SYLLABUS IS TENTATIVE
IT WILL BE UPDATED on a WEEKLY BASIS
ACCORDING to PROGRESS in CLASS

Course Code	**BME3142**
Course Title	**Biomedical Modeling and Simulation**
Instructor	**Kamuran A. Kadıpaşaoğlu** **kamuran@yildiz.edu.tr** http://avesis.yildiz.edu.tr/kamuran/
Graduate Assistant	**Ümmühan Zengin Özer**
Textbooks	**Guyton AC and Hall JE** Textbook of Medical Physiology, 11th edition Elsevier, Philadelphia, 2006 **Michael CK Khoo** Physiologic Control Systems IEEE Press Series in BME, 2000 **Neumann DA** Kinesiology of the Musculoskeletal System, 3rd Ed Elsevier, St. Louis, MO, 2017
Recommended Reading	**J.T. Ottesen, M.S. Olufsen, and J.K. Larsen** Applied Mathematical Models in Human Physiology BioMath-Group, Depts Mathematics & Physics Roskilde University, Denmark, 2003 **Batzel JJ, Kappel F, Schnedits D, Tran HT** Cardiovascular and Respiratory Systems: Modeling, Analysis and Control SIAM (Society for Industrial and Applied Mathematics), Philadelphia, 2007

Course Objectives

The objective of the course is to introduce and apply general theories for modelling and simulation of systems relevant within biomedical engineering. This includes both physical and physiological models.

Course Content

Introduction to concepts of system modeling, model formalism and its relationship to different simulation strategies. Application of general and specific methods to analyze and model systems. Implementation and simulation of models in a computing environment (Matlab/Simulink). Discrete-time and stochastic simulation methods. Evaluation of model applicability, accuracy, and robustness.

Course Learning Outcomes

1. Identify and describe general principles for modeling and simulating a system.
2. Apply these principles when designing mathematical models for a number of realistic systems.
3. Implement and use computer-based modeling and simulation for studying research relevant problems within the field of biomedical engineering.
4. Analyze simulation results obtained from produced models using visualizations, graphics, and other tools.
5. Evaluate the applicability and usability for different models and simulation techniques.

Program Outcomes (PO)

1. Understanding of the ethics and principles of engineering.
2. Understanding the concept of biomedical engineering and its main fields of study.
3. Learning the basic terminology and the analogies between systems used in biomedical engineering.
4. To gain awareness about entrepreneurship, project management, sustainability in engineering.
5. Establishing effective oral and written communication

Program Outcomes (PO) Relevant to the Course

4. **PO-2.1)** Ability to define, formulate and solve complex engineering problems.
5. **PO-2.2)** Ability to choose and apply appropriate analysis and modeling methods for this purpose.
8. **PO-4.1)** Ability to develop, select and use modern techniques and tools necessary for the analysis and solution of complex problems encountered in engineering applications.
9. **PO-4.2)** Ability to use information technologies effectively.

Course Learning Outcomes & Program Outcomes Matrix

CLO	1	2	3	4	5
PO-4	5	5	4	5	3
PO-5	5	5	5	5	5
PO-8	3	3	5	5	5
PO-9	3	3	5	5	4

Welcome to Class everyone.

Before starting this semester, it may be wise to be advised about the course organization so as to maximize your classroom performance and get the most fun out of the experience.

To begin, please follow the steps below.

1. Go to http://avesis.yildiz.edu.tr/kamuran/
2. Click on My Shares (**Duyuru ve Dokümanlar)**
3. Find the file "**Rules and Guidelines**"

    a. Download & save and print it
    b. Read, understand, and even memorize its contents.
    c. Pay particular attention to **Homework Policy** and **Grading Policy**

4. On the same page, find the file "**YourCourseCode_Syllabus_Semester_Year_#"**.

    a. The file will be updated on a weekly basis.
    b. Make sure you read the assignment(s) **BEFORE** coming to each class, **STARTING THIS WEEK**!
    c. Download and save any **Textbook**(s) that is (are) posted.

5. It is highly recommended that you

    a. Read the assigned chapter
    b. Solve the example and homework problems
    c. Prepare your questions for me

    BEFORE COMING TO CLASS.

6. There will be a quiz assignment every week.

I am looking forward to an educational and productive semester.

Good luck to all.

KAK

HOMEWORK and GRADING POLICY

1. There will be a HW assignment every week, except the first week, the weeks before the exams, and the holiday weeks (if any) for a maximum total of 11 HWs.
2. Overall HW grade counts for 35% of final grade.
3. You can follow up weekly HW grades from BME3142_GRADES, check out the solution sheet from the updated syllabus, and see the highest and lowest scoring submissions when the Homework link on the relevant week becomes active (past the HW submission deadline).
4. Midterm and Final exam grades count for 30% and 40% of the final grade, respectively.

Overall Homework Grade	%40
Midterm	%20
Final	%40

WK HR SUBJECT

I. Classroom Rules

II. Recap:

1. Differential Equations and Laplace Transform
Lecture Link 1

2. System Analogies
Lecture Link 2

III. Cell Membrane: Introduction
Lecture Link 3
Physiology Web

IV. Homework

1. Read Academic Dishonesty
   Krishna Bista (2011)
2. Study Lecture Links above
3. Study **Class Notes_Chapter 1_Cell Membrane**
4. Prepare for quiz next week

WK	HR	SUBJECT
2		

I. TRANS-MEMBRANE POTENTIAL

MUST STUDY: [Class Notes_Chapter 1_Cell Membrane]

Chemical and Electrical Gradient
Chemical and Electrical Flux, Fick's Law
Gibb's Free Energy, Nernst Equation
Gibson-Hodgkin-Katz Equation (Link from LibreTexts)

II. PERSONA

Alan Hudgkin
Andrew Huxley
Kenneth Cole
Hugh Huxley
Jean Hansen

III. Action Potential Propagation

Neuron Anatomy: Axon, Dendrite, Synapse
Polarization, Depolarization, Repolarization
External Input:

- Depolarization: Action Potential
- Repolarization: Na-K Pump (ATP)

Rigor Mortis

IV. Modeling the Membrane: Hudgkin-Huxley Model

$$C_m(dV/dt) = I - I_m = I - g_{Na}\boldsymbol{m}^3\boldsymbol{h}(V - V_{Na}) - g_K\boldsymbol{n}^4(V - V_K) - g_L(V - V_L)$$

$$d\boldsymbol{m}/dt = \alpha_m(1-\boldsymbol{m}) - \beta_m\boldsymbol{m}$$

$$d\boldsymbol{n}/dt = \alpha_n(1-\boldsymbol{n}) - \beta_n\boldsymbol{n}$$

$$d\boldsymbol{h}/dt = \alpha_h(1-\boldsymbol{h}) - \beta_h\boldsymbol{h}$$

where,

V	= Membrane potential
I	= Sum of external and synaptic currents entering the cell
I_m	= Membrane current
$\boldsymbol{m, n, h}$	= State variables
V_{Na}	= Equilibrium (or reversal) potential at which the net flow of Na ions is zero
V_K	= Equilibrium (or reversal) potential at which the net flow of K ions is zero
V_L	= Equilibrium (or reversal) potential at which leakage is zero
C_m	= Membrane capacitance
g_{Na}	= Sodium channel conductivity
g_K	= Potassium channel conductivity
g_L	= Leakage channel conductivity
$\alpha_{m,n,h}$	= Suitable rate coefficients
$\beta_{m,n,h}$	= Suitable rate coefficients

$V_{rest} = -60$ mV
$V_{Na} = 50$ mV
$V_K = -77$ mV
$V_L = -54.402$ mV
$g_{Na} = 120$ mmho/cm^2
$g_K = 36$ mmho/cm^2
$g_L = 0.3$ mmho/cm^2
$\boldsymbol{E} = \boldsymbol{V} - V_{rest}$
$\alpha_m = 0.1(25-\boldsymbol{E})/(e^{(25-\boldsymbol{E})/10} - 1)$
$\beta_m = 4e^{-\boldsymbol{E}/18}$
$\alpha_n = 0.01(10-\boldsymbol{E})/(e^{(10-\boldsymbol{E})/10} - 1)$
$\beta_n = 0.125e^{-\boldsymbol{E}/80}$
$\alpha_h = 0.07e^{-\boldsymbol{E}/20}$
$\beta_h = 1/(1 + e^{(30-\boldsymbol{E})/10})$

$$\propto_n = \frac{0.01(v+50)}{1-\exp\left(\frac{-(v+50)}{10}\right)}$$

$$\beta_m = 4.0\exp(-0.0556(v+60))$$

$$\alpha_h = 0.07\exp\left(-0.05(v+60)\right)$$

$$\beta_n = 0.125\exp\left(\frac{-(v+60)}{80}\right)$$

$$\beta_h = \frac{1}{1+\exp(-0.1(v+30))}$$

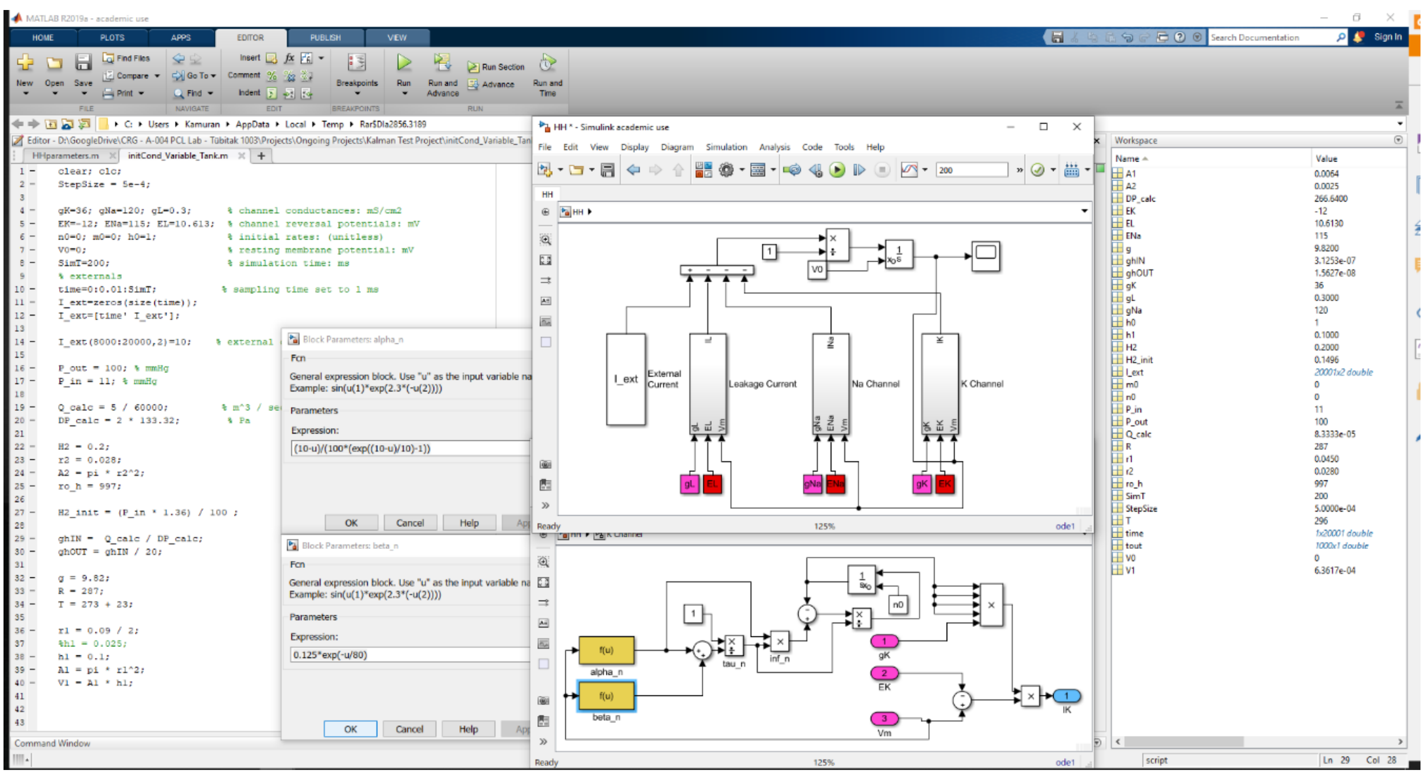
$$\propto_m = \frac{0.1(v+35)}{1-\exp\left(\frac{-(v+35)}{10}\right)}$$

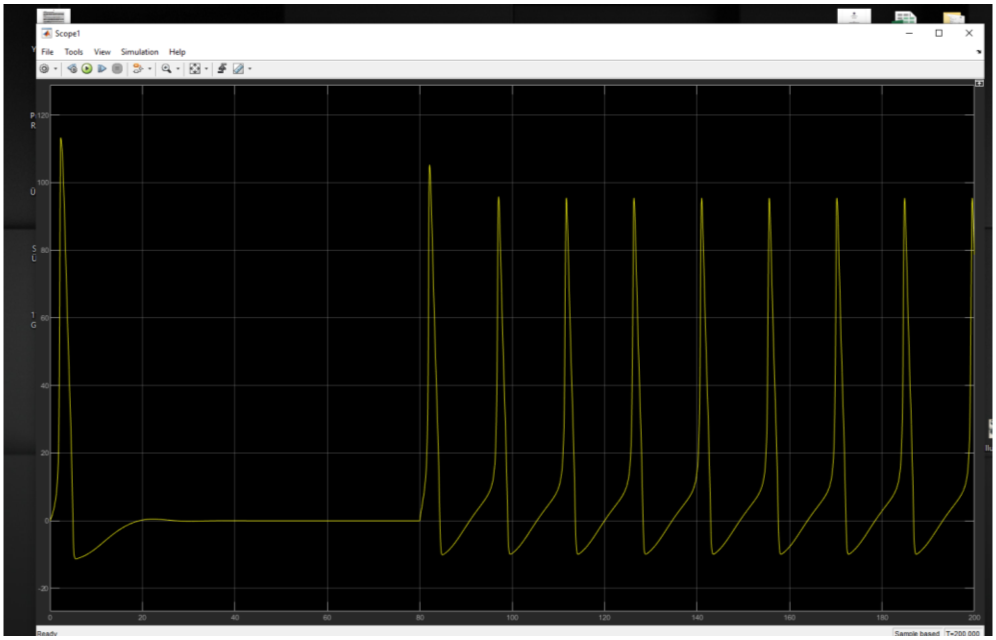
$$C_m = 0.01\ \mu\mathrm{F/cm^2} \qquad g_{Na} = 1.2\ \mathrm{mS/cm^2}$$

$$E_{Na} = 55.17\ \mathrm{mV} \qquad g_K = 0.36\ \mathrm{mS/cm^2}$$

$$E_K = -72.14\ \mathrm{mV} \qquad g_l = 0.003\ \mathrm{mS/cm^2}$$

$$E_l = -49.42\ \mathrm{mV}$$





V. HOMEWORK

1. **Read** plagiarism article
2. **Study:**
   - Solution of 1st order diff. equation
   - **System Analogies**
   - Class Notes Chapters 3 and 4
3. **Study**
   - Equilibrium Potential
   - Nernst Equation
   - Gibson-Hodgkin-Katz Equation
   - Give Examples
4. **Study:**
   - **Proteins and Hudgkin-Huxley Model**
   - **Spiking Neuron Models: Single Neurons, Populations, Plasticity (Chapter I-2.2: Hudgkin-Huxley Model, In Gerstner and Kistler, Cambridge University Press, 2002)**
   - **Neocleous and Schizas**: Paper format, Formulas available, Simulink complicated
   - **Murat Sağlam**: MathWorks example**,** No formulas, Simulink very clear.
   - **Various Membrane Models**
5. **Create and simulate HH model in Simulink**
   Bring laptop for Quiz 2

WK	HR	SUBJECT
3		

I. Nervous Tissue/System Overview

Nerve and Nervous System

Action Potential, Depolarization, Repolarization
Nervous System
Neuron, Axon, Dendrite, Synapse (**Ramon y Cajal**)
Sensory (afferent) and Motor (efferent) nerve fibers
Reptilian/Limbic/Cortical Brain
Voluntary and Involuntary Systems
Sympathetic and Parasympathetic Systems
Acetylcholine (**Loewi**) /Atropine (**Linneaus**)
Neurotransmitters

II. Introduction to Muscle

Rhoades_Ch 8
Muscle Slides_1
Skeletal, Smooth, and Cardiac Muscle
Skeletal Muscle Anatomy and Physiology
Fascia, Fiber, Fibril, Filament
Sarcomere Anatomy
Actin/Myosin Bridge and Sliding Filament Theory
Active Force Generation
Force vs. Time: Twitch, Treppe (Summation), Tetanus,
Parallel and Series Arrangement of Sarcomeres
Active State

III. Modeling the Muscle: Active Force-Length Curve

Muscle Slides_2
Contractile Element (CE, Active State)
Sarcomere Length-Tension Relationship
Resting vs Stretched Muscle
Titin Elasticity (PE)-Nonlinear
Passive Force (Preload): Initial stretch
Total Force= Active Force+ Passive Force

IV. HOMEWORK: Study

Khan Academy, Biology Library, Human Biology (GO to Unit 33): **The neuron and the nervous system (all 10 entries) AND Muscles (all 4 entries)**
Muscle Slides_3

WK HR SUBJECT

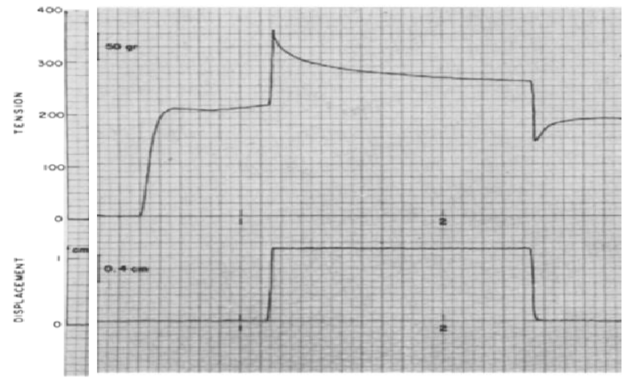
4

I. Modeling the Muscle-IV: Force-Length Relationship

Inbar & Adam (1976) (Original Paper)

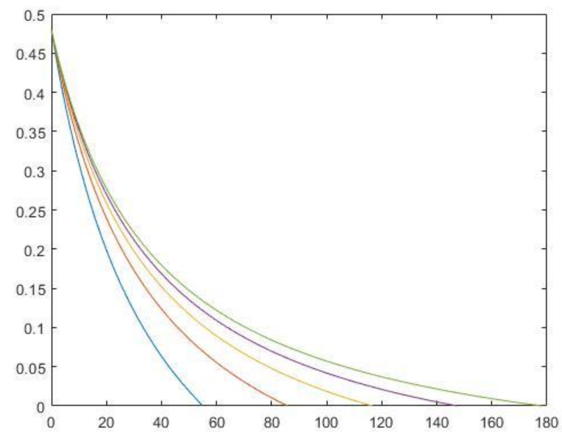
Simple Muscle Model (Derivation of Model Equations)

1. Most General Muscle Equation:
   $\dot{T} = -a.T + b.\dot{x} + c.x + d.AS$
2. Sudden Stretch
3. Special Cases:
   No Parallel Elastic Element ($k_{PE}=0$)
   Isotonic Shortening ($\dot{F}_{ex} = 0$) and linear F-v Relationship
   Isometric Tetanus ($\dot{F}_{CE} = \dot{x}_m = 0$)



II. Modeling the Muscle-V: Force-Velocity Relationship

1. AV Hill (1938) (Original Paper)
2. Teaching from classic papers
   This paper provides an explanation of model's logic for
   a. Creating the Isometric L-T Curve
   b. Sudden Release and Isotonic Shortening
   c. External Mechanical Work and Heat of Shortening



Hyperbolic Force-Velocity Relationship

III. Consequences of the Hill Model

Study Well:

1. Non-dimensional Form of the Hill Equation
2. Modeling the nonlinear series elasticity
3. Modeling the time course of a twitch

HOMEWORK 4:

1. STUDY and CREATE all MODELS in Matlab

   a. Modeling the Active State (Tension vs. Length Relationship)

      Inbar & Adam (1976)
      Theory_Guidelines
      Model_Guidelines

   b. Hill Model (Muscle Power: Force-Velocity Relationship)

      Teaching from classic papers

      - Derive the non-dimensional version of Hill Equation
      - Starting from Hill equation, derive an expression for the velocity-dependent damping coefficient of the muscle.
      - Create an m.file to reproduce the F-v relationship of skeletal muscle, for varying preloads and afterloads.
      - Get inspired by the Matlab model in it but do not copy it.
      - Add Figure Legends and Axis Labels
      - Produce **constant-afterload** gridlines.

   c. Modeling the Passive Force

      Consequences of the Hill Model
      Problem 1 (McMahon TA, Chapter 1, Solved Problems):
      - Model active force (CE) and passive force (SE)
      - Model the exponential decay of isometric force
      - **Modeling the Tetanus**
        Duration of stimulation is t_1 (C in Problem)
        Duration of rest between stimulations is t_2 (A in Problem)
        Time between two consecutive stimulations is $T=t_1+t_2$
        Maximum force that can be reached is AS (active state at tetanus)
        AS will be achieved at $t= nT+t_1$
        Model as much as you can, from this point on, about the contractile properties of the muscle (characterized by b and k) in terms of n and T.

2. Bring laptop for quiz

WK	HR	SUBJECT
5		

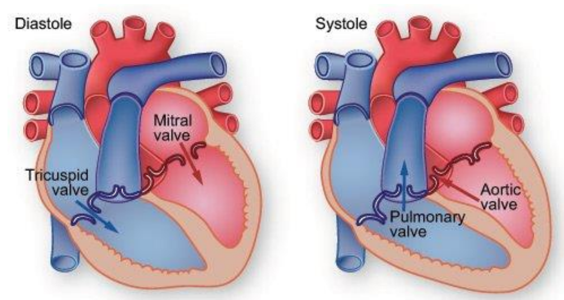
I. **REFLEX MODEL (Lecture 2nd hour):**
Feedback Control of Reflex (Modeling the Muscle-Spindle System)

Soechting et al_1971 (Original Paper)
Khoo_NM Reflex: Textbook version using Torsional Mechanical System (Moments and Angles as variables)
Class Notes: Spinal Reflex Mechanism: Derivation of Textbook version equations using Translational Mechanical System (Forces and Distances)

a. Derive the Khoo Model Equations
b. Create Reflex Model in Simulink for different versions of β
c. Add transport Delay, T_d

II. **CARDIOVASCULAR SYSTEM-I: INTRODUCTION (Lecture 3rd hour)**
Guyton Ch.9 **and/or** Meiss Ch 10

1. **Anatomy**
   a. Nouns and Adjectives
   b. Cardiac Chambers
   c. Cardiac Valves
   d. Major Arteries and Veins
   e. Systemic and Pulmonary Circulations



Ashkan Jamali, Study of the influence of different inflow configurations on Computational Fluid Dynamics in mechanical heart valve prostheses, MS Thesis, February 2017

HOMEWORK 5 for Quiz 4

1. **Spinal Reflex Model: Prepare Working Simulink Model**

   a. Derive the Khoo Model Equations. Use Translational (Force and Displacement) instead of Rotational (Moment and Angle) system
   b. Create the Model in Simulink for different versions of β
   c. Add transport Delay, T_d
   d. Discuss

2. **Cardiovascular System: Read and Learn**

   Guyton Ch.9 and/or Meiss Ch 10

MIDTERM PREPARATION

1. **Study Problem 1 for tetanus. Assume**

2. **Study the modeling of the time course of a twitch based on Consequences of the Hill Model**

3. **Study:**

   a. **Guyton Ch.9 and/or Meiss Ch 10**
   b. **https://folk.ntnu.no/stoylen/strainrate/What_does.html**
   c. **ClassLecture-Introduction**
   d. **Class Notes: Intro to CVS**

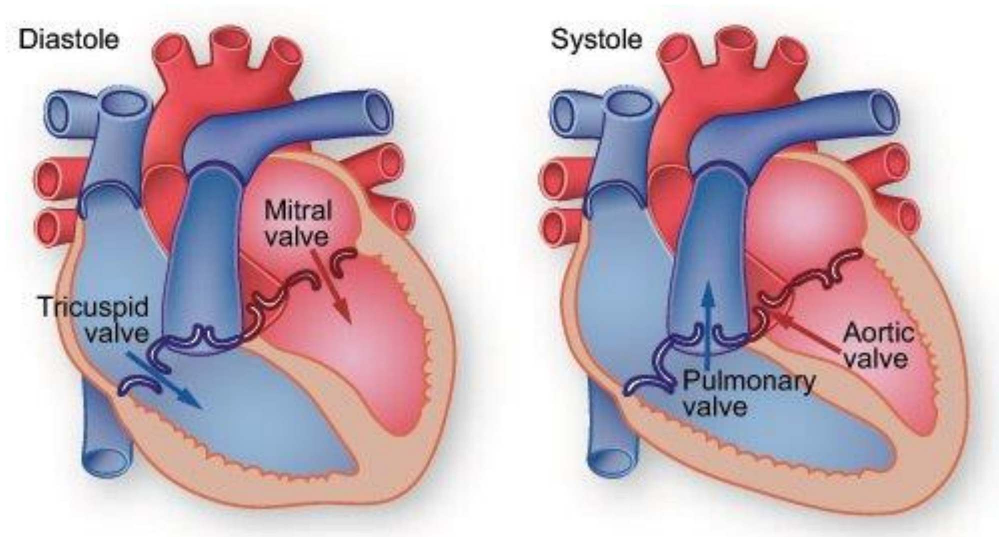
WK	HR	SUBJECT
6		No Quiz

INTRO to HEART (WATCH ppt)
(Lecture Notes 2)

I. CARDIOVASCULAR SYSTEM-I: INTRODUCTION
Guyton Ch.9 and/or Meiss Ch 10

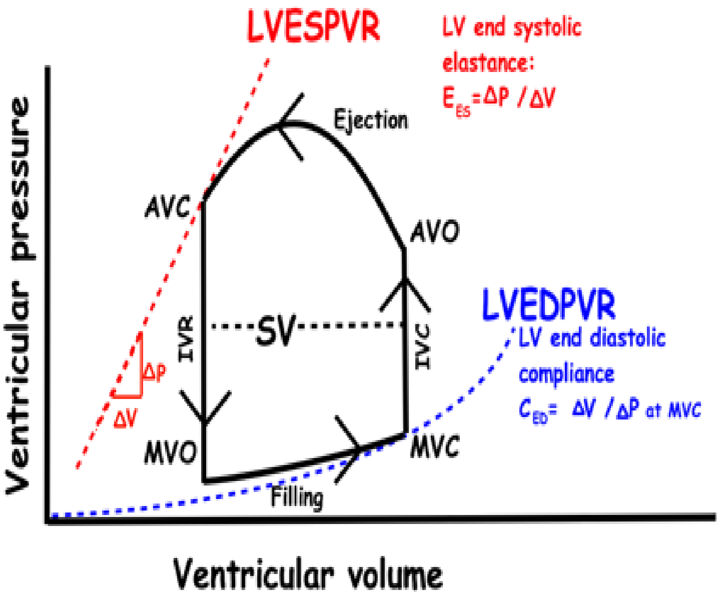
1. Anatomy
   a. Nouns and Adjectives
   b. Cardiac Chambers
   c. Cardiac Valves
   d. Major Arteries and Veins
   e. Systemic and Pulmonary Circulations

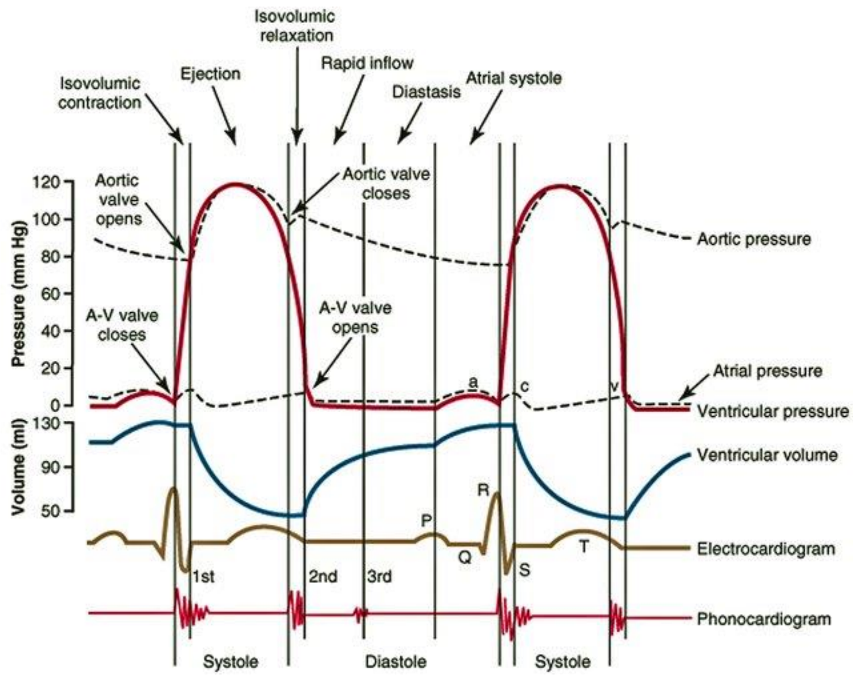
Ashkan Jamali, Study of the influence of different inflow configurations on Computational Fluid Dynamics in mechanical heart valve prostheses, MS Thesis, February 2017

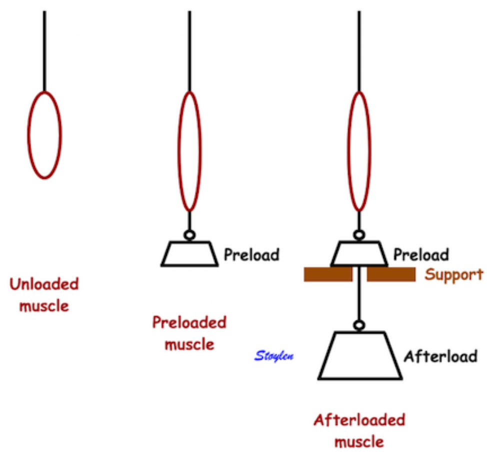


2. Wiggers Diagram (Watch)
   a. Pressures (LV, Ao, LA) and LV Volume
   b. Exponential (1st order) Response
   c. Cardiac Phases
      i. Diastole (IVR and Filling)
      ii. Systole (IVC and Ejection: Auxotonic Contraction)

3. PV Loop
   a. Opening and Closure of the Valves
   b. Cardiac Phases
   c. Ventricular Stiffness (P-V Relationship)

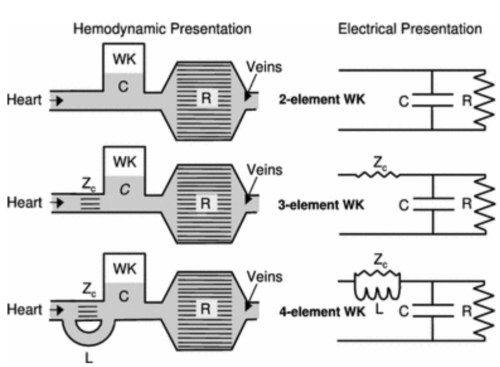






II. Modeling Cardiac Physiology (RC Circuits)

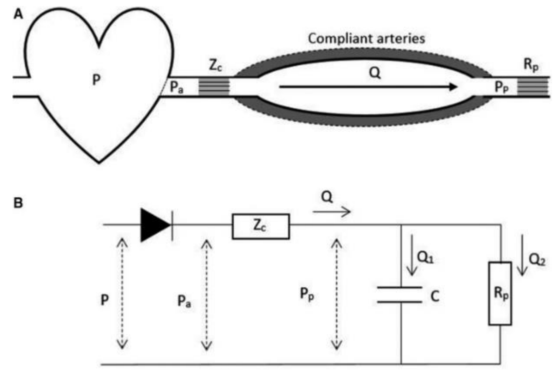
1. Hydraulic Analogue



Read: Westerhof, N., Lankhaar, JW. & Westerhof, B.E. The arterial Windkessel. *Med Biol Eng Comput* **47**, 131–141 (2009). https://doi.org/10.1007/s11517-008-0359-2

2. **Electrical Analogue: The Windkessel Simplification**

This is a subject that we have already covered in relation to 1st order system response. Here, the exponential response of the arterial system is calculated and the shape of the aortic pressure during systole and diastole are explained. Make sure that you can understand the derivation and interpretation of EACH equation.



C

Physiological Parameter	Windkessel Electrical Equivalent	Windkessel Symbol
Pressure	Voltage	$P(t)$
Flow	Current	$Q(t)$
Aortic Impedance	Aortic Resistance	Z_c
Peripheral Impedance	Peripheral Resistance	R_p
Arterial Compliance	Capacitance	C

Garrett AS, Pham T, Loiselle D, Han JC, Taberner A. Mechanical loading of isolated cardiac muscle with a real-time computed Windkessel model of the vasculature impedance. Physiol Rep. 2019 Sep;7(17):e14184. doi: 10.14814/phy2.14184.

III. HOMEWORK

1. **Solve [Dynamic Model] using ALL concepts you studied, particularly those relevant to modeling, system analogies, isometric and isotonic contraction**
   Windkessel (4-Node) Modeling

   a. Electrical analogue circuit
   b. System dynamics
   c. State-space representation
   d. Matlab

IV. Start working on your Midterm Exam

a. H&H Membrane Model
- Neocleous and Schizas: Paper format, Formulas available, Simulink complicated
- Murat Sağlam**:** MathWorks example**,** No formulas, Simulink very clear.

b. Inbar and Adam Muscle Model
- Theory Guidelines (Explanation of Model Logic)
- Model Guidelines (Explanation of Simulink Model)

c. Hill Model for F-v Relationship
   - AV Hill (1938) (Original Paper)
   - Teaching from classic papers

d. Tetanus Model
   MacMahon's Twitch Model-Extended

e. Khoo Reflex Model
   - Soechting et al 1971 (Original Paper)
   - Khoo_NM Reflex: Textbook version using Torsional Mechanical System (Moments and Angles as variables)
   - Class Notes: Spinal Reflex Mechanism: Derivation of Textbook version equations using Translational Mechanical System (Forces and Distances)

f. Study and Explain the Cardiovascular System
   - Guyton Ch.9
   - Lecture Slides 6

g. Static Model (Khoo from Guyton)
   Understand and explain
   - Starling's Law of the Heart
   - The concept of **Mean Systemic Filling Pressure;**
   - **Build** the Simulink model

WK	HR	SUBJECT
7		

I. STATIC MODEL of the PERIPHERAL CIRCULATION: Cardiac Output-Venous Return Balance (Khoo)

Physiologic Control Systems

This section covers the Guyton model as described in Khoo 3.5.
You should know/learn the following concepts

- Length-Tension Relationship (Skeletal Muscle)
- Pressure-Volume Relationship (Cardiac Muscle)
- Cardiac P-V Loops
- Cardiac Cycle
- Wiggers Diagram
- Stroke Volume, Heart Rate and Cardiac Output
- Stroke Work
- Contractility
- Elastance vs Compliance of LV
- Electrical/Hydraulic Modeling

II. MODELING IN LIFE SCIENCES

1. Uses
   a. Educational
   b. Performance Testing of Novel Devices
2. Types
   a. in silico (Computational/Numeric/Mathematical)
   b. in vitro (Physical/Benchtop)
   c. in vivo (Experimental/animal)
   d. Clinical (Human trials in phases)
3. Model Accuracy vs. Model Complexity
   a. *in silico* model can be made as complex as desired for high accuracy
   b. *in silico* model must be duplicated *in vitro* for
      i. reproducibility of *in silico* environment
      ii. duplicability of *in silico* findings
   c. Therefore, complexity of *in silico* model is limited for practical considerations

III. From *in silico* to *in vitro*

1. Modeling Ventricles
    a. Piston-in-cylinder
    b. Fluid-filled sac
    c. Flexible membrane
2. Modeling Capacitances
    a. Constant Capacitance (see below, Section II:2-a.ii)
    b. Variable Capacitance (next week)
3. Modeling Pressures
    a. Low Pressure ($P_{LA}, P_V \leq 20\ mmHg$)
    Hydraulic pressure only
    b. High Pressure ($P_{LA}, P_V \geq 80\ mmHg$)
    Hydraulic plus Pneumatic Pressure

WK	HR	SUBJECT
8		Holiday

WK	HR	SUBJECT
9		MIDTERM EXAM

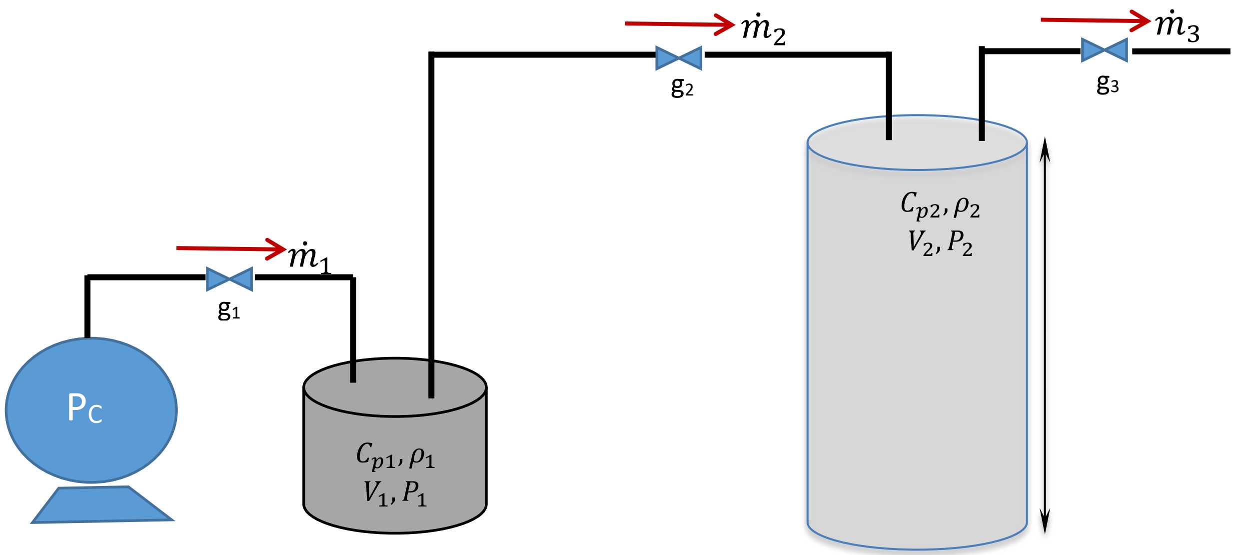
Open Notes
Laptop with MATLAB
No Internet

WK	HR	SUBJECT
10		PNEUMATIC SYSTEM

1. **Analogy**

Independent Variable	Mass	m
Dependent Variables		
Effort	Pressure	P
Motion	Mass Flow Rate	$\dot{m}$
System Constants		
PE Storage	Variable Capacitance	RT/V
HE Dissipation	Valve Resistance	1/g

2. **Governing Equations**



a. **Case 1: Single Tank with Constant Volume**

i. **Ideal Gas Law**

$$P_2 = P_{atm} = 0 \text{ (gauge pressure)}$$

ii. **Capacitance Equation**

$$PV = mRT = \rho VRT$$

$$P = \rho RT = \frac{m}{V}RT = \frac{RT}{V}m = e_p m$$

$$\text{Pneumatic Elastance} \triangleq e_p = \frac{1}{C_p} = \frac{RT}{V}$$

iii. **Kirchhoff's Current Law**

$$\dot{m}_1 - \dot{m}_2 = \dot{m}$$

iv. **Ohm's Law**

$$P_C - P_1 = R_1\dot{m}_1$$

$$g_1(P_C - P_1) = \dot{m}_1$$

3. **Putting it all Together**

$$\dot{P}_1 = ?$$

IV. HOMEWORK (Use this format)

1. **Guyton Circulatory Equilibrium Model**
   a. **Matlab**
   b. **Discussion**

2. **Pneumatic Modeling**
   a. **Single Constant-Volume Reservoir with inlet and outlet valves**

$$P_2 = P_{compressor}$$
$$P_2 = 0 < P_{vacuum} < P_{atm}$$

WK	HR	SUBJECT
11		Lecture Notes 1st hr, 2nd hr

I. Left Ventricle as Pneumo-Hydraulic System

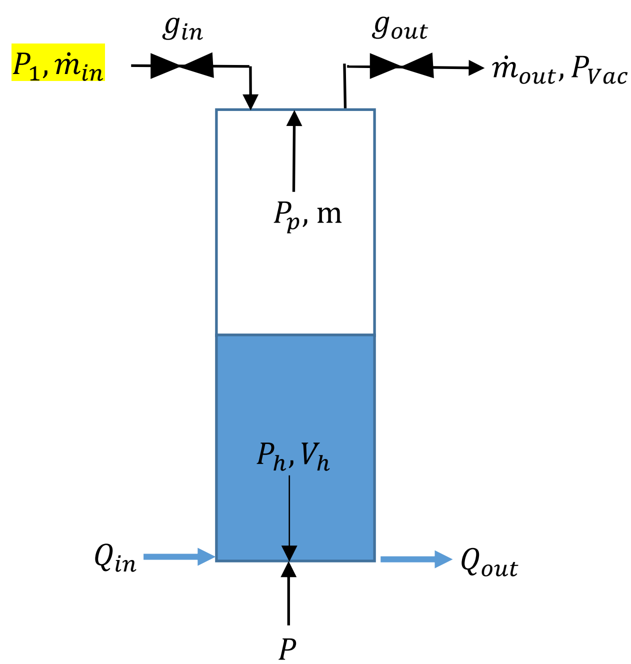


Figure 2. Detail from the MCL schematic, showing the gas pressure regulation for the preload and afterload reservoirs. Symbols are P: Pressure, Q: Flow, g: Viscous Admittance, $\dot{m}$: Gas Mass Flow Rate. Subscripts are Com: Compressor, vac:Vacuum, h: Hydraulic, p: Pneumatic.

II. System Dynamics and Lyapunov Controller

Read and Learn, but **DO NOT** Copy
If you cannot write **ALL** equations from memory, **DO NOT** write anything at all!
Because if you do, it will be tantamount to academic suicide!

III. HOMEWORK (Use this Format)

Simulink model of 1-tank system using vacuum tank to suck air out

1. Set reference pressure to
   a. Constant
   b. Square wave
   c. Sinusoidal wave

2. Show reference and control pressures and valve action for each case.

WK	HR	SUBJECT
11		**Lecture 1st hr, 2nd hr** **Modeling the LV**

HOMEWORK

For a pneumo-hydraulic bench-top system constructed with an air compressor ($P_C = 10\ atm$), a pressure reduction tank (P_1), a tank partially containing water as shown below (P_T), and a vacuum pump ($P_V = 0.5\ atm$), all placed in series,

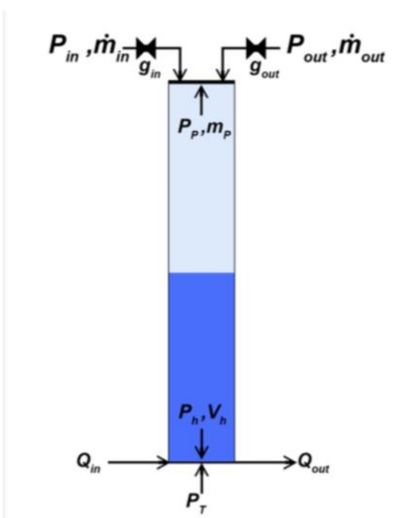
1. Calculate the dynamics of P_1 and P_{LV}

2. The control law for the valves so that the two error terms below are driven to zero

   a. $\in_1 = 1\ atm - P_1$
   b. $\in_2 = P_{LV} - P_T$

   Obtain P_{LV} from your electrical analogue *in silico* system

3. Operate the system in Simulink



WK	HR	SUBJECT
12		Congestive Heart Failure Mechanical Circulatory Assistance Left Ventricular Assist Devices (LVAD) Preclinical Performance Testing LVAD Characteristic H-Q curves Cardiovascular Mock Circuits Hybrid Circuits Class Lectures 1st hr, 2nd hr, 3rd hr. PowerPoint Presentation

WK	HR	SUBJECT
13		**OPTIMAL CONTROL THEORY: Introduction**

MUST READ:

Class Notes (Chapter X-1): Optimal Control-Historical Background

Lecture 11_Class Notes 1, 2, 3

Lecture 11_Recording

I. What is Optimal in Nature

1. Catenary: Minimize potential energy
2. Stone throw: Minimize Lagrangian
3. Light: Minimum time or trajectory?
4. Plants: Minimize volume, maximize exposure to light
5. Ants, Spiders and Dogs: Minimize time to target
6. Heart: Maximize Stroke Efficiency?

II. Calculus of Variations:

Historical Overview: **Review Article (in Turkish)**

Lagrangian and Action

1. Definition of the Lagrangian, L

$$\boldsymbol{\mathcal{L}} = \boldsymbol{\mathcal{L}}\,[\mathrm{KE}(\dot{x})\text{-}\mathrm{PE}(\mathrm{x})] = \boldsymbol{\mathcal{L}}(\dot{x}, x, t)$$

2. Cost Function (Action): Definite Integral of Lagrangian

$$\boldsymbol{\mathcal{A}}[y(x)] = \int_{x_1}^{x_2} \boldsymbol{\mathcal{L}}\left[y(x), \frac{d}{dx}y(x)\,, x\right] dx$$

III. Euler-Lagrange Equations

Derivation of E_L Equations

IV. Tautochrone and Brachistochrone Problems

Cycloid, Tauto- and Brachistochrone Equations

V. HOMEWORK 8:

1. **SYLLABUS**
2. **WEEKLY SPECIAL**
   a. Derive the E-L Equation
   b. Derive the Cartesian coordinates of a **Cycloid**
   c. Solve 3 problems using the E-L Equation
      i. Dog catches bone in sea
      ii. Pendulum
      iii. Your problem

WK	HR	SUBJECT
14	(May 23)	**OPTIMAL CONTROL THEORY**
		Lecture 12_Class Notes 1, 2, 3
		Lecture Recording

I. Constrained Optimization

Read and Study Example Problems:

a. Lagrange Multipliers
   Lagrange Multipliers

II. State-Space Analysis

Configuration Space, Phase Space, State Space
Expression of System Dynamics as All-Integral Block Diagram
State Variables= Output of Integrator Blocks
State Matrix, Input Matrix, Output Matrix,

III. Beyond Euler-Lagrange

Read and Study Examples:

Hamiltonian and PMP

a. Legendre Transformation
b. Hamiltonian
c. Introduction to Pontryagin Maximum Principle (PMP)
   i. Setting up the Problem in State-Space
   ii. Defining the Hamiltonian
   iii. Solving the Adjoint Dynamics

IV. Examples

Theory and Examples

a. Minimum Energy (Linear Pendulum, Polar Coordinates
   Pendulum
b. Minimum Path (2 points, Cartesian Coordinates)
   Channel Crossing: Ferry Problem (Example 3)
c. Minimum time
   Moon Landing (Example 1)
d. Catenary, Rocket Car, Life Guard (Dog)

V. HOMEWORK 9:

Read: Class Notes 10
Read: Optimal Control of CV System (Article in Turkish)
Hamiltonian and PMP
Study: Moon Landing

WK	HR	SUBJECT

15 (Make up)

OPTIMAL CONTROL THEORY

Lecture 12_Class Notes 1, 2, 3

Lecture Recording

(Unfortunately, I forgot to share the screen for the first hour. So, you might want to just listen for the first hour and start viewing after 59:30 (unless you want to see nothing but my face close up on the screen for a full hour)

I. PMP Applications to CVS

1. Yamashiro
2. Litvak and Yamashiro
3. Noldus

II. FINAL EXAM:

1. Syllabus:
   a. Correct/Update all weeks
   b. Improve Examples
   c. Solve **ALL** Weekly Special Problems

2. Article 1 or 2 above:
   a. Explain
   b. Discuss
   c. Criticize
   d. Solve and Plot