L1.2: The Cell as a Machine

Prof Rickus
In this lecture …

• Consider Cells as
  • Fundamental Unit of Life
  • A Living Machine
• Power Consumption of Cells
• Energy
  • input, conversion, storage and utilization
• Energy Utilization
  • What is the Work of Cells?
A Cell is a Living Machine

What is a machine?

“a piece of equipment with moving parts that does work when it is given power.” - Merriam Webster

What defines living?

“an organismic state characterized by capacity for metabolism, growth, reaction to stimuli, and reproduction” – Merriam Webster
The “Job” of the Cell

Make more cells:
• Make Building Blocks
• Self-Assemble Blocks into Devices
• Take in & Store Energy

Stay Alive:
• Sense Environment
• Sense Internal State
• Change in Response
• Communicate with Other Cells

Specialized Tasks or Functions
• Multi-cellular organisms
• Division of Labor
• Special Skills for Unique Environments
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**Biological Framework**

- Metabolism
- Cell Division
- Cell Growth
- Gene Expression
- Signal Transduction
- Cell Migration
- DNA Repair
- Cell-Cell Comm.
- Paracrine Signaling
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Machine Framework

Energy Storage
Manufacturing
Catalysis
Pump

Sensor
Actuator
Processor
Clock

Integrated
System
Network
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Engineering Disciplines
- Thermodynamics
- Mass Transport
- Kinetics
- Electrochemistry
- Controls
- Dynamics
- Mechanics
- Signal Processing
- Networks
- Informatics
Minimal model of the *E. coli* “machine”

1. Energy/Raw Material input
2. Convert into usable energy
3. Use energy to make ribosomes
4. Use ribosomes to make more ribosomes & all other proteins
5. Proteins assemble to form new cells & participate in energy conversion

under ideal lab conditions

What is a machine?

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What are the energy inputs of a cell?
- in what form?
- how much?
- at what rates?

What work is a cell doing?
- what types?
- what magnitude?
- what rates?
Cellular Energy and Storage

Energy Inputs
- sunlight
- molecular food

Stored / Usable Energy
- electrochemical potential
- stored polymers

Energy / Electron Rich Molecules
- ATP
- NADH

References:
- Qian H. et al. (2011)
Energy Input
Accessing the Energy Stored in Sugars (a primary molecular food for cells)
Via Oxidation

What is the rate of energy consumption via glucose?

Flux, \( J \)  
\[ \text{[\# m}^{-2} \text{s}^{-1}] \]

Shi et al. 2010 Analyt. Biochem.

\[
\left( \frac{5 \text{ mmol}}{\text{cm}^2 \cdot \text{s}} \right) \left( \frac{3000 \text{ kJ}}{\text{mole}} \right) \left( \frac{\text{mol}}{10^6 \text{ mmol}} \right) \left( \frac{10^3 \text{ J}}{\text{kJ}} \right) = \frac{15 \text{ W}}{\text{cm}^2}
\]

measured flux  
free energy released by glucose oxidation  
power input per surface area of \( \beta \) cell

pancreatic \( \beta \) cell

glucose transporter inhibited cell poisoned

glucose flux in culture

transporter inhibited cell poisoned
What is the rate of energy consumption via glucose?

Flux, $J \left[ \text{mol m}^{-2} \text{s}^{-1} \right]$  

This measured glucose flux is particularly large. Most measured cell flux are in 10-100’s pmol cm-2 s-1.
Job of Metabolism to Convert Molecular Food into ATP, reducing power

Generally ~ 20 – 36 ATP generated per glucose molecule

Free energy change:  
- Glucose oxidation → 3000 kJ / mole
- ATP Hydrolysis → 50 – 70 kJ / mole

http://www.nature.com/scitable/content/metabolism-in-a-eukaryotic-cell-glycolysis-the-14705577
Usable Energy

high energy phosphate bond

ATP + H₂O ⇄ ADP + P_i

~ 50 – 70 kJ / mol

electrochemical potential

NADH

~100 mV

Energy Storage

animal cells  plant cells  paramecium

glycogen  starch  lipids

\[
\left( \frac{\sim 350 \text{ g glycogen}}{\text{human}} \right) \left( \frac{4.2 \text{ kJ}}{\text{g glycogen}} \right) \sim 1500 \text{ kJ}
\]

energy stored as glycogen in a typical human

Power consumption of a single bacterial cell?

Ballpark estimate to give a sense of scale. Build intuition. Based on general, standard conditions. Likely to vary widely with cell state, environment, type. Challenge remains to measure power directly.

http://book.bionumbers.org/what-is-the-power-consumption-of-a-cell/
Coming up …

• Cellular Work
  • Power Consumption of Cell motility
    • Actin mediated
    • Flagellar motor mediated

• Cellular Pumps

• Thermodynamic view of Life/Death