Robot Casserole

FIRST® Robotics Competition Team 1736

Battery Load Limiting

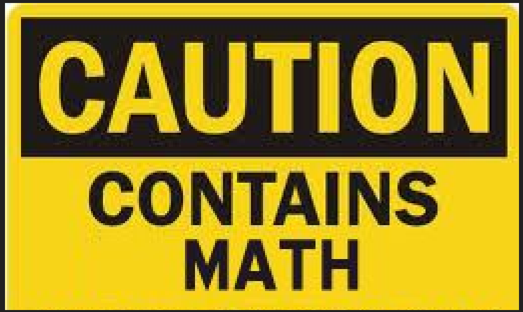
...All models are wrong, but some are useful.

Overview

- Background on Brownouts
- Physics Intro
- Modeling the Drivetrain
- Limiting the Battery Load
- Results from 2016

Warning: (some) Math Ahead.

- Minimal, Simplistic, Hand-wavey
- See the whitepaper for proofs



What is a brownout?

- Undesired component shutdown, due to **low system voltage.**

- System voltage gets low, sometimes.
    - Dead Battery?
    - Old Battery?
    - Big Load?

Background on Brownouts

- New-ish on roboRIO
- Low system voltage causes problems
- Defined thresholds for certain events
    - Vsys < 6.8V
        - Motors & Servos turned off
    - Vsys < 6.3V
        - Power removed from SPI & I2C Devices
    - Vsys < ~4.5V
        - RIO reboot

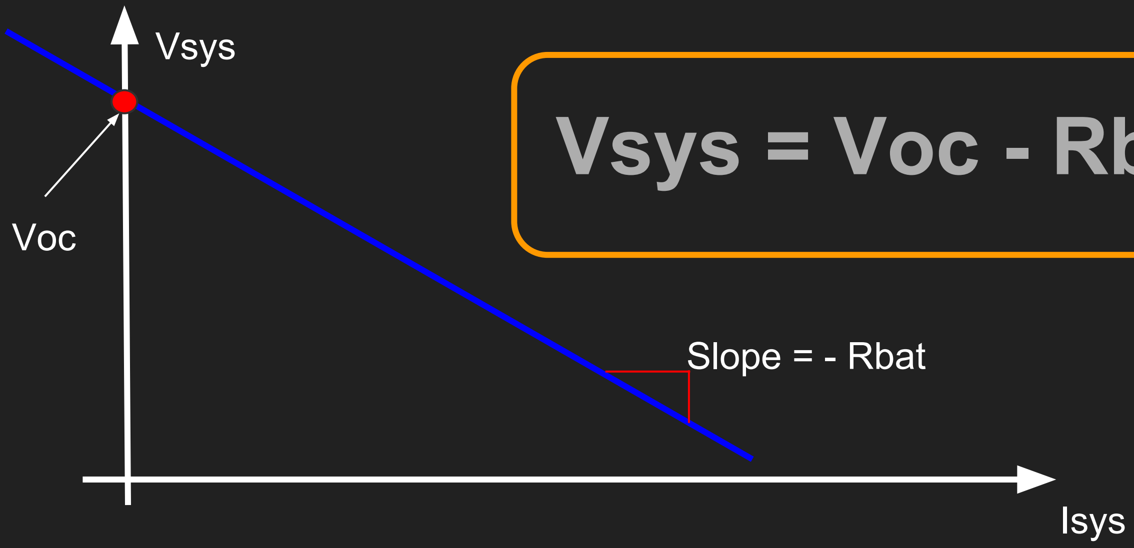
Pre-Existing Solutions

- Mechanical design updates
  - Fewer motors
  - Less-aggressive gearing
  - Wheel modifications (more slippy)
  - Good answers, but compromises may not be acceptable
- Ramp motor commands in software
  - Also good, but requires some tuning...

Understanding Batteries

Electrical Model for Battery

- Batteries convert chemical energy into electrical energy
- Chemical reaction provides a voltage (Voc), some internal resistance (Rbat)
- Battery provides an output voltage to the robot (Vsys).
- Robot exerts a load on the battery (Isys)



Vsys = Voc - Rbat* Isys

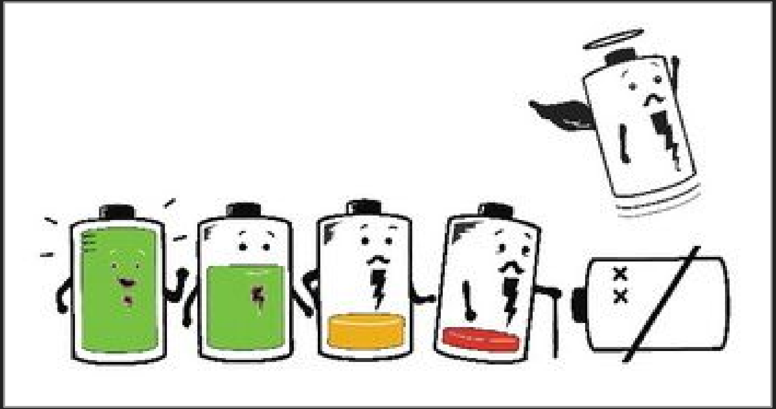
Why This Matters:

- **Vsys = Voc - Rbat* Isys**
- Given Voc, Rbat, and Isys, we can calculate Vsys
- If we can calculate Vsys for a theoretical Isys, we can *predict* a system voltage drop before it happens
- If we foresee brownout-inducing Vsys levels, we can also *prevent* them.
- The 3-part quest:
  - *Characterize Battery (calculate **Voc** & **Rbat**)*
  - *Calculate theoretical **Isys** (motor physics)*
  - *Prevent bad behavior*

Part 1: Characterizing Batteries

Battery Discharge

- Open Circuit Voltage (**Voc**): *Down slightly*
- Internal Resistance (**Rbat**): *Increases*



- Bigger **Vsys** variation with changing load (**Isys**)
- When load gets bigger, **Vsys** will dip a *lot* lower.

Vsys = Voc - Rbat* Isys

Battery Discharge

- Open Circuit Voltage (**Voc**): *Down slightly*
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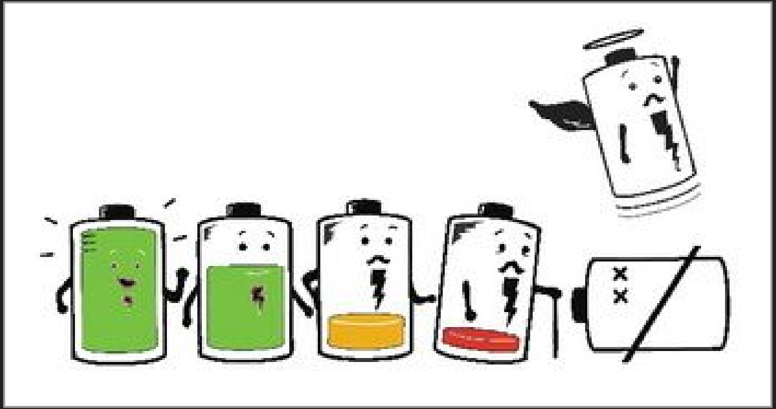


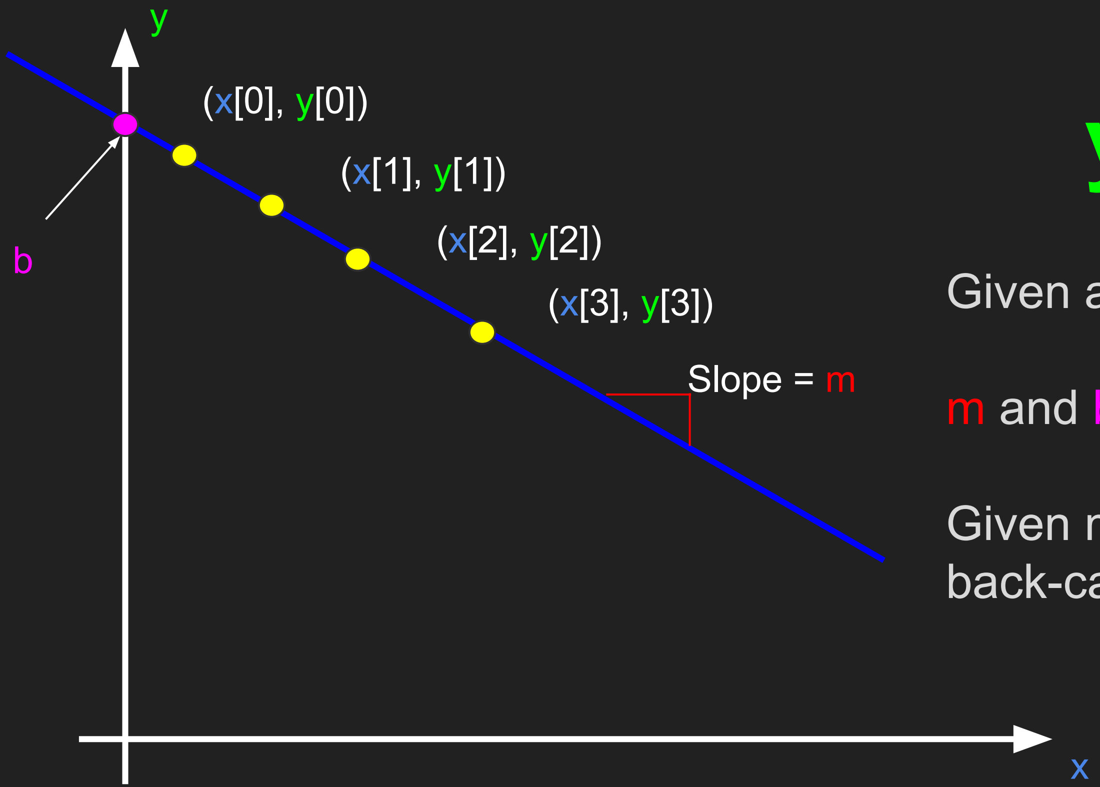
↓ ***CAUSES***

- Bigger **Vsys** variation with changing load (**Isys**)
- When load gets bigger, **Vsys** will dip a *lot* lower.

Vsys = Voc - Rbat* Isys

Knowing these matters

Review - Slope-intercept form



$$y = mx + b$$

Given an input x, you can find an output y.

m and b are assumed constant.

Given multiple input x & y pairs, you can back-calculate values for m and b .

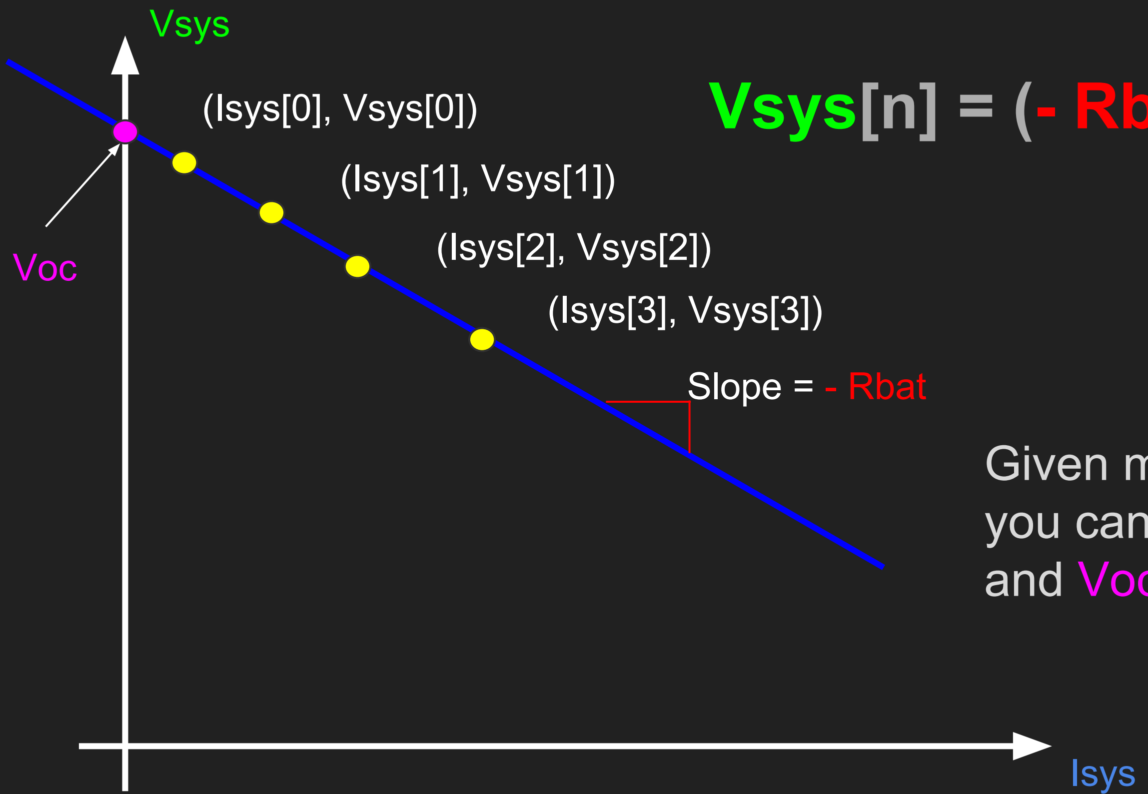
Battery Characterization

- We *do* know Vsys and Isys - measured from the PDP
  - Slower, somewhat noisy, and delayed….
    - Not good for rapid decisions
    - But, battery parameters change slowly over time.
- We use measured Vsys and Isys pairs to characterize the battery
- Recall **Vsys = Voc - Rbat * Isys**
  - This is nearly in **y** = **mx** + **b** (slope intercept) form:
  - **Vsys = (- Rbat) * Isys + Voc**
- Algorithm:
  - Measure & remember a set of **Vsys**, **Isys** pairs over recent history
  - Find a best-fit line through those pairs
  - The **slope** and **y-intercept** of this line are your battery parameters

Battery Characterization - Ideal

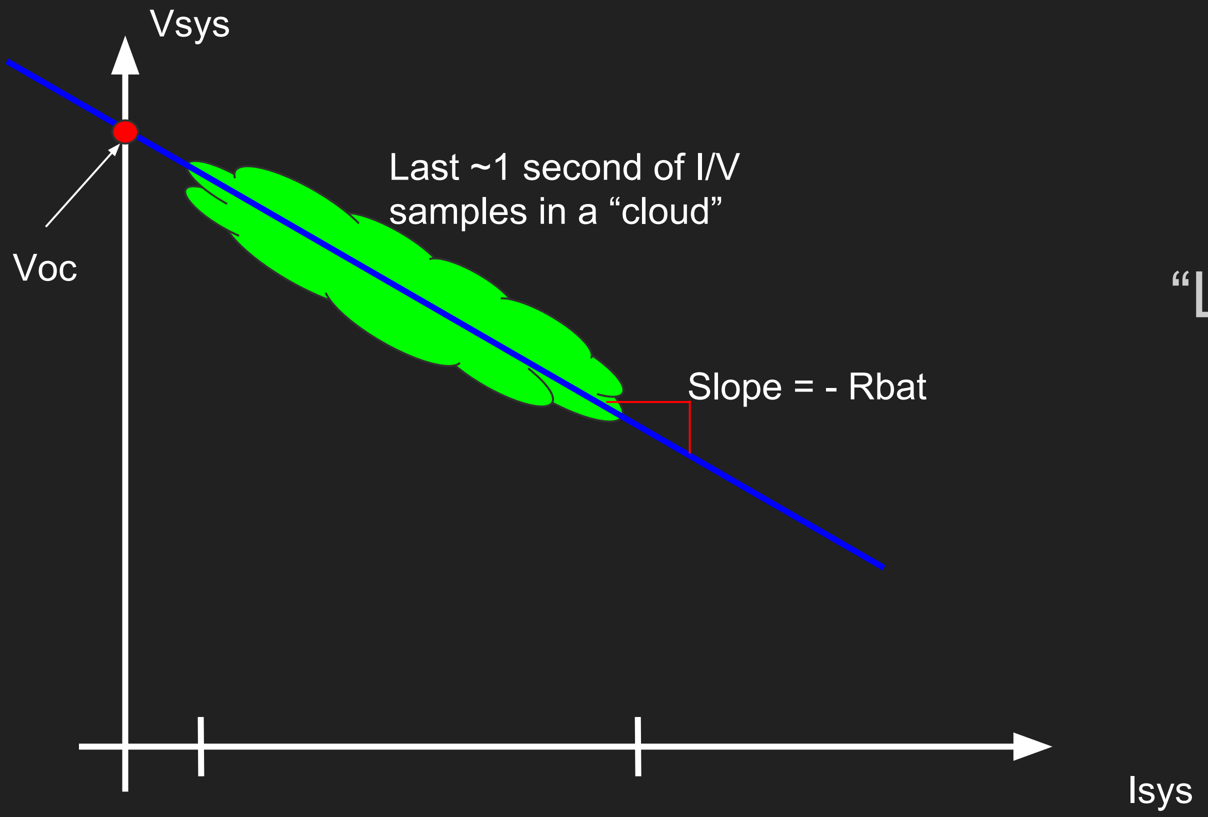
$y = mx + b$

$Vsys[n] = (-Rbat) * Isys[n] + Voc$



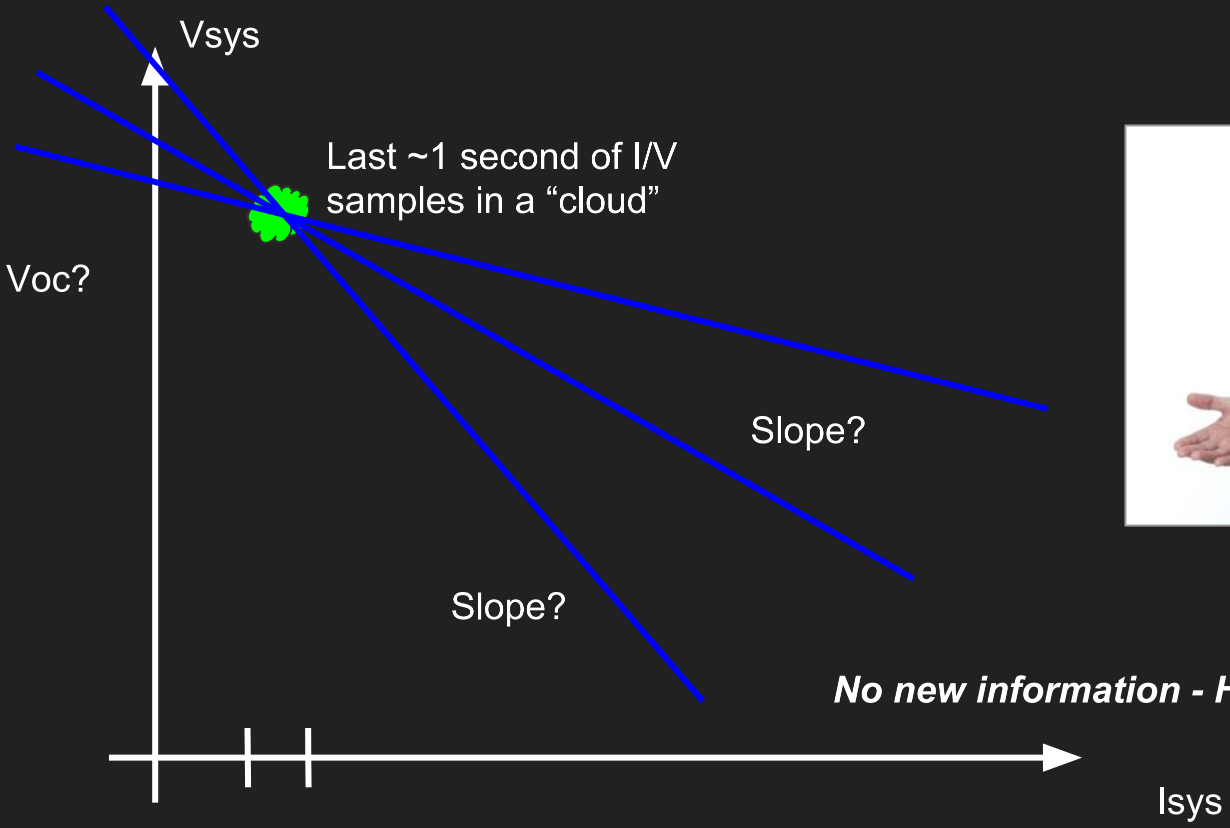
Given multiple input Isys & Vsys pairs, you can back-calculate values for Rbat and Voc .

Battery Characterization - Noise & More Samples



“Least Squares”

Battery Characterization - Constant Load



No new information - Hold last good value

Battery Characterization - Conclusion

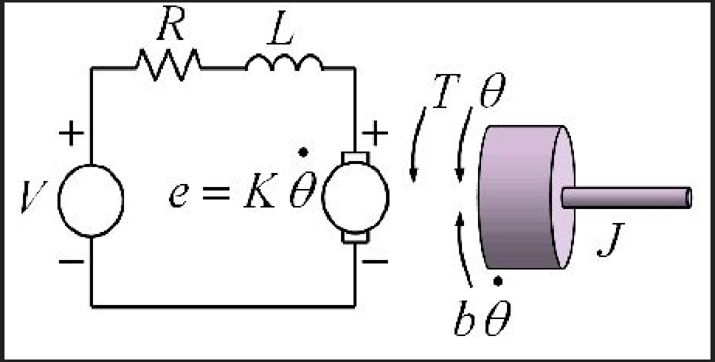
- By remembering measured Voltage and Current pairs from the PDP…
- We can do some math….
- Then, we can estimate battery parameters **Voc** and **Rbat**

Part 1 of quest… Completed.

Part 2: Calculating Motor Current Draw

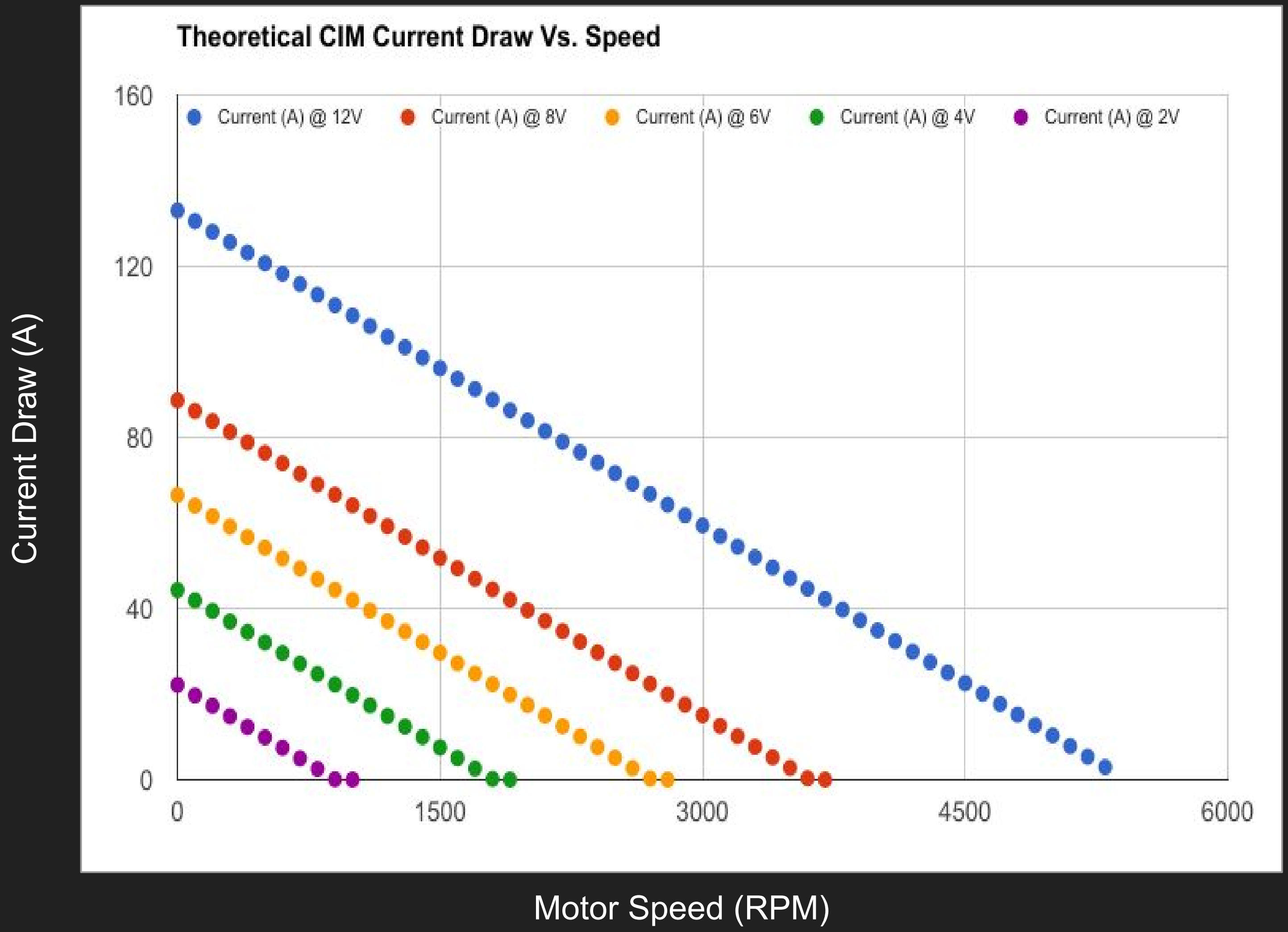
Motor Physics

- Motors convert electrical energy into mechanical energy
- Motor Current → Torque (rotational pushing) on output shaft
- Motor Counter Electromotive Force (CEMF) → Opposing voltage generated within motor due to rotation
  - Motors == Generators because of this effect
  - Speed-to-Voltage Ratio is defined as the “motor velocity constant” (Kv)



Motor CEMF Effects

- CEMF Opposes the applied voltage to the motor
  - Voltage is applied by the speed controller
- The *bigger* the speed, the *bigger* the CEMF.
- The *bigger* the CEMF, the *lower* the current draw
- For the same CEMF, lowering the applied voltage will lower current draw


Theoretical CIM Current Draw Vs. Speed
Current (A) @ 12V
Current (A) @ 8V
Current (A) @ 6V
Current (A) @ 4V
Current (A) @ 2V
160
120
80
40
0
0
1500
3000
4500
6000
Current Draw (A)
Motor Speed (RPM)

Estimating Motor Current Draw

- Inputs needed:
  - Winding Resistance (calculated from motor's stall characteristics)
    - **Rm** = Vstall/Istall
  - Velocity Constant (calculated from motor's free-load characteristics)
    - **Kv** = (Vfree - Rm*Ifree)/ωfree
  - Motor Speed (Measured from encoder in RPM) (ωm)
- Use Formulas:

$$Im = \frac{Vm - \omega m * Kv}{Rm}$$

Estimate Total Current Draw - Conclusion

- Get driver commands
- Do some math to get the predicted **Im** for each motor
- Add up all **Im** terms.
- This is your predicted **Isys**

$$\mathbf{Isys = \Sigma\ Im + \ldots}$$

Part 2 of quest…. Complete

Part 3: Preventing Bad Behavior

Pulling it all together

- Recall: **Vsys = Voc - Rbat * Isys**

Pulling it all together

- Recall: **Vsys = Voc - Rbat * Isys**
  - ***Voc***, ***Rbat*** *were calculated in Part 1*
  - ***Isys*** *was calculated for the present driver commands in Part 2*
- By applying the above equation we now have an **estimate** for what **Vsys** will become if we execute the driver's commands exactly
- *IS IT OK???*

Limiting

- If your estimated Vsys is too low, we shouldn't do exactly what the driver commanded.
- Required mitigation: Reduce battery load.
    - Scale back drivetrain commands?
    - Power/Energy budget for all components?
- Complete answer is implementation dependent.
    - 1736: Try smaller and smaller scaling factors on drivetrain until we find one that works

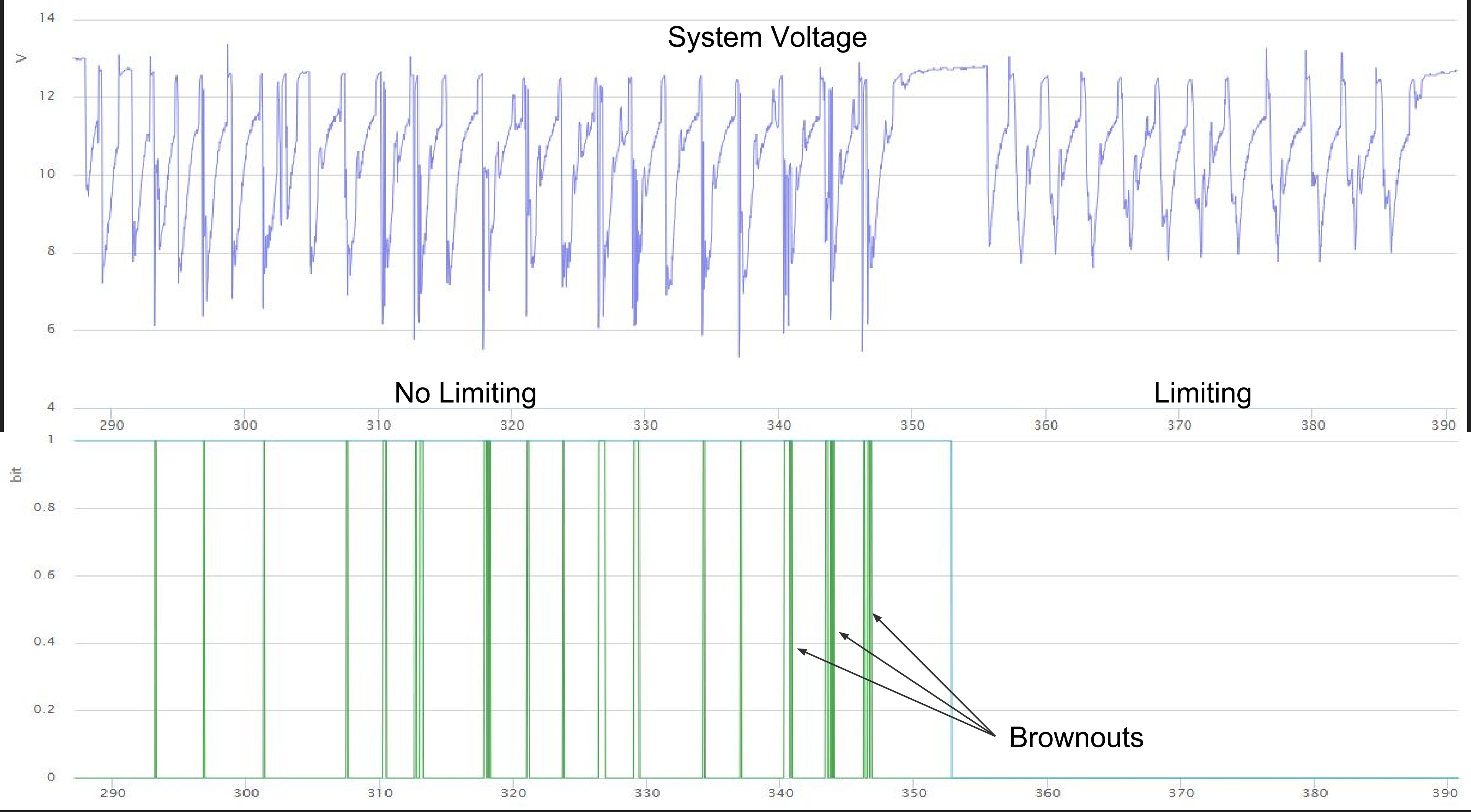
$$Isys = \sum Im + ...$$

Part 3 of quest…. completed!

Real-world implementation

- Many resistances unaccounted for
  - Wiring, Speed Controllers, circuit breaker, connectors, etc.
- Capacitance/Inductance not modeled
- Some math presumes slowly-changing signals
- Battery parameters assumed independent of present load… mostly true?
- Not all current draw sources accounted for
- Filtering on measured values required
- But…. Good enough?
  - *All models are wrong….*

Results


System Voltage
V
No Limiting
Limiting
bit
Brownouts


System Voltage
V
14
12
10
8
6
4
7.5V
No Limiting
Limiting
290
300
310
320
330
340
350
360
370
380
390
bit
1
0.8
0.6
0.4
0.2
0
Brownouts

Questions?

Special Thanks To:
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Key Content Reviewers: Jeremey Lee, Larry Schmidt, Ether

Backup Slides

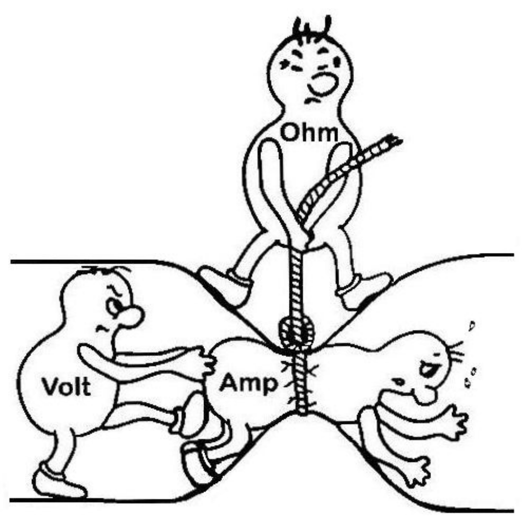
Electrical Primer

Voltage & Current

- Electricity = movement of electrons
- Voltage = how much force we’re pushing on those electrons with
  - Always measured between two points
  - Measured in units of Volts (V)
  - Variable is usually V
- Current = how many electrons are moving
  - Always measured at a single point
  - Measured in units of Amperes (A)
    - Aka Amps
  - Variable is usually “I”

Resistance

- Opposes the flow of current
  - “Opposes” means it generates a push in the opposite direction
  - Recall that voltage is an electrical “push”
- Everything* has some resistance
- “Nice” resistors have the property:
  - **V = I * R**
  - V = pushback voltage
  - I = current going through the resistor
  - R = some ratio (the “Resistance” of the material, measured in ohms)



The “Lumped Circuit” Model

- We group the various properties of a device into “lumps”
- We connect those lumps to show relationship
- The Resistance lump:

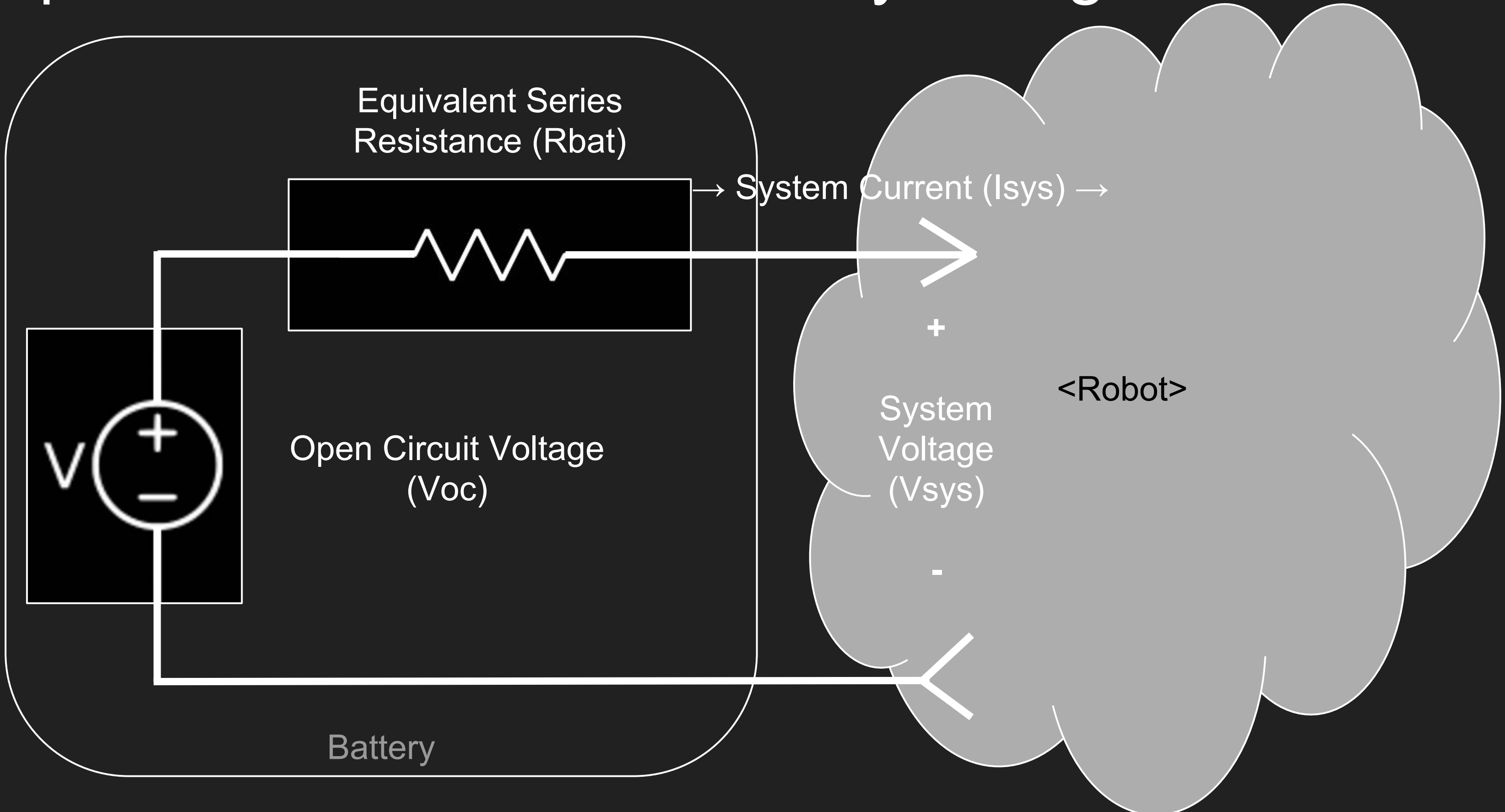
- The Voltage lump:

Battery Load

- For this presentation, we define “Load” to be the amount of current pulled from the battery
    - Isys
    - Can be measured at the PDP
    - Big load = lots of current (~150A or more)

Battery Lumped Circuit Model

Lumped Circuit Model for Battery - Diagram



System Voltage vs. Motor Speed Calculations

Steady-State System Voltage Vs. Motor Speed @12V