# *Enzymatic Batteries for Implantable Medical Devices: Focus on Glucose Monitoring*

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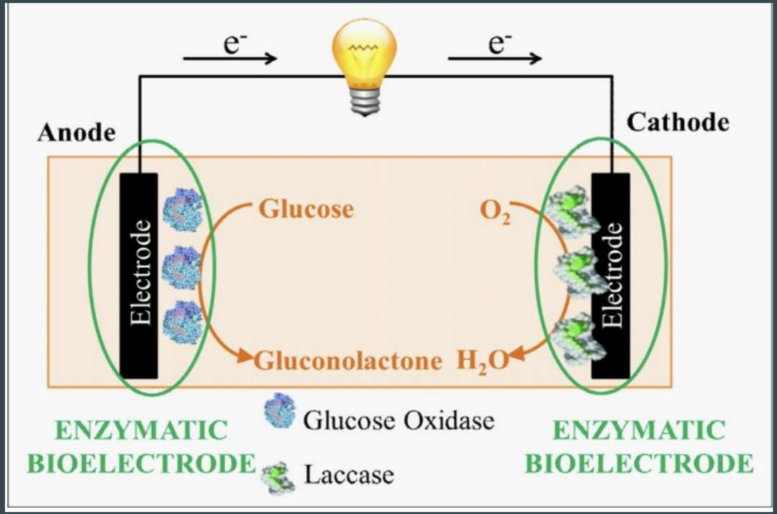
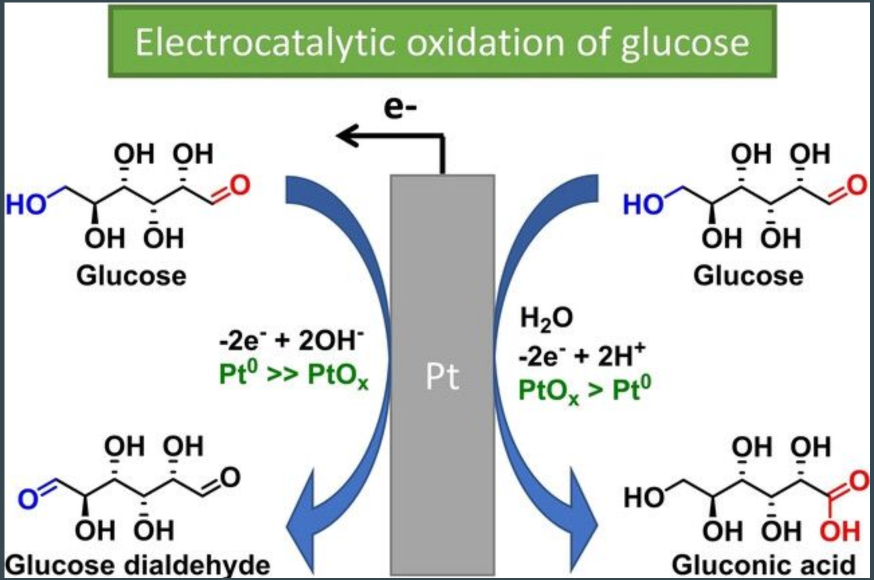
# Background

- Implantable medical devices need reliable and long-lasting power sources.
- Traditional batteries pose limitations:
  - Size
  - Lifespan
  - Environmental impact.
- Lithium-ion batteries are too large for implantable medical devices, and lose performance



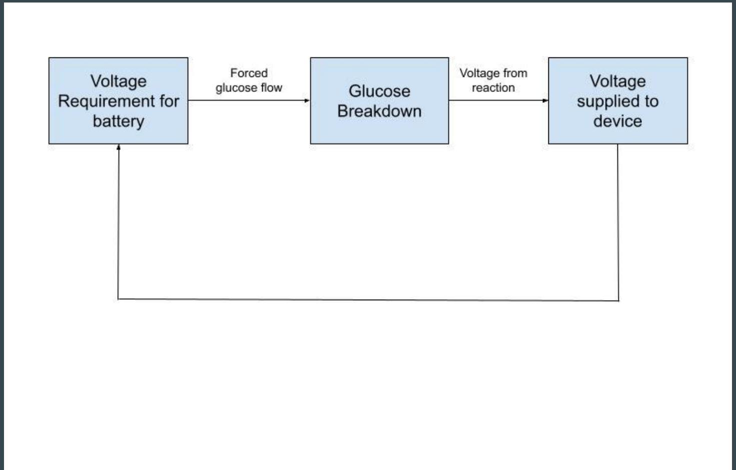
# Background

- Bio-batteries can create electrical power using organic compounds
    - Sugar battery: break down units of glucose at the cathode and produce electrical flow through a substrate to the anode.
- ODE model for battery consumption is needed to determine feedback system and keep a stable flow rate of glucose into the battery and multiple blood sugar levels for implants.
- Limited ODE modeling in respect to variable glucose changes
    - Most studies supply ideal glucose concentrations directly to system as it is outside of the body



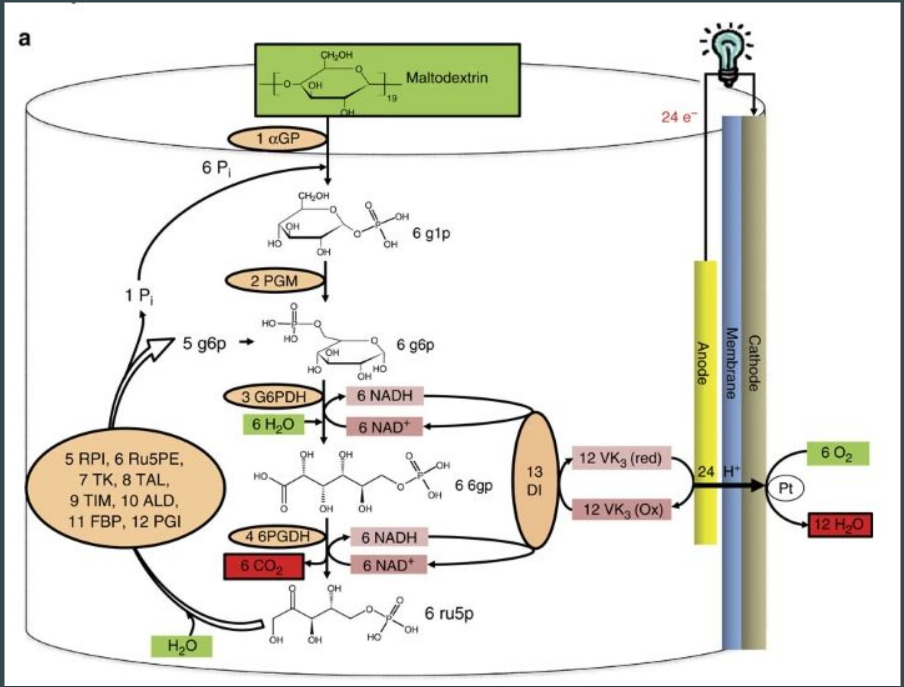
# Specific Aim of this project

- Assessment of glucose concentration in the battery with perturbations from the body
  - Using the blood sugar levels of the body as a fuel source
  - Pathway for feedback(inducing glucose flow into the battery)
- Make sure this battery can accommodate for a range of perturbations(varying blood sugar levels)
- Determine if it’s possible to run the battery off of blood sugar



# Assumptions

- Enzymatic pathways within the battery allow cyclical concentrations of oxygen, hydrogen, carbon dioxide
  - Allows for modeling the voltage from gluconic acid production(24 electrons per one glucose breakdown)
  - Closed battery system-allows for cyclical battery chemical cycles
- Glucose Conditions
  - Gluconic Acid: 0.001M
  - Glucose: Dependent on Blood Sugar case
    - Refer to dynamic response slides
    - Hyperglycemic: 0.0069 mol/L
    - Hypoglycemic: 0.0029mol/L
- Assume time constant of 1 for PID feedback response



# Equations

$$C_6H_{12}O_6 + 0.5O_2 \leftrightarrow C_6H_{12}O_7 \quad (1)$$

$$\frac{dg}{dt} = \frac{1}{k_e}e(t) - k_1[g][O_2]^{1/2} + k_2[P] \quad (2)$$

$$\frac{dP}{dt} = - k_2[P] + K_1[g][O_2]^{1/2} \quad (3)$$

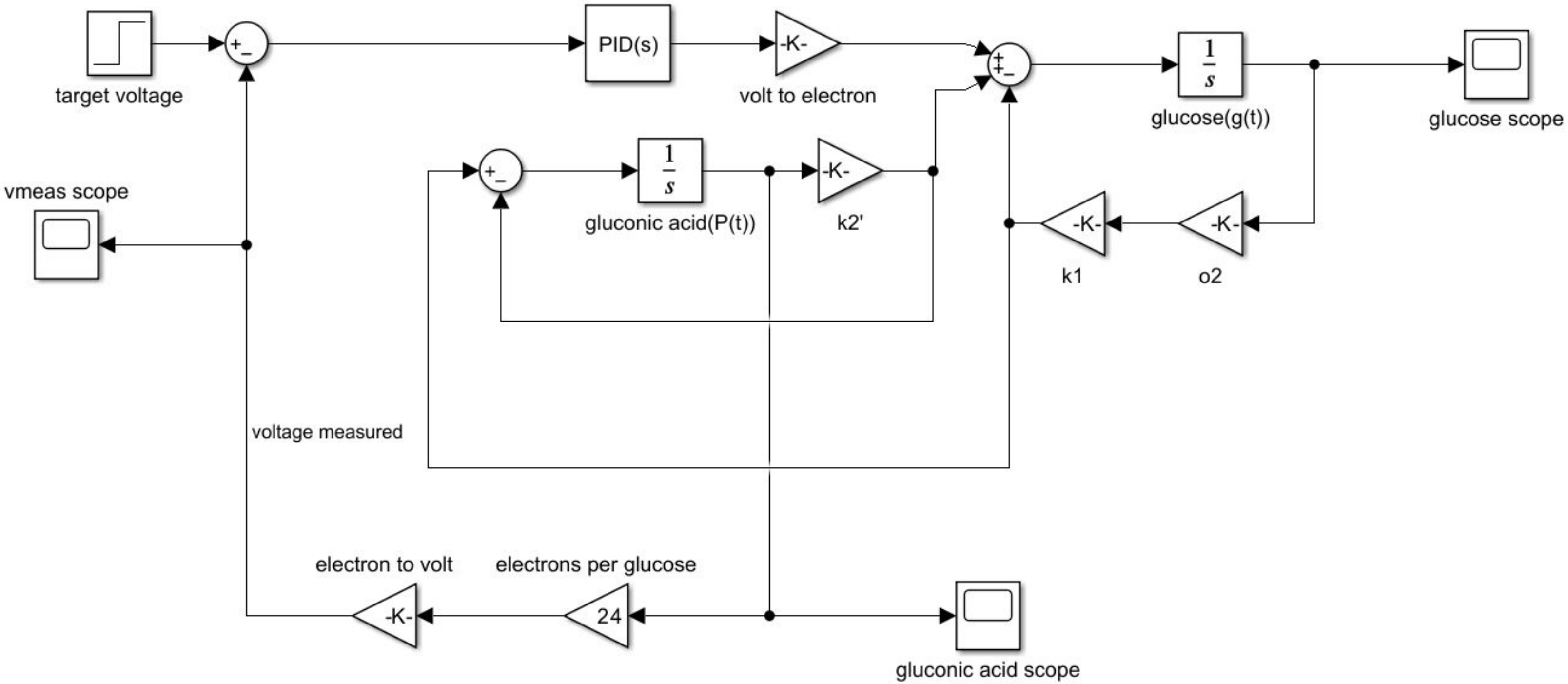
$$V_{measured} = 24k_eP(t) \quad (4)$$

$$V(t) = V_{target} - V_{measured} \quad (5)$$

$$e(t) = K_pV(t) + \int_{-\infty}^{t} K_iV(t)dt + K_d\frac{d}{dt}V(t) \quad (6)$$

| Constant | Value |
|---|---|
| $k_1(1/s)$ | 0.00116 |
| $k_2(1/s)$ | 0.0003 |
| $[O_2](M)$ | 0.0355 |
| Electron conversion ($e_k$) | $1.602 \times 10^{-19}$ |
| Volt conversion ($1/e_k$) | $6.242 \times 10^{18}$ |
| $k_p$ | 0.1 |
| $k_i$ | $2.5872 \times 10^{-5}$ |
| $k_d$ | 85.4226 |

# Simulink: Block Diagram



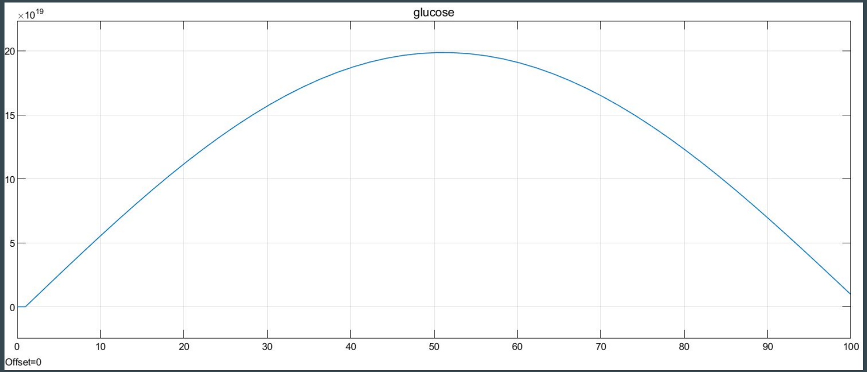
# Open Loop Transfer Function

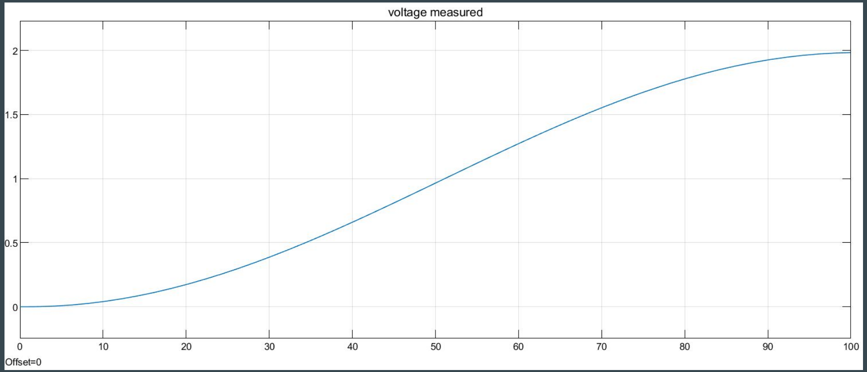
$$\frac{1.04e18}{s^3 + 0.001181\, s^2 + 0.00116\, s + 1.235e\text{-}08}$$

$$\frac{6.242e18}{s + 1.065e\text{-}05}$$

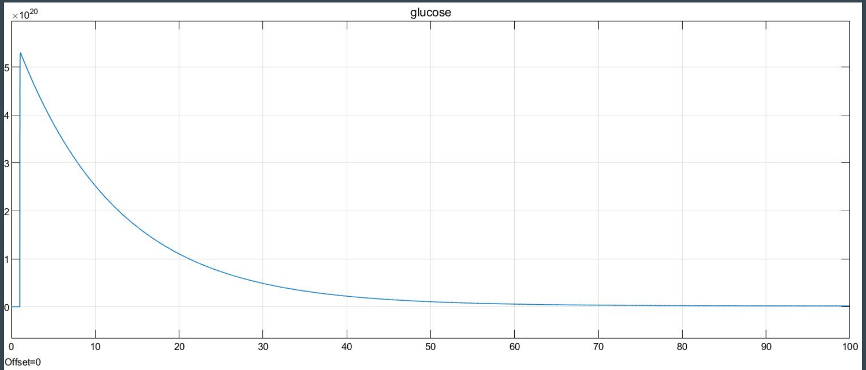
# Dynamic Response

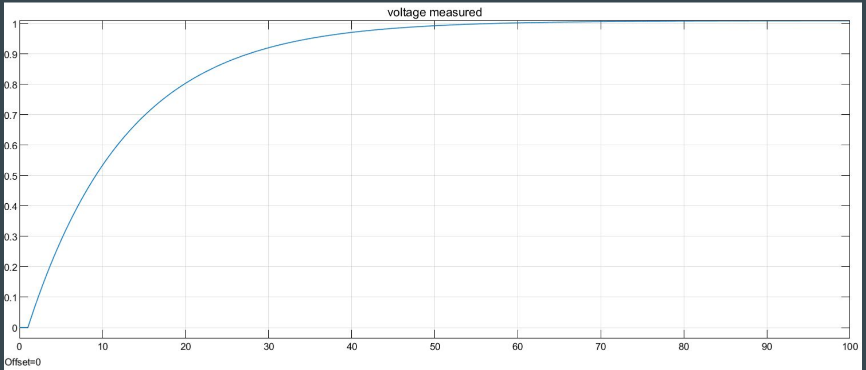
## Glucose & Voltage Measured Without PID



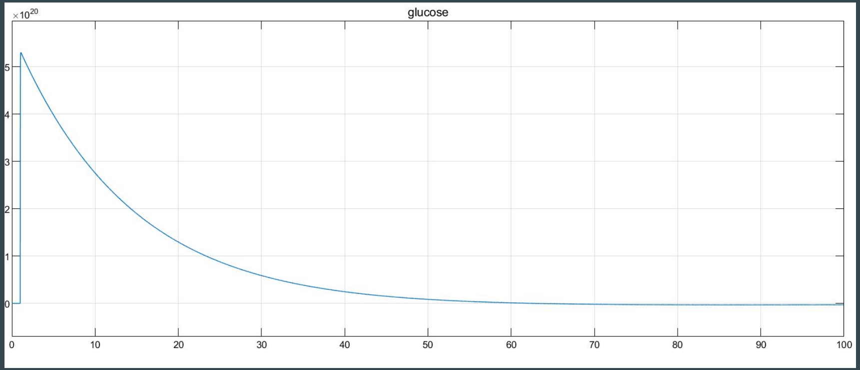

## Glucose & Voltage Measured With PID

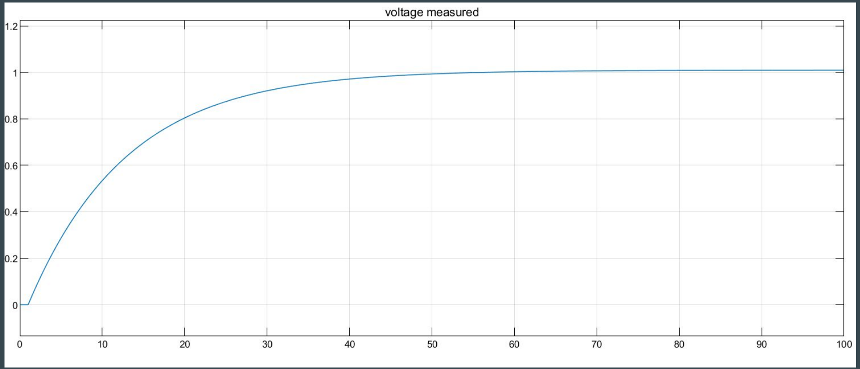


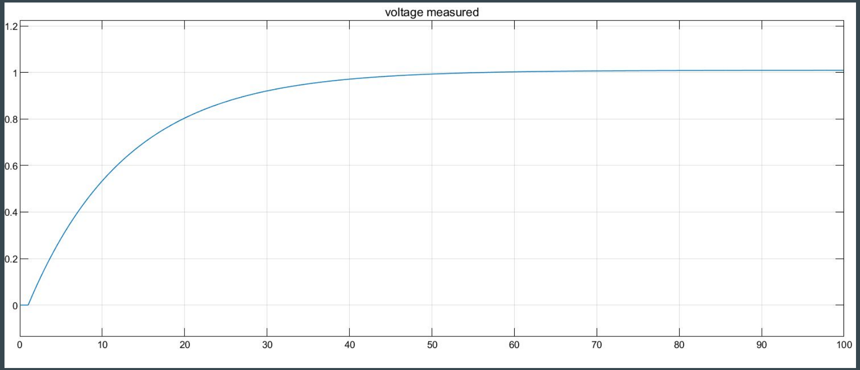
# Dynamic Response: Varying Blood Sugar Levels

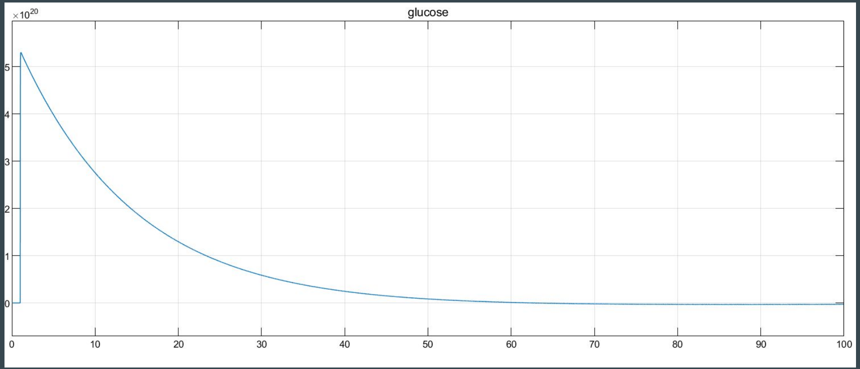
## Hypoglycemic Conditions



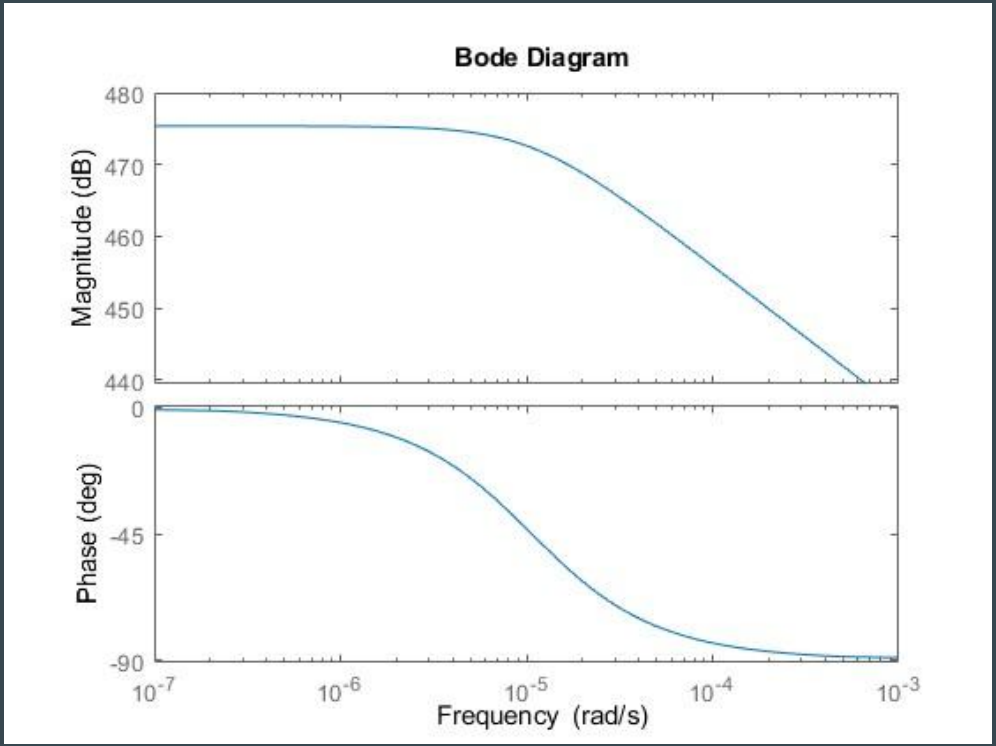

## Hyperglycemic Conditions



# Bode plot

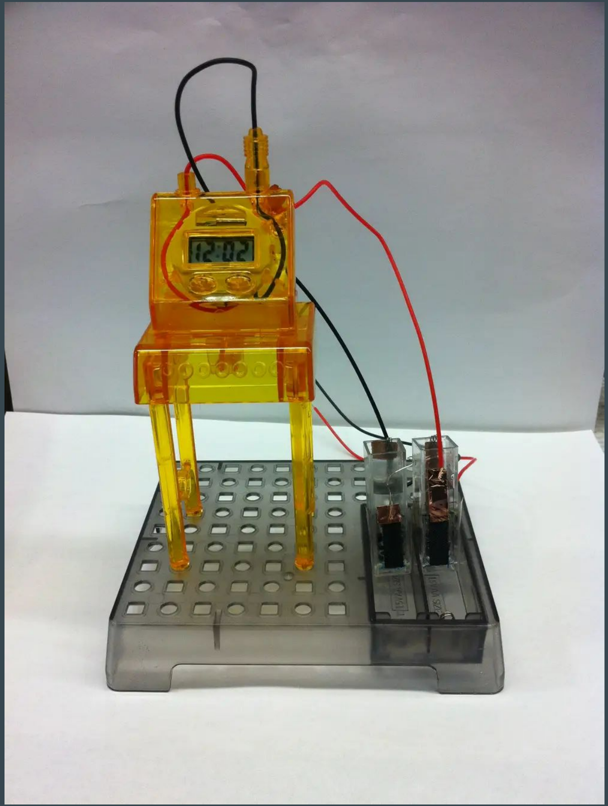
Open loop response




- PID coefficients eliminate two of the three poles
  - Much smaller phase change
  - High magnitude due to this function being in relation to each glucose molecule
- Phase Margin of 90 degrees

# Clinical Applications

- Helps create an understanding of fuel requirements for bio-battery cells
  - Tackles the question: Is it possible to use a sugar battery inside the body?
  - Opens doors to other bio-battery models for implants
  - Environmentally friendly device models
- Uses for Implantable devices
- Renewable energy source due to enzymatic pathways and sugar



# Why this model?

- Could allow for continuous monitoring of glucose levels(provides real time data)
- Less invasive than traditional methods of glucose monitoring
- The ability of these batteries to generate power from the enzymatic reactions, such as glucose oxidation, allows for a continuous and sustainable energy source.

Possibilities Going into the Future:

- Integration of enzymatic batteries with sensors for other biomarkers or therapeutic capabilities can make the implantable device multifunctional

# References


Kinetic Studies on Enzyme-Catalyzed Reactions: Oxidation of Glucose, Decomposition of Hydrogen Peroxide and Their Combination - PMC (nih.gov)

A high-energy-density sugar biobattery based on a synthetic enzymatic pathway | Nature Communications

Mathematical modelling of enzymatic glucose fuel cell and numerical validation - ScienceDirect

Sony Develops 'Bio Battery' Generating Electricity from Sugar (phys.org)

Releasing the Potential of Biobatteries (bio-itworld.com)

New Flow Battery Lasts All Year On Simple Sugar (cleantechnica.com)

Mean fasting blood glucose (who.int)