

Lava Lamp

Faster. Brighter. Safer. Decoupled.

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TA: James Norton



Outline

- Introduction to Lava Lamps
- Client Requirements
- Design
- Integration
- Comparative Results
- Future Work
- Acknowledgements



A photograph of a store display featuring two rows of lava lamps. The top row includes a purple lamp with red speckles, a rainbow-colored lamp, a purple lamp with white bubbles, a lamp with a dog's face, a white lamp with a black grid pattern, a purple lamp with white speckles, a blue lamp with white speckles, and a pink lamp with white bubbles. The bottom row includes a yellow and orange lamp, a blue lamp with white bubbles, a pink lamp with white bubbles, a purple lamp with white bubbles, a blue lamp with white bubbles, an orange lamp with white speckles, a green lamp with white speckles, and a pink lamp with white bubbles. A caution sign is visible at the bottom of the display.

What is a lava lamp?

LAMPS ARE HOT! CAUTION: LAVA LAMPS ARE HOT! LAVA LAMPS ARE HOT! LAVA LAMPS ARE HOT! CAUTION: LAVA LAMPS ARE HOT! LA

Client Requirements

Clients: James Norton & Sung Soo Shin

Faster

Problem: Heats rather slowly

Solution: Provide more power to the lamp / Improve heat transfer

Brighter

Problem: Light is dim and can only be one color

Solution: Use high power multicolor LEDs

Safer

Problem: Heats past optimal operating temperature

Solution: Implement a temperature controller

De-coupled

Problem: We can't adjust heating and lighting independently

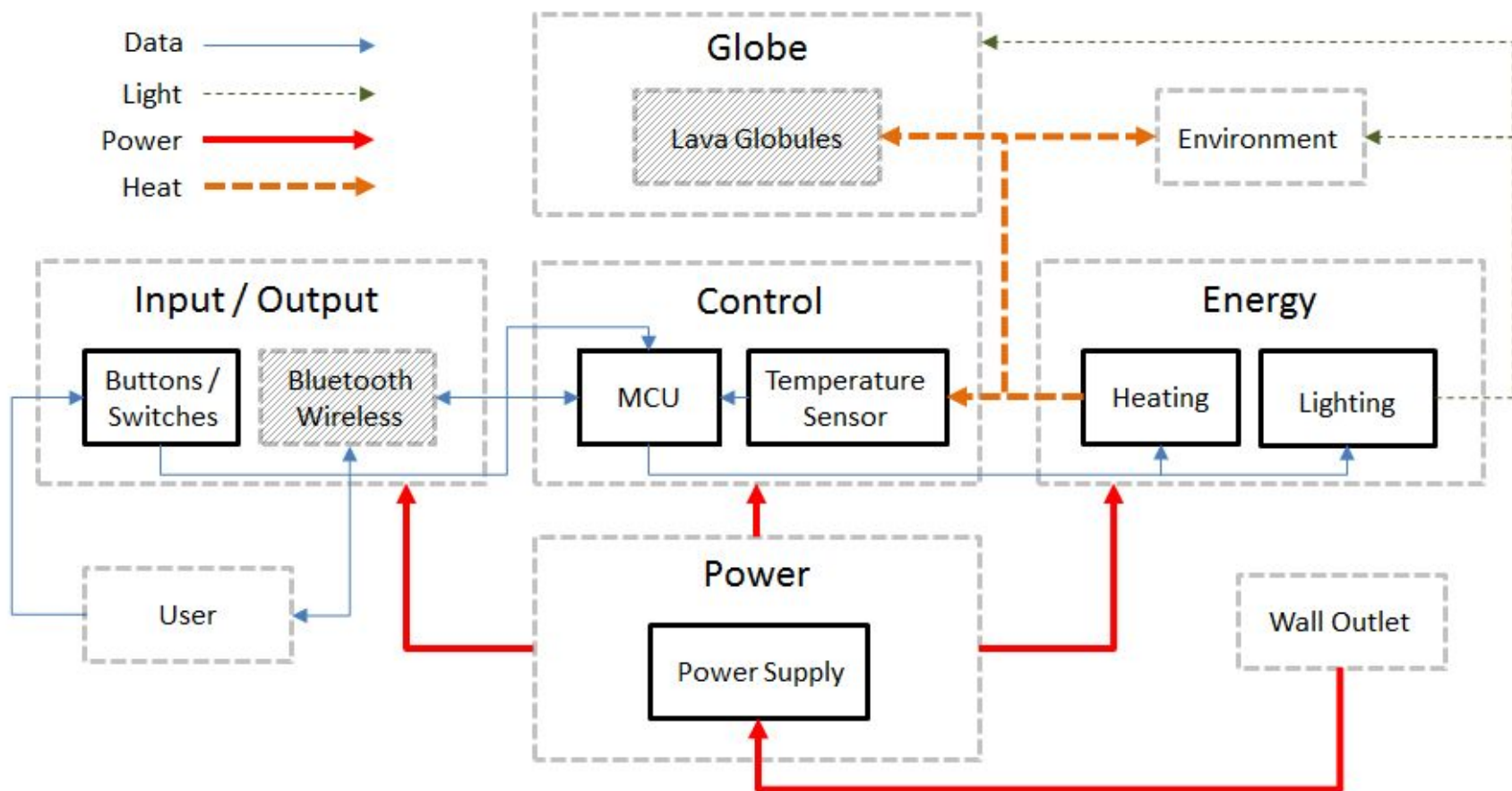
Solution: Use a separate heat source and light source



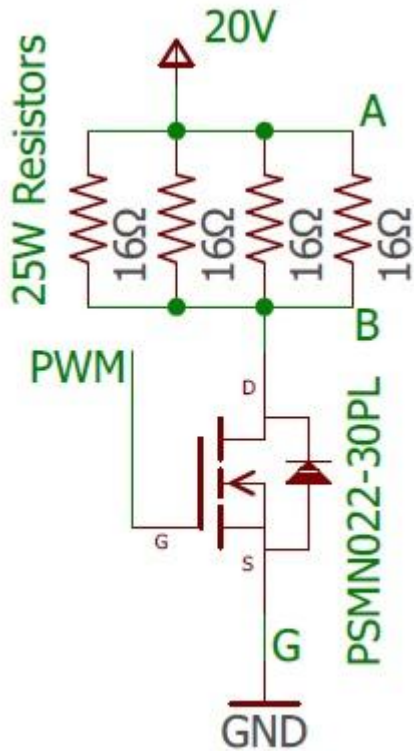
Possible explosion hazard



Initial lab safety measures



Design



Heat Source - *Faster.*

Requirements

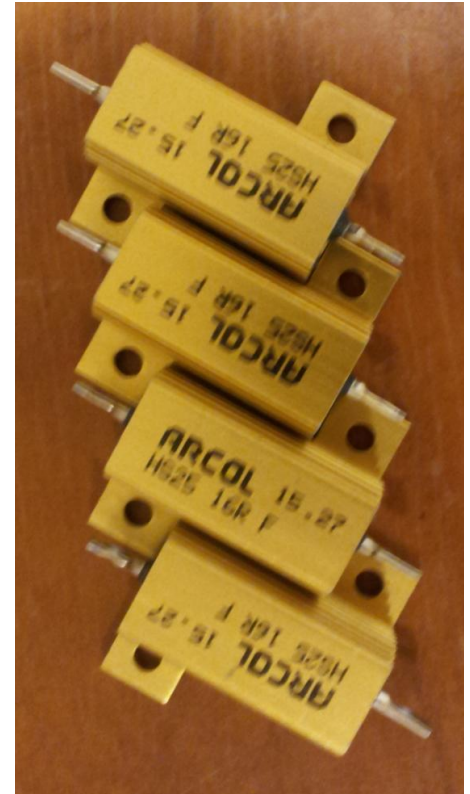
- High wattage ($> 50 \text{ W}$)
- High Max Temperature ($> 90 \text{ }^{\circ}\text{C}$)
- Adjustable ($\sim 1 \text{ W}$)

HS25 16R F Power Resistors

- Max Power: 100 W
- Max Temperature: $110 \text{ }^{\circ}\text{C}$ [1]

PSMN022-30PL nMOS [2]

- Drain-Source Voltage: 30 V
- Drain Current: 30 A



25 W Resistors

Traditional: $\sim 36 \text{ min.}$ Our's: $\sim 11 \text{ min.}$

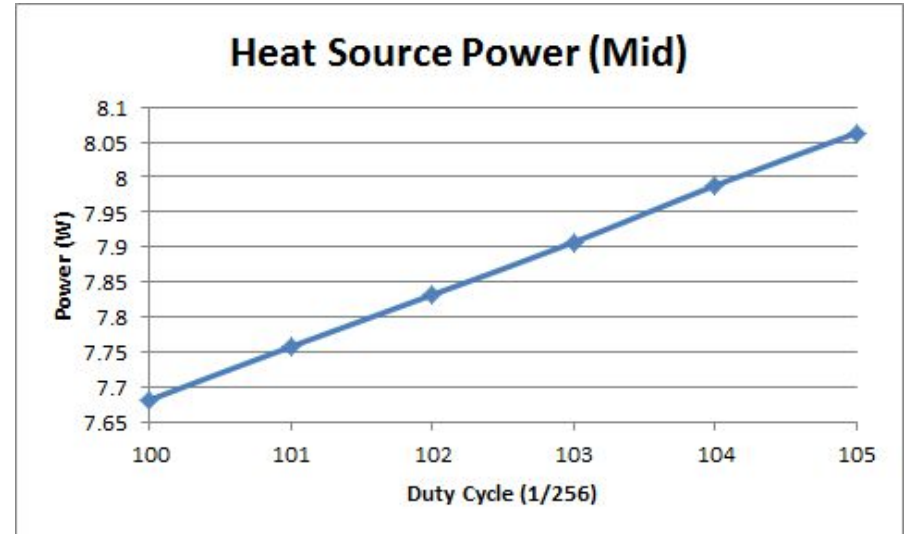
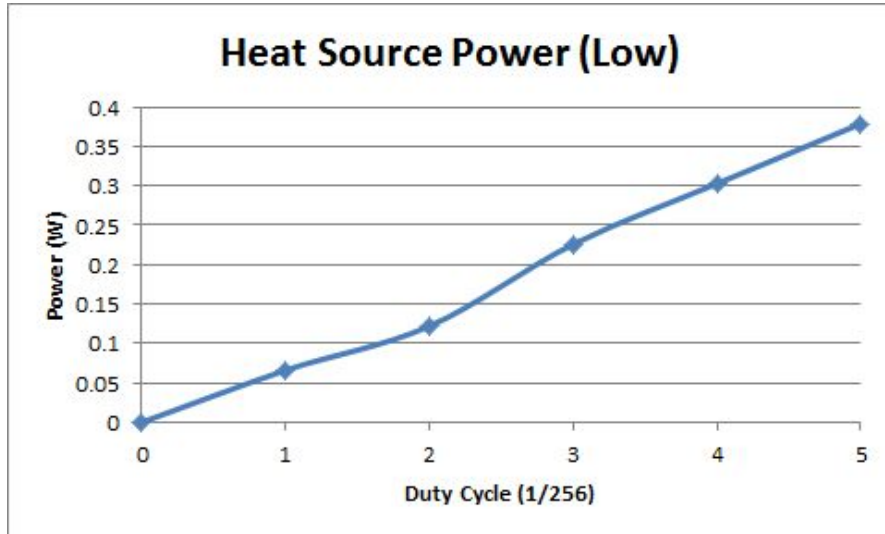
Heat Source Requirements

Must be able to have power adjusted in increments as small as 1W.

Resistance = 4.121Ω

$$P = \frac{V^2}{R}$$

Smallest Increment: $\sim 0.01\text{W}$



Faster... ✓ Decoupled from light... ✓

Light Source - *Brighter*

Requirements

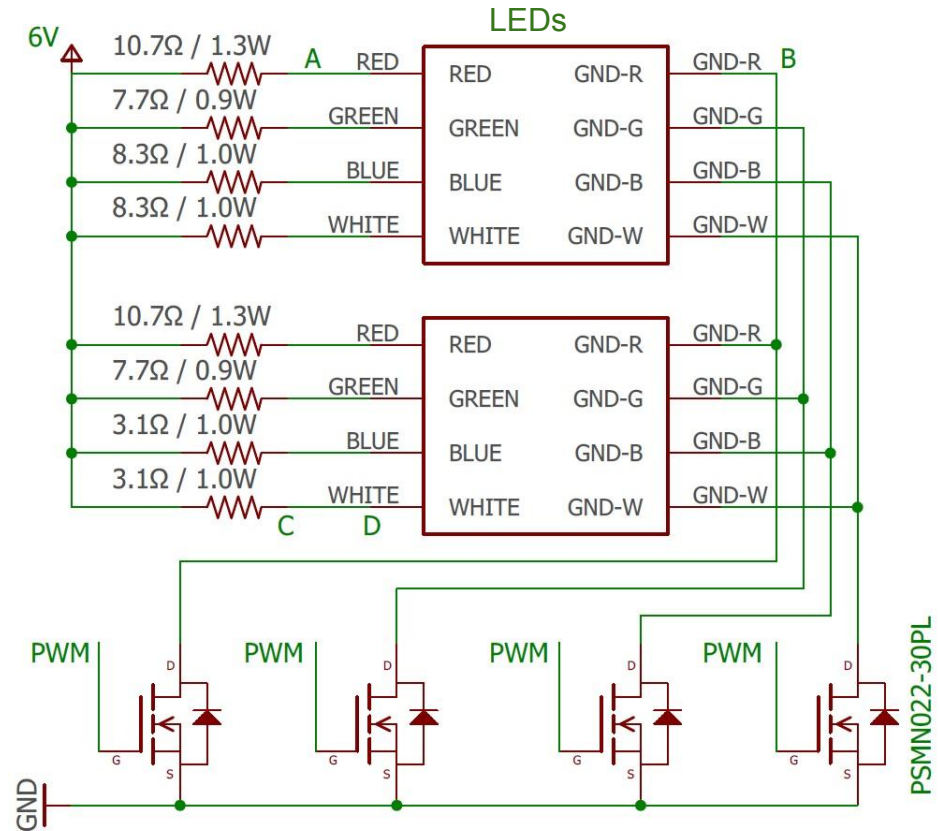
- Bright (10 lux at glass)
- Multicolored ■ ■ ■ ■ ■
- Adjustable (Step ~ 0.05 lux)

CREE XLamp XM-L Color LEDs [3]

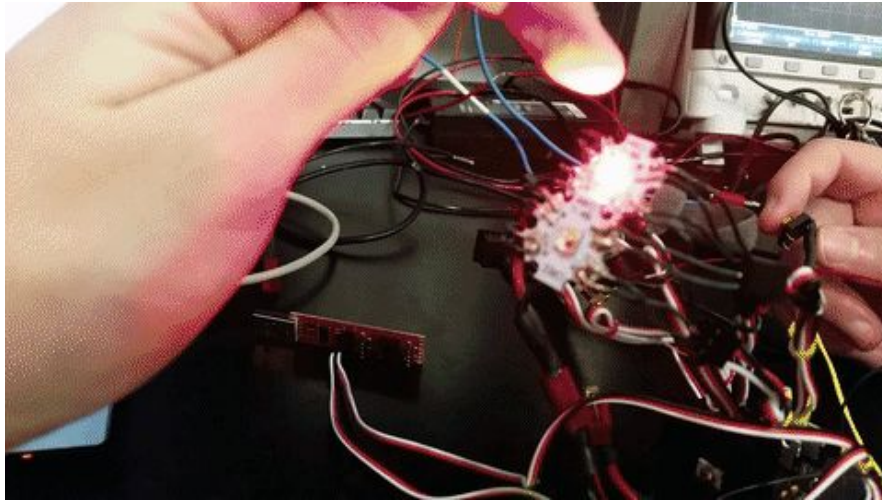
- Current: 350 mA
- Light output: 13.9-100 lumens/channel

PSMN022-30PL nMOS

- Same as heat (simplify design)



Light Source Verifications



Color changes

Provide red, green, blue, purple, and aqua lighting.

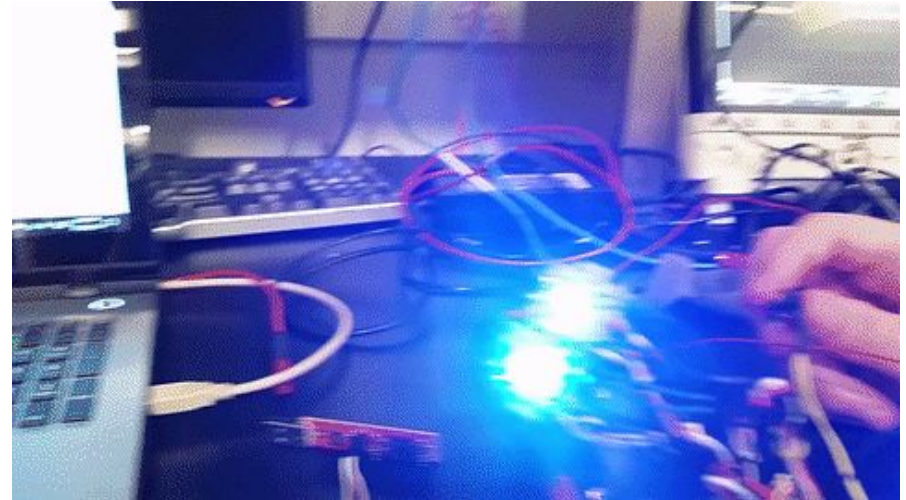
Traditional

12.54 lux

Our lamp

7.21 lux ✖

Decoupled from heat... ✔
Brighter... Not quite...



Brightness adjusted

Required Step

0.05 lux

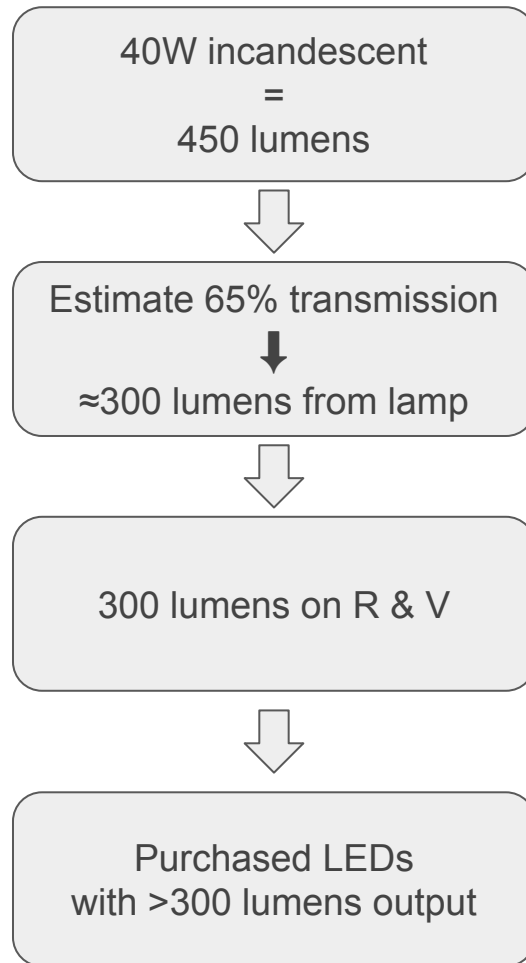
Our Increment

0.04 lux ✔

Brighter?

We purchased parts according to R&V, but didn't meet client requirements. Why?

- R&V was written in complex manner
- Confusing R&V interpreted incorrectly



Power Supply

Requirements

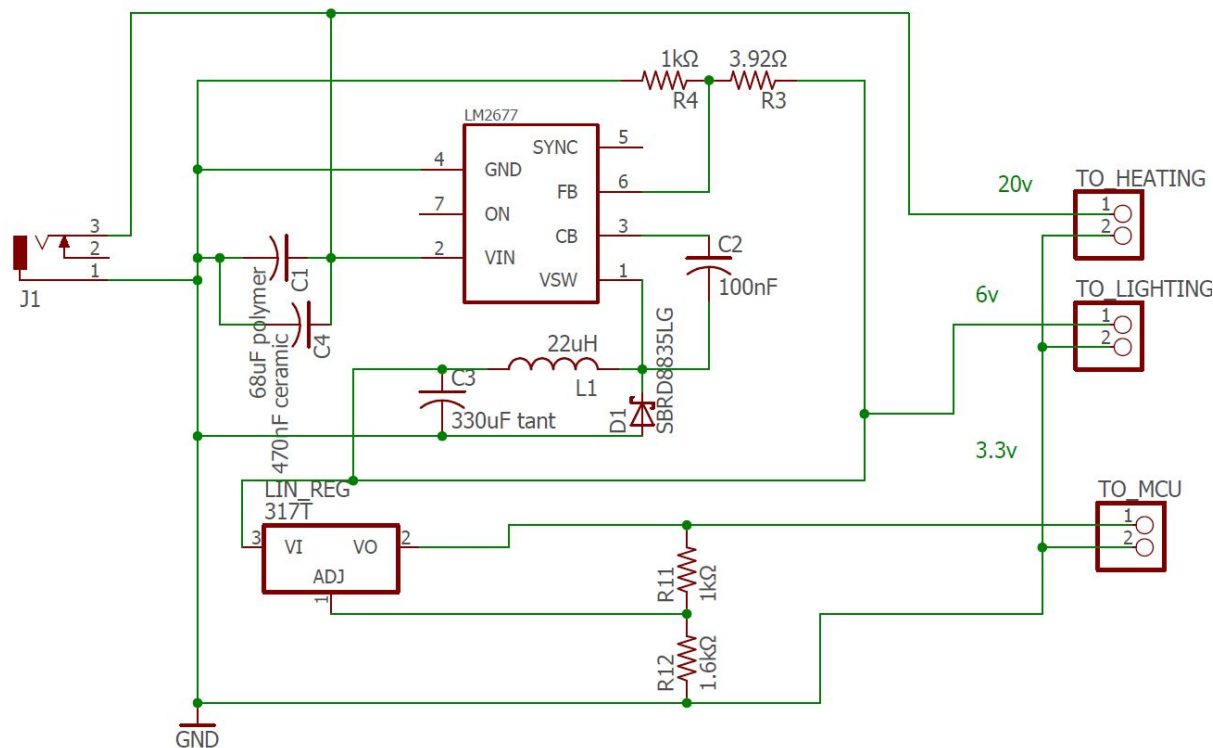
- Supply 2.8V - 3.4V at 500mA
- Supply 5.5-6.2V at 3A

LM2677

- Buck regulator capable of up to 5A
- 6V for lighting

LM317T

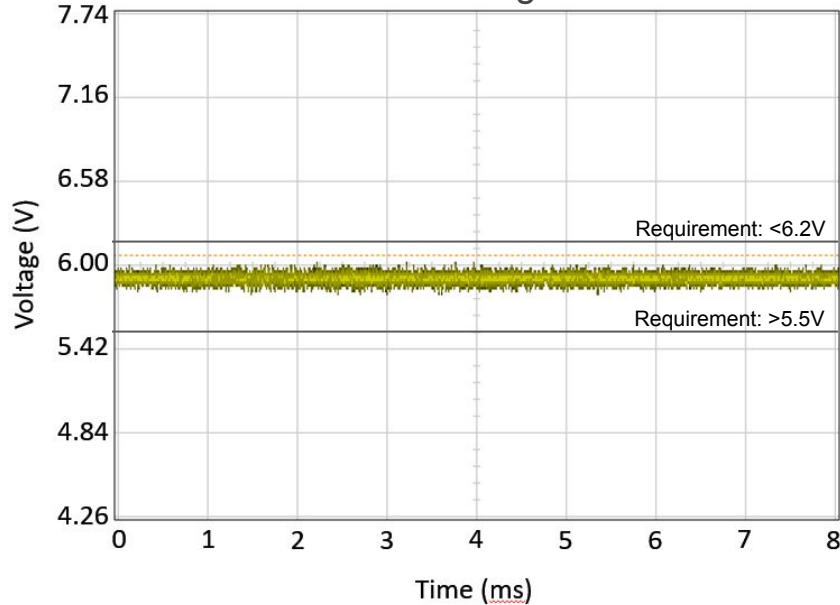
- Linear regulator
- 3.3V for microcontroller



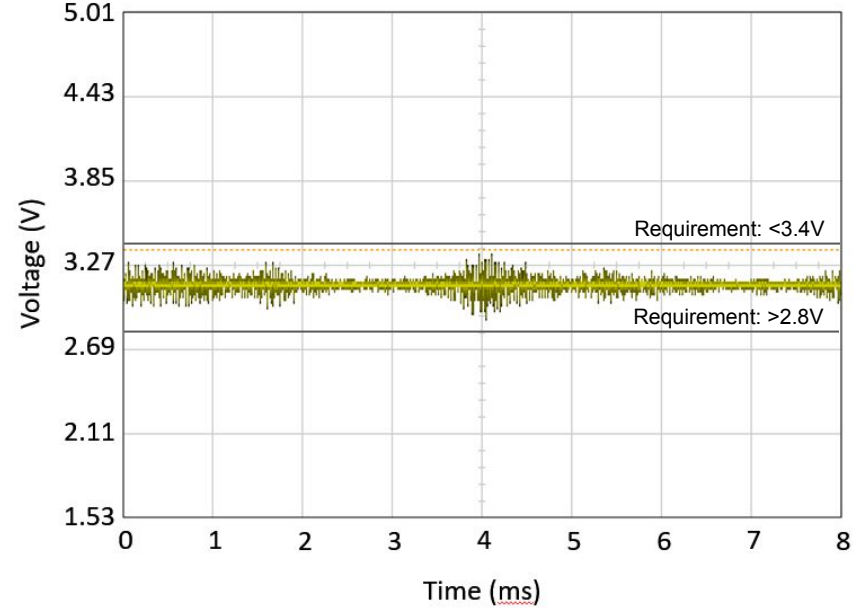
Schematic of power supply, including linear regulator and buck converter.

Power Supply: Verification

6 V Rail Voltage at 3 A

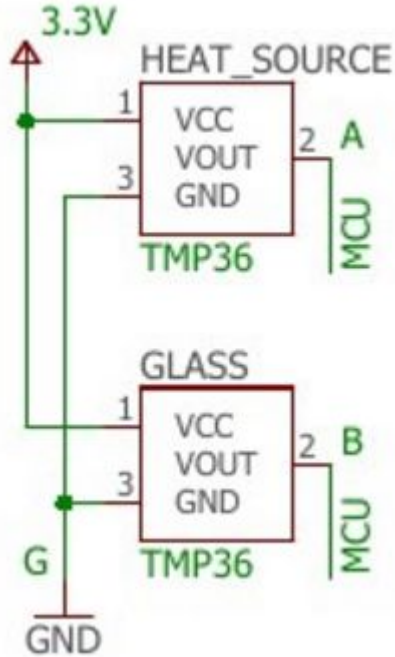


3.3 V Rail Voltage at 500 mA



Notice noise from switching regulator

Temperature Sensors



Requirements

- Fast (≥ 1 Hz)
- Accurate ($\pm 2^\circ\text{C}$)
- Operate from 25°C to 100°C

TMP36 Temp. Sensor [5]

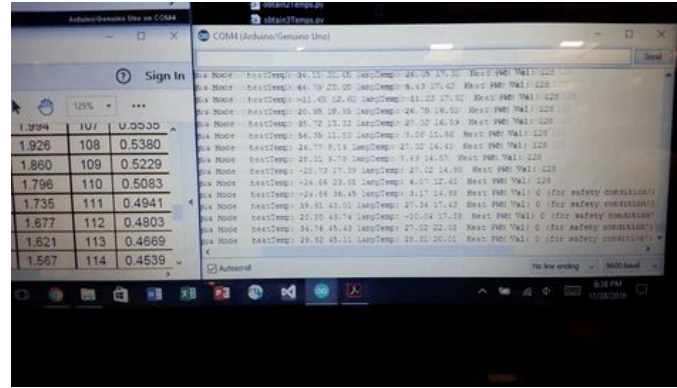
- Analog Sensor
- Calibration-free with a $\pm 2^\circ\text{C}$ Temperature Accuracy
- Operates from -40°C to $+125^\circ\text{C}$



$$(\text{Temp in } ^\circ\text{C}) = (V_{\text{OUT}} - 500\text{mV}) * 100$$

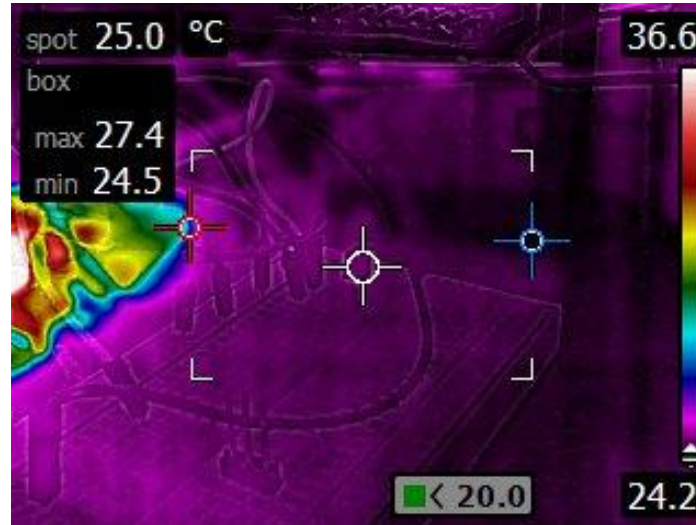
Temperature Sensors Verification

Able to read temperature at least once every second.



Accurate to $\pm 2^{\circ}\text{C}$

Reading	IR ($^{\circ}\text{C}$)	Sensor ($^{\circ}\text{C}$)
1	25.4	25.6
2	25.0	24.1
3	24.3	23.0



Temperature Sensor Issues and Solutions

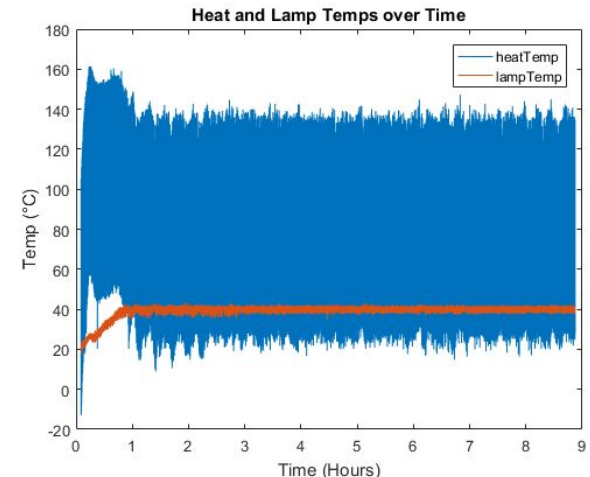
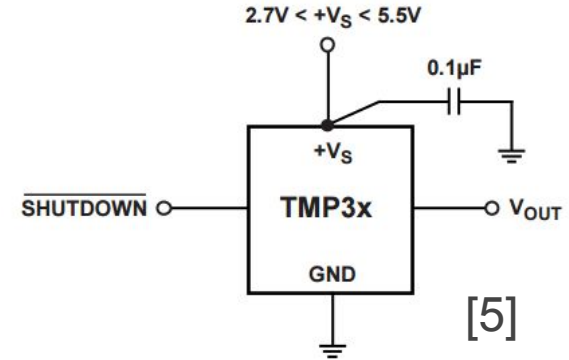
Problem: A large amount of noise in the readings.

Hardware solutions:

- Strategically placed 0.1 uF capacitors according to data sheet [5].
- Lower noise from power supply (future)
- Digital sensors or thermistors (future)

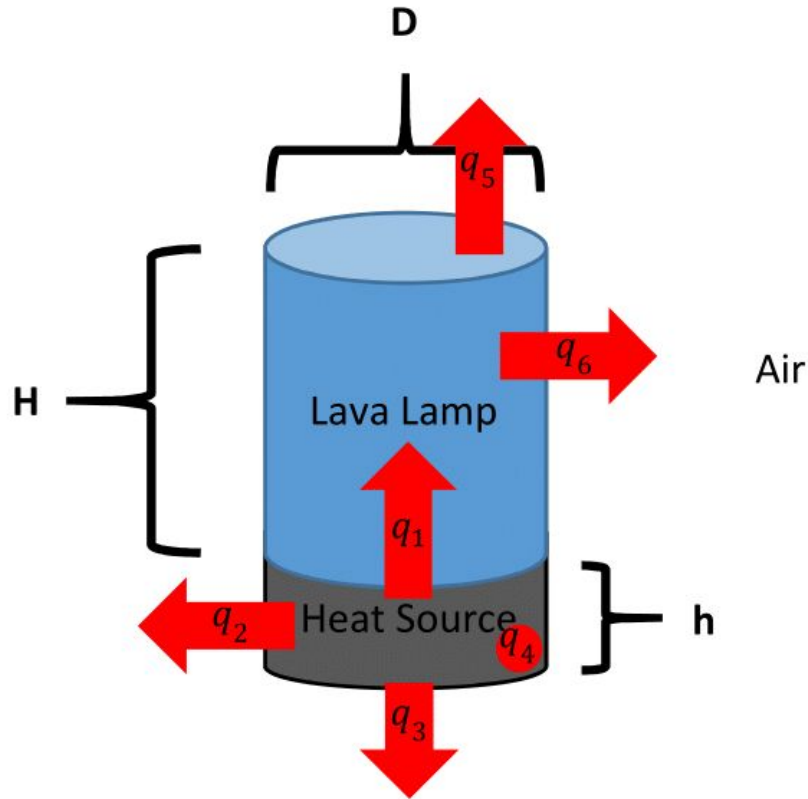
Software solutions:

- Averaging filter



Raw Sensor Data

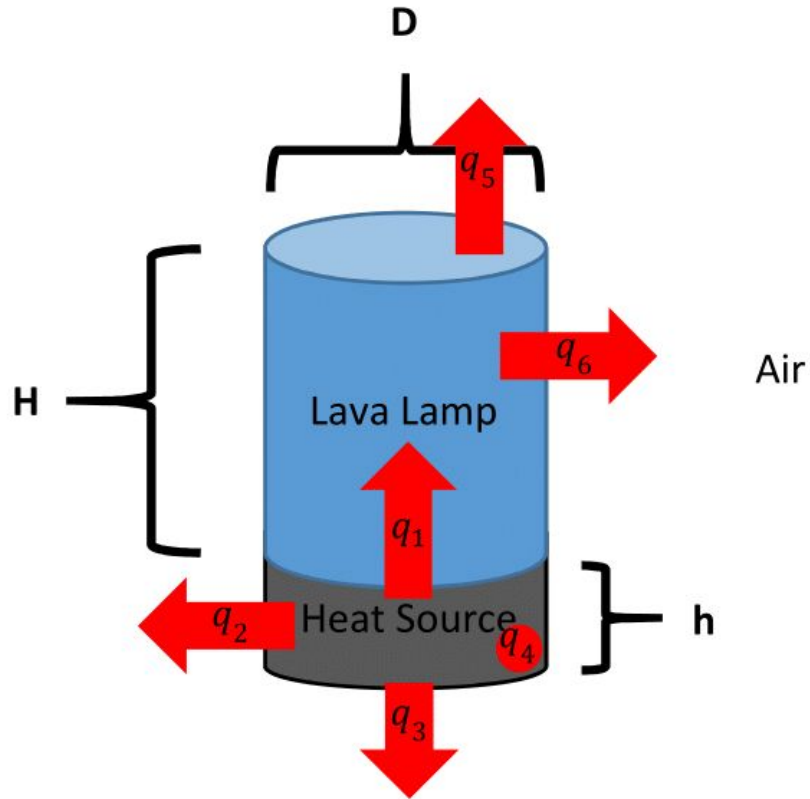
Control



Requirements

- **Faster**
 - Rise Time of 40 minutes or less (of Lava Lamp Temperature to first movement)
- **Safer**
 - Overshoot of 10 °C or less (of Lava Lamp Temperature)
- Accurate
 - Steady-State Error of 1.0 °C or less (of Lava Lamp Temperature)

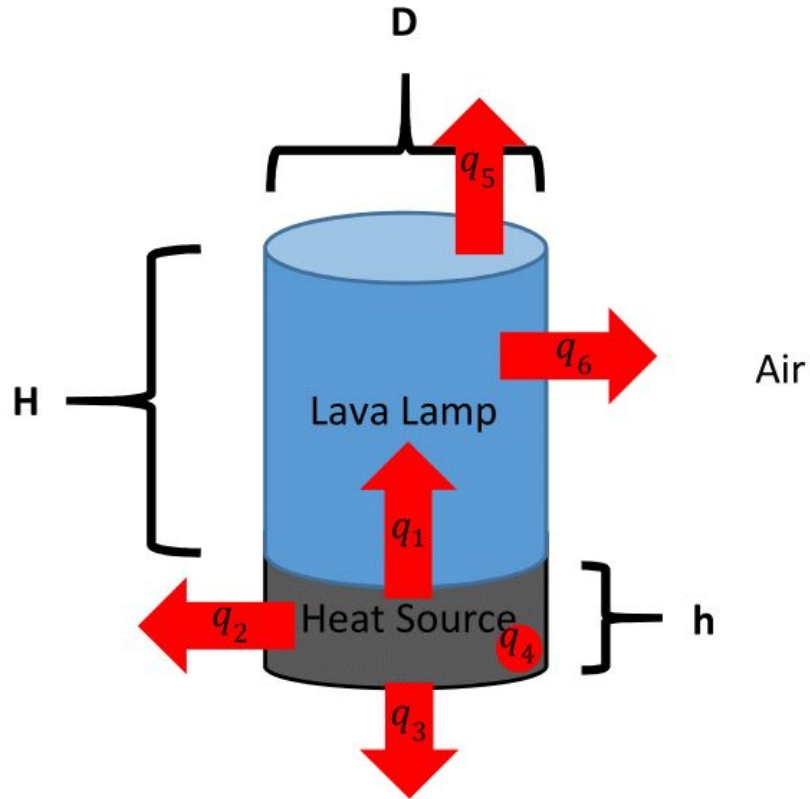
Control - Model



$$q = \frac{1}{R} (T_1 - T_2)$$

$$\dot{T} = \frac{1}{C} q$$

Control - Model



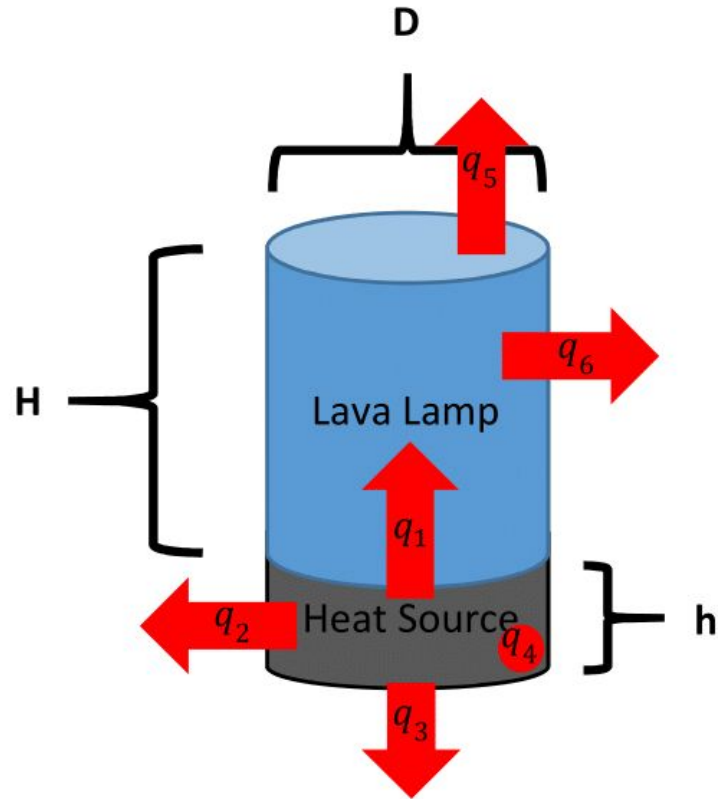
$$q = \frac{1}{R} (T_1 - T_2)$$

$$\dot{T} = \frac{1}{C} q$$

$$q_{Heat} = q_4 - q_1 - q_2 - q_3$$

$$q_{Lava} = q_1 - q_5 - q_6$$

Control - Model



$$q = \frac{1}{R} (T_1 - T_2)$$

$$\dot{T} = \frac{1}{C} q$$

$$q_{Heat} = q_4 - q_1 - q_2 - q_3$$

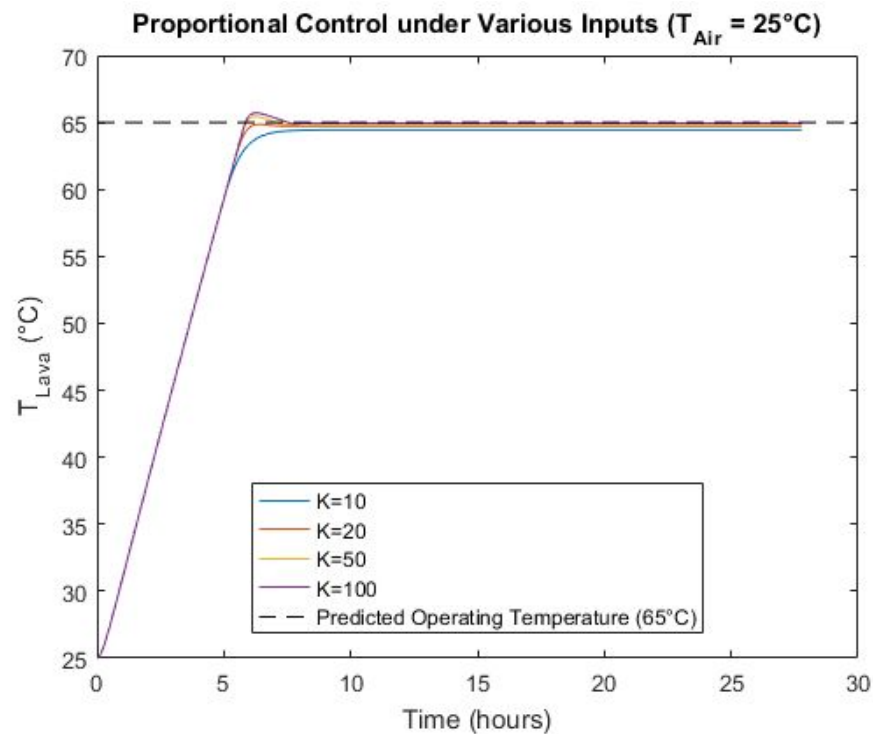
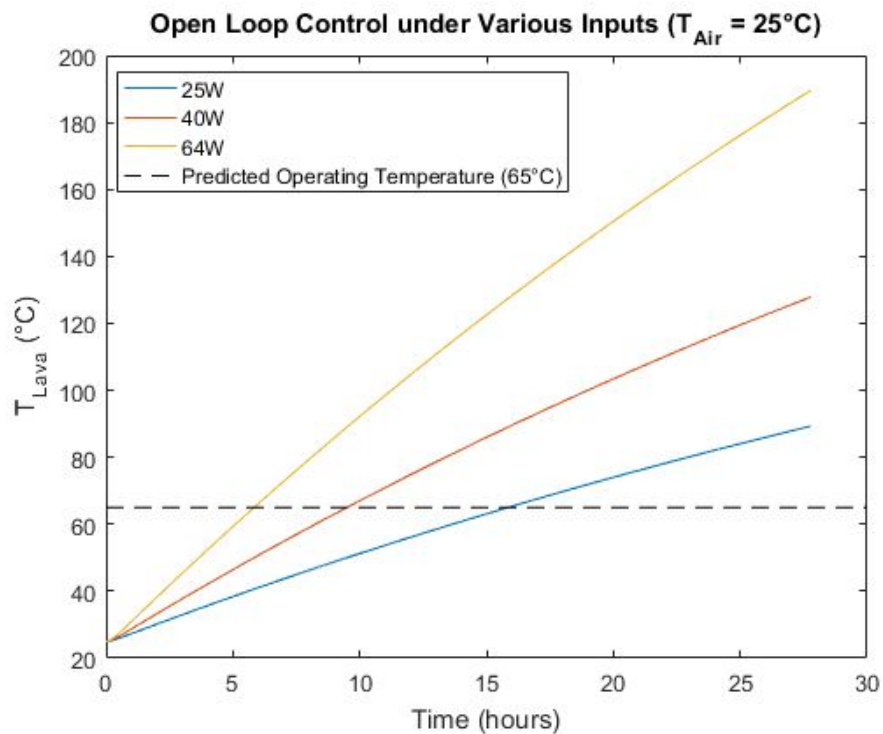
$$q_{Lava} = q_1 - q_5 - q_6$$

Air

$$\dot{\tilde{T}}_{Heat} = \left(\frac{-1}{R_{1,2,3} C_{Heat}} \right) \tilde{T}_{Heat} + \left(\frac{1}{R_1 C_{Heat}} \right) \tilde{T}_{Lava} + \left(\frac{1}{C_{Heat}} \right) q$$

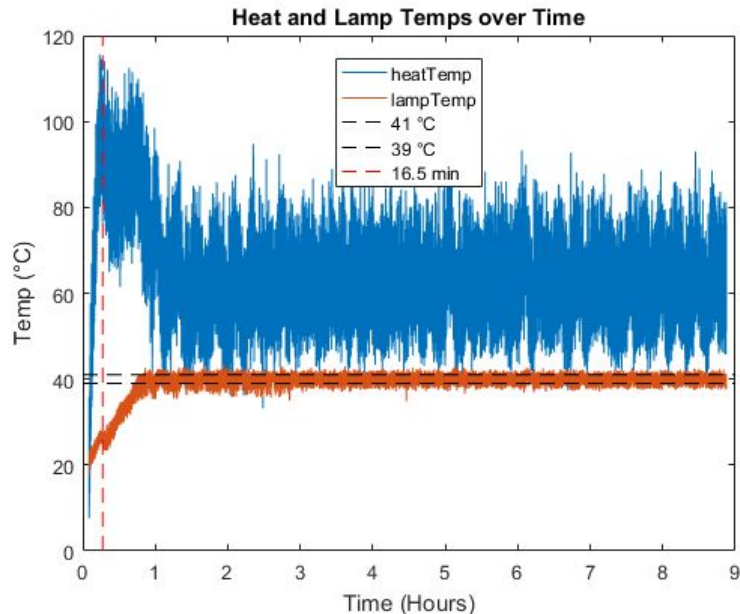
$$\dot{\tilde{T}}_{Lava} = \left(\frac{1}{R_1 C_{Lava}} \right) \tilde{T}_{Heat} + \left(\frac{-1}{R_{1,5,6} C_{Lava}} \right) \tilde{T}_{Lava}$$

Simulations



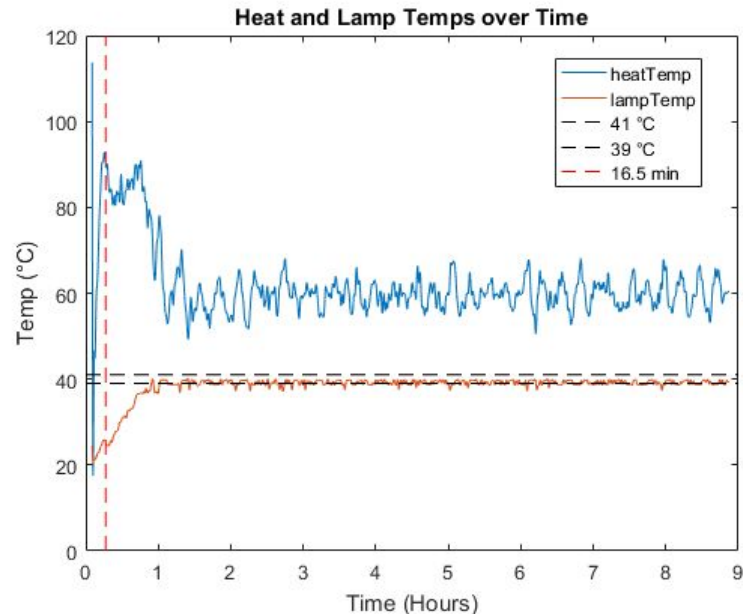
Experimental Data

Smoothed (implemented)



Faster... Safer... ✓

Butterworth Filter (future)



Credit: Jamie for helping us with MATLAB

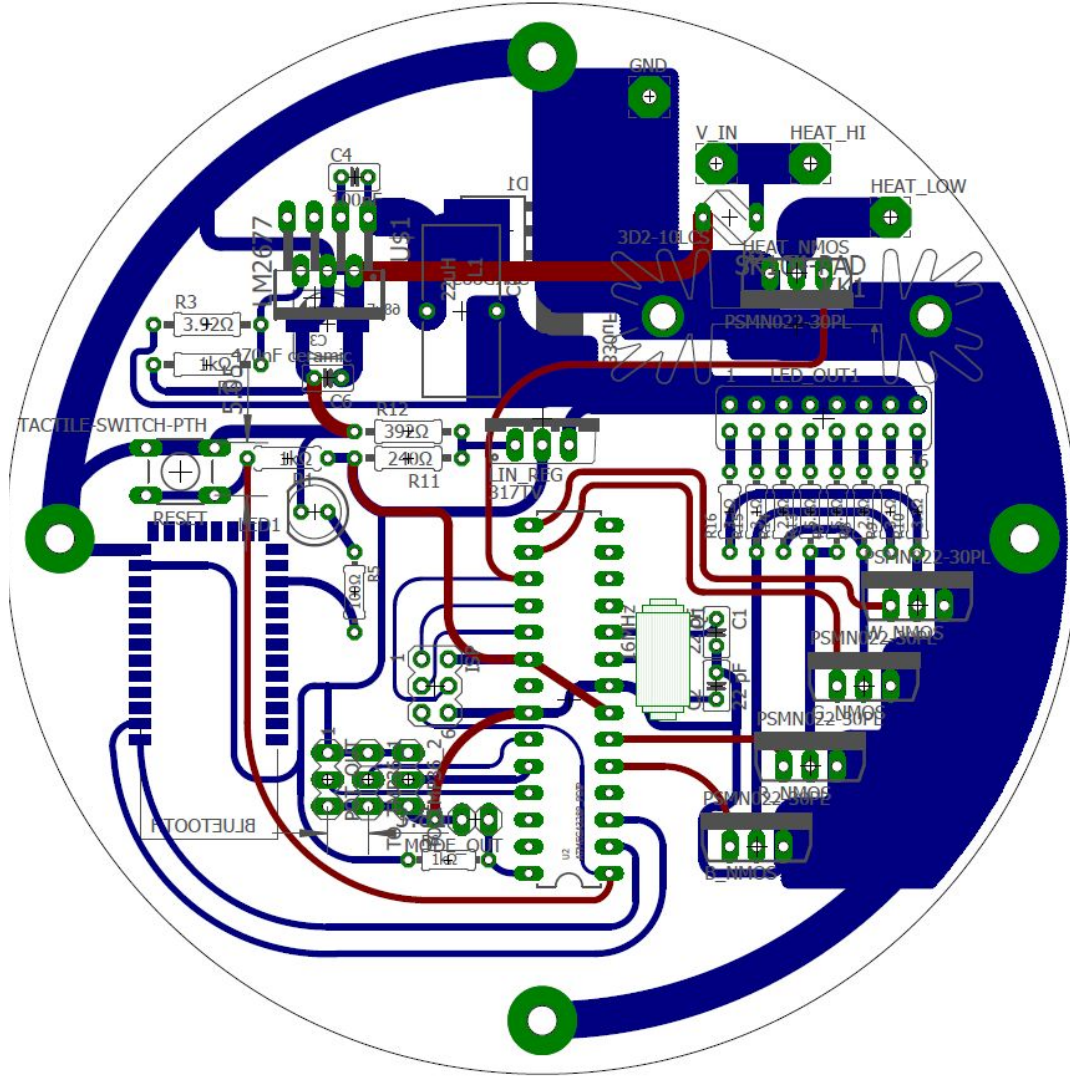
Traditional: ~36 min. Our's: ~11 min.

Integration

Section	10/10/2016 - 10/14/2016					10/17/2016 - 10/21/2016					10/24/2016 - 10/28/2016				
	M	T	W	R	F	M	T	W	R	F	M	T	W	R	F
Administrative	Wait for Parts to Arrive					PCB Design and Testing					Wait for PCB Fabrication				
											Progress Report				
											Compile Test Data / Update Papers				
											Industrial Design Contact				
Experiments	Experiment 1														
	Experiment 2														
Control	Luke					Luke	Draft and Debug MCU Software				Luke	Draft and Debug MCU Software			
Mechanical / PCB	Draft PCB Design					Draft PCB Design									
				Mech. Design		Mechanical Design					Mechanical Design (Submission)				
	Ask PCB Questions		Current Control												
Sensors											Test and Calibrate Sensors				
Input / Output						Test I/O Switches									
Heating						Heating Circuit Tests									
Lighting	Cheap LED Circuit Tests					Star LED Test									
MCU									Test Pins						
Power						Power Circuit Tests									
				P	S				O				P		
				A	O				R				C		
				R	L				D				B		

10/10/2016	Assigned	Due	Description
Wait for Parts to Arrive	Everyone	None	Get as much preliminary work done as possible while we wait for parts to arrive.
Soldering Assignment	Everyone	10/14/16	
Experiment 1	Matthew	10/14/16	PURPOSE: Obtain temperature constants for control problem (light bulb). EXPERIMENT: Use an IR gun to test how hot the light bulb gets after XX amount of time. MATERIALS: Lava lamp base, IR gun from Bird (the TA). DESIRED RESULTS: 1. Light bulb temperature vs. time graph 2. Data chart 3. Temperature constant 4. Picture of experimental setup
Experiment 2	Matthew	10/14/16	PURPOSE: Obtain temperature constants for control problem (lamp external). EXPERIMENT: Use an IR gun to measure how hot the glass gets after XX amount of time. MATERIALS: Lava lamp, IR gun from Bird (the TA). DESIRED RESULTS: 1. Glass temperature vs. time graph 2. Data chart 3. Temperature constant 4. Picture of experimental setup
Experiment 3	Matthew	10/14/16	PURPOSE: Obtain temperature constants for control problem (lamp internal). EXPERIMENT: Use a liquid compatible temperature sensor to see how hot the internal liquid gets after XX amount of time. MATERIALS: Lava lamp, liquid compatible temperature sensor. DESIRED RESULTS: 1. Liquid temperature vs. time 2. Data chart 3. Temperature constant 4. Time to get to operational temperature (and what that temperature is) 5. Time to overheat (and what that temperature is) 6. Picture of experimental setup

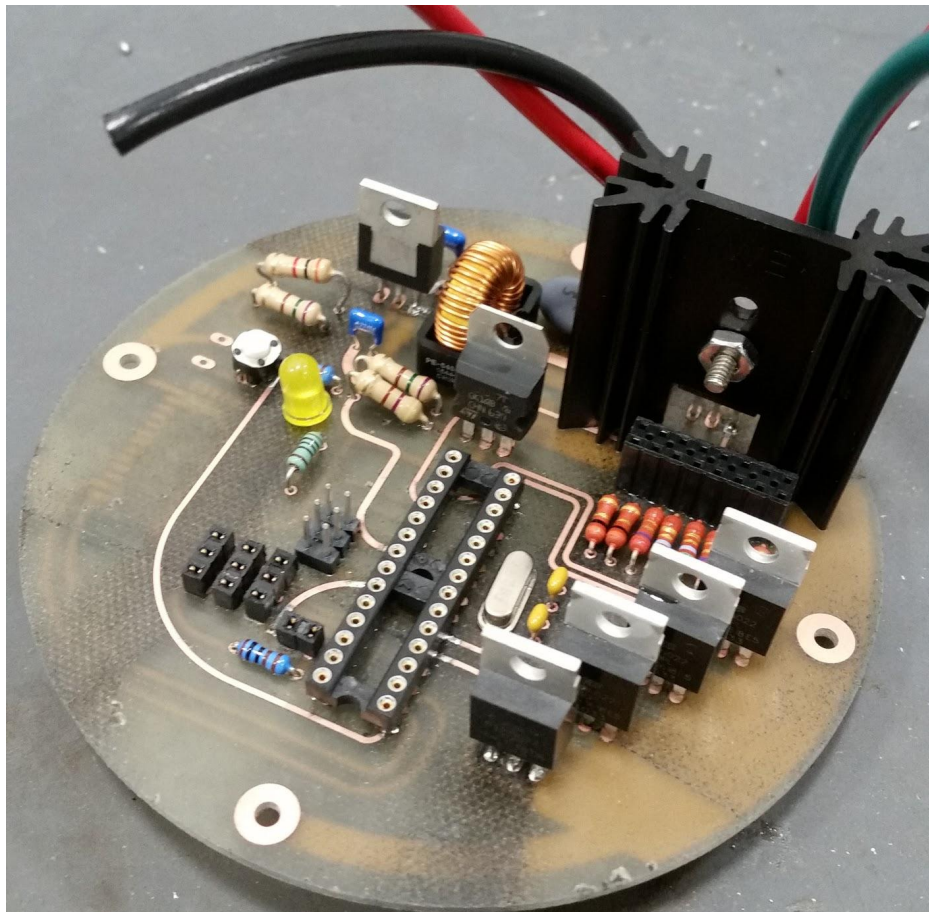
Sample of our detailed schedule on Google Sheets



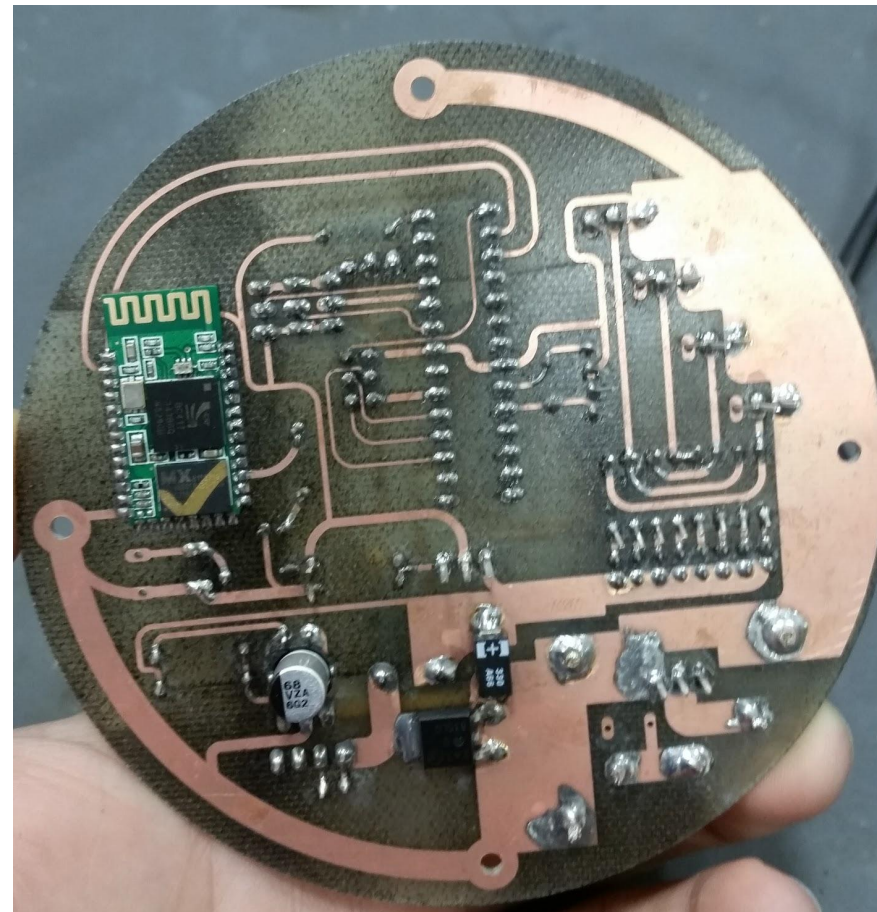
PCB

Design Considerations

- Circular
- Mounting holes
- Minimize vias and top routed traces to pins
- Through hole where possible



PCB (top)



PCB (bottom)

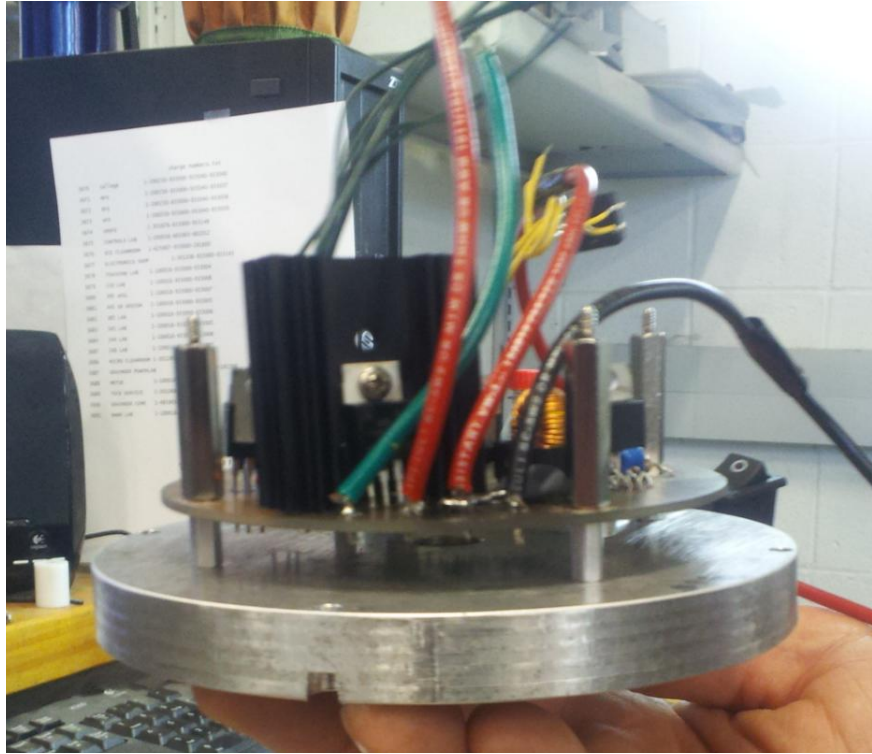
Mechanical Design



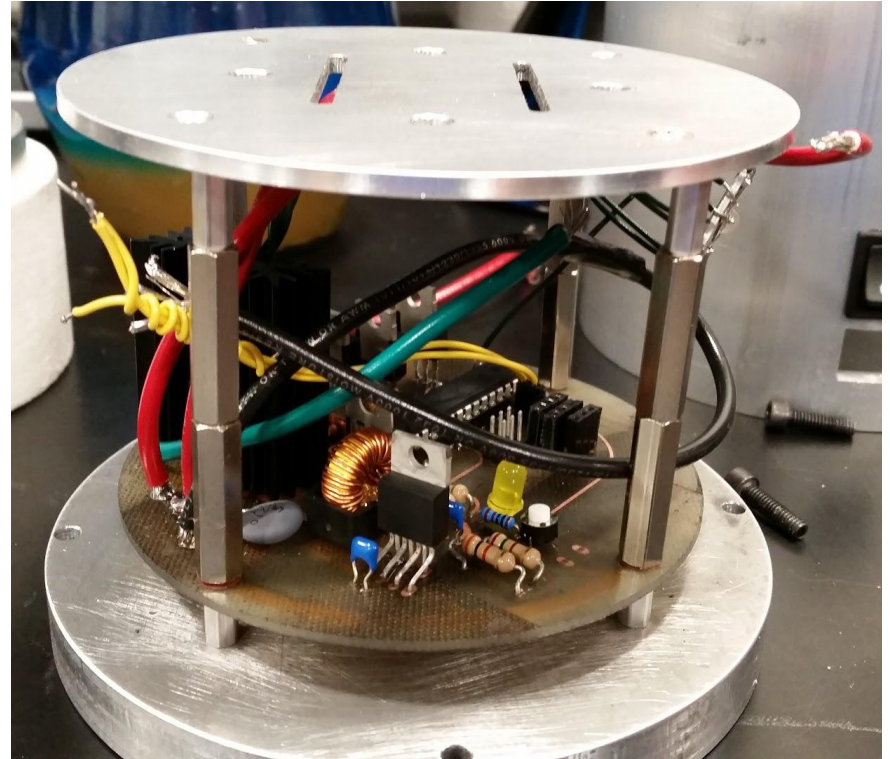
Heat spreader (bottom) thermal isolator (top)



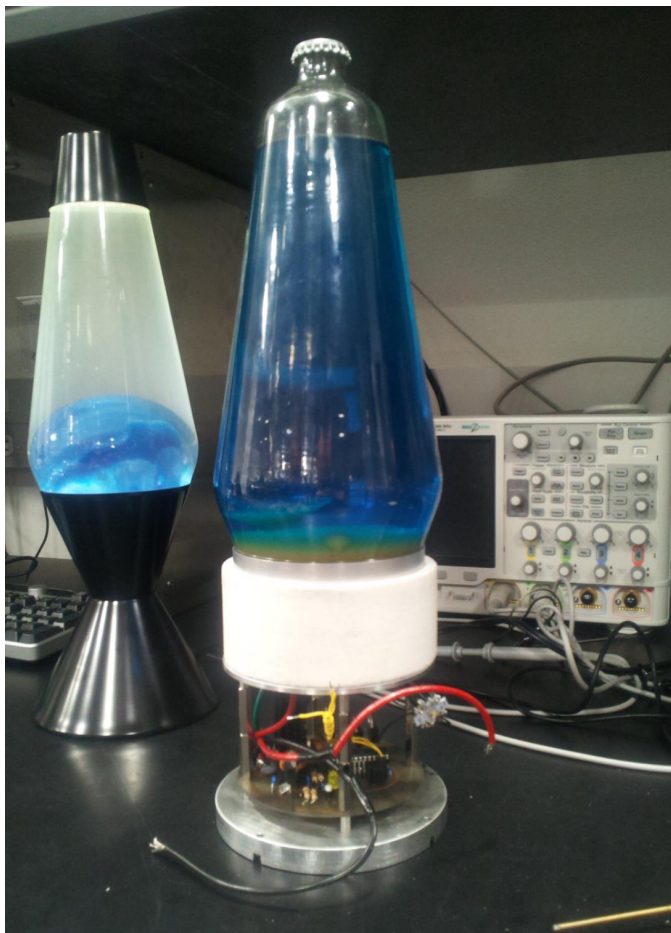
Heat spreader inside thermal isolator



PCB mounted to bottom base plate



PCB mounted between base and LED plates



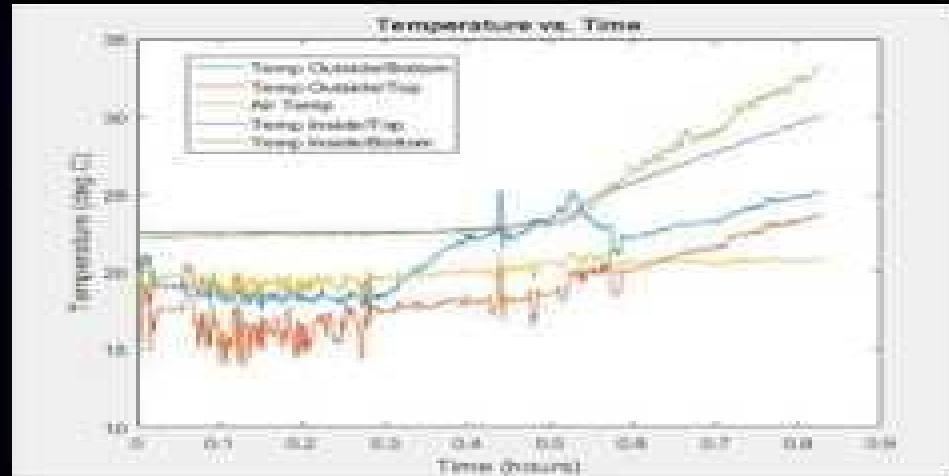
Base assembly without shell



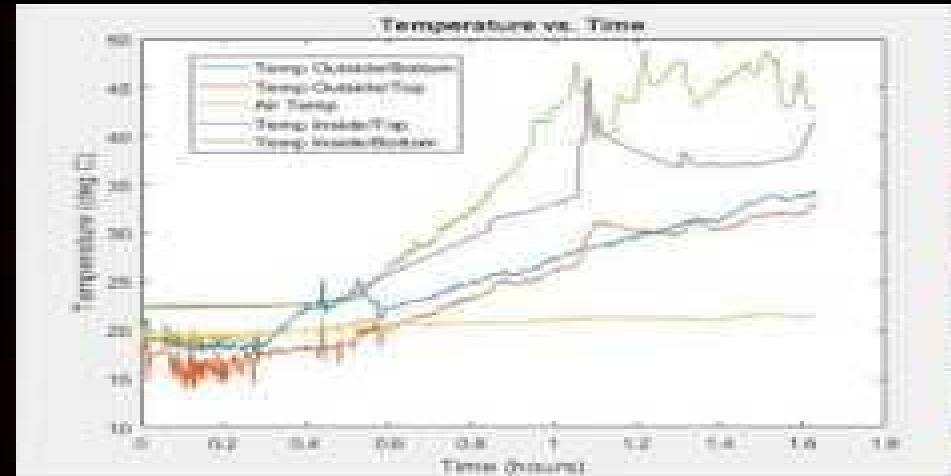
PCB et. al. mounted inside of the shell

Comparative Results

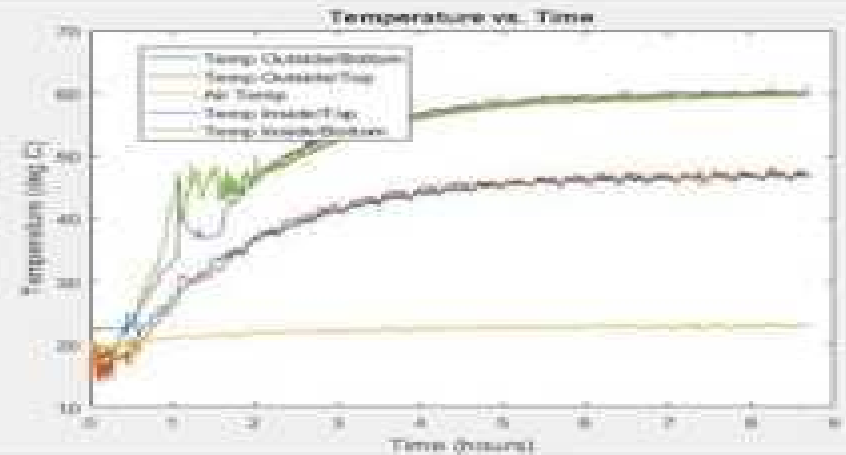
Results - Traditional Lava Lamp



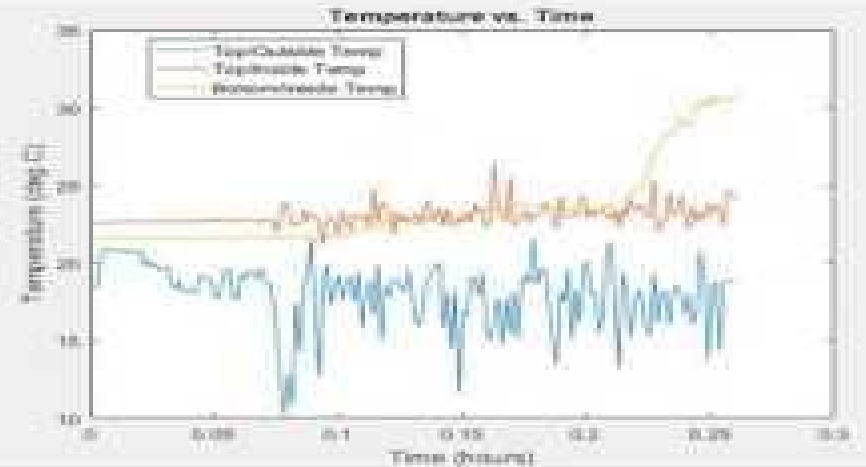
Results - Traditional Lava Lamp



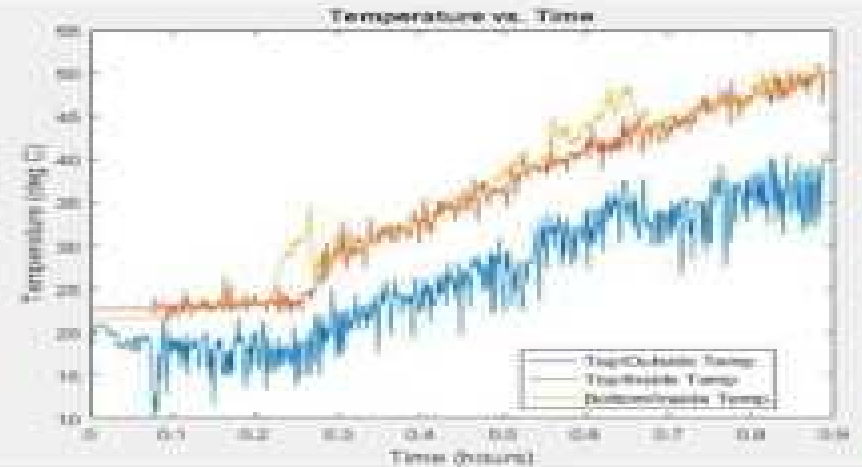
Results - Traditional Lava Lamp



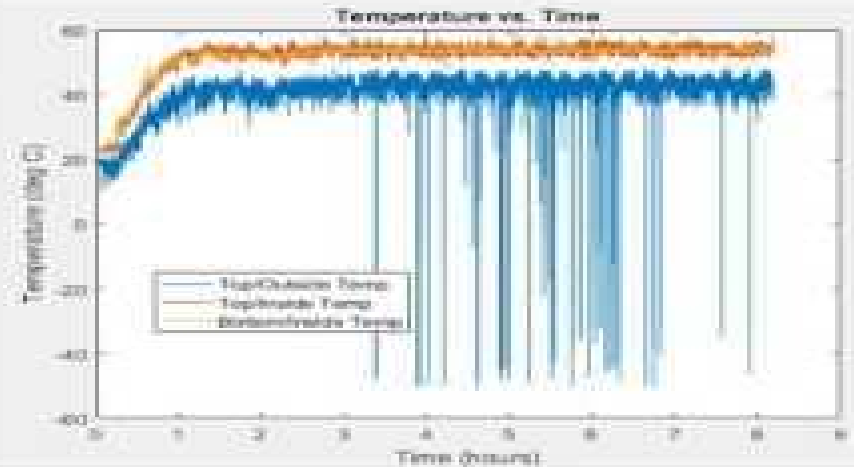
Results - Improved Lava Lamp



Results - Improved Lava Lamp



Results - Improved Lava Lamp



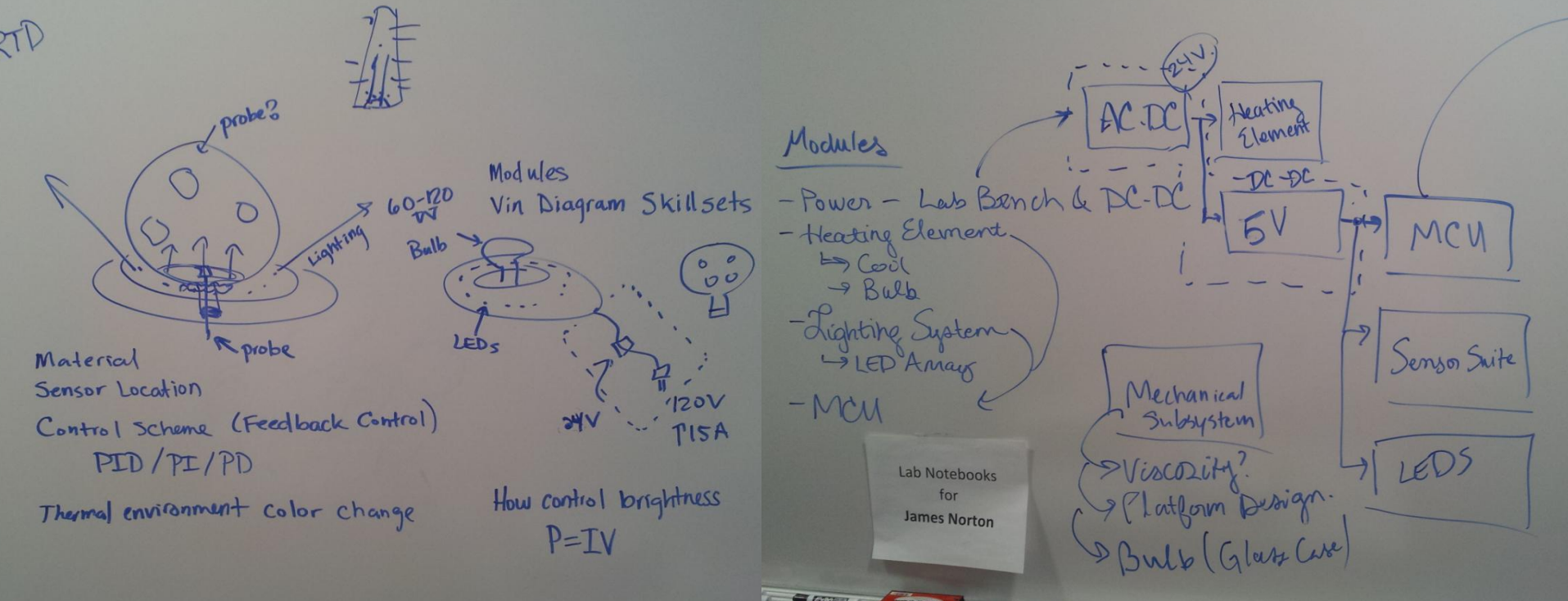
Future Directions

- Continue pursuing an industrial design model
- Inductive heating
- LEDs in a ring around base for better lighting
- Wireless capability with companion application
- Improved PCB layout
- More accurate/less noisy temperature sensors
- Auto-calibration to determine system parameters and air temperature for more accurate and advanced control schemes



Acknowledgements

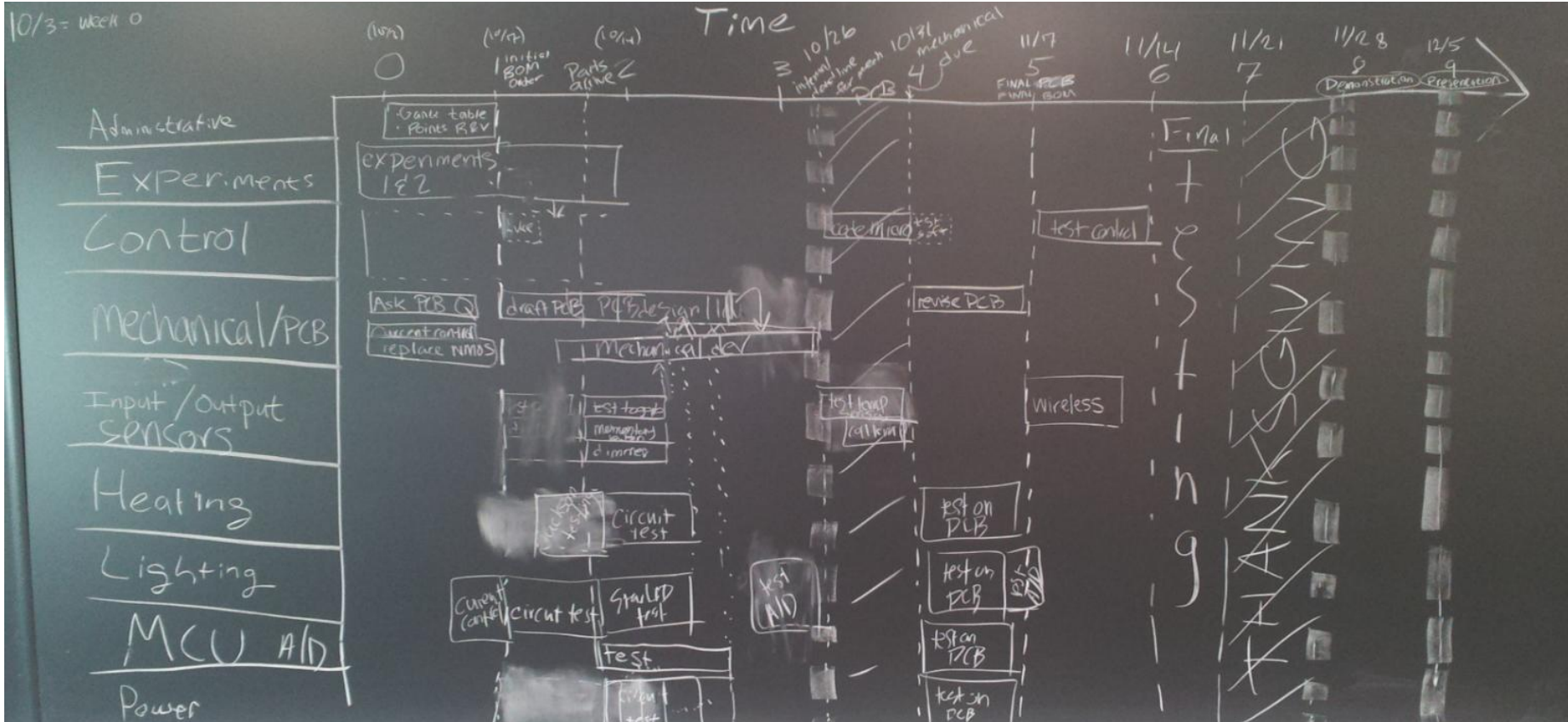
Teaching Assistants: Jackson Lenz & Katherine O'Kane



Little Baby Lava Lamp

Jackson also helped us not kill ourselves on the high power supply in the lab.

Teaching Assistant: James Norton



The conception of the Gantt chart schedule

Teaching Assistant: Luke Wendt

Control problem guruship

$$\begin{aligned} \begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} &= \begin{bmatrix} A & 0 \\ 0 & A \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u \\ y &= \begin{bmatrix} C & 0 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \end{aligned}$$

Free matrix can set to zero

$$\hat{z} = A' \hat{z} + B' u + L (y - C \hat{z})$$

$$L = L_1 I (A', C', \hat{Q}, R)$$

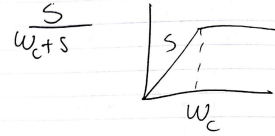
$$u = -K \hat{z}$$

$$K = L_2 (A', B', \hat{Q}, R)$$

$$\dot{\hat{z}} = (A' - L C') \hat{z} + B' (u + Ly)$$

$$\begin{aligned} \dot{e} &= Ae + Bu \\ &= (A + BK)e \\ \|A + BK\| &< 1 \\ \|A\| &\leq 1 \\ LQR \end{aligned}$$

• Back to use Finite diff. method



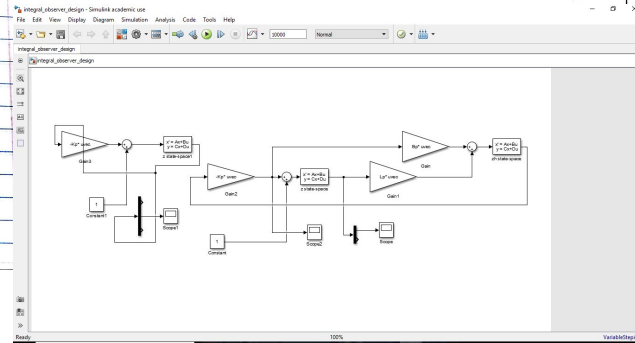
$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \\ \dot{e} &= (A - LC)e \\ \hat{x} &= A\hat{x} + Bu + L(y - C\hat{x}) \\ L &= (\dots) \\ &= LQR \end{aligned}$$

Could use Adaptive M

Franklin (17,10 ish)
Integral control to help

"Internal Model Estimation"
17,10,2 (506)

Luke's Model



disturbance identification
vs.
disturbance rejection

"persistent excitation"

(Step input w/ Least-Squares)
won't work very well

(Reduced-Order Observer)
Will get better results

depends slightly less on the model

in:

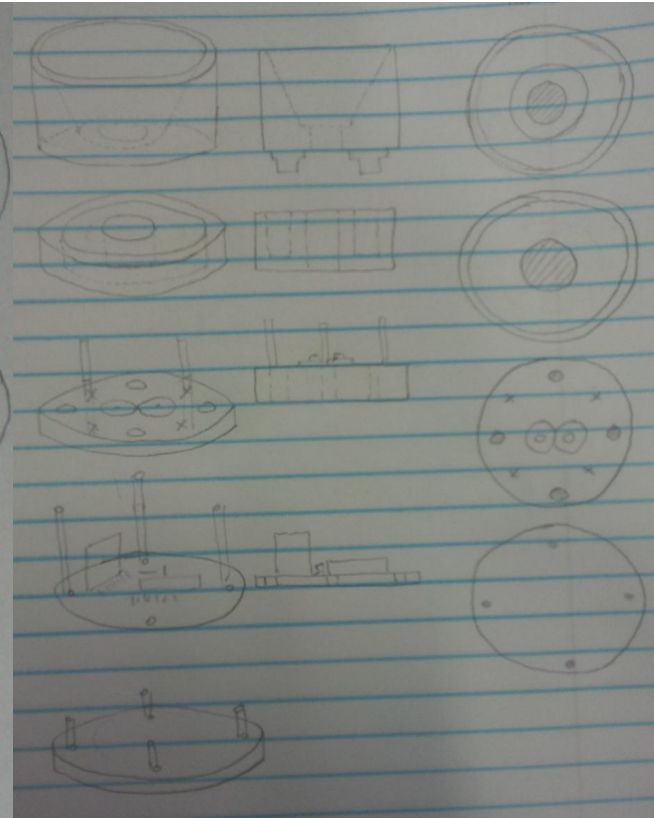
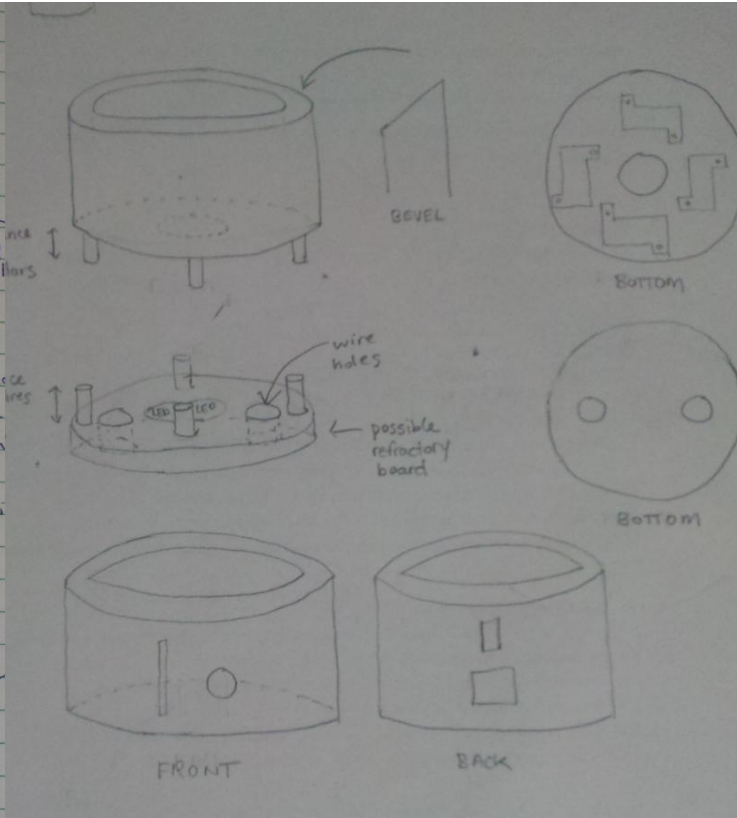
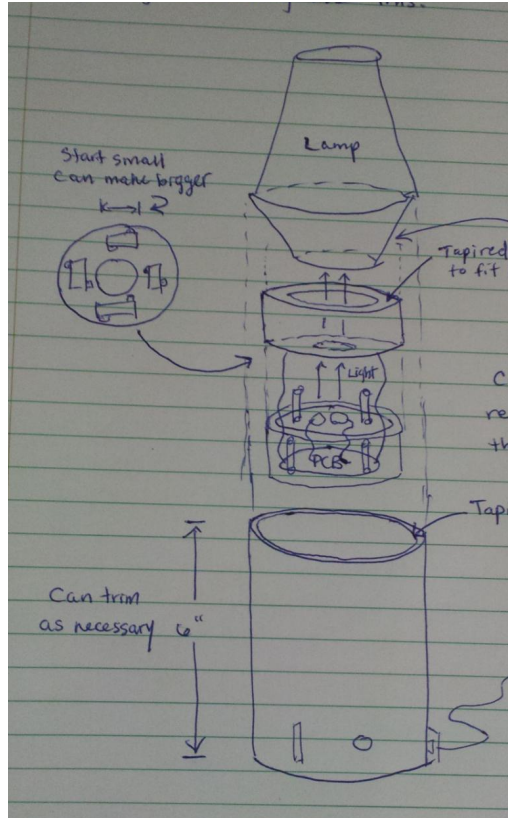
$$\begin{aligned} z_{i+1} &= Ax_i + Bu_i \\ \begin{bmatrix} z_2 \\ z_3 \\ z_4 \end{bmatrix} &= \begin{bmatrix} A \\ A^2 \\ A^3 \end{bmatrix} z_1 + \begin{bmatrix} B \\ AB \\ A^2B \end{bmatrix} u \\ C &= \text{diag}(A, B) \end{aligned}$$

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = C^T (C C^T)^{-1} (-A^T x + f)$$

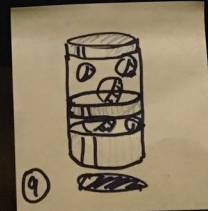
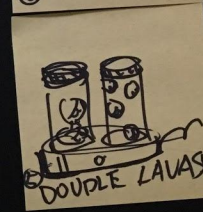
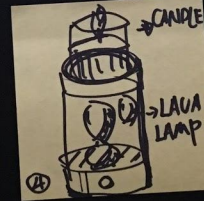
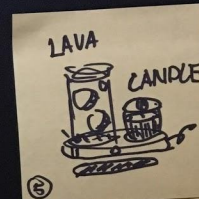
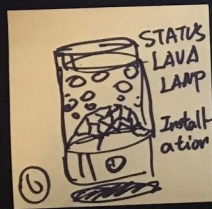
$$x_4 = f$$

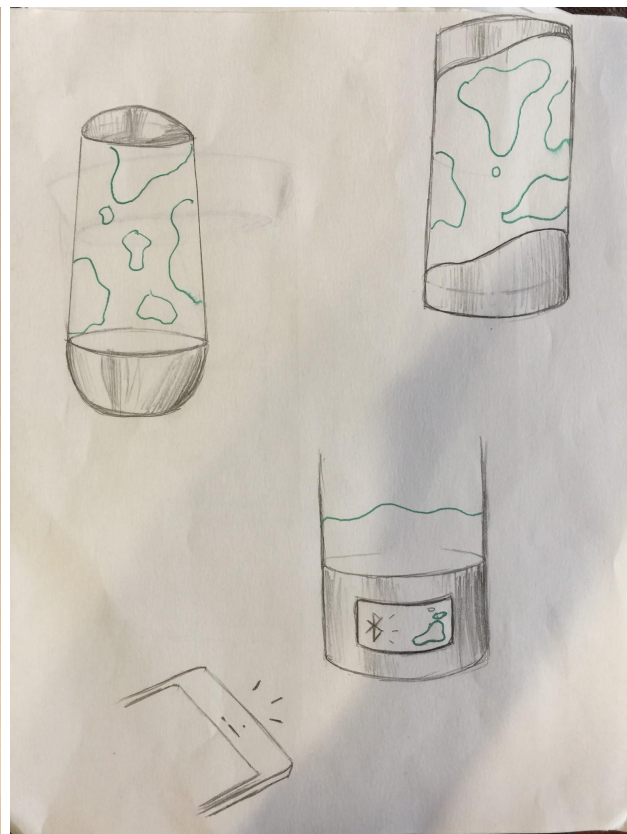
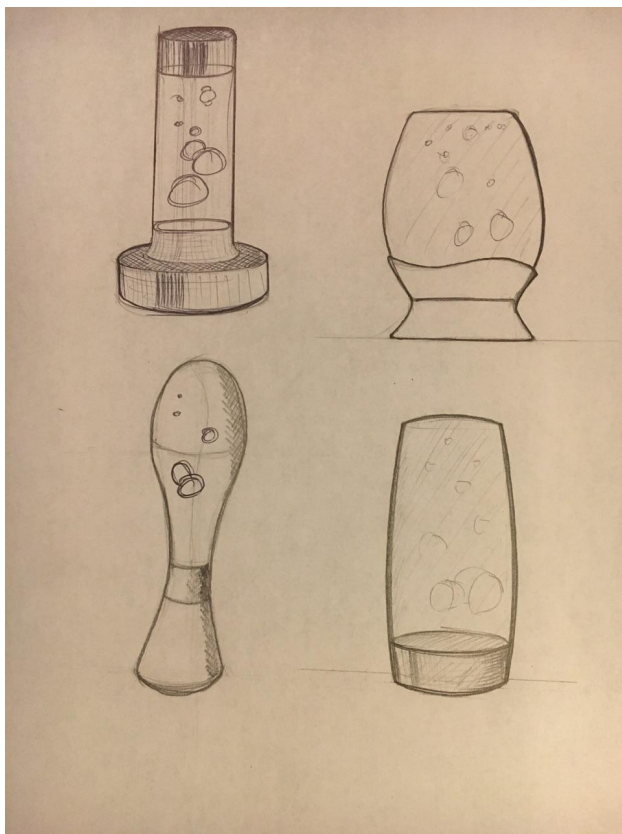
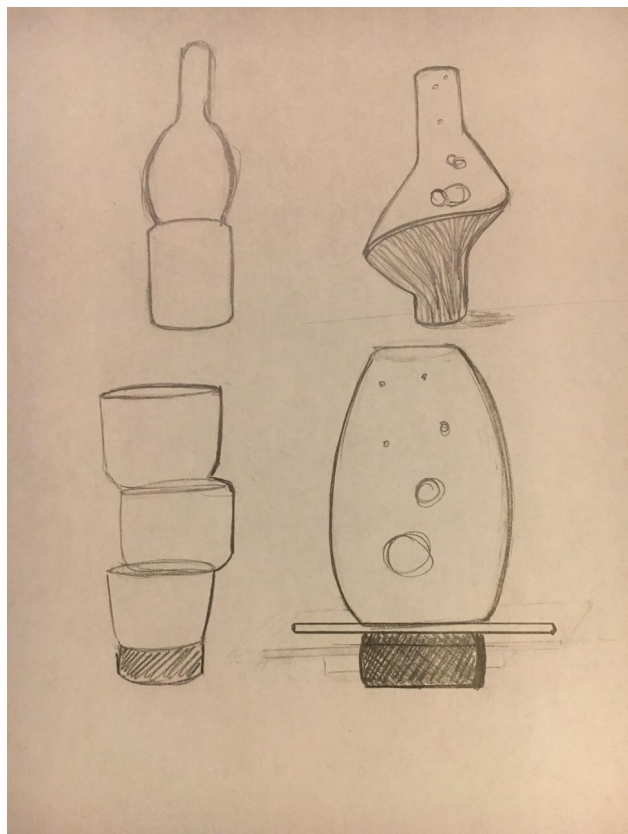
$$\begin{aligned} \begin{bmatrix} 0 \\ 0 \end{bmatrix} u + \begin{bmatrix} 0 \\ 1 \end{bmatrix} &= \frac{1}{s} \begin{bmatrix} 0 \\ 1 \end{bmatrix} u + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \\ \frac{1}{s} \begin{bmatrix} 0 \\ 1 \end{bmatrix} u + \begin{bmatrix} 0 \\ 1 \end{bmatrix} &= Ax + Bu \\ Bu + d &= \begin{bmatrix} 0 \\ 1 \end{bmatrix} u + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \\ B(u+d) &= \begin{bmatrix} 0 \\ 1 \end{bmatrix} u + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \end{aligned}$$

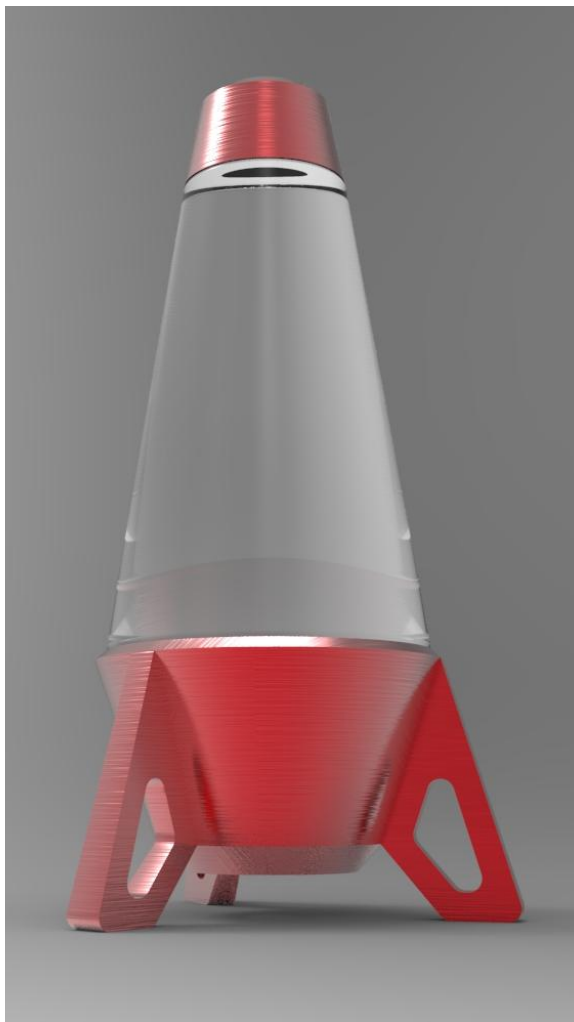
ECE Machine Shop: Skee G. Aldrich & Scott A. McDonald



Industrial Design Team: Sarah Spalding, Jarek Diaz, Jill Moore, and Lucas Mai

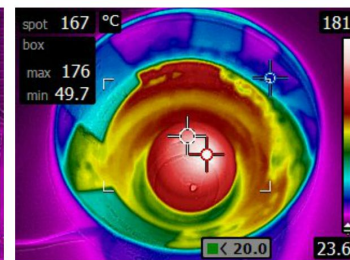
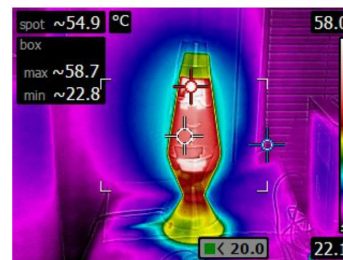
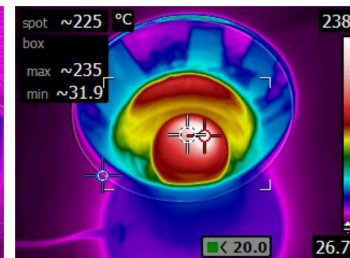
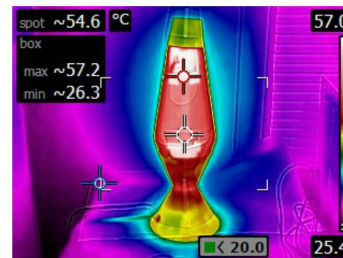
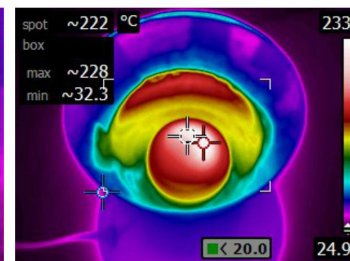
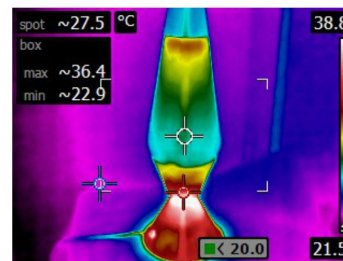
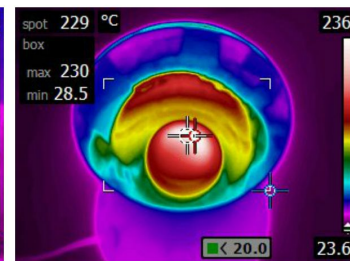
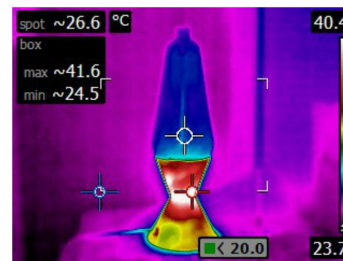
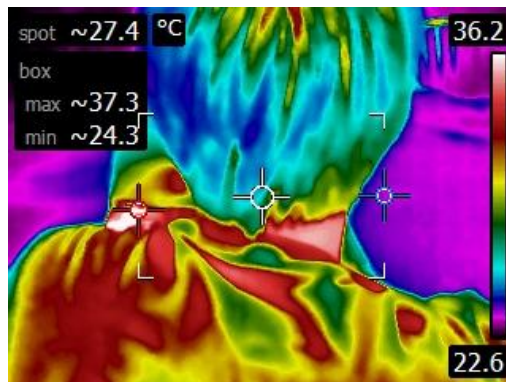
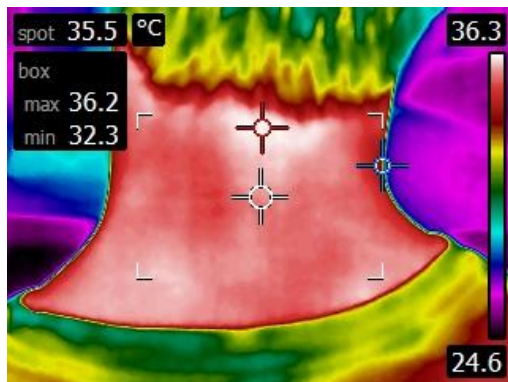
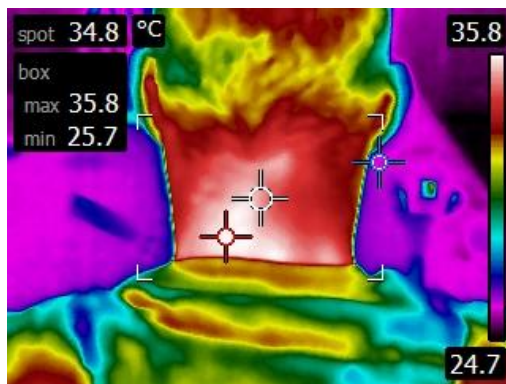






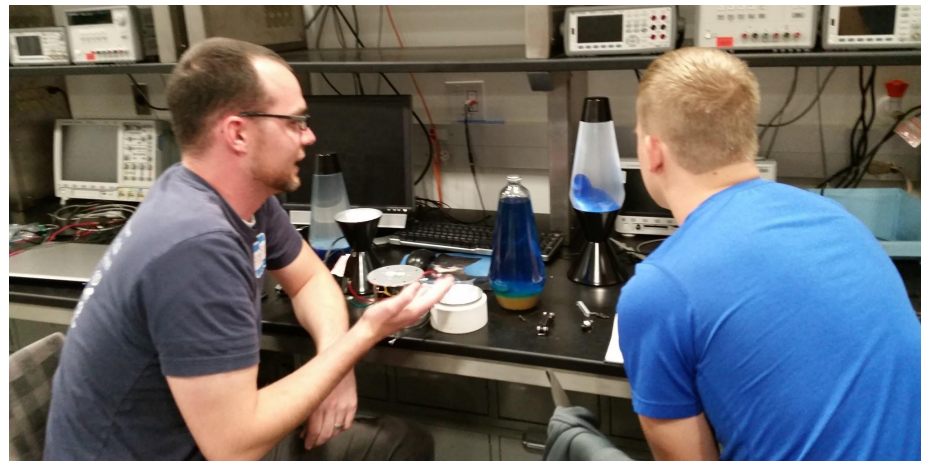
Teaching Assistant: Bird

IR Gun



Team Lava Lamp

Awesome semester



Conclusions

Faster - About twice as fast!

Safer - Temperature controller!

Decoupled - Independent and adjustable light and heat!

Questions?



Devin Bryant

- Schedule
- LED and Heating Circuit
- Mechanical Design
- Organization
- Co-pilot



Matthew Romano

- Control
- Data Collection
- Videos
- Experiments
- Pilot



Daniel Frei

- Power Supply
- PCB Design
- Soldering
- Industrial Design Contact
- Knowledge Shinobi

References

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