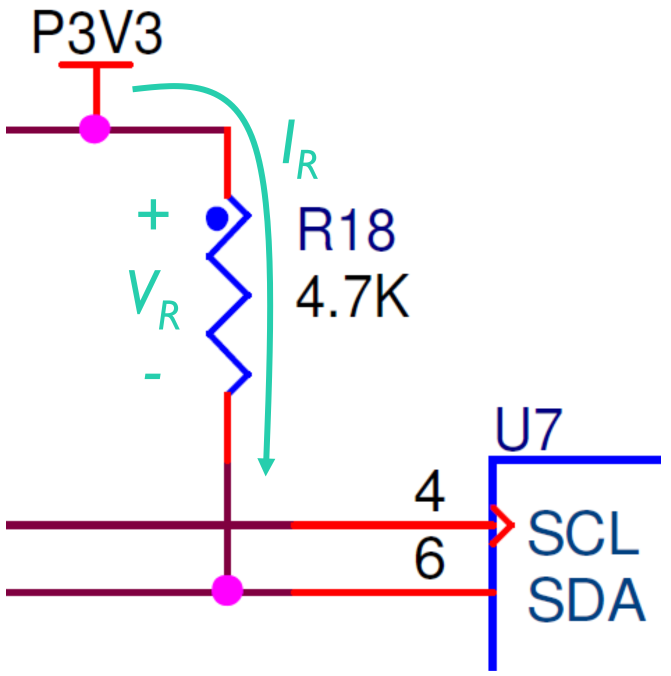
Modeling of Switching Regulator

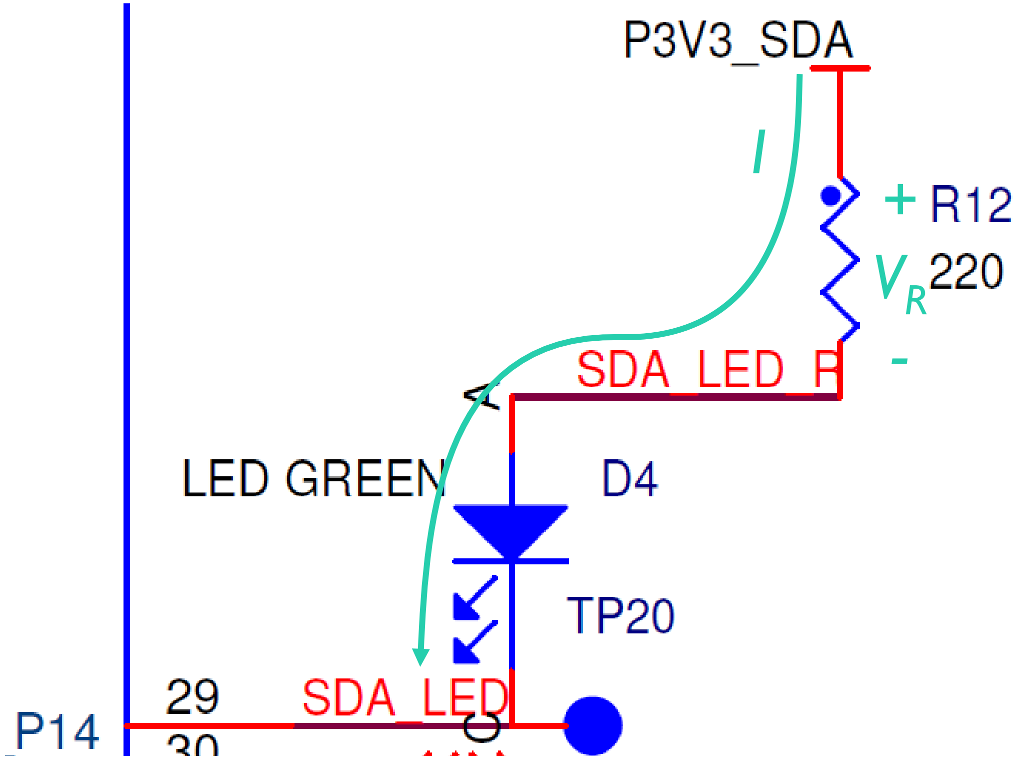


Parasitic resistances and capacitances waste power, reducing efficiency

- Efficiency limited by *parasitics*
- Two types of losses
- **Conduction losses** depend on load current: I^2*R, or $I*V$
  - Resistance of Switches (S1, S2) when on: R_{DS}, R_D
  - Resistance of inductor: R_L
  - Voltage drop across diode when on: V_D
  - Equivalent series resistance of input and output capacitors: R_C
- **Switching losses** depend on switching frequency: $f_{sw}*C*V^2$
  - Each switching transition requires charging/discharging parasitic capacitances in transistor and diode
  - The slower the transition, the more time transistors are not fully on or fully off

Power Models for Resistors and LEDs

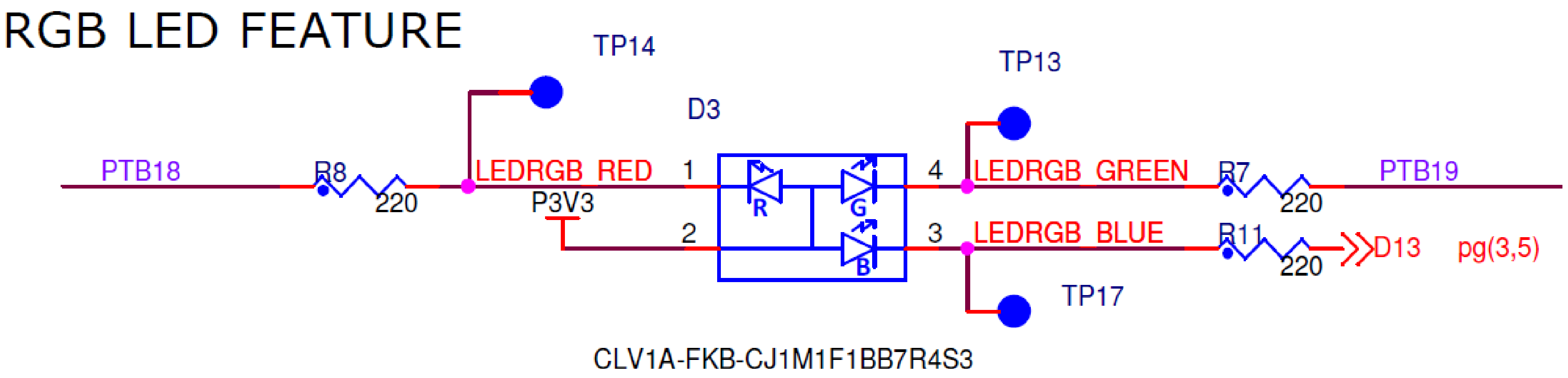




- Pull-up or pull-down resistor
  - Start with $P = V_R^2/R$
- Need to factor in duty cycle D
  - Fraction of time component is powered
  - $P_R = DV_R^2/R$
  - $P_R = DI_R^2R$

- LED with current-limiting resistor
  - Measure V_R across resistor with LED turned on
  - $P_R = DV_R^2/R$
  - $I = DV_R/R$
  - $P_{LED} = DI * (V_{CC} - V_R)$

RGB LED Power Modeling



- Measure voltage at test points (TP) to determine V, I, P for resistors and LEDs
- Evaluate total power for LED+R

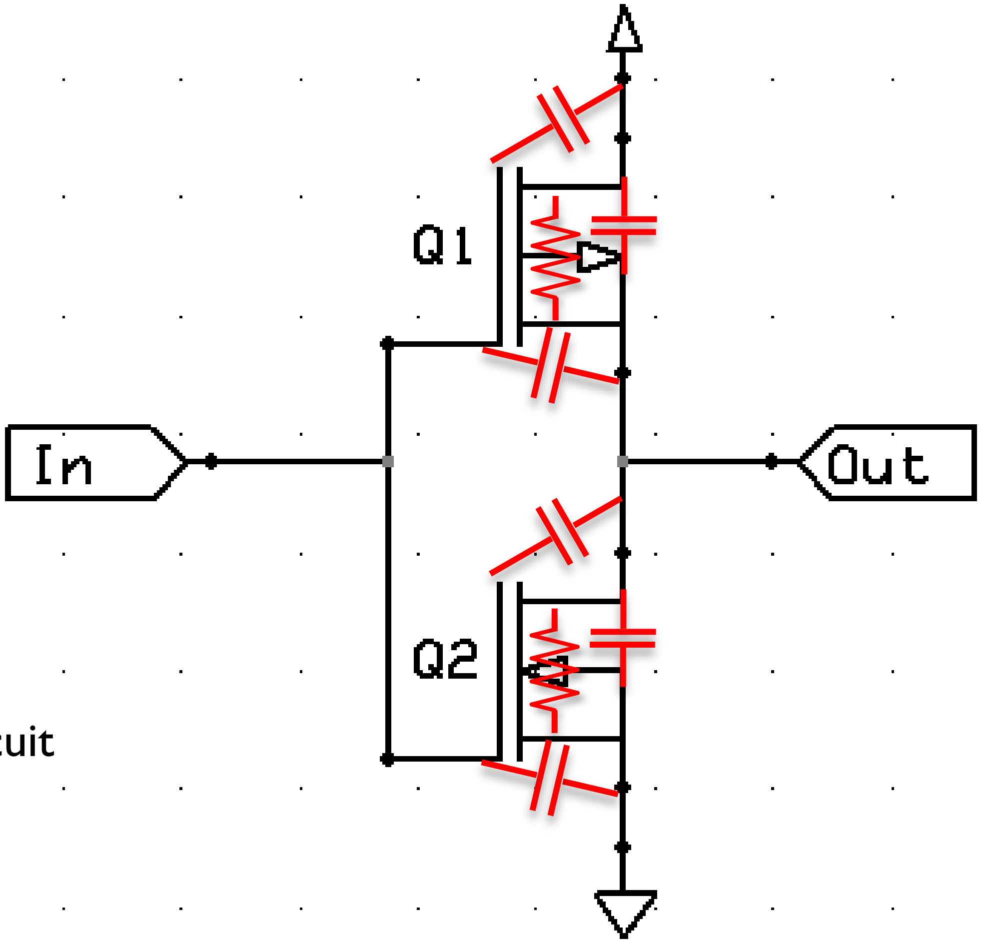
Color	V_TP	I (mA)	V_R	P_R (mW)	V_LED	P_LED (mW)
Red	1.272	5.782	1.272	7.354	2.02	11.679
Green	0.494	2.245	0.494	1.109	2.798	6.283
Blue	0.46	2.091	0.46	0.962	2.832	5.921

R	220
V	3.292

Digging deeper: https://en.wikipedia.org/wiki/Diode_modelling#Explicit_solution

Power Model for Digital Logic Circuits

- Digital logic power: $P = P_{Static} + P_{Dynamic}$
- Must consider the parasitic circuit elements
- Static component from leakage currents
  - $P_{Static} = (W/L)I_{S0}e^{(-Voff+Vth)/(nVt)}V_{cc}^2$
  - Current which flows even when transistor is off: Conductivity S_P
  - Approximate as *quadratic* with supply voltage V_{CC}: $P_{Static} = S_PV_{CC}^2$
  - Grows as supply voltage get closer to transistor threshold voltage
  - Can cut off power to unused regions of chip
- Dynamic component from switching activity
  - $P_{Dynamic} = C_PV_{CC}^2f_{Clock}$
  - "Capacitance" C_P describes capacitances (gates, wires) and short-circuit currents
  - *Quadratic* with supply voltage V_{CC} and *linear* with frequency f_{Clock}
  - Can reduce by supplying clock only to transistors which need to do something (clock gating)
- Model: $P = S_PV_{CC}^2 + C_PV_{CC}^2f_{Clock}$



Modeling a Different Frequency: KL25Z MCU

- Want MCU power model in form $P_i = V_i^2 (S_{P,i} + C_{P,i} f_{Clock,i})$
  - Then can tweak supply voltage and clock frequency
- Examine KL25Z MCU datasheet for current and power consumption
- Datasheet Figure 2
  - Peripheral clock gating can reduce dynamic power use
  - Horizontal axis obscures relationship between current and core frequency

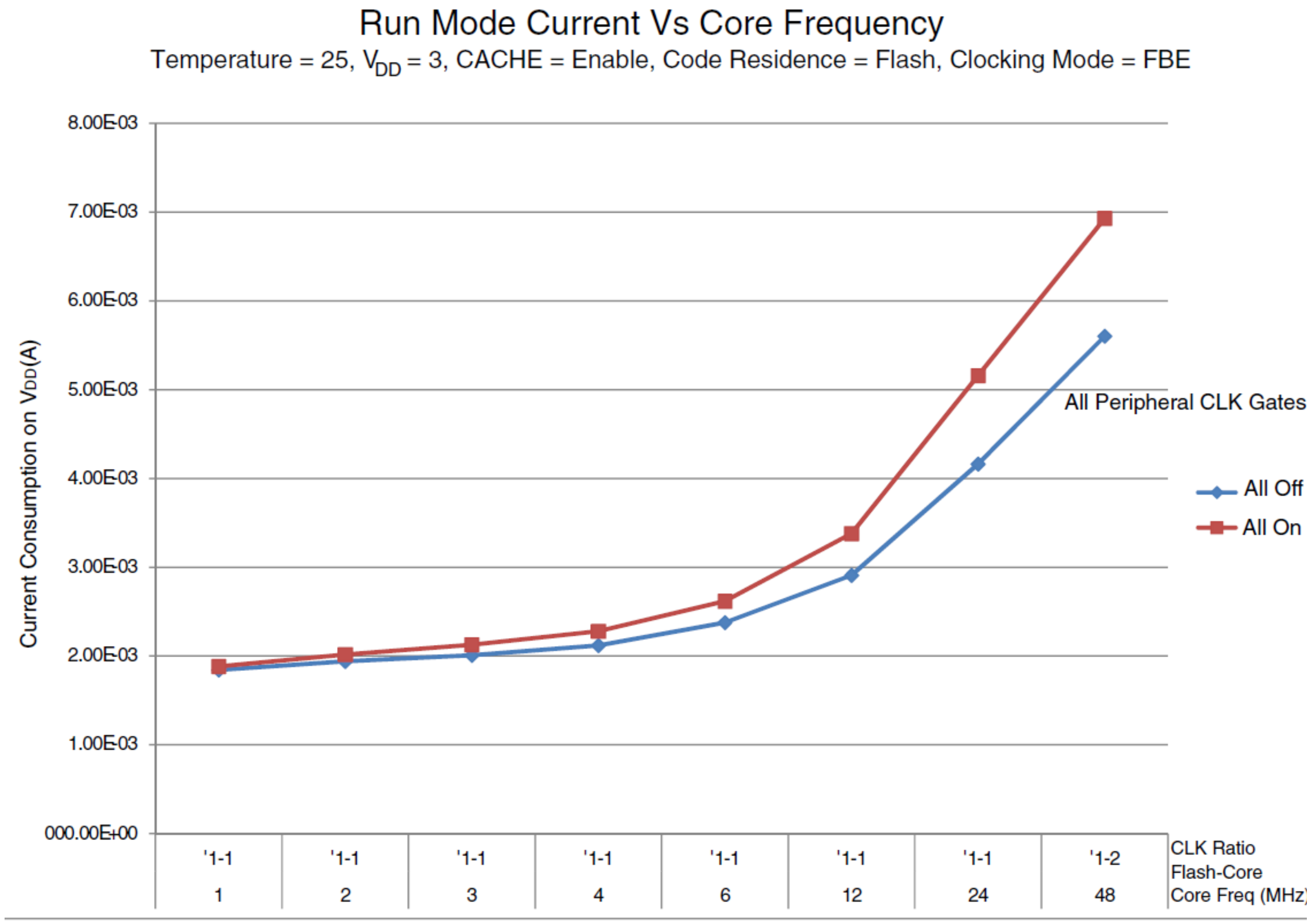
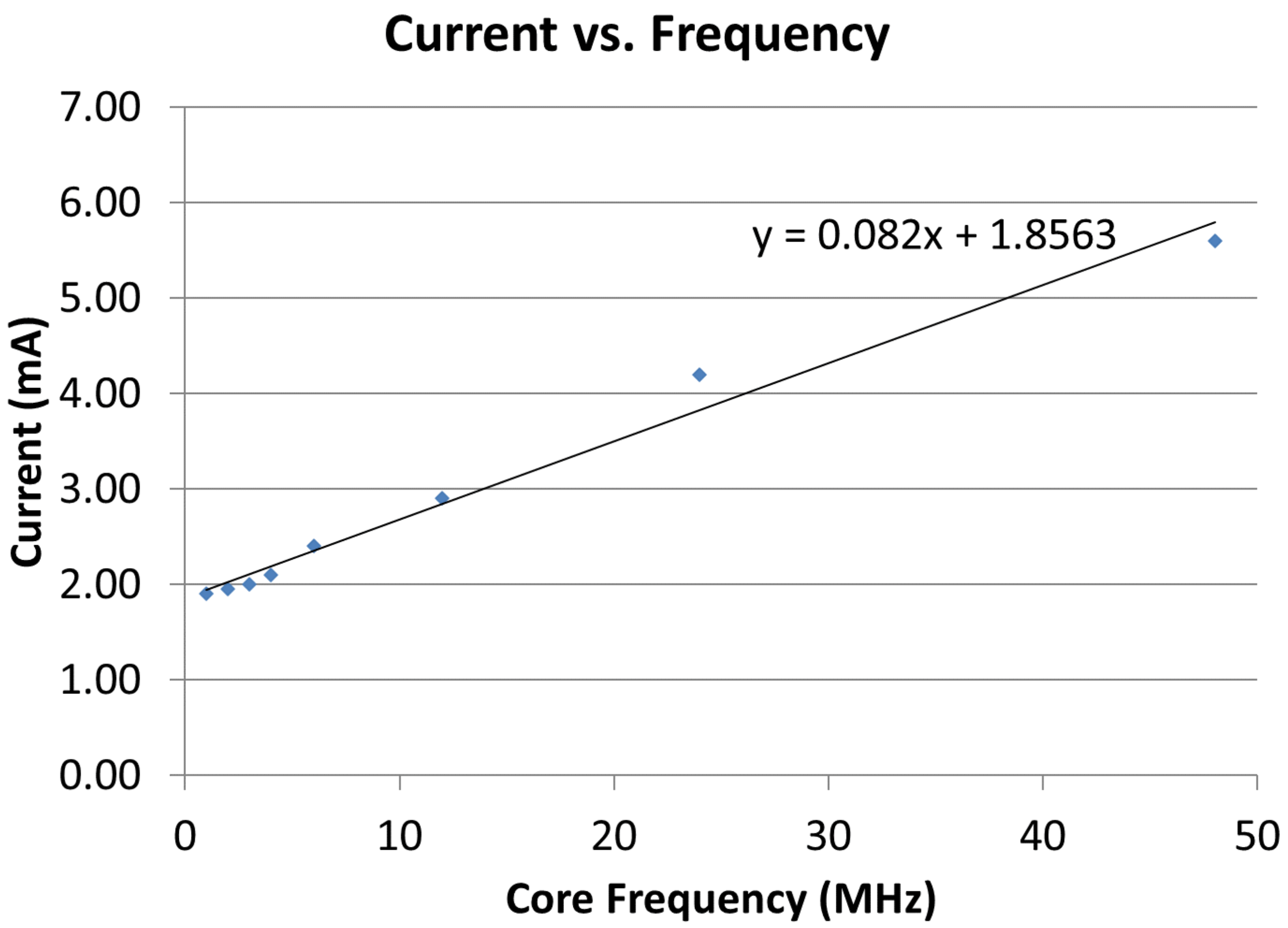


Figure 2. Run mode supply current vs. core frequency

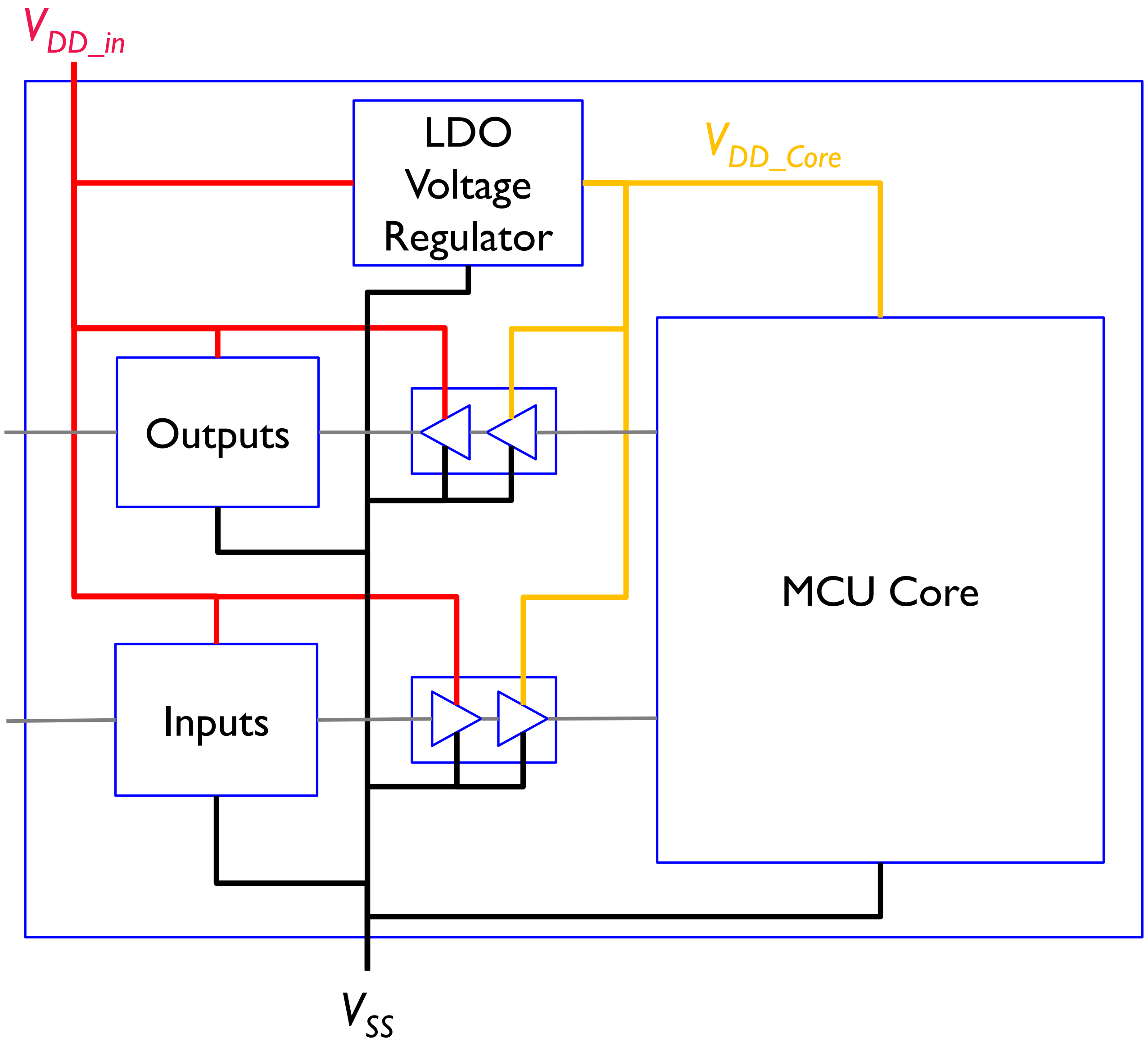
Modeling a Different Frequency: KL25Z MCU

- Plot previous data with linear X axis
  - Here, all peripheral clock gates are OFF
- Linear curve fitting
  - $I_{MCU}(f_{Clock}) = (f_{Clock} * 82\ \mu A/MHz) + 1.8563\ mA$



Modeling a Different Voltage: KL25Z MCU

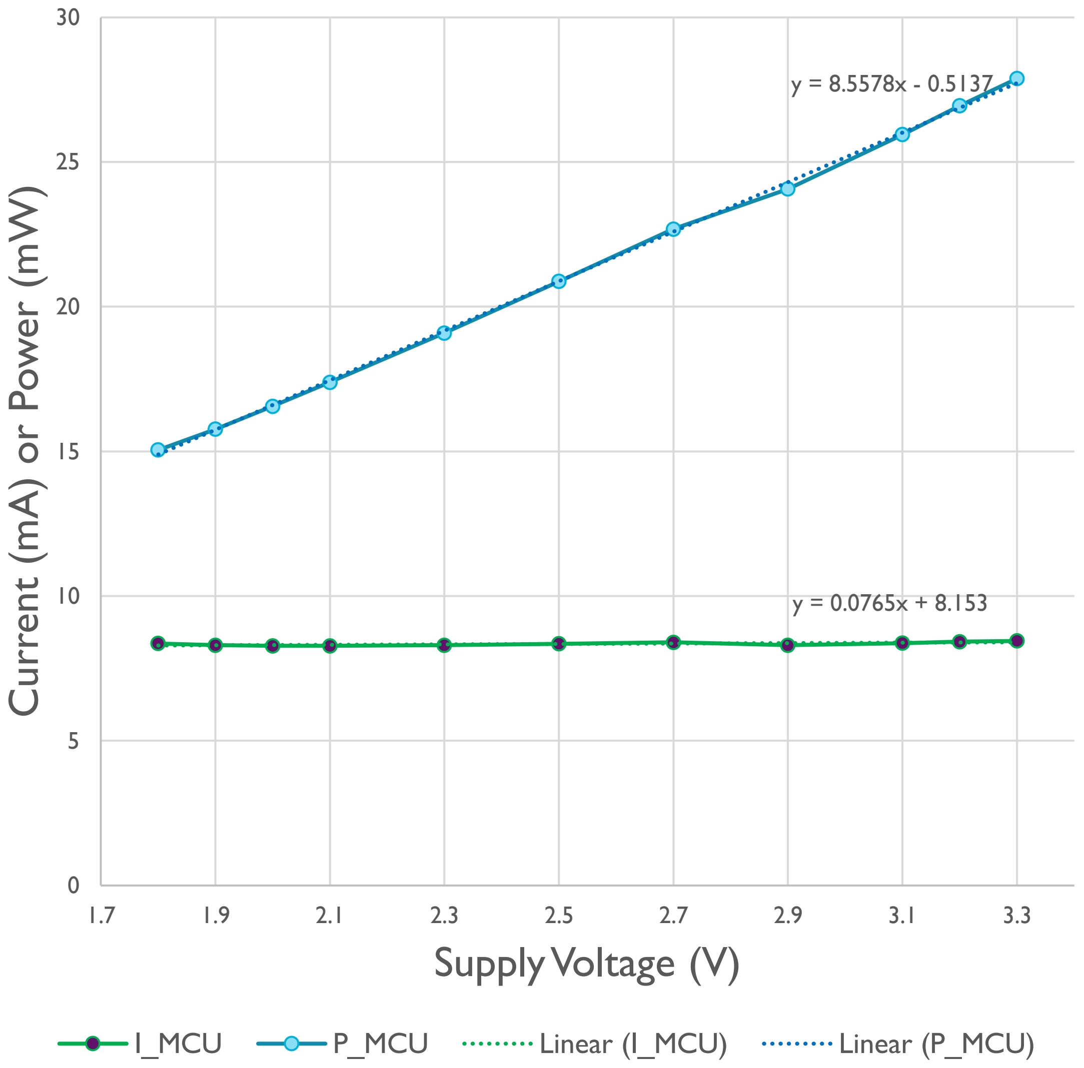
- General case: $P_i = V_i^2 \, (S_{P,i} + C_{P,i} f_{Clock,i})$
- Doesn't apply to KL25Z MCU and many other MCUs
- Use multiple voltage domains to save power
  - Run I/O circuits at supplied voltage
  - Run core at lower voltage
- Support circuits needed
  - Internal low-dropout linear voltage regulator (LDO) drops supplied voltage
  - Digital level shifter buffers translate signals between voltage domains



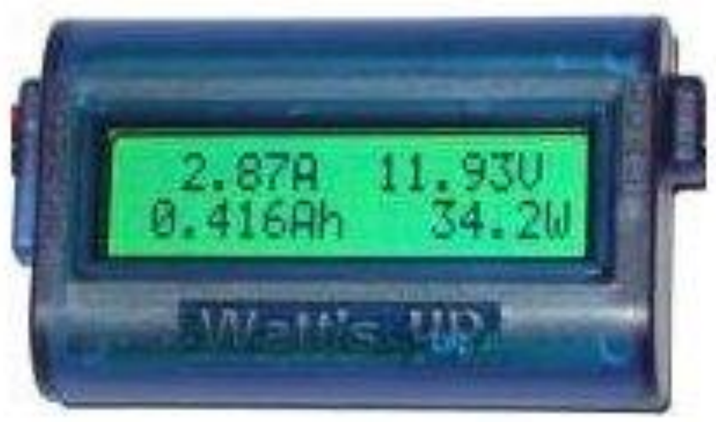
KL25Z MCU Current and Power with Varying Voltage

- Test conditions
  - Powered MCU with AD2 adjustable voltage supply,
  - MCU running Lab 2 code
  - Measured MCU current with FRDM-KL25Z's built-in shunt resistor

- Results
  - Current is nearly flat: 8.28 to 8.45 mA
  - Power rises nearly linearly with voltage
    - P = (8.5578 mA * V_i) – 5.137 mW



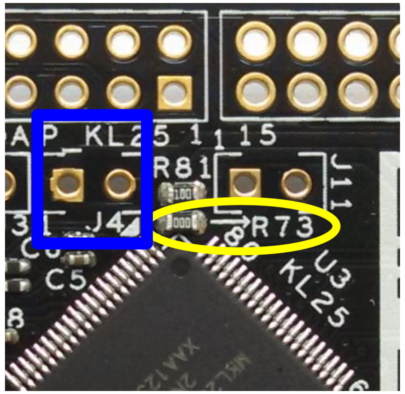
How Do We Measure Power?

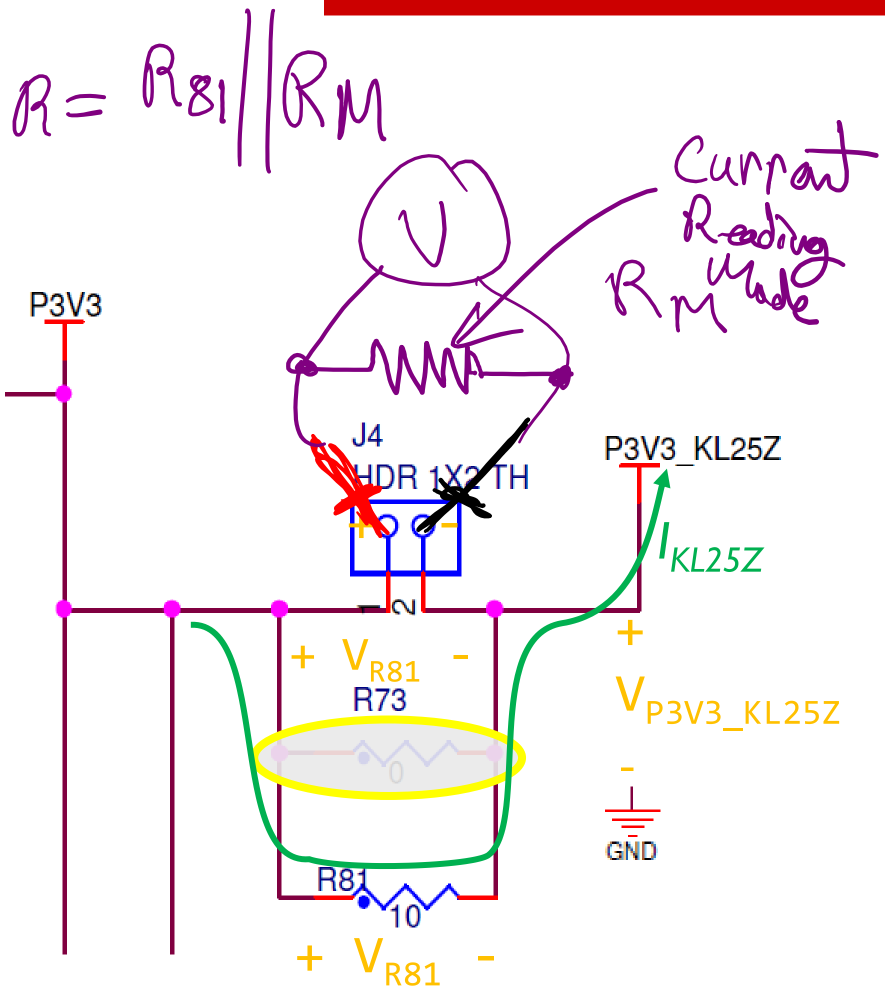


- Power = V*I
- Use a multimeter if we have a fixed, known voltage
  - Measure current, multiply by voltage
- Use a power meter if we have a varying voltage
  - USB power meters available
  - Make a power meter with another Freedom KL25Z board!

How Can We Measure MCU Current?

- P3V3: Output voltage from linear 3.3 V regulator
- P3V3_KL25Z: Connected only to MCU power (and VREF) pins
- Remove shorting resistor R73
- MCU current I_{KL25Z} will flow through R81
- Measure voltage V_{R81} across J4 (P_KL25 on PCB). Not ground-referenced!
- MCU current $I_{KL25Z} = V_{R81}$ / R81
  - Nominally 10 ohms
- Power = $V_{P3V3\_KL25Z} * I_{KL25Z}$



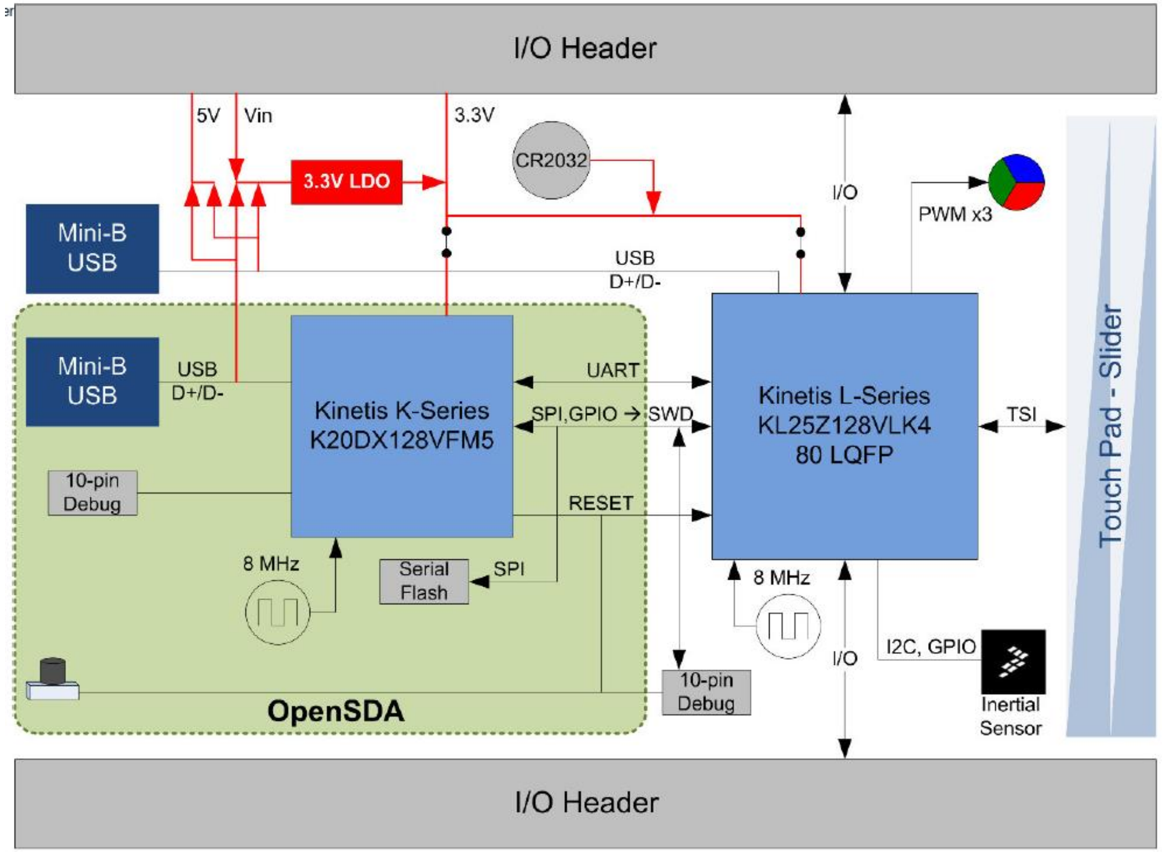


- *Warning*: Putting a DMM across J4 to measure current will give inaccurate results because the DMM's shunt resistor is in parallel with R81 (and R73, if not already removed)
- Insert J4 header and short with jumper for normal operation (no drop across R81)

$$I_{KL25Z} = V_{R81}/10\Omega$$

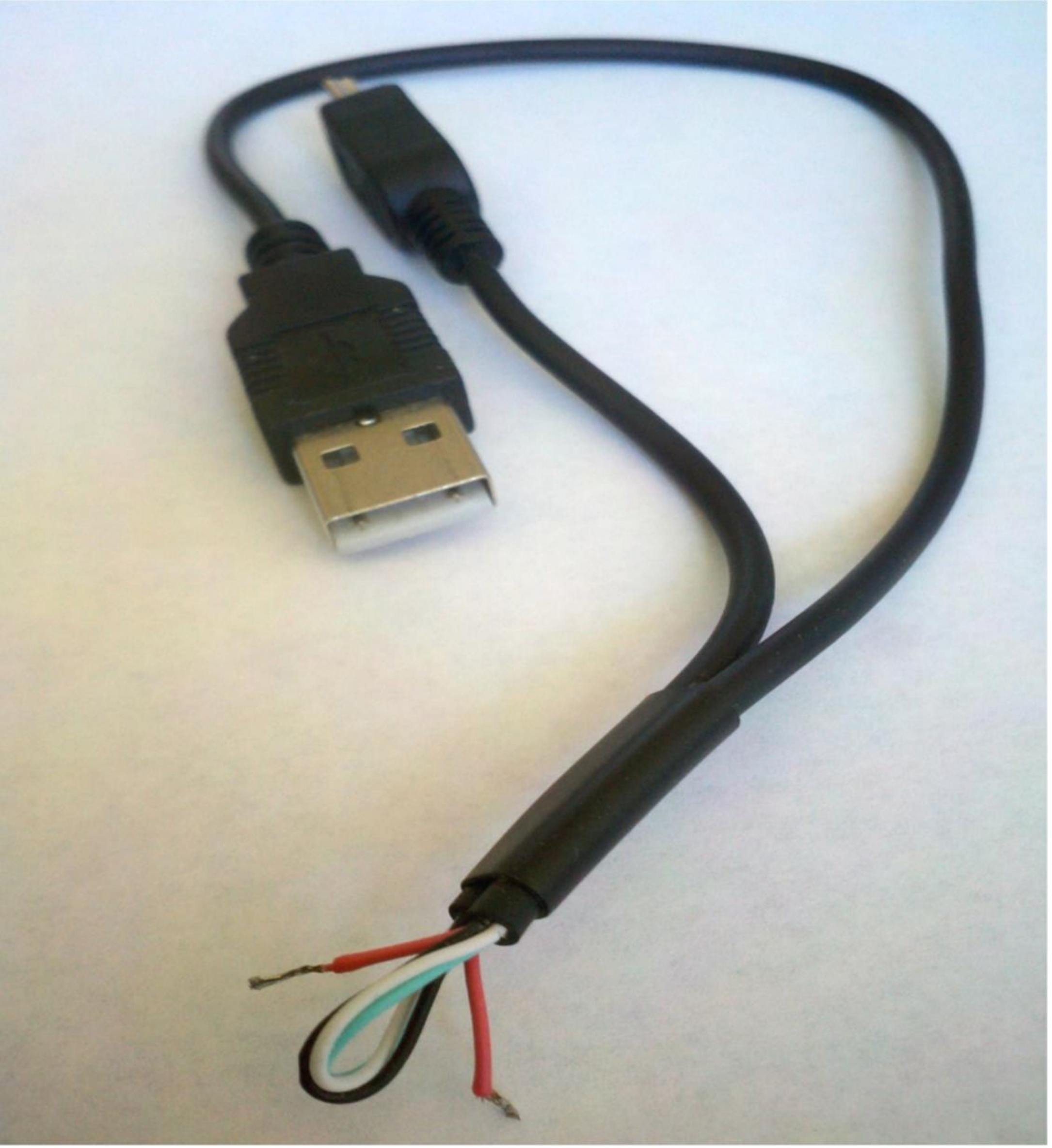
$$P_{KL25Z} = V_{P3V3\_KL25Z} * I_{KL25Z} = V_{P3V3\_KL25Z} * V_{R81}/10\Omega$$

System Power vs. MCU Power



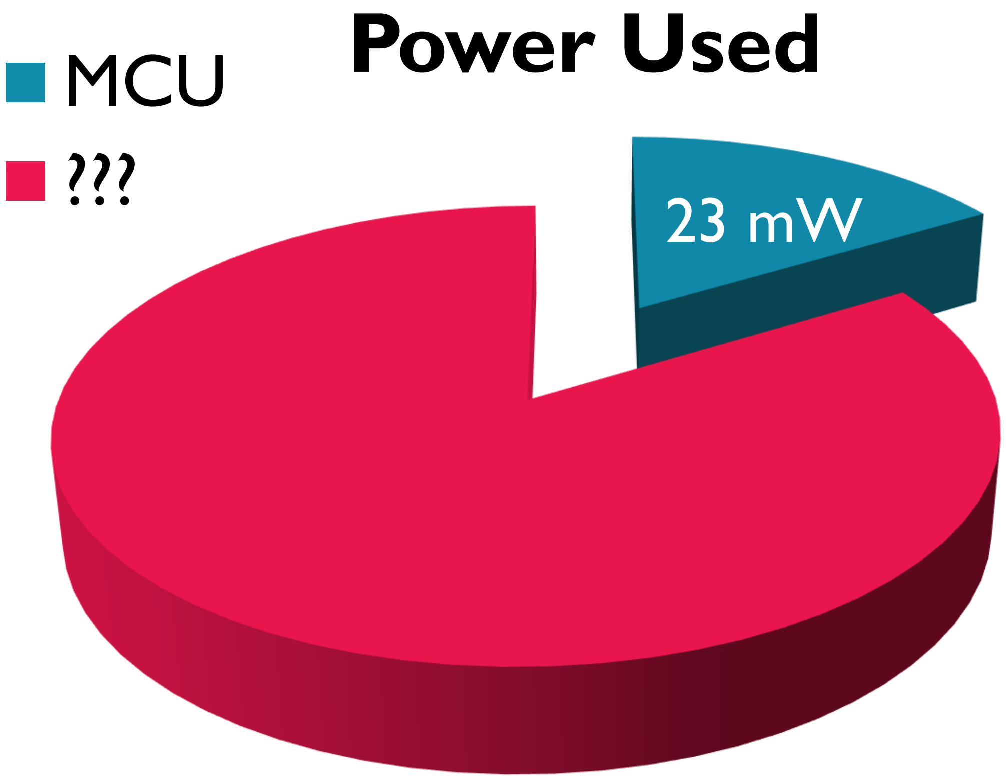
- The MCU uses up to 3.3 V * 7 mA ~ 23 mW
- Many embedded systems have peripheral circuitry, and that also draws power! So we need to consider that as well.
- The Freedom board is no exception – it is a good example.

Freedom Board Power Analysis



- Measure current and voltage, multiply together to find power
- First measure current by putting ammeter in series with power supply line
  - Hack a USB cable
    - Remove outer insulation
    - Cut the red wire and strip off a little insulation from each end
  - Connect the ammeter across the two red ends
  - Measure current I_{USB}
- Second, multiply by voltage to get power
  - $P_{USB} \approx 5 * I_{USB}$
  - USB supply voltage is nominally 5V, but may be 4.8 V to 5.1 V. Should measure to confirm actual value.

Results of Freedom Board Power Analysis



- Wow! How surprising!
  - If we've built a power model, this measurement is *not* a surprise
- Where is the rest of the power going?
  - You will see in the power and energy lab

How Do We Measure Energy (W)?

- Harder to measure, need to integrate power over time

$$W(T) = \int_0^T V(t)I(t)dt$$

- V and I will vary as we turn on and off devices, change clock speeds, etc.
- Use energy meter? Consider performance requirements
- Voltage range: 1.8 V to 5.1 V
- Current range: 1 µA to 100 mA
- Fast sampling rate
  - MCU may wake up for only a few tens of microseconds before going to sleep.
  - Too low of a sample rate will reduce accuracy.

Capacitor-Based Energy Measurement

- Power the circuit from a large capacitor (e.g. 0.1 F)
- Measure capacitor voltage before operation (V_1)
- Measure capacitor voltage after operation (V_2)
- Calculate energy *W* used for the operation:

$$W = C\frac{V_1^2 - V_2^2}{2}$$

- Average power is energy divided by time

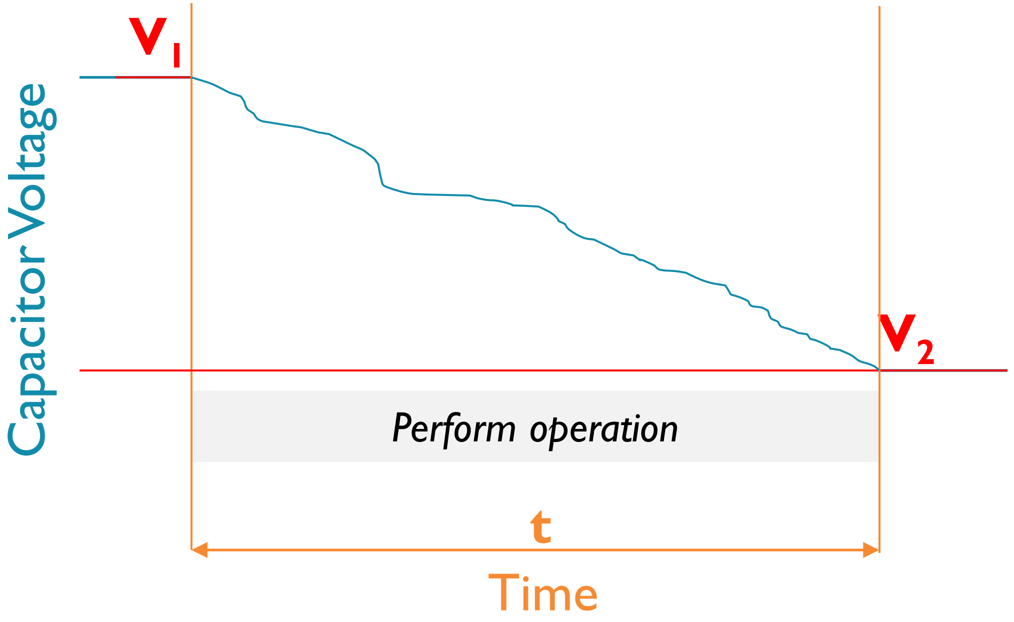
$$P = C\frac{V_1^2 - V_2^2}{2t}$$

- How low can the MCU go? Check datasheet

5.2.1 Voltage and current operating requirements

Table 1. Voltage and current operating requirements

Symbol	Description	Min.	Max.	Unit
V_{DD}	Supply voltage	1.71	3.6	V
V_{DDA}	Analog supply voltage	1.71	3.6	V



- Note that current drawn by circuit may depend on supply voltage, changing over time as V falls

Useful References

- A **constant current load** *I* will take *t* seconds to discharge the capacitor from V_1 to V_2:

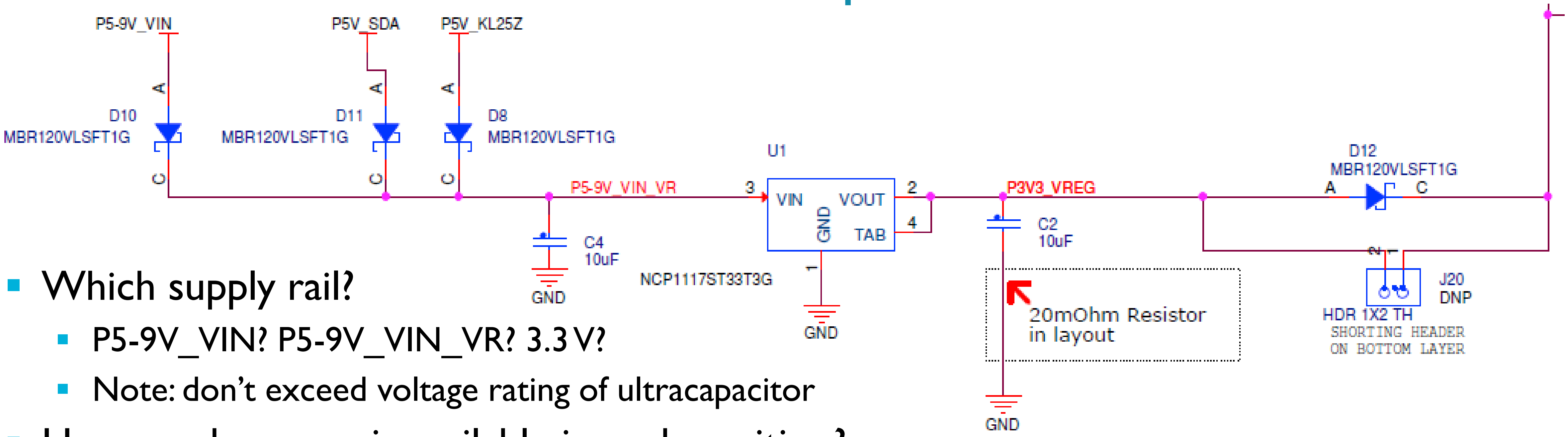
$$t = C\frac{(V_1 - V_2)}{I}$$

- A **constant resistance** load R will take *t* seconds to discharge the capacitor from V_1 to V_2:

$$t = -CR\, ln\frac{V_2}{V_1}$$

- Example reference cases
  - Assume C = 0.1 F, V_1 = 3.3 V, V_2 = 1.8 V
- Constant current: I = 10 mA
  - t = 0.1F(3.3 V-1.8V)/10 mA = 15 seconds
- Constant load resistance: R = 1 kΩ
  - t = -0.1F*1kΩ ln(1.8V/3.3V)= 60.6 seconds

Where Should We Put the Ultracapacitor?

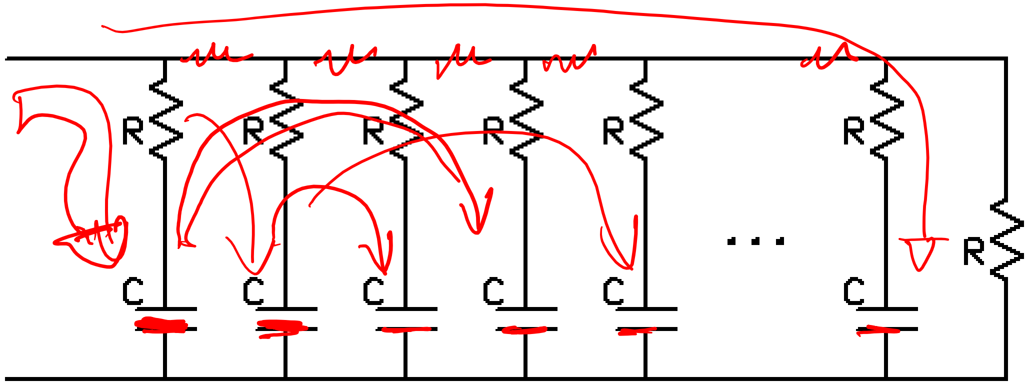


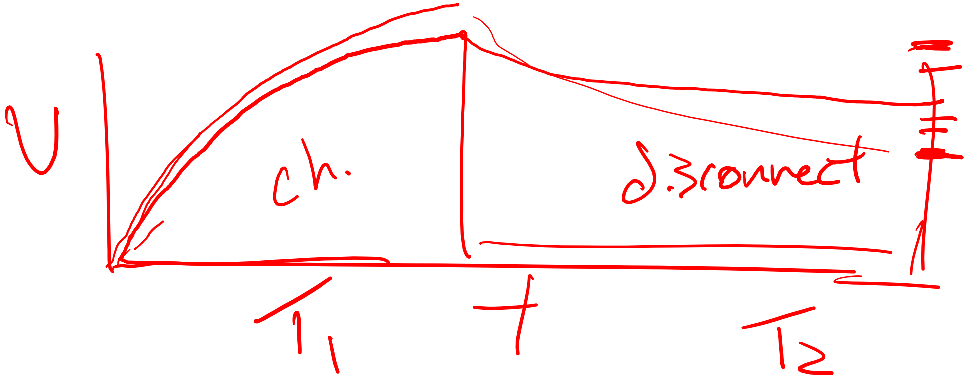
- Which supply rail?
  - P5-9V_VIN? P5-9V_VIN_VR? 3.3 V?
  - Note: don't exceed voltage rating of ultracapacitor
- How much energy is available in each position?
  - $W = C\frac{V_1^2 - V_2^2}{2}$
  - 3.3V: W = C(3.3^2-1.7^2)/2 = C*4.0 J
  - 5.0V: W = C(5.0^2-1.7^2)/2 = C*11.055 J
- Almost 3x energy available if we charge to 5 V
- Trade-offs: Higher voltage vs. more circuitry to power. Will examine in lab.

Cautions

- Equivalent circuit
  - Many small capacitors connected with resistors
  - Time is needed for charge equalization
  - Long time constant
  - Solution: When testing, charge for a fixed amount of time (e.g. 2 minutes)

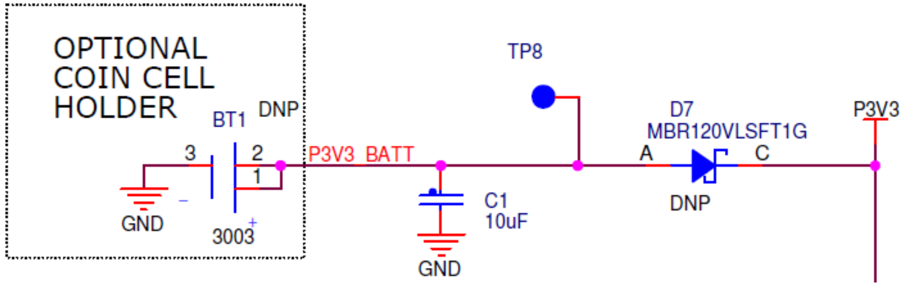
- Value tolerance
  - Example: real capacitance may be between 20% less and 85% more than rated capacitance
  - Solution: Consistently use one capacitor for testing, don't switch

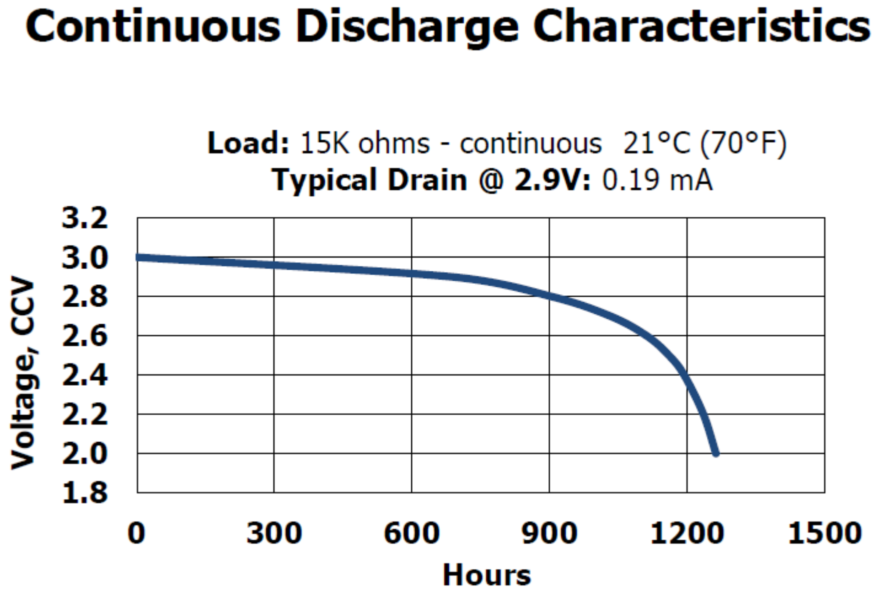




KL25Z Optional Power Source

- CR2032 Lithium coin cell
- Add cell & holder to bottom of PCB
  - Diode D7 blocks other source on P3V3 rail from powering battery
  - DNP = Do Not Populate. Not included, so must add diode
- Characteristics
  - 3.0 V nominal output
  - 240 mAH nominal capacity until reaching 2 V

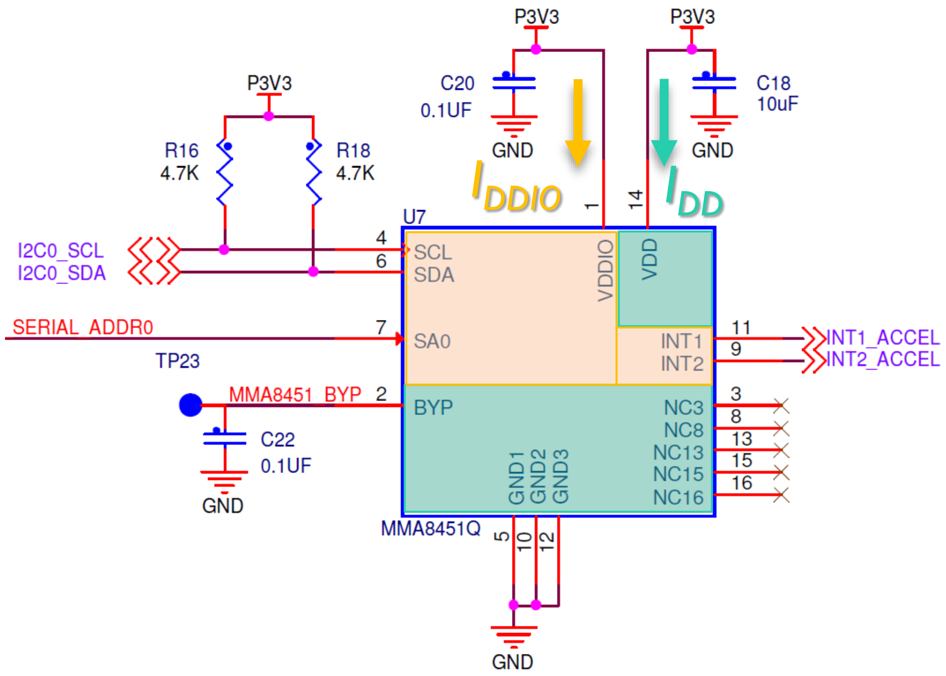




Average Current	Battery Life
2 mA	5 days
200 µA	50 days
20 µA	500 days

Extra

Modeling a Different Supply Voltage: Accelerometer



2.2 Electrical Characteristics

Table 3. Electrical Characteristics @ VDD = 2.5V, VDDIO = 1.8V, T = 25°C unless otherwise noted.

Parameter	Test Conditions	Symbol	Min	Typ	Max	Unit
Supply Voltage		VDD(1)	1.95	2.5	3.6	V
Interface Supply Voltage		VDDIO(1)	1.62	1.8	3.6	V
Normal Mode	ODR = 50 Hz	I_{dd}		24		µA
	ODR = 100 Hz			44		
	ODR = 200 Hz			85		
	ODR = 400 Hz			165		

- Examine MMA8451Q accelerometer data sheet
- Which output data rate (ODR)?
  - Let's pick 400 Hz
- Two power supplies:
  - VDD for Accelerometer
  - VDDIO for I2C interface, interrupt outputs

- Current drawn
  - Datasheet: current I_{dd} at V_{DD} = 2.5 V, V_{DDIO} = 1.8V
  - What about current $I_{dd\ IO}$? Negligible? Assume is in I_{dd}
- What about at $V_{DD} = V_{DDIO}$ = 3.3 V?
  - Need to scale up current; assume is proportional to voltage
- But which voltage do we scale up from?
  - How much of I_{dd} comes from V_{DD} and how much from V_{DDIO}?

Analyze Boundary Conditions for Power Use

2.2 Electrical Ch

Table 3. Electrical Characte 25°C unless otherwise noted.

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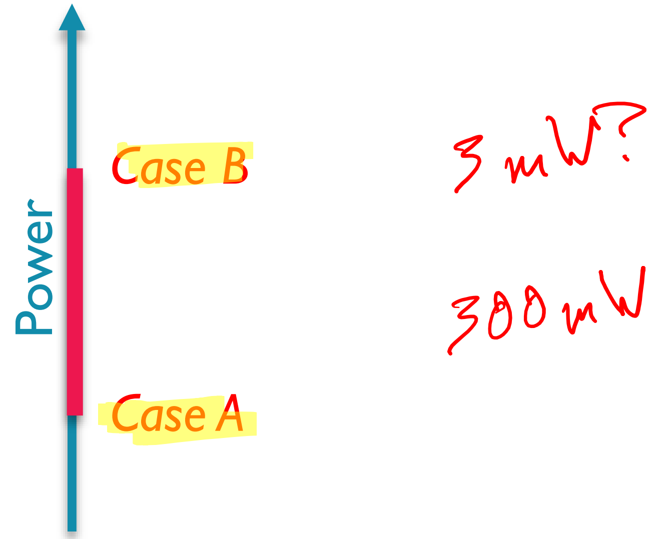
Interface Supply Voltage	VDDIO(1)	1.62	1.8	3.6	V
Normal Mode	I_{dd}		24		µA
			44		
			85		
			165		



- Don't know exact split between main and I/O supplies, so consider limits (boundary cases)
  - Case A: All I_{dd} comes from V_{DD}: Scale up current by 3.3V/2.5V = 1.32
  - Case B: All I_{dd} comes from V_{DDIO}: Scale up current by 3.3V/1.8V = 1.83
- Estimate power
  - P = current scaling factor * current * voltage
- Estimate power at ODR = 400 Hz
  - Case A
    - 3.3V/2.5V * 165 µA * 3.3 V
    - 1.32 * 165 µA * 3.3 V = 0.719 mW
  - Case B
    - 3.3V/1.8V * 165 µA * 3.3 V
    - 1.83 * 165 µA * 3.3 V = 0.999 mW

Modeling a Different Frequency or Voltage

- Replot data and model it
  - Plug data points into spreadsheet
  - Perform curve fitting to create power model
    - Excel: add trend line to plot, or use linest function
- Power at given supply voltage V_{Data}
  - Static power is 5.5689 mW (y-intercept)
  - Dynamic power ~ proportional to frequency: 0.246 mW/MHz
  - $P = 0.246\ mW/MHz * f_{CPU} + 5.5689\ mW$
- Power at different supply voltage $V_{Operating}$
  - No internal regulator? Current rises linearly with voltage
    - Scale power by $(V_{Operating}/V_{Data})^2$
  - Internal regulator?
    - Best case: Current is constant. Scale power by $(V_{Operating}/V_{Data})$
    - Worst case: Current α $V_{Operating}$. Scale power by $(V_{Operating}/V_{Data})^2$