PhD Qualifying Exam Example 1
CAE-Design RAG, March 2021

Suppose that you are a project manager in an engineering R&D firm and your new project is to design a new generation of ergonomic chair similar to the one in the figure below. Your goal is to identify the latest engineering design technologies and implement them so that the designed solution and final product can be realized. The new prototype needs to be tested and validated before it can be finalized for manufacturing.

Your R&D team is suggested to study the following papers to identify the necessary technologies. After studying the papers, you are supposed to provide a brief to your manager and answer the listed questions. Feel free to search other literature and references if necessary.

O. Sigmund, "A 99 line topology optimization code written in Matlab," *Structural and Multidisciplinary Optimization*, **21**, 120-127, 2001.

Wang, M. Y., Wang, X., & Guo, D. (2003). A level set method for structural topology optimization. *Computer Methods in Applied Mechanics & Engineering*, **192**(1-2), 227-246.

From the above two papers, answer these questions:

1. What is the SIMP (Solid Isotropic Material with Penalization) method? What is level set method and how is it used for topology optimization? Compare and contrast how the two methods make topological changes in a part designWhat are the design variables in the SIMP and level-set methods? Can you identify a relationship between the design variables used in the two methods?
2. What is the role of the mesh independency filter that modifies element sensitivities? What effect does this filter have on the topology optimization process and solutions?
3. Do you think that one of these methods leads to parts that are more manufacturable (easier to manufacture) than the other? Explain why or why not.
4. Which method, SIMP or level-set, do you think will work better on the chair design? Explain your reasoning.
5. In the Matlab implementation of the SIMP method, what are the primary limitations that may preclude its usage on real engineering problems? What are the potential issues of numerical implementations of level-set methods related to efficiency and accuracy? How did the authors propose to solve them? What issues authors did not discuss?

P Kulkarni, D Dutta, "An accurate slicing procedure for layered manufacturing," *Computer-Aided Design*, **28**(9): 683-697, 1996.

1. In the proposed adaptive slicing algorithm, where does the main computational bottleneck occur?

2. Can the algorithm be directly applied to manufacture the topologically-optimized chair in your project? If yes, how to apply? If not, why and what are the possible extensions/revisions as the solution?

Example PhD Qualifying Exam – Automaton, Robotics and Control RAG

Three Papers Selected by Examination Committee.

1. Singer, Neil C., and Warren P. Seering. "Preshaping command inputs to reduce system vibration." *ASME Journal of Dynamic Systems, Measurement, and Control*, (1990): 76-82.

2. Eppinger, Steven D., and Warren P. Seering. "Three dynamic problems in robot force control." *IEEE Transactions on Robotics and Automation* 8.6 (1992): 751-758.

SUGGESTED EXAM FORMAT (1 hour duration).

Presentation. (10 min)

The trainee presents a 10-15 minute presentation reviewing their research interests and how that is connected to the papers assigned.

Generic Questions. (10 mins)

These are broad overview questions that (could/should) be the same for all trainees.

e.g.:

1. How do the assigned papers relate to your current research interests?

2. Can you identify some knowledge gaps that you discovered when reading the assigned papers?

3. Describe one future study/project that you believe would extend the knowledge you gleaned from the assigned papers?

Niche Questions. (30 mins)

These 3-5 questions should focus at the interface between <u>analysis and synthesis</u> in Bloom's taxonomy and progress from analysis to synthesis.

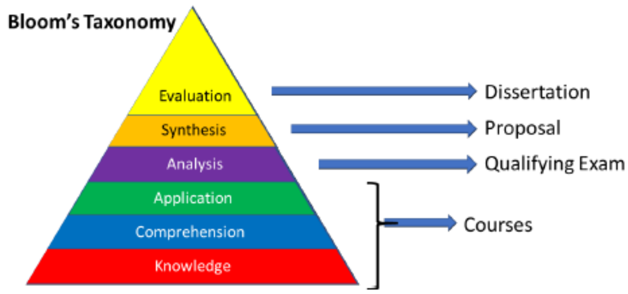

Figure 1: Relationship between educational objectives and elements of our Ph.D. program.

1. Please explain the concept of input shaping. Please describe how such inputs can be determined to generate vibration-free outputs in a flexible system. What assumptions did you make about the flexible system?

2. For input shaping control, what parameters should be chosen to better design the controller to be adaptable to modeling errors? Draw a diagram and explain how robustness is archived. What are methods to obtain a high-fidelity model of a flexible system?

3. Please explain how the locations of compliant elements characterize the open-loop dynamic properties of the plant. What are the key differences between three dynamic problems discussed in the paper? Please discuss how flexibilities in a dynamic plant affect the stability and bandwidth of force control.

4. Is there a novel control architecture not outlined here that you feel could better solve the goal of precise and robust flexible system control?

Closing Discussion (10 min)

This is time for examiners to follow-up and tie loose ends.

Example PhD Qualifying Exam – Fluids RAG

Three Papers Selected by Examination Committee.

1. Princen, H. M., I. Y. Z. Zia, and S. G. Mason. "Measurement of interfacial tension from the shape of a rotating drop." Journal of colloid and interface science 23.1 (1967): 99-107.

2. Zhao, Yunduo Charles, et al. "Hemodynamic analysis for stenosis microfluidic model of thrombosis with refined computational fluid dynamics simulation." Scientific reports 11.1 (2021): 1-10.

3. Herzhaft, Benjamin, Sarkis Kakadjian, and Michel Moan. "Measurement and modeling of the flow behavior of aqueous foams using a recirculating pipe rheometer." Colloids and Surfaces A: Physicochemical and Engineering Aspects 263.1-3 (2005): 153-164.

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EXAM FORMAT (1 hour duration).

Introduction. (5 min)

The student explains their research interests and how that is connected to the papers assigned.

Questions. (50 mins, 15 minutes per paper) student selects the order in which the papers are discussed

Paper 1

Consider a horizontal tube filled with fluid of density ρ. A volume of fluid V of lower density, $\rho - \Delta\rho$, is injected near the center of the tube and the apparatus is rotated rapidly, at angular speed Ω, about the long axis of the tube. At steady state, the drop of low density fluid has length L and radius (at the center) a_0, which depends on the various parameters in the problem, and the system experiences a solid body rotation. With an appropriate solution of the Young-Laplace equation, measurement of L or a_0 is sufficient to estimate the interfacial tension. Neglect the influence of gravity. It is simplest to consider this problem in cylindrical coordinates (r, z).

1. Using dimensional analysis, what can you conclude about the equilibrium drop length or drop radius a_0 as a function of the various parameters in the problem statement?
2. Assume the drop shape can be approximated as a cylinder of radius a_0 with hemi-spherical end caps. Provide a physical argument for the functional form of a0 as a function of the other parameters. Hint: You can obtain the pressure distribution in the system since the fluid undergoes a rigid-body rotation at steady state, which you should show leads to a pressure variation proportional to $\Delta\rho\Omega^2 r^2$ (find the missing constant of course). Then, a

force balance on a hemi-spherical end cap can be used to introduce the effect of surface tension and so find a solution.

Paper 2

1. What is the Reynolds number in this stenosis? What type of flow do you expect because of this Reynold number? Is there a simplification of the Navier-Stokes equation (eg. Eq. 3) that would make the solution of wall shear rate more time/cost efficient?
2. What is the sensitivity of peak shear rate to contraction angle or eccentric stenosis? Is this surprising given the Reynolds number? In Figure 3, the downstream streamlines look almost identical to the upstream streamlines. Why is this? What do you expect the velocity profile to look like at the throat of the stenosis?
3. Others have shown that Wall Shear Stress is strongly affected by the length of the stenosis. Explain from boundary layer theory why this would be true.
4. This study uses a variety of viscosity models for non-Newtonian effects. Considering the flow conditions in a stenosis, do you think the different viscosity models will have a major or minor effect on the wall shear rates in the stenosis? Why or why not?

Paper 3

3. What physical interfacial phenomena or surface tension effect in high-density foam results in yield stress in bulk flow; in other words, how can you relate yield stress in bulk flow of high-density foam to the microstructure of the air-liquid interface?
4. Based on the relation between the interfacial phenomena and yield stress, explain why the yield stress increases very sharply with foam quality?

Closing Discussion (5 min)

This is time for examiners to follow-up and tie loose ends.

Example Quals Questions

Y. Taitel and A. E. Dukler "A model for predicting flow regime transitions in horizontal and near horizontal gas-liquid flow" AIChE Journal, 1976, 22(1), 47-55

M. K. Dobson and J. C. Chato "Condensation in Smooth Horizontal Tubes," J. of Heat Transfer, 1998, 120, 193-213.

- In what regime do you think the technique proposed on analyzing the effect of acoustic waves on condensation will and will not be effective? And why?
- Do you expect the technique to affect the flow regime transition thresholds? Are there regime transitions where the effect would actually be detrimental to condensation?
- How would you modify the models/correlations in Dobson and Chato to semi-empirically account for the effect?
- How would you do so in the annular flow regime?

Example PhD Qualifying Exam – Manufacturing RAG

Three Papers Selected by Examination Committee.

1. Nakashima, K., Horita, Z., Nemoto, M., & Langdon, T. G. (1998). Influence of channel angle on the development of ultrafine grains in equal-channel angular pressing. Acta materialia, 46(5), 1589-1599. https://doi.org/10.1016/S1359-6454(97)00355-8

2. Sagapuram, D., Viswanathan, K., Mahato, A., Sundaram, N. K., M'Saoubi, R., Trumble, K. P., & Chandrasekar, S. (2016). Geometric flow control of shear bands by suppression of viscous sliding. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 472(2192), 20160167. https://doi.org/10.1098/rspa.2016.0167

3. Childs, T. H. C. (2006). Friction modelling in metal cutting. Wear, 260(3), 310-318. https://doi.org/10.1016/j.wear.2005.01.052

SUGGESTED EXAM FORMAT (1 hour duration).

Presentation. (10 min)

The trainee presents a 10-15 minute presentation reviewing their research interests and how that is connected to the papers assigned.

Generic Questions. (10 mins)

These are broad overview questions that (could/should) be the same for all trainees.

e.g.:

1. How do the assigned papers relate to your current research interests?

2. Can you identify some knowledge gaps that you discovered when reading the assigned papers?

3. Describe one future study/project that you believe would extend the knowledge you gleaned from the assigned papers?

Niche Questions. (30 mins)

These 3-5 questions should focus at the interface between analysis and synthesis in Bloom's taxonomy and progress from analysis to synthesis.

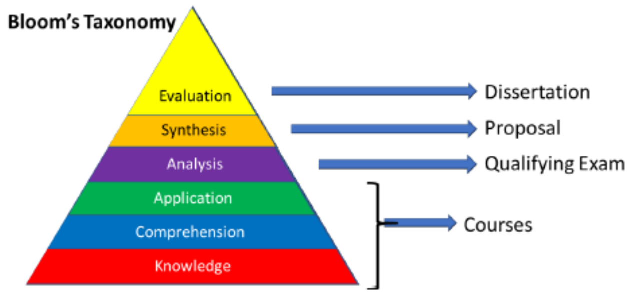

Figure 1: Relationship between educational objectives and elements of our Ph.D. program.

1. Compare and contrast the processing mechanics and microstructure evolution underpinning material removal processes (e.g., machining, passive geometric flow control) and bulk large strain deformation processes (e.g., equal angular channel pressing). Point out major similarities and differences.

2. Differentiate what the potential impacts of contact lubrication methods would be on process outcomes and processing goals for material removal processes and bulk large strain deformation processes.

3. Discuss limitations of idealized shear plane models for describing mechanics of deformation for highly shear banded materials. Explain how such methods would be insufficient with regard to modeling material outcomes and process outcomes for material removal and bulk deformation processes.

Closing Discussion (10 min)

This is time for examiners to follow-up and tie loose ends.

Mechanics of Materials (MoM) Example Oral Exam

Paper #1: R. Koerver, et al. Chemo-mechanical expansion of lithium electrode materials – on the route to mechanically optimized all-solid-state batteries, *Energy & Environmental Science*, (2018), 11, 2142-2158. This paper presents theoretical analysis and experiments results that detail the stress changes in solid-state battery cells comprised of different types of electrode materials during charge and discharge. Electro-chemo-mechanical changes are linked to thermodynamics, and an effort is made to reduce volume change by blending different electrode materials.

- The authors estimate the pressure in the cell using a linear elastic assumption. Describe other factors that you would have to take into account to obtain a better estimate of the pressure due to volume changes of the active material.
- In these experiments, the authors measure the uniaxial stress σ_{11}, but it is unclear how much of the volume change of the active material actually translates into measurable uniaxial stress. How might you design a setup to accurately measure additional stress components in the system?
- In Fig. 4c (the Li/NCM cell), the pressure changes linearly with state of charge, but in Fig. 4d (the graphite/NCM cell), the pressure change is not linear. What do you think is giving rise to these differences?
- Why is the (effective) partial molar volume of lithium constant in $LiFePO_4$, while it varies in graphite and other cathode materials?
- From an atomistic perspective, why is the partial molar volume of lithium greater in cathode materials (i.e., high voltage vs. Li/Li^+) compared to anode materials (i.e., lower voltage vs. Li/Li^+)?
- Consider the stress measured in these experiments, which results from volumetric strain within the entire battery stack. Now consider lithium insertion/extraction into individual active particles within the electrodes. How would stress and strain manifest due to electrochemical reactions manifest in active electrode particles, and why might it be difficult to investigate with stack pressure measurements?
- Formulate the chemomechanical stress-strain relation at a material point that accounts for the combined elastic strain and chemical strain due to Li insertion? Consider the following two cases: the volumetric expansion due to Li insertion is 1% (for a cathode material) or 100% (for an anode material).

Paper #2: Jaya, Kirchlechner, and Dehm, Can microscale fracture tests provide reliable fracture toughness values? A case study in silicon, J. Mater. Res., 30(5), 2015, pp. 686-698. This paper concerns nanomechanics and fracture mechanics. It touches on key concepts in the course Fundamentals of Fracture Mechanics (ME7772) and relevant research issues.

- What are the linear elastic fracture mechanics (LEFM) validity equations that are mentioned in the paper? What are their physical meanings (in term of plastic zone size, in term of the stress profile ahead of crack tip)?
- The paper mentions "rising R-curve". Can you provide an example of a test to measure the R-curve? What are key aspects of such test?

- Based on the results of the paper, which of the 4 techniques would you prefer to use to measure K_{IC} of a brittle material at the micrometer scale? Provide your rationale.
- Can you discuss 3 critical aspects of the specimens and loading frame to ensure successful K_{IC} measurements?
- The tests in the paper are performed inside a SEM. What about TEM? What would be the pros and cons, opportunities / challenges in doing in situ TEM fracture mechanics tests?

Paper #3: Marian, Cai, and Bulatov, Dynamic transitions from smooth to rough to twinning in dislocation motion, Nature Materials, 30, 2004, pp. 158-163. This paper is relevant paper for students doing research on atomistic simulations / computational mechanics. Key concepts involved includes Fundamentals of Linear Elasticity (ME6769) and Inelastic Deformation of Solids (ME 6203).

- Write down the equations for the strain and stress field due to an edge and a screw dislocation. (Cite appropriate reference that you used)
- What is the Peierls Nabarro model of dislocations? Express the stress needed to move a dislocation in terms of elastic constants and dislocation parameters. (Cite appropriate reference that you used)
- "Dislocations are central to the understanding of mechanical properties of crystalline solids." Explain what this statement means. What would happen in a crystalline solid free of dislocations. Give three examples where this statement might be applicable.
- How does a screw dislocation in bcc metals move under low stress conditions?
- Describe the behavior of the dislocation at high stress that causes it to deviate from "lamellar" behavior.
- What is the implication of this dislocation motion for plasticity under high stresses/temperatures?

1. **Suggested exam format:**

- **Presentation by student** (15 min)

The student makes a 10-15 minute brief presentation on his/her research and the three papers.

- **Questions** (45 min)

The question and answer session can start with generic questions first and evolve into more detailed questions.

2. **Committee deliberation:**

The student is excused and the committee discusses and decides on the outcome of the exam.

Example PhD Qualifying Exam – MNE RAG

Three Papers Selected by the Faculty Examination Committee.

1. [Peter Hesketh] Stephen R. Quake, et al., *From Micro- to Nanofabrication with Soft Materials*, Science 290, 1536 (2000)
2. [Levent Degertekin] Ladabaum et al., *Surface Micromachined Capacitive Ultrasonic Transducers*, ieee transactions on ultrasonics, ferroelectrics, and frequency control, vol. 45, no. 3, (1998)
3. [Hong Yeo] Kaltenbrunner et al., *An ultra-lightweight design for imperceptible plastic electronics*, Nature, 499, 458 (2013)

SUGGESTED EXAM FORMAT (1-hour duration).

1. Student Introduction Presentation (10 mins)

The student presents a 10–15-minute presentation reviewing their research interests and how that is connected to the papers assigned.

2. Questions from each examiner (15 mins = generic questions + niche questions)

[Faculty #1]

General Question:

What kind of applications, are soft microfluidics devices most suitable for ?

Niche Questions:

- For an immunoassay what are some of advantages gained from using microfluidics and why does this help ?
- For a submicron feature, can you suggest what lithography process could be used to define this feature and how it is formed in the layers.
- How can the features be transfer into the soft material layer ? What are the desirable mechanical and surface properties for successful pattern transfer ?

[Faculty #2]

General Question:

Can you compare piezoelectric and capacitive transducers for ultrasonic wave and pressure measurements in general?

Niche Questions:

- Can you comment on the linearity of the CMUT device? Does it change when it is used as a transmitter and receiver? How can you analyze it from the given equations?
- When is a small signal equivalent circuit is valid?
- What is the main change in device dynamics when the CMUT is moved from air environment and immersed in water? Does the collapse voltage change?

Wrap up questions:
How would you change the design of a CMUT operating at 3-4MHz to have a pressure sensor? What parameters in the design become more/less important?

[Faculty #3]
General Question:
Why did the authors in the paper try to develop flexible/stretchable electronics? What's wrong with the existing electronics? The biggest limitations of the existing wearable systems?

Niche Questions:

- What is the key mechanism of the presented plastic electronics that could endure both cyclic bending and stretching?
- This paper used a pre-stretched elastomer when integrated a transistor. What other methods can you use to design a stretchable transistor without using pre-stretching? Pros and cons of each method?
- What's the main concept of a neutral mechanical plane (explain it in a schematic drawing)? What are the key parameters that govern the position of the neutral mechanical plane? How can you allow for the NMP for different layered circuits – 2, 3, or more layers?

CLOSING DISCUSSION (5 min)
This is time for faculty examiners to discuss the student's performance and fill out the evaluation forms individually.

Example PhD Qualifying Exam – Robotics RAG

Three Papers Selected by Examination Committee.

1. Michael F. Eilenberg, Hartmut Geyer, and Hugh Herr, **Control of a Powered Ankle–Foot Prosthesis Based on a Neuromuscular Model** *IEEE Transactions on Neural Systems and Rehabilitation Engineering,* Vol. 18, No. 2, April (2010)

2. Jeffrey R. Koller, Daniel A. Jacobs, Daniel P. Ferris and C. David Remy **Learning to walk with an adaptive gain proportional myoelectric controller for a robotic ankle exoskeleton.** *Journal of NeuroEngineering and Rehabilitation* 12:97 (2015)

3. Kirby A. Witte, Pieter Fiers, Alison L. Sheets-Singer, Steven H. Collins **Improving the energy economy of human running with powered and unpowered ankle exoskeleton assistance** *Science Robotics* 5, eaay9108 (2020)

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SUGGESTED EXAM FORMAT (1.0 hour duration).

Presentation. (10 min)

The trainee presents a 10 minute presentation reviewing their research interests and how that is connected to the papers assigned.

Generic Questions. (10 mins)

These are broad overview questions that (could/should) be the same for all trainees.

e.g.:

1. How do the assigned papers relate to your current research interests?

2. Can you identify some knowledge gaps that you discovered when reading the assigned papers?

3. Describe one future study/project that you believe would extend the knowledge you gleaned from the assigned papers?

Niche Questions. (30 mins)

These 3-5 questions should focus at the interface between <u>analysis and synthesis</u> in Bloom's taxonomy and progress from analysis to synthesis.

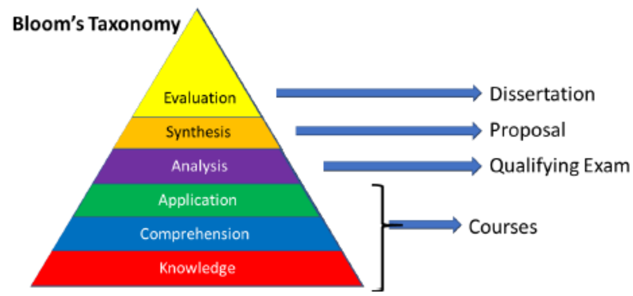

Figure 1: Relationship between educational objectives and elements of our Ph.D. program.

1. Please draw a block diagram for each of the three controllers described. (1) a powered exoskeleton proportional myoelectric controller with adaptive gains; (2) a powered prosthesis neuromuscular model based controller (3) a powered exoskeleton controller with a human-in-the loop optimized controller

2. For each controller, please describe the parameters that can be adjusted by an engineer to improve performance?

3. Please discuss the key differences between the three controllers in the context of adaptability? i.e. Which of these controllers would be most adaptable in unstructured terrain.

4. Please identify ways to merge at least two of these controller types to gain some new functionality. Use a block diagram to demonstrate your idea.

5. Is there a novel control architecture not outlined here that you feel could better solve the goal of continuously, adaptive biorobotic control with respect to the user and the environment.

Closing Discussion (10 min)

This is time for examiners to follow-up and tie loose ends.