



Mechatronic Modeling and Design with Applications in Robotics

Course Outline and Introduction

Course Website:

<https://grasplab.ca/modeling.html>

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Director of the GRASP Lab @ OntarioTech

Design, development and application of advanced technologies for autonomous systems and processes

- Mechatronics
- Robotics
- Machine vision
- Advanced Control
- Artificial intelligence

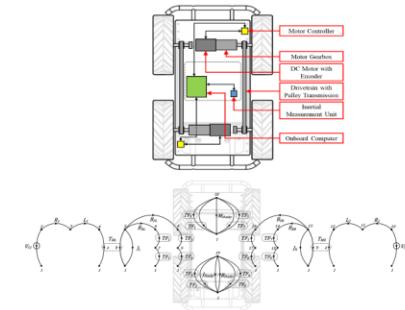
Mechatronic Modeling and Design with Applications in Robotics

Course Description

This course will introduce a unified multi-domain modeling tool, named Linear Graph and its applications. It provides students with the tools required to design, model, analyze and control mechatronic systems; i.e. smart systems comprising electronic, mechanical, fluid and thermal components. The techniques for modelling various system components will be studied in a unified approach developing tools for the simulation of the performance of these systems. A comprehensive example of the modeling and design of a mobile robotic system will be included and discussed.

Students who successfully complete the course should have reliably demonstrated the ability to:

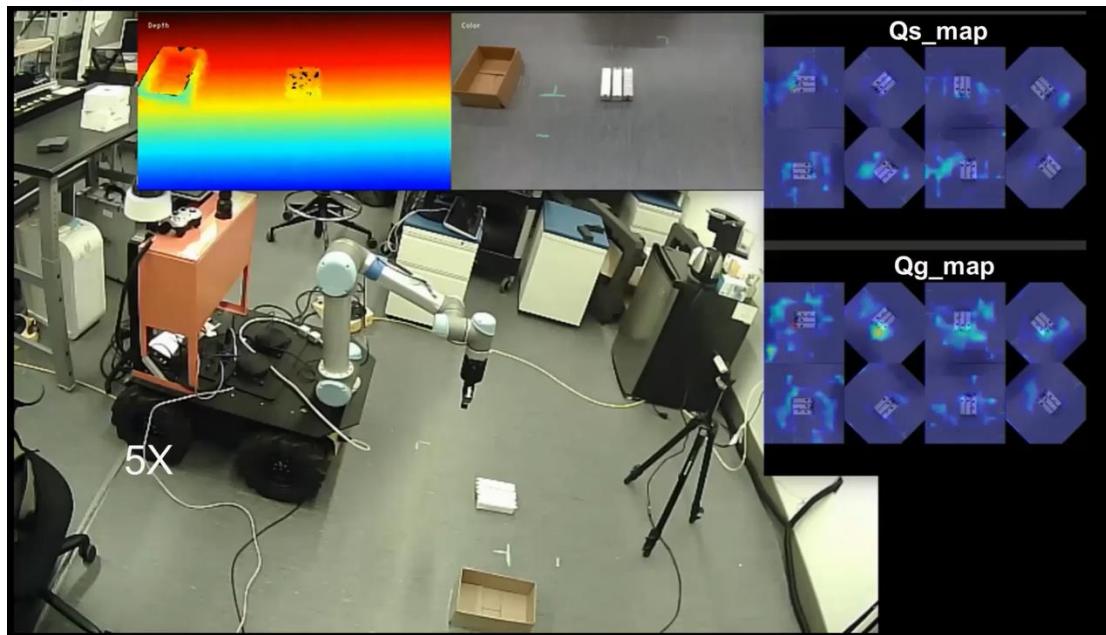
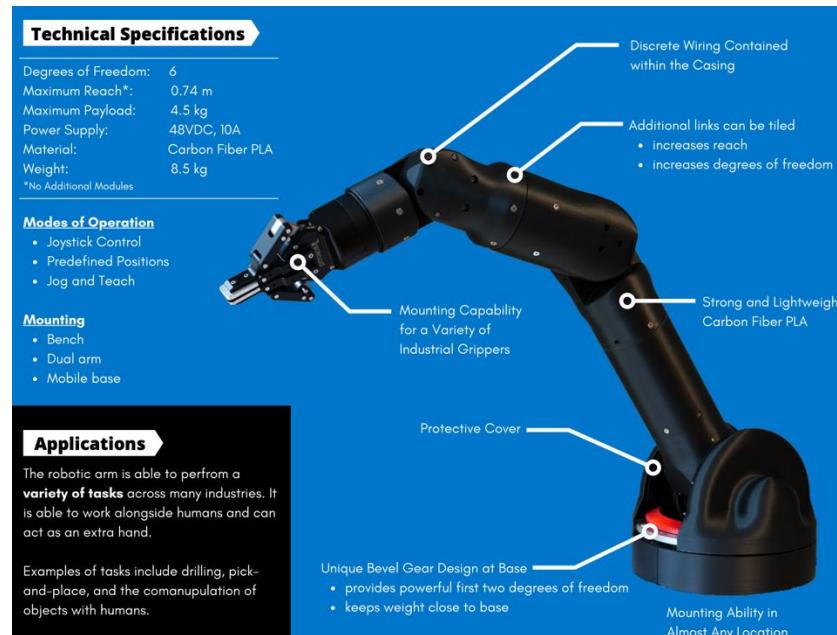
- Use the basic tools required to design, model, analyze and control mechatronic systems
- Work with smart systems comprising electronic, mechanical, fluid and thermal components
- Model a wide variety of system components in a unified way
- Analyze various components needed to design and control mechatronic systems
- Apply AI and Machine Learning in advanced design and optimization



A snapshot of the course website

Selected Projects in GRASP Lab

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- Course Overview and Introduction
- Introduction to Modeling
- Basic Model Elements
- Analytical Modeling
- Graphical Models
- Linear Graph
- Linear Graph Examples
- Frequency Domain Models
- Transfer-Function Linear Graph
- Examples in Applications

Mathematic models

key to this course

one of the graphical models.

physical system

car

Analytical model

Math abstraction of physical system

- Understand the formal meanings of a **dynamic system** of multi-physics systems (e.g., **mechatronic systems**).
*Mechanical
Electrical
Computer*
- Recognize different types of models (e.g., physical, analytical, computer, experimental) and their importance, usage, comparative advantages and disadvantages.
- Under analytical models, recognize the general and specific pairs of model categories.
- Understand the concepts of **through-variables** and **across-variables** and their physical significance, and relationship to state variables.
→ engineering domain
- Recognize similarities or analogies among the four physical domains: **mechanical**, **electrical**, **fluid**, and **thermal** (this is the basis of the “unified” approach to modeling).
examples
- In each physical domain, recognize the lumped elements that store energy and that dissipate energy, based on the analogy among different physical domains.
energy storage elements
dissipating elements
- Model a wide variety of system components in a unified way
- Apply AI and Machine Learning in system modeling and design optimization

Clarence W. de Silva, *Mechatronics: A Foundation Course*, CRC Press, 2010.

Haoxiang Lang, Eric McCormick and Clarence W. de Silva, Appendix B of *Modeling of Dynamic Systems with Engineering Applications*

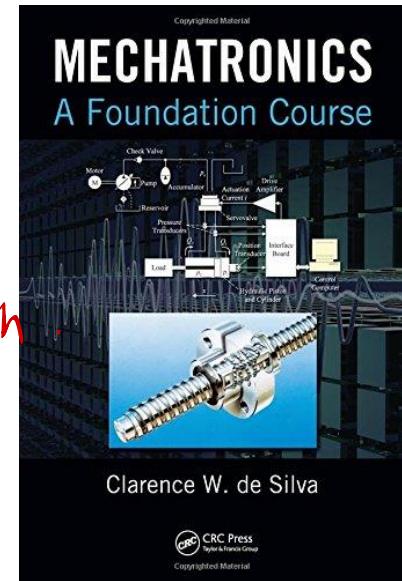
Linear Graph

Matlab Toolbox: GitHub Link

https://github.com/GRASP-ONTechU/Linear_Graph

Three Reference Articles: (downloadable on the course website)

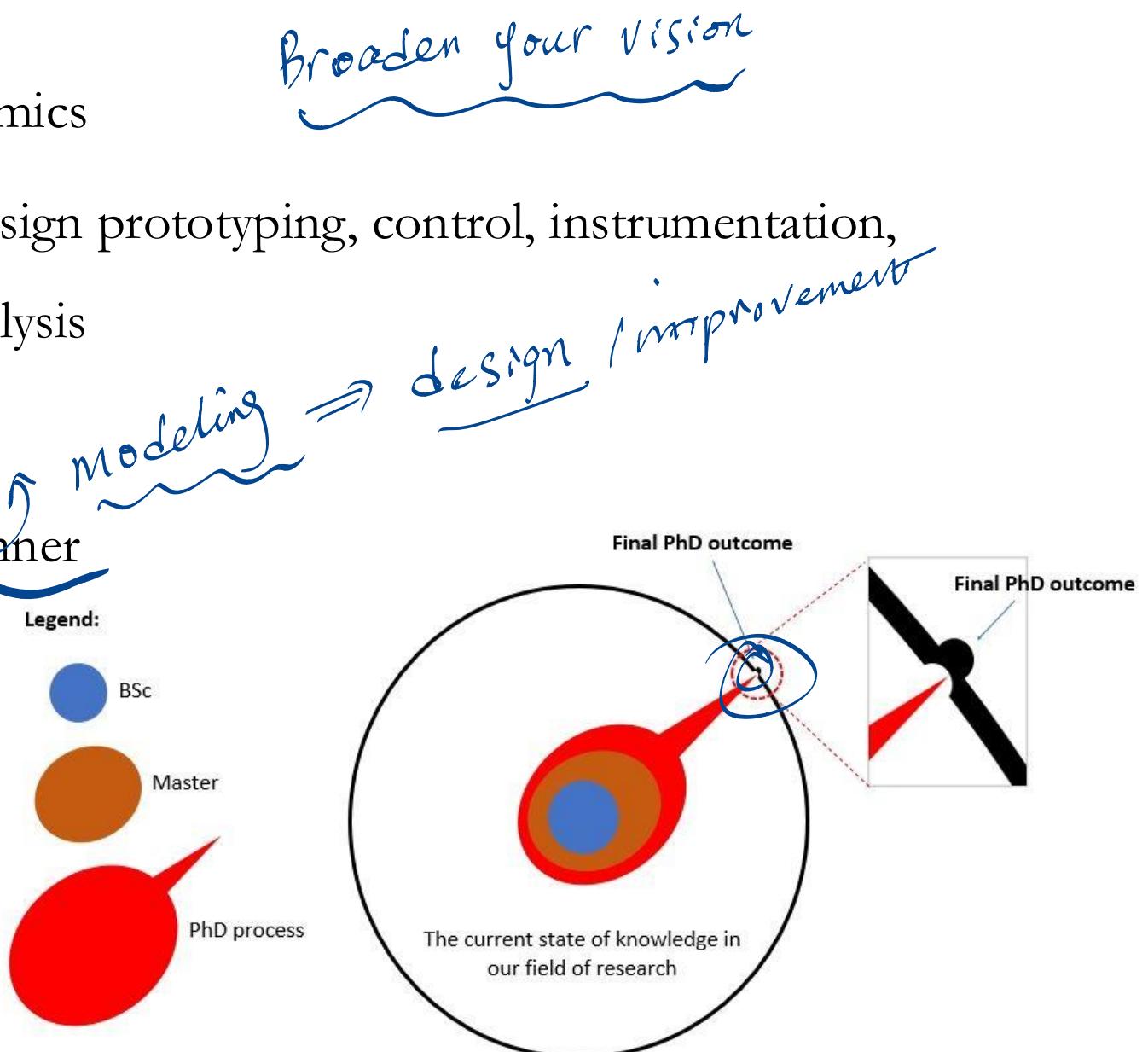
- Research and Development of a Linear Graph-based Matlab Toolbox.
- Automated Multi-domain Engineering Design through Linear Graphs and Genetic Programming.
- Dynamic Modeling and Simulation of a Four-wheel Skid-Steer Mobile Robot using Linear Graphs.



Goals:

- To understand basic modeling of dynamic systems and its procedure
- To formulate realistic modeling/design and possible control problems
- To do analysis and design for the problem using the course material
- To design and analyze of the multi-physics systems in Matlab, and implementation if possible

- Cutting-edge insight into system dynamics
- Foundation to develop expertise in design prototyping, control, instrumentation, experimentation and performance analysis
- Discussion of system dynamics
- Systematic, unified and integrated manner
- Introduce tools of modeling



A Course Final Report: Template is downloadable from the course website.

Note:

- **DO NOT** change the format of the template
- The current introduction part is an explanation of how you are expecting to complete the report. You can remove all the text and rewrite the introduction section using the given section titles after the text **“Follow each of section below to complete the final report!”**
- You need to use your own word to write the report, copying and pasting from online or other reference is not acceptable.

Warning: Your final report will be submitted to Turnitin.com for similarity check.

July 2022

Final Report: Mechatronic Modeling and Design with Applications in Robotics

Student Name (Student Number)

Abstract—These instructions give you guidelines for preparing final report for Mechatronic Modeling and Design with Applications in Robotics. Use this document as a template to complete the final report of the course.

I. INTRODUCTION

THIS document is a template for Microsoft Word versions 6.0 or later. And it is prepared as the template for the final reports of Mechatronic Modeling and Design with Applications in Robotics course.

Final report (maximum in 8 pages) should be a complete technical document including introduction, literature review, methodology, simulation and experimentation results, and conclusion. It should be considered as an engineering technical report which is planning to be published. DO NOT change the format of this document.

A. Figures and Tables

If your figure has two parts, include the labels “(a)” and “(b)” as part of the artwork. Please verify that the figures and tables you mention in the text actually exist. Please do not include captions as part of the figures. Do not put captions in “text boxes” linked to the figures. Do not put borders around the outside of your figures. Use the abbreviation “Fig.” even at the beginning of a sentence. Do not abbreviate “Table.” Tables are numbered with Roman numerals.

Figure axis labels are often a source of confusion. Use words rather than symbols. As an example, write the quantity “Magnetization,” or “Magnetization M ,” not just “ M . Put units in parentheses. Do not label axes only with units. As in Fig. 1, for example, write “Magnetization (A/m)” or “Magnetization ($A \cdot m^{-1}$).” not just “ A/m .” Do not label axes with a ratio of quantities and units. For example, write “Temperature (K),” not “Temperature/ K .”

Please check the figure and table below for reference.

TABLE I. UNITS FOR MAGNETIC PROPERTIES

Symbol	Quantity	Conversion from Gaussian and CGS EMU to SI*
Φ	magnetic flux	$1 \text{ Mx} \rightarrow 10^{-8} \text{ Wb} = 10^{-8} \text{ V}\cdot\text{s}$
B	magnetic flux density, magnetic induction	$1 \text{ G} \rightarrow 10^{-4} \text{ T} = 10^{-4} \text{ Wb/m}^2$
H	magnetic field strength	$1 \text{ Oe} \rightarrow 10^{4}/(4\pi) \text{ A/m}$
m	magnetic moment	$1 \text{ erg G} = 1 \text{ emu}$ $\rightarrow 10^{-8} \text{ A} \cdot \text{m}^2 = 10^{-8} \text{ J/T}$
M	magnetization	$1 \text{ erg/(G cm)} = 1 \text{ emu/cm}^3$

This report is the final course report of Mechatronic Modeling and Design with Applications in Robotics course in July 2022.

$4\pi M$	magnetization	$\rightarrow 10^3 \text{ A/m}$
σ	specific magnetization	$1 \text{ G} \rightarrow 10^6/(4\pi) \text{ A/m}$
j	magnetic dipole moment	$1 \text{ erg/G} = 1 \text{ emu}$
J	magnetic polarization	$\rightarrow 4\pi \times 10^{-10} \text{ Wb.m}$
χ	susceptibility	$1 \text{ erg/(G cm)} = 1 \text{ emu/cm}^3$
χ_s	mass susceptibility	$\rightarrow 4\pi \times 10^{-10} \text{ T}$
μ	permeability	$1 \rightarrow 4\pi$ $1 \text{ cm}^3/\text{g} \rightarrow 4\pi \times 10^{-3} \text{ m}^3/\text{kg}$ $1 \rightarrow 4\pi \times 10^{-7} \text{ H/m}$ $= 4\pi \times 10^{-7} \text{ Wb/(A.m)}$
μ_r	relative permeability	$\mu \rightarrow \mu_r$
w, W	energy density	$\mu \rightarrow \mu_r$
N, D	demagnetizing factor	$1 \text{ erg/cm}^3 \rightarrow 10^{-4} \text{ J/m}^3$ $1 \rightarrow 1/(4\pi)$

Vertical lines are optional in tables. Statements that serve as captions for the entire table do not need footnote letters.
*Gaussian units are the same as cgs emu for magnetostatics; M_x = Maxwell, G = gauss, Q_s = oersted; W_b = weber, V = volt, s = second, T = tesla, m = meter, A = ampere, J = joule, kg = kilogram, H = henry.

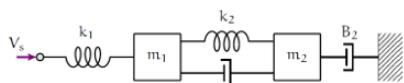


Fig. 1. Schematic model of a Mass-Spring-Damper System.

B. MATH

If you are using Word, use either the Microsoft Equation Editor or the MathType add-on (<http://www.mathtype.com>) for equations in your paper (Insert | Object | Create New | Microsoft Equation or MathType Equation). “Float over text” should not be selected.

C. References

Number citations consecutively in square brackets [1]. The sentence punctuation follows the brackets [2]. Multiple references [2], [3] are each numbered with separate brackets [1][2], [3]. When citing a section in a book, please give the relevant page numbers [2]. In sentences, refer simply to the reference number, as in [3]. Do not use “Ref. [3]” or “reference [3]” except at the beginning of a sentence. “Reference [3] shows [2]” Please do not use automatic endnotes in Word, rather, type the reference list at the end of the paper using the “References” style.

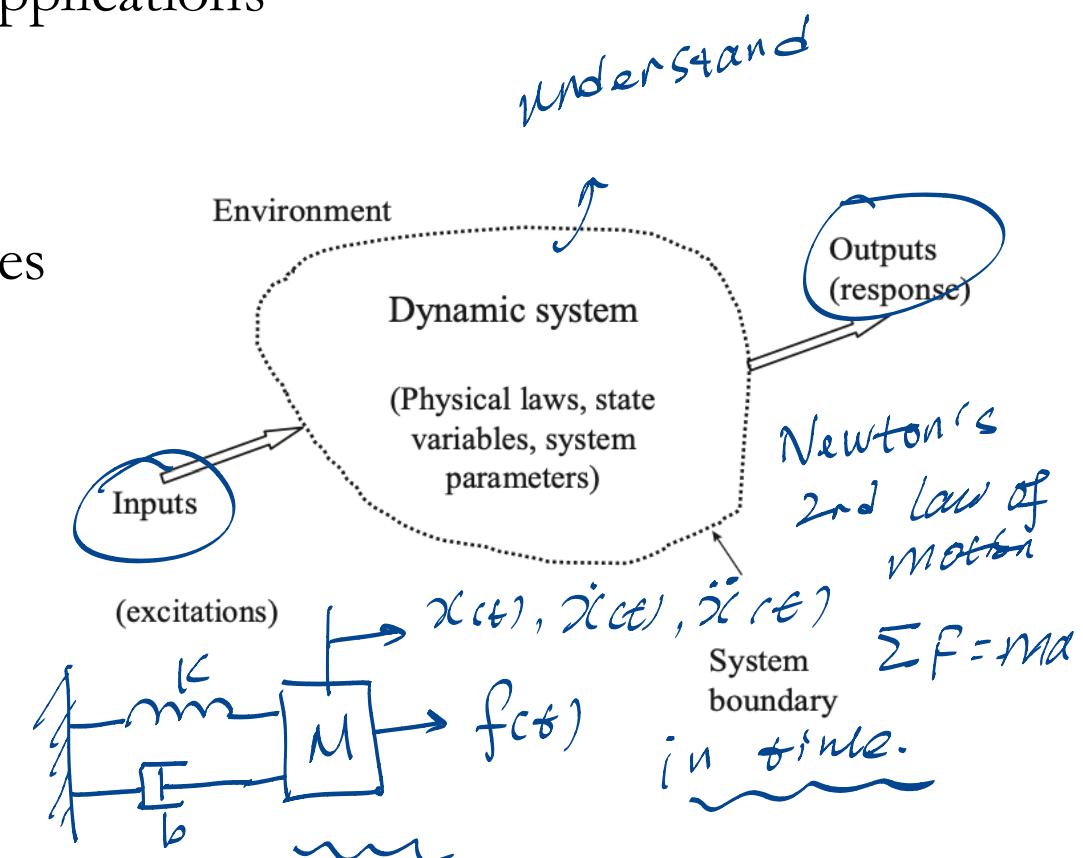
Follow each of section below to complete the final report!!

Note: This report will be submitted to Turnitin.com for similarity check!!!

1. Download three reference work from the course website *1 option*
2. Read the first and second reference papers and try to understand them during the course. *Read*
3. Repeat the implementation of the circuit design in the second reference paper using Matlab, and report your results in the final report. Compare your results and discuss your findings and your understanding in the final report
4. Or complete the take home exam in the end of the course *2 option*

The maximum page number of your final report is 6. Please put the most important information in your report. Codes or other figures can be submitted as appendices if necessary (will not be counted as a part of the main report).

- Introduce the subject of modeling, with focus on multi-physics engineering dynamic systems.
- The importance of dynamic modeling in various applications
- The use of models in the design and control
- Common types of models and modeling techniques and their advantages and disadvantages
- The idea of integrated, unified, systematic mechatronic modeling method

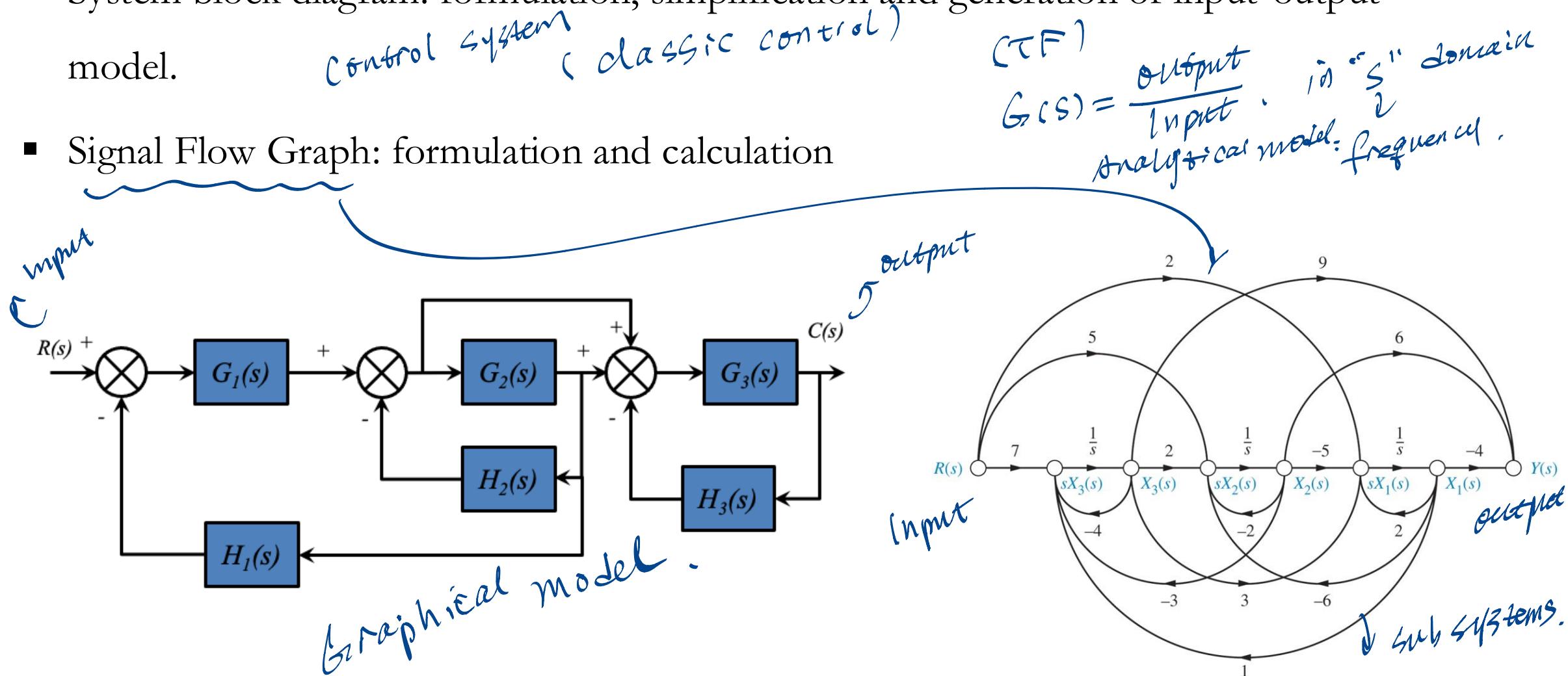


- Re-visit basic elements in mechanical, electrical, fluid and thermal domain
 - * additional reading → examples.
- Introduce two new concepts: across-variables and through-variables
- Discuss similarities across domains
- Re-define basic elements with new categories for energy storage elements, energy dissipation elements and sources.
- Identification of proper and physically meaningful state variable across multiple physics domains.

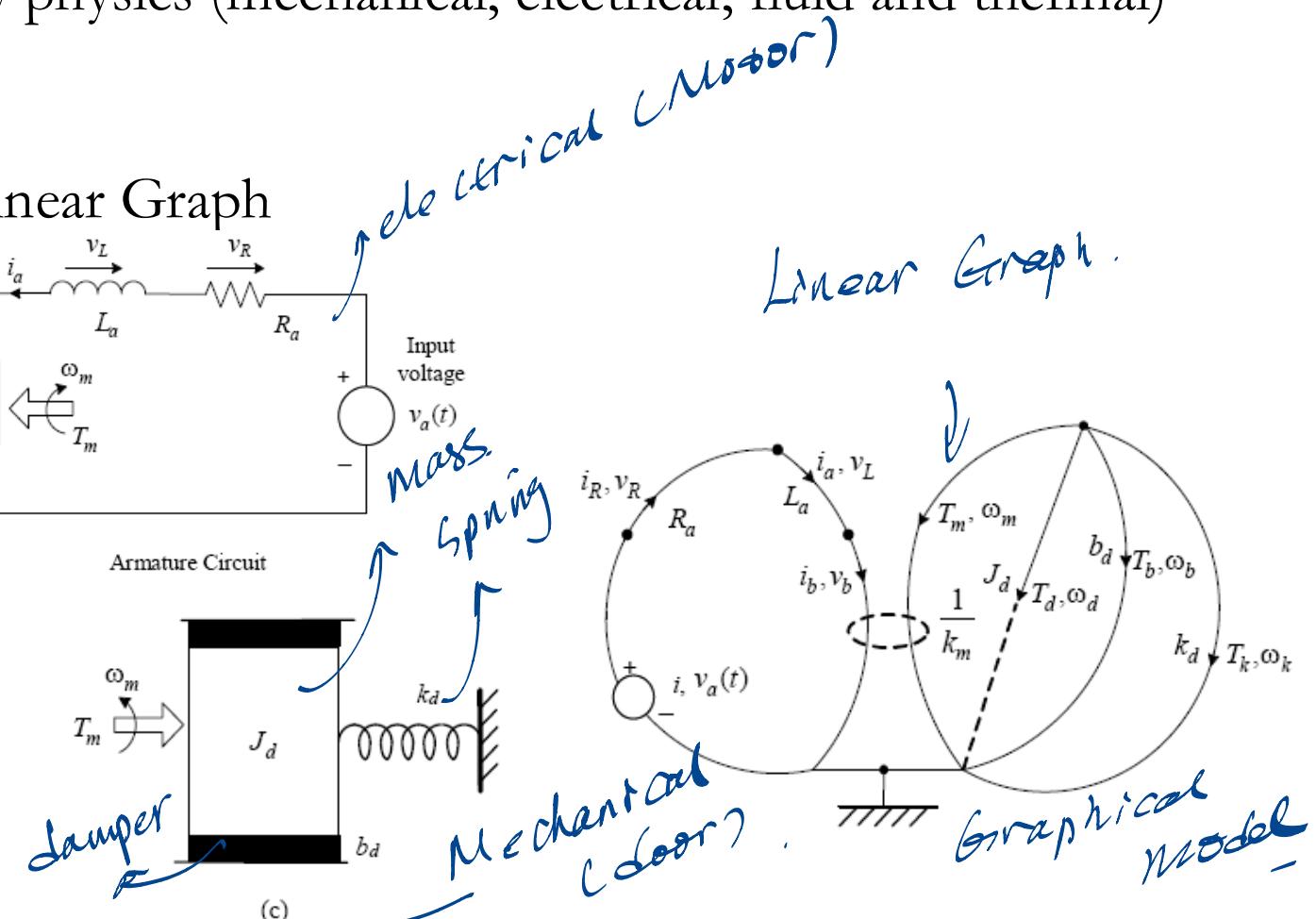
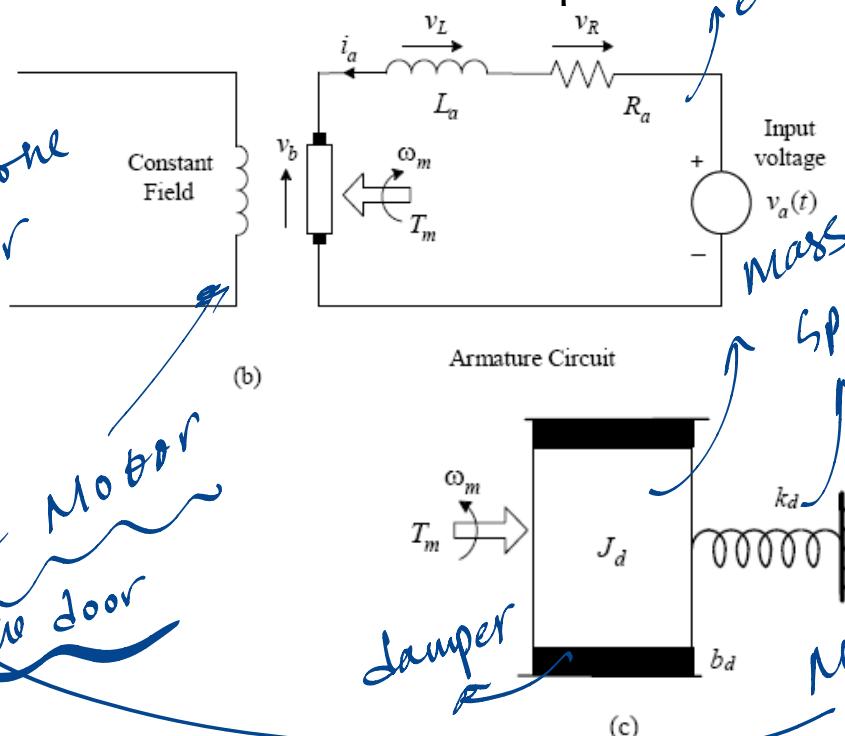
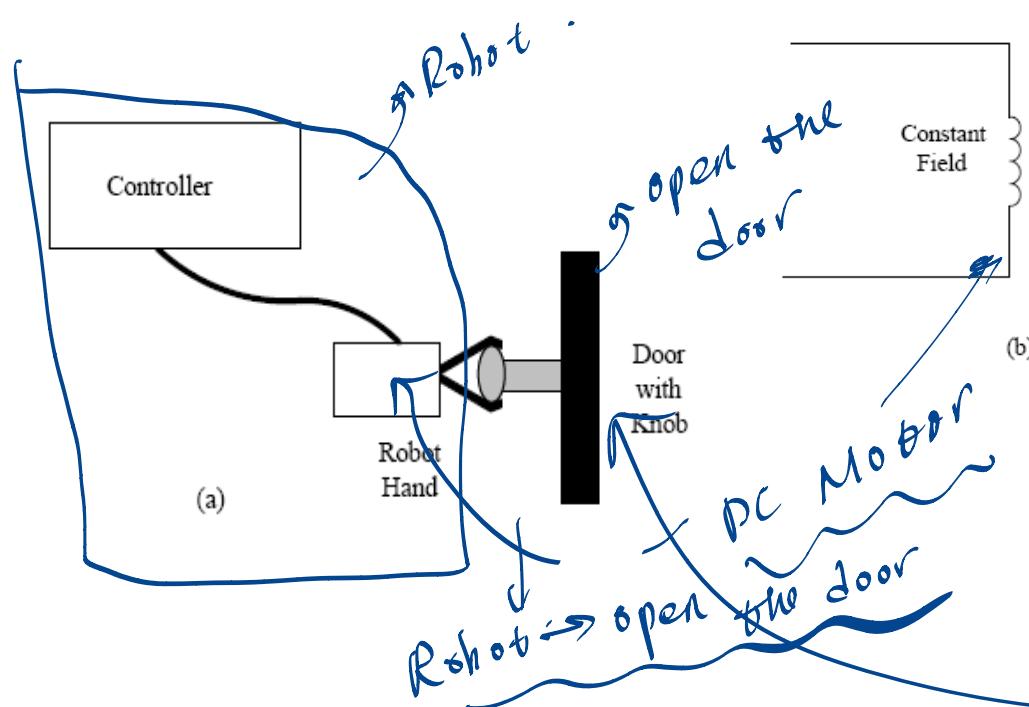
- Formally introduces analytical modeling of dynamic systems
- Systematic development of state-space models of engineering systems in fours physical domains (2 physical domains: mechanical, electrical)
- Frequency domain models: Transfer Function
- A general methods of converting a state-space model into an input-output model TF.
- Indicate the advantages and limitations
- Examples will be discussed

Transfer Function (TF)
Input-output model
State-space model

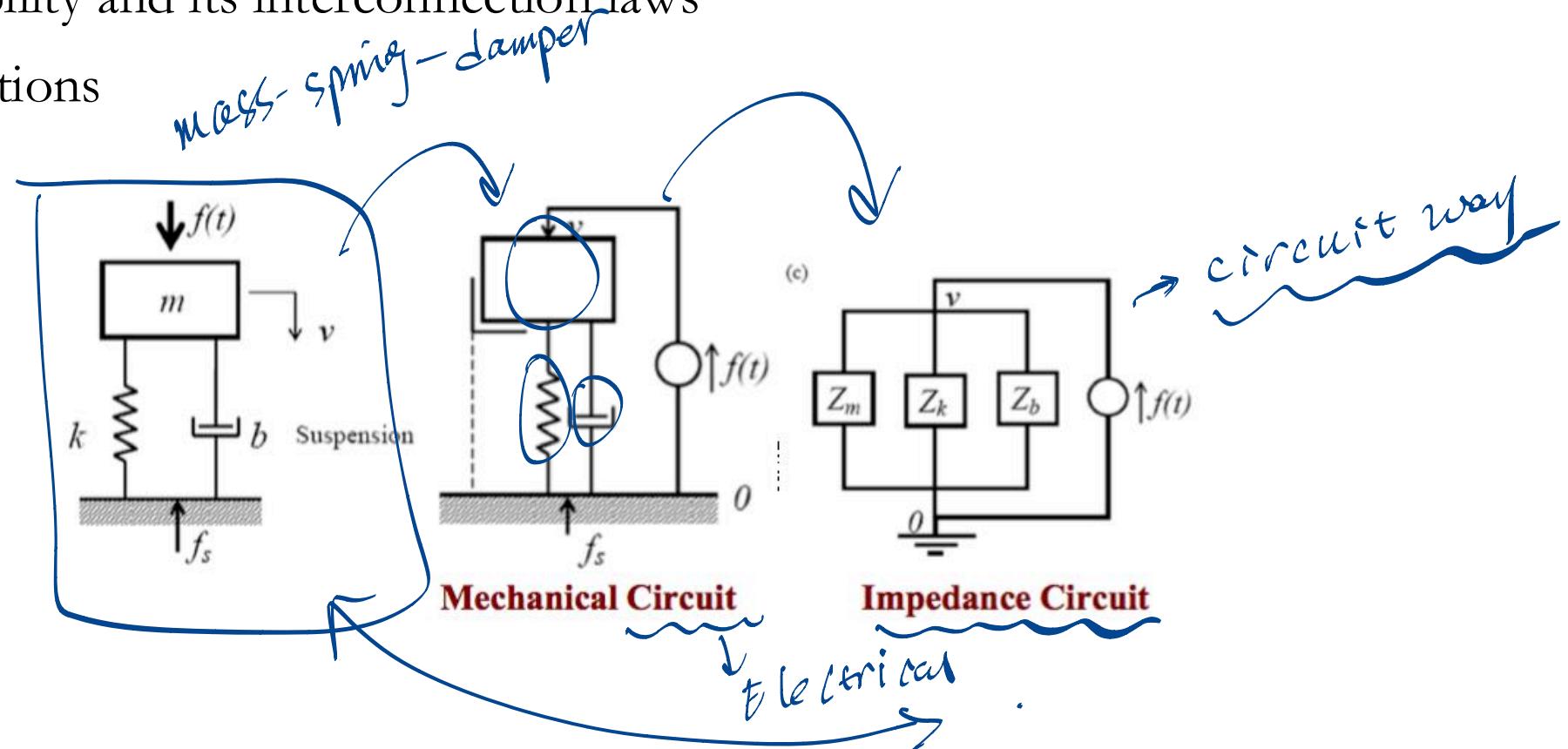
- System block diagram: formulation, simplification and generation of input-output model.
- Signal Flow Graph: formulation and calculation



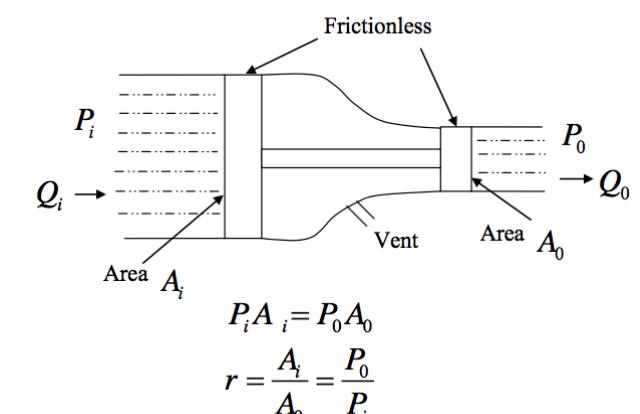
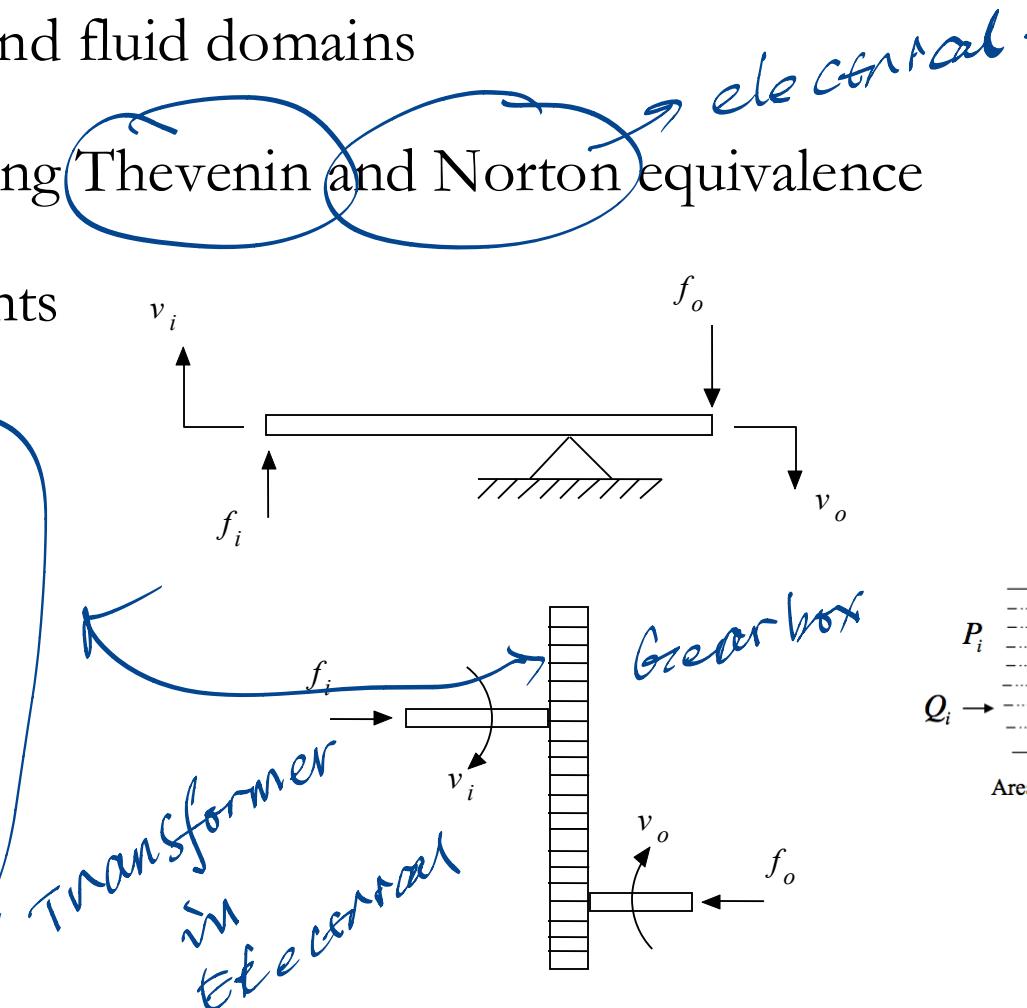
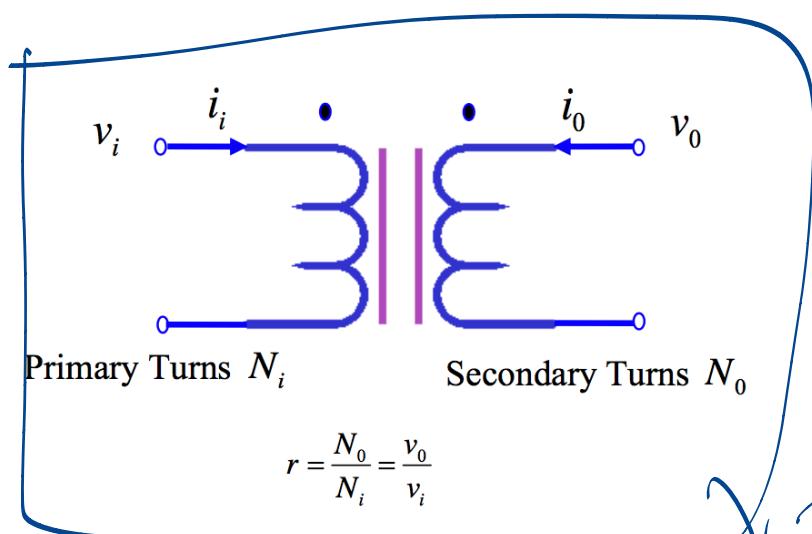
- Introduce the graphical tool for developing models of dynamic systems
- State-space model formulation of any physics (mechanical, electrical, fluid and thermal) or multi-domain (mixed) systems
- Discuss more advanced method in Linear Graph



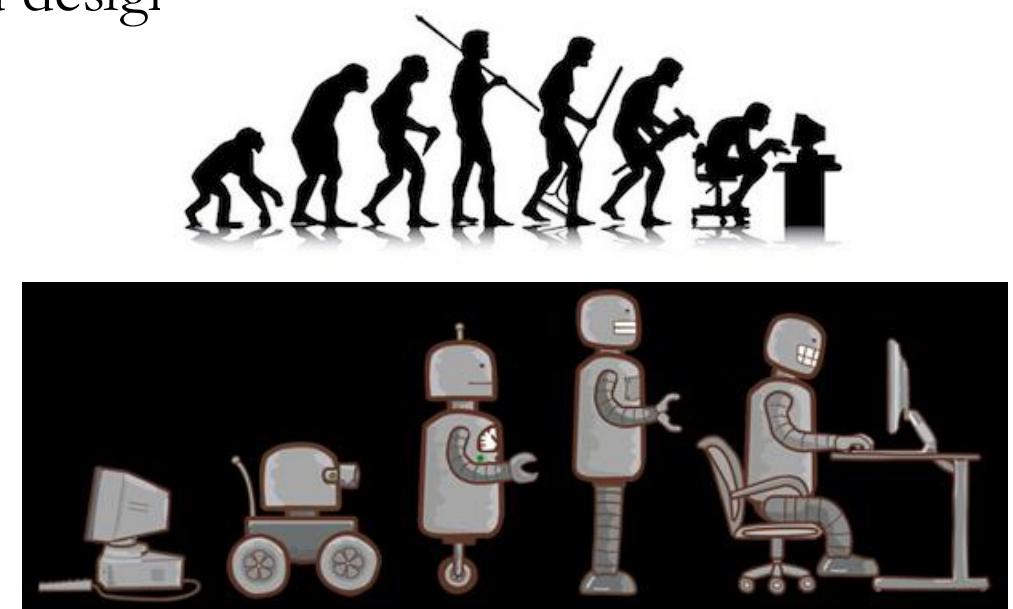
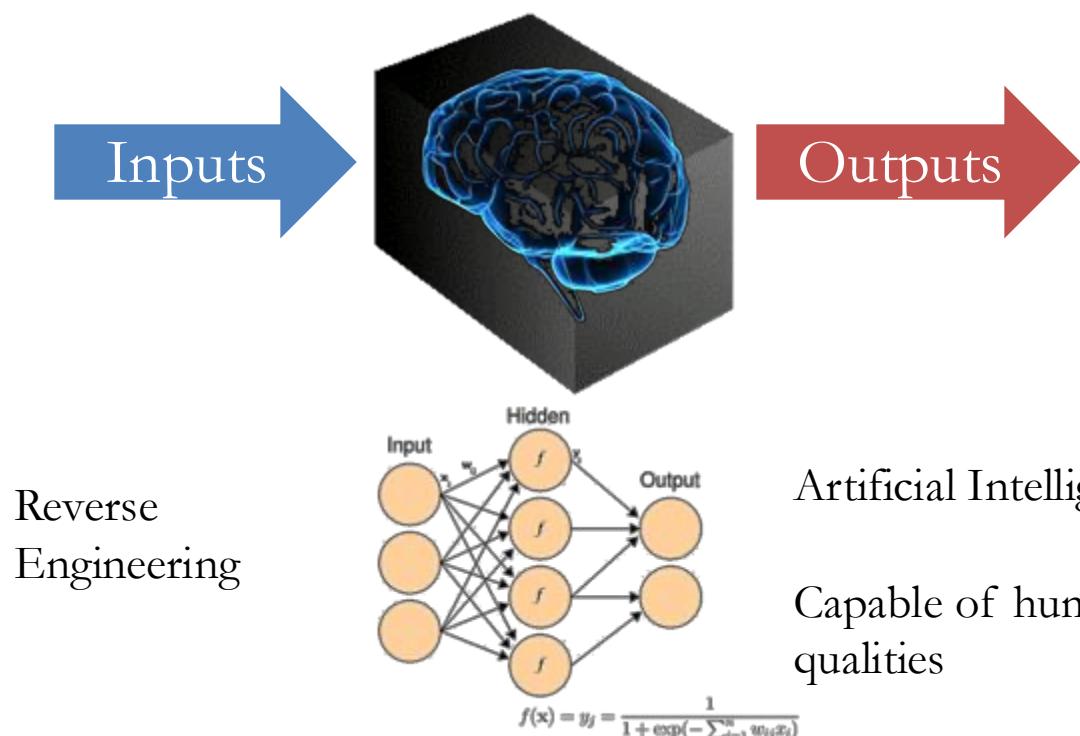
- Mechanical Circuit
- Mechanical and electrical impedance
- Mechanical mobility and its interconnection laws
- Practical applications



- Extension of the equivalent circuits (commonly in electrical domain) to other physical domain such as mechanical and fluid domains
- Reduction of linear graph using Thevenin and Norton equivalence
- Two port linear graph elements



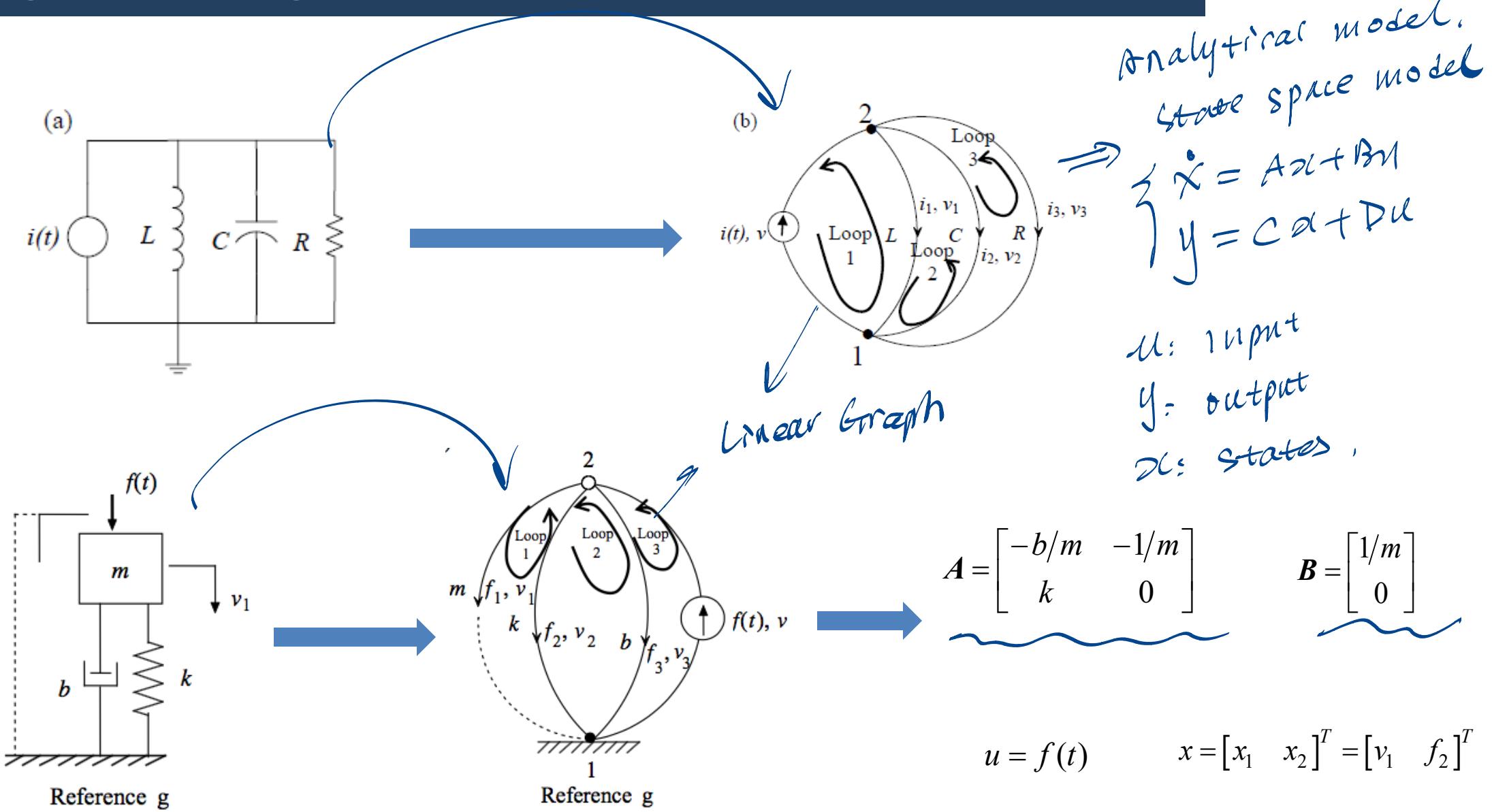
- Introduce general AI algorithms including NNs, GA and Machine Learning
- Discuss possible integration of AI in modeling and design
- Introduce examples



- ✗ Understanding the system (e.g., human brain)
- !
- The driving force behind the creation/evolution

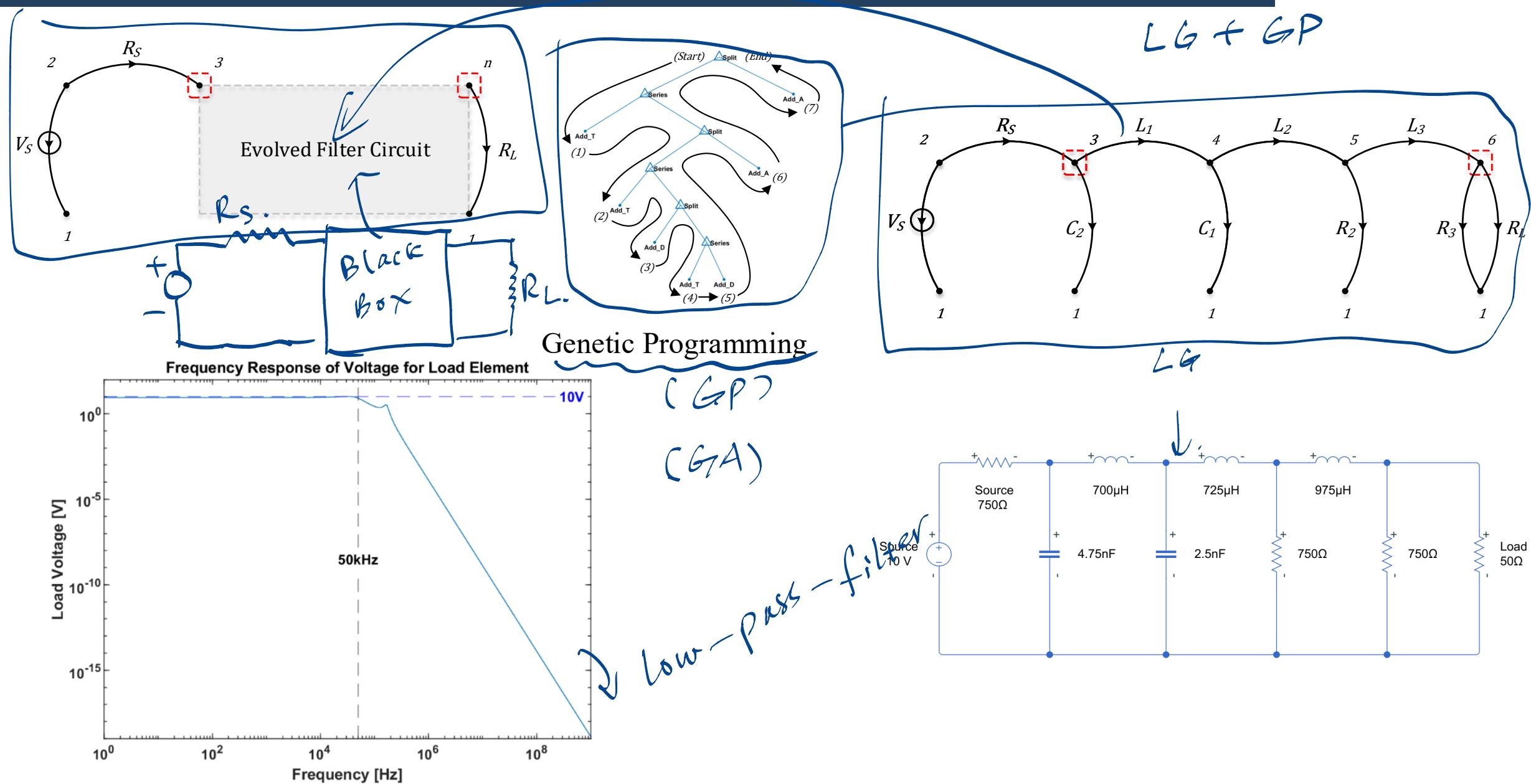
Modeling and Design Example 1

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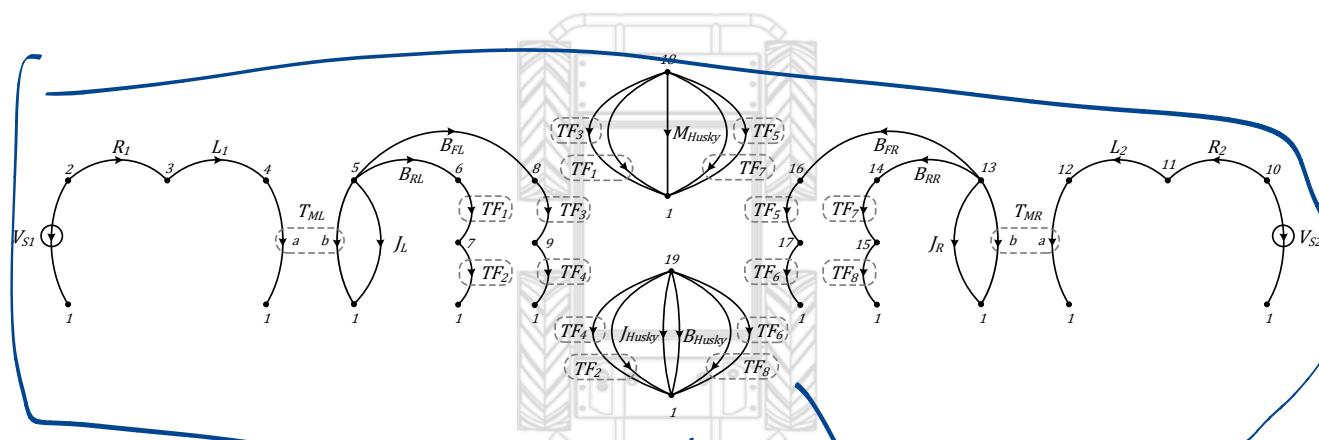
Modeling and Design Example 2

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Modeling and Design Example 3

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$$A = \begin{bmatrix} \frac{-B_{FL} - B_{RL}}{J_L} & 0 & \frac{B_{FL}TF_3 + B_{RL}TF_1}{J_L} & \frac{B_{FL}TF_4 + B_{RL}TF_2}{J_L} & \frac{T_{ML}}{J_L} & 0 \\ 0 & \frac{-B_{FR} - B_{RR}}{J_R} & \frac{B_{FR}TF_5 + B_{RR}TF_7}{J_R} & \frac{B_{FR}TF_6 + B_{RR}TF_8}{J_R} & 0 & \frac{T_{MR}}{J_R} \\ \frac{B_{FL}TF_3 + B_{RL}TF_1}{M_H} & \frac{B_{FR}TF_5 + B_{RR}TF_7}{M_H} & \frac{-B_{RL}TF_1^2 - B_{FL}TF_3^2 - B_{FR}TF_5^2 - B_{RR}TF_7^2}{M_H} & \frac{-B_{FL}TF_3TF_4 - B_{FR}TF_5TF_6 - B_{RL}TF_1TF_2 - B_{RR}TF_7TF_8}{M_H} & 0 & 0 \\ \frac{B_{FL}TF_4 + B_{RL}TF_2}{M_H} & \frac{B_{FR}TF_6 + B_{RR}TF_8}{M_H} & \frac{-B_{FL}TF_3TF_4 - B_{FR}TF_5TF_6 - B_{RL}TF_1TF_2 - B_{RR}TF_7TF_8}{M_H} & \frac{-B_{RL}TF_2^2 - B_{FL}TF_4^2 - B_{FR}TF_6^2 - B_{RR}TF_8^2 - B_H}{J_H} & 0 & 0 \\ \frac{J_H}{L_1} & \frac{T_{ML}}{L_1} & 0 & 0 & 0 & -\frac{R_1}{L_1} \\ 0 & -\frac{T_{MR}}{L_2} & 0 & 0 & 0 & -\frac{R_2}{L_2} \end{bmatrix}$$

Great Space Model

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{1}{L_1} & 0 \\ 0 & \frac{1}{L_2} \end{bmatrix} \quad C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \quad D = [0]_{4 \times 2}$$



Description	Parameter	Value	Units
Voltage Inputs	V_{S1}, V_{S2}	± 24	V
Internal Motor Resistance	R_1, R_2	0.46	Ω
Internal Motor Inductance	L_1, L_2	0.22	mH
Motor Torque Constant	k_t	0.044488	N · m/A
Gear Ratio	GR	78.71 : 1	Gear Ratio
Motor Transformer Ratio	T_{ML}, T_{MR}	$k_t \times GR$	N · m/A
Drivetrain Inertia	J_{LW}, J_{RW}	0.08	$kg \cdot m^2$
Drivetrain Damping	$B_{RL,FL,FR,RR}$	Unknown	$rad/(N \cdot m \cdot s)$
Power Conversion Transformer Ratios	TF_{odd}	Equation (7)	
	TF_{even}	Equation (8)	
Husky Mass	M_{Husky}	48.39	kg
Husky Rotational Damping	B_{Husky}	Unknown	$rad/(N \cdot m \cdot s)$
Husky Inertia	J_{Husky}	3.0556	$kg \cdot m^2$

