Pew Research Proposal
Union University
(For Fall 2016)

Name(s) of Applicant(s): **Georg Pingen**

Title of Proposed Project:

Simulation and Design Optimization of Microfluidics using Extended Hydrodynamics

Primary Discipline: **Engineering** Secondary Discipline(s): **NA**

Has this proposal been submitted to another agency, publication, or program? **No**

Location of proposed research: **Union University, Jackson TN**
and University of Colorado, Boulder, CO

Desired start date: **June 1st, 2017**

Sponsoring Scholars (and discipline, please):

External: **Dr. Kurt Maute,** Joseph Negler Endowed Professor in Aerospace Engineering, University of Colorado at Boulder

Union: **Dr. Michael Salazar**, Associate Professor of Chemistry, Union University

Signature of the Dean in your discipline: ______________________________ Date: __________

Overall Checklist:

_x__Request for Letters of Recommendation
_x__Project description with major goals and brief examination of scholarly literature
_x__Essay on Christian faith and academic discipline
_x__Brief budget
_x__Plan for completion and dissemination
_x__Current *curriculum vitae*
_x__Seven copies of complete proposal

N.B. The Center for Faculty Development may offer additional checklists and resources to assist in grant writing; see http://www.uu.edu/centers/faculty/ Also, successful applications can be reviewed at http://www.uu.edu/programs/pew/past.cfm
and in a white binder marked “Grant Proposal Examples” in the Emma Waters Summar Library.

Project Title:

Simulation and Design Optimization of Microfluidics using Extended Hydrodynamics

Statement of End Products:

Primary Objective: Article

Secondary Objective: Identification of undergraduate research projects for Union engineering students.

Project Overview and Description:

The focus of the proposed research is the development, implementation, and validation of simulation and design optimization methodologies for fluid flows governed by non-equilibrium extended hydrodynamics as relevant in micro- and nano-fluidic applications. The particular focus is on velocity slip, temperature creep, and temperature jump effects. When we consider a traditional fluid flow application – such as water flowing down a river – we expect the flow velocity to be approximately zero at the boundaries (at the bottom & sides of the river) and reach a maximum in the center (the middle of the river). This is true for most large scale problems, however, as the problem size becomes smaller – such as in biomedical lab-on-a-chip devices – the fluid begins to "slip" along boundaries, which is counterintuitive based on our everyday experiences. Analogous to velocities, which "slip" along a wall in micro-flows, similar effects can be observed for temperatures. This leads to the underlying research question at the heart of this proposal: **Will these microscopic flow effects fundamentally change engineering designs at the micro-scale or can they be neglected by engineering designers** working on, for example, microscopic drug delivery systems?

This question can be explored through the development of topology optimization methodologies for flows governed by extended hydrodynamics. Such development of fluidic topology optimization approaches has been the primary focus of my research, starting with the basic implementation of flow topology optimization for steady-state continuum flows with the Lattice Boltzmann Method as part of my Ph.D. research (Ref 1) and more recently including the extension to transient flows (Ref 2), non-Newtonian flows (Ref 3), thermal flows (Ref 4), coupled fluid-structure interaction (Ref 5), and multi-species flows (Ref 6). The basic idea is to enable designers/engineers, who have conceptual ideas, to obtain computer generated optimal design solutions that are often non-intuitive. This process is illustrated in Figure 1, which shows the design of a static tesla valve from my Ph.D. research. It is the goal of this proposed research to apply this approach to flows governed by non-equilibrium effects (extended hydrodynamics) in order to address the underlying research question stated above.

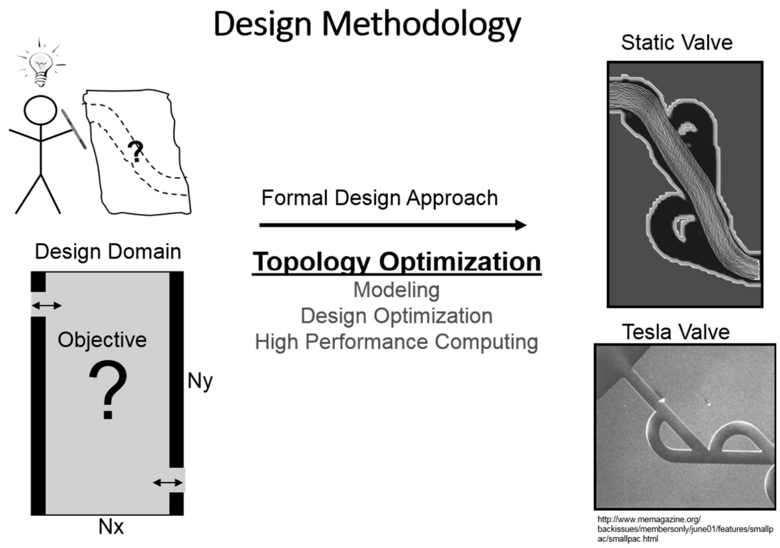

Figure 1: Illustration of the basic topology optimization design methodology from a designers problem description to the computer generated "optimal" design.

Demand for micro- and nano-scale devices has increased rapidly in recent years, and many of the unique features of such flows are discussed in a recent review article by Stone et al. (Ref 7). Some specific examples for designs governed by non-equilibrium processes are found in environmental monitoring (Ref 8), biological/pharmaceutical/medical applications (Ref 9) often with an emphasis on Point-of-Care (POC) medical/pharmaceutical devices, and in atomic layer deposition (Ref 10) among others. As an example of a microscopic design that utilizes non-equilibrium effects, a Knudsen pump designed and manufactured by An et al. (Ref 11) is shown in Figure 2. Different

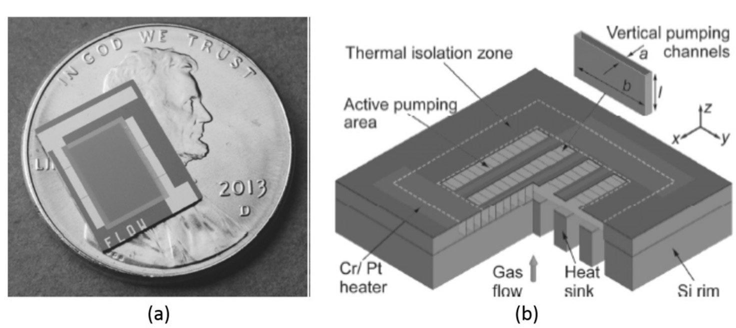

Figure 2: A manufactured microfluidic Knudsen pump is shown in (a), while (b) shows a conceptual illustration with a minimum flow channel dimension of a=2µm (Ref 5)

from large scale pumps, this pump functions without any moving parts and has a critical length scale of L=2μm.

With increased demand for such small-scale fluidic devices, the development of simulation and design optimization methodologies that incorporate the small-scale physical effects not captured by traditional methods has become an area of ever-increasing interest and great potential. As the size of fluidic devices shrinks, the critical length-scale 'L' of the devices approach the mean-free-path 'λ' (the average distance traveled by fluid/gas molecules before colliding with neighboring molecules), non-equilibrium effects such as velocity slip and temperature jumps at flow boundaries must be considered. The ratio between the mean free path 'λ' and critical length 'L' is the Knudsen number ($Kn = \frac{\lambda}{L}$) and allows differentiation between continuum and rarefied flows as illustrated in Figure 3. Continuum flow problems are generally well understood and can be accurately modelled with the Navier-Stokes-Fourier (NSF) equations, which are transport equations that utilize averaged macroscopic properties: velocity, pressure, density, temperature. This continuum flow approach is valid for small Knudsen numbers (e.g. a flowing river), in which a large number of molecular collisions typically leads to smooth variations of averaged properties, resulting in a near equilibrium flow state. As the Knudsen number increases due to a decrease in device size (see Figure 4) or due to a decrease of density (such as found at high altitudes), the NSF equations are insufficient to capture the relevant flow phenomena encountered in the transition regime ($10^{-2} \lesssim Kn \lesssim 1$). Extended fluid dynamic (extended hydrodynamic) approaches must be utilized in order to model the relevant non-equilibrium flow physics (see Figure 3). One example of flow phenomena not captured by the NSF equations is the slipping of a fluid along channel boundaries as illustrated in Figure 5.

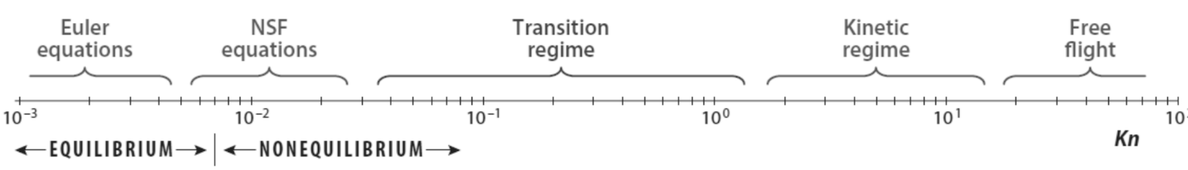

Figure 3: Transition between flow regimes as a function of Knudsen number: from continuum (small Kn) to rarefied (large Kn) flows (Ref 12)

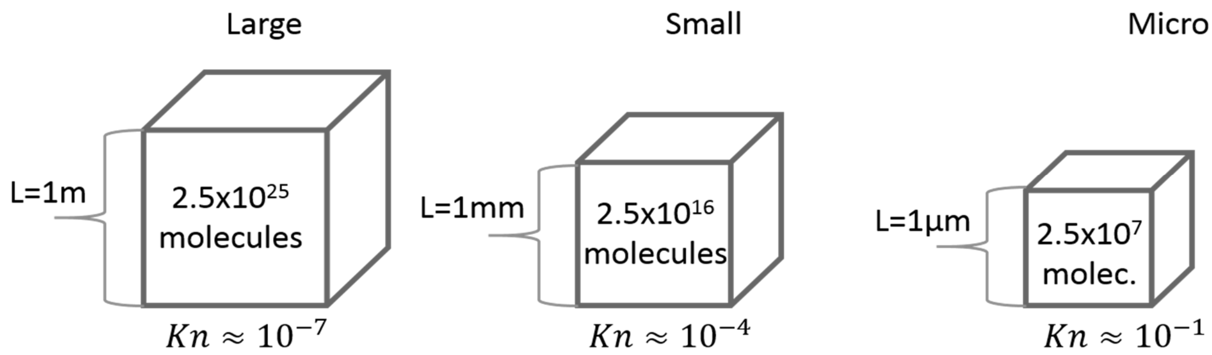

Figure 4: Increase of Knudsen number with decreasing domain size for air at standard conditions with a mean free path of 68nm (drawings not to scale)

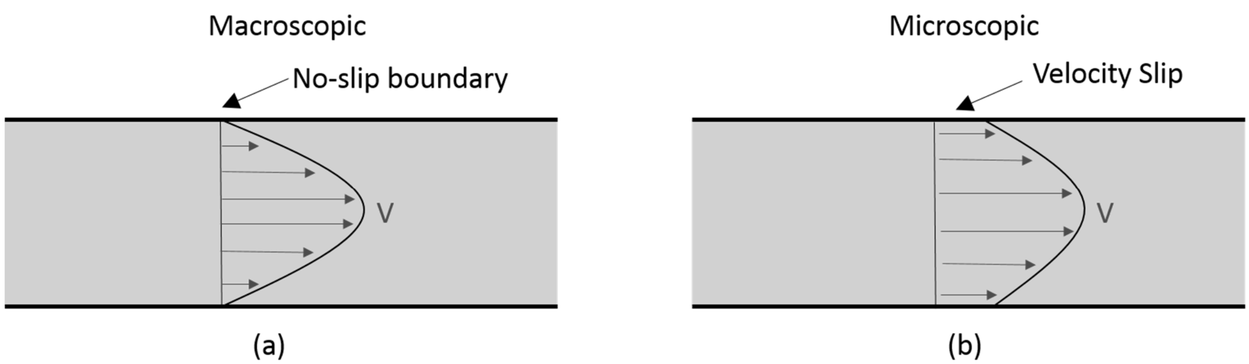

Figure 5: Difference between no-slip boundary conditions (a) for macroscopic flows and velocity slip (b) for microscopic flows is one example of flow phenomena that must be captured for micro-/nano-scale devices.

To adequately utilize the extended hydrodynamic effects at moderate Knudsen numbers, new simulation and design optimization methodologies must be developed, implemented, and validated. Two common options are as follows: (i) an expansion of the NSF equations through the use of slip velocity and temperature jump boundary conditions for flows with Kn≤0.1 and (ii) solutions to the hydrodynamic Boltzmann transport equation (HBTE), which is generally valid for all flows.

For flows with Kn≤0.1, non-equilibrium effects typically only occur in the boundary region of the flow and can be modelled by expanding the NSF equations through the use of slip velocity (u_{slip}) and temperature (T) boundary conditions (Ref 13) – option (i) above:

$$u_{slip} = \alpha \frac{2-\sigma_v}{\sigma_v} \lambda \left(\frac{\partial u}{\partial n} + \frac{\partial v}{\partial s} \right)\Big|_{wall} + \frac{3\mu R}{4P} \frac{\partial T}{\partial s}\Big|_{wall} \quad (1)$$

$$T_{fluid} - T_{wall} = \beta \frac{2-\sigma_v}{\sigma_v} \frac{2\gamma}{\gamma+1} \frac{\lambda}{Pr} \frac{\partial T}{\partial n}\Big|_{wall} \quad (2)$$

In collaboration with colleagues at the University of Colorado in Boulder, we recently incorporated these boundary conditions into an existing NSF solver based on the finite-element method as part of my summer 2016 research. Here, we have just started to scratch the surface of addressing our research question and are in the final stages of preparing a first manuscript entitled "Fluid topology optimization with a slip boundary model at finite Knudsen numbers" (Ref 14), which shows that slip-boundary conditions can have considerable design effects. Much work remains and as part of this Pew Research grant, I will particularly explore the effect of temperature creep and temperature jump boundary conditions on optimal engineering designs.

To explore flows beyond the range of the NSF equation – general transition region flows that include Kn>0.1 – non-equilibrium effects must be considered everywhere in the flow domain. These can be accurately described by the hydrodynamic Boltzmann transport equation (HBTE):

$$\frac{\partial f}{\partial t}+\vec{\xi}\cdot\frac{\partial f}{\partial \vec{x}}=-\frac{1}{\tau}\left(f-f^{eq}(\rho,\vec{u})\right) \qquad (3)$$

The HBTE describes the time evolution of the distribution function $f(\vec{x},\vec{\xi},t)$ which defines the number of particles at location $\vec{x}$ and time t with microscopic particle velocity $\vec{\xi}$. One of the possibilities for solving the hydrodynamic Boltzmann transport equation (HBTE) is the use of moment-based solutions, the most famous of which is Grad's moment method (Ref 15). Grad proposed that the infinite number of possible particle velocities $\vec{\xi}$ in the HBTE could be reduced through the use of a finite number of polynomials by representing

$$f(\vec{x},\vec{\xi},t)=w(\vec{\xi})\sum_n a_n(\vec{x},t)H_n(\vec{\xi}) \qquad (4)$$

in which $w(\vec{\xi})$ is a weight function, $a_n(\vec{x},t)$ are the polynomial coefficients to be determined, and $H_n(\vec{\xi})$ are Hermite polynomials used to approximate the dependence of the distribution function $f(\vec{x},\vec{\xi},t)$ on the particle velocity $\vec{\xi}$. It can be shown that when the complete set of Hermite polynomials is used ($n\rightarrow\infty$), an exact solution to the HBTE is recovered (Ref 16). An overview of the current state of Moment Methods can be found in the recent review article by Torrilhon (Ref 12).

A basic finite-element based 3rd order moment method was developed and implemented in collaboration with colleagues at the University of Colorado in Boulder as part of my summer 2014 PEW Research Grant and during our continued collaboration. Applying the Maxwell accommodation boundary conditions (Ref 6) in a finite element framework has been one of the challenges of this work and the small number of "benchmark" problems for flows with moderate Knudsen numbers (transition region flows) has made testing/validation of this implementation an ongoing challenge. The implementation of non-equilibrium boundary conditions for the NSF model allows us to cross-compare both models to ensure that accurate simulations of flows governed by the non-equilibrium extended hydrodynamic effects are achieved. Furthermore, we have been asked by Manuel Torrilhon at the RWTH Aachen to compare our model/solver against some recent results obtained by his students with moment method based solvers. This aspect will be a secondary focus of the proposed Pew summer research.

Proposed Summer 2017 Pew Research Grant

Support through the Pew summer research program will enable focused work on this research project during a 1 month research visit to the University of Colorado at Boulder during summer 2017. The ability to spend this time at CU-Boulder will be instrumental to the success of the proposed research by enabling daily face-to-face collaboration with Dr. Maute and his research students. Two key tasks are:

1. To explore the effect of temperature creep and temperature jump boundary conditions on optimal engineering designs, addressing the underlying research question: **Will these microscopic flow effects fundamentally change engineering designs at the micro-scale or can they be neglected by engineering designers?** The objective is to prepare a publication of this work by the end of Summer 2017.
2. To explore the solution of the hydrodynamic Boltzmann equation for flows at larger Knudsen numbers Kn>0.1.

In addition, the opportunity for a summer research visit to Boulder will further strengthen our ongoing collaboration, making it more sustainable, mutually beneficial for Union and CU Boulder, and providing continuous research opportunities for our engineering undergraduate students at Union. Since starting at Union in 2010, this collaboration has directly led to research project involvement for six Union undergraduates: Caroline McConnell (2013 graduate – Georgia Tech

Research Assistantship), Andrew Tan (2015 graduate), Dillon Lisk (2016 graduate), Zachary Benson (expected 2017 graduation), Chelsea Johnson (2016 graduate – Georgia Tech Presidential Fellowship & NDSEG Fellowship), and Matthew Owen (current). This collaboration has also permitted me to co-advise 3 graduate students at the University of Colorado, where I am currently co-advising Luis Negrete.

Finally, the work supported through the Pew Summer Research Grant will provide a strong foundation for my future research plans, which include the plan to apply for Research Leave to conduct research at RWTH Aachen during fall 2018. Manuel Torrilhon and his colleagues in Aachen are leading experts on Moment Methods for extended hydrodynamics and my proposed PEW summer research will help to further enhance those opportunities for collaboration. RWTH Aachen is one of Germany's leading research institutions and to qualify for a sabbatical position in Aachen it is important to show continuing active research engagement – support through the PEW research grant will help me to do so.

Brief Survey of Relevant Literature and Contributions of Research:

While the previous project description has highlighted many of the relevant references from scholarly literature, the proposed research will make a distinct contribution to the field of computational fluid dynamics, namely the application of topology optimization to flows governed by non-equilibrium extended hydrodynamics.

Topology optimization for fluid flows started with the pioneering work of Borrvall and Petersson (Ref 17) in 2003 and has been the primary focus of my research over the last 12 years, starting with my Ph.D. research (Ref 1) and including recent and ongoing research projects with Union University undergraduates. Much progress has been made in recent years, as highlighted in the recent review article on "Topology Optimization for Microfluidics" by Chen (Ref 18). However, despite the importance of non-equilibrium effects for many microfluidic applications, current topology optimization frameworks do not model these effects due to their high computational complexity and cost. To the best of my knowledge, our manuscript currently under preparation (Ref 14) will be the first work exploring the effect of slip boundary conditions on topology optimization. The work as part of this proposed Pew Research Grant constitutes the first work that will explore the effect of thermal creep and temperature jump for topology optimization and will help address whether or not these micro-scale flow phenomena should be considered by design engineers.

Past PEW Research Grant Results

In September of 2014, I provided Micah Watson - chair of the Pew Research Committee – with a brief summary of my summer 2014 PEW research grant funded visit to the University of Colorado, where I closely collaborated with my former PhD advisor and one of his graduate students, Luis Negrete. I also provided a brief overview of this work during the 2015 Spring Pew Luncheon. The PEW funded summer research has since led to the following completed and ongoing research:

1. We implemented a 3rd order moment method based solver for the HBTE. I presented a brief overview of this work at the Fields Institute Moment Method Workshop in Toronto, Canada during October 2014. This workshop has led to the exchange of research ideas with Dr. Manuel Torrilhon and his students at the RWTH Aachen in Germany, and I had the opportunity to visit Manuel and his students while in Germany during summer 2015. Related to this research, I have been co-advising a Master's student (Luis Negrete) at the University of Colorado through weekly/biweekly Skype research meetings. Luis will graduate this upcoming spring, and we are currently preparing our collaborative research for publication (Ref 14) – a copy of the first page of the current draft is included in the appendix.
2. In addition to the HBTE research, I investigated the possibility of efficient iterative solvers for fluidic topology optimization with the lattice Boltzmann method, a topic closely related to my Ph.D. research. Several recent publications in this area have misrepresented the theoretical origin of these approaches. Following the PEW funded summer research, I prepared a "Brief Note" on this topic, highlighting mistakes/misconceptions in the current literature, which was submitted to the Journal of Structural and Multidisciplinary Optimization during spring 2015. The reviewers requested that we revise our submitted work to not only explain the misconceptions in the existing literature, but to also include examples of the proposed alternatives, which I explored with one of our undergraduate students – Chelsea Johnson – from fall 2014 until her graduation last spring. This ability to involve undergraduates at Union in research on a continuous basis was one of the key motivators for my last PEW research application and is one of the most rewarding aspects

of working at Union. Chelsea's involvement in this project has exposed her to undergraduate research, prepared her for a National Science Foundation summer research experience for undergraduates (REU) at the University of Alabama during summer 2015, and motivated her to pursue graduate studies in Aerospace Engineering. She just recently started graduate school at Georgia Tech where she is supported by prestigious fellowships from Georgia Tech (Presidential Fellowship) and the Department of Defense (NDSEG). This work is still ongoing and we hope to publish our findings in the future.

Receiving the PEW Research grant during summer 2014 played a significant role in these research achievements, undergraduate research opportunities, and ongoing activities.

Essay on Faith and the Discipline:

"In the beginning God created the heavens and the earth" (Gen 1:1 NIV) and has made us "ruler over the works of [his] hands; [he has] put everything under [our] feet." (Ps 8:6) As such, God is the Master Engineer (Ref 19) who has designed all of creation. While Genesis does not provide much insight into God's attention to detail while 'engineering' Creation, God uses engineering terminology to describe his work while questioning Job (Job 38-39).

> "Where were you when I **laid the earth's foundation**? Tell me, if you understand. Who **marked off its dimensions**? Surely you know! Who stretched a **measuring line** across it? On what were its **footings set**, or who laid its **cornerstone**?" (Job 38:4-6 NIV).

As Christian engineers, following in God's creative footsteps as designer and creator of all things, we are held to a high standard in our work, which can be both encouraging and daunting at times. The official definition of engineering by ABET (the accrediting body for engineering) highlights indirectly that as engineers, we are tasked with using God's creation to benefit mankind.

> "Engineering is the profession in which a knowledge of the mathematical and natural sciences gained by study, experience, and practice is applied with judgment to develop ways to utilize economically the materials and forces of nature for the benefit of mankind." (Ref 20)

John Turnbull, in an article on the philosophy of engineering (Ref 21), emphasizes that while engineering is often associated with technology, engineering design is driven by social issues and enabled by technology. He states that "Engineers have the skill and ability to design … They can combine science based technologies with social insight, to improve the quality of life."

In an attempt to create improved engineering designs, engineers are frequently looking at nature to reproduce and use its myriad of fascinating designs in engineering applications – for example, the strength of spider webs or the ability of a gecko's feet to stick to almost anything. In a 2008 article published in National Geographic, "Biomimetics – Design by Nature" (Ref 22), Andrew Parker, an evolutionary biologist and research fellow at the National History Museum in London comments on this trend. Parker attributes these phenomena in nature to millions of years of evolution and natural selection and refers to them as "a treasure-trove of brilliant design." As Christian engineers, we attribute these 'brilliant designs' to God as our perfect Creator. Considering that the world's best scientists and engineers are often puzzled by the task of recreating these designs should cause us as engineers to be in awe of our Creator. We can look at these designs in nature from a point of reverence towards God and a clear example of His 'invisible qualities' as indicated in Rom 1:20:

> "For since the creation of the world God's invisible qualities – his eternal power and divine nature – have been clearly seen, being understood from what has been made, so that men are without excuse." (Rom 1:20 NIV)

Considering God's handiwork in natural revelation leads us to admit that we are limited in our own ability and mimicking the work of our Creator presents an avenue for praising God through our work as engineers.

Grounded in my faith and this understanding of the engineering discipline in light of God's handiwork in creation, I am motivated by my faith through three particular aspects related to my ongoing and proposed research: an improved understanding of creation, improved stewardship of our resources, and mentorship opportunities with undergraduate students. First, the development of new computational models for extended hydrodynamics will lead to an improved understanding of those physical phenomena. By gaining an improved understanding of natural phenomena and designs, we in turn gain a more intimate and detailed understanding of God, our Creator. Second, God has given us stewardship over creation. Improving/optimizing flow devices through design optimization methodologies enables us to be better stewards of the resources entrusted to us by God. Third, I view discipleship and mentorship as key aspects of our Christian life and have benefited greatly from excellent research mentorships as a student. I see undergraduate research mentorships analogous to Jesus' mentorship of Peter, James, and John who had a special role among his disciples and received unique insights into Jesus' life. Jesus preached powerful messages to great crowds, but it was the one-on-one mentorship he had with his apostles that turned the world upside down. In fact, the Bible is full of examples that demonstrate the power and value of one-on-one mentorships, including Moses and Joshua, Eli and Samuel, Paul and Timothy, and Paul and Titus. This serves as motivation to pursue research projects that emphasize close collaboration with undergraduate students.

Tentative Schedule and Plan for Dissemination:

My past research on computational fluid dynamics and design optimization has led to eleven journal and twelve conference publications, with an additional journal publication currently in preparation. The proposed research promises exciting contributions to the field of simulation and design optimization for extended hydrodynamics. Upon successful completion of this work, I expect to submit the findings to a peer-reviewed conference or journal focused on computational engineering, such as the Journal of Structural and Multidisciplinary Optimization.

Fall 2016/Spring 2017	Research at Union in collaboration with Matthew Owen (undergraduate research grant), as well as continued collaboration with Luis Negrete and Kurt Maute through biweekly Skype research meetings. Focus will be placed on validating the thermal creep and temperature jump boundary conditions as well as integrating these models into the topology optimization framework.
Summer 2017	One month research visit to CU-Boulder (4-6 weeks), allowing focused time spent on implementing the optimization framework in the software package developed at CU Boulder, collaborating face-to-face with researchers and graduate students, and exploring new research project opportunities for undergraduate engineering students at Union.
Late Summer/Fall 2017	Preparation of an article to be presented at a peer-reviewed conference or submitted to a peer-reviewed journal.
Spring 2018	Pew Research Presentation at Union

Budget:

A budget of $4500 is requested as a **Researcher Stipend** to support a 1-month (4-6 week) research visit to the University of Colorado in Boulder, CO. This time will be devoted to the proposed research and to identifying additional research projects suitable for Union University undergraduate engineering students. A large portion of the stipend will be utilized to cover the costs of travel to Boulder (2242 miles round trip @ $0.54/mile = $1210) as well as the cost of living while in Boulder (e.g. furnished apartments are typically around $2500-$3000/month in Boulder, CO).

Researcher Stipend ……………………………………………………………………………$4500

TOTAL:…………………………………………………………………………………...$4500

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Appendix: Page one of Manuscript under Preparation (Ref 14)

Fluid topology optimization with a slip boundary model at finite Knudsen numbers

Luis F Negrete, Kurt Maute, Georg Pingen

1 Introduction: The Knudsen Number

The Knudsen number is a non-dimensional parameter that characterizes the rarefaction of a fluid (typically, a gas). It is defined as

$$Kn = \frac{\lambda}{L_r} \approx \frac{\lambda}{\Phi_0}\left|\frac{d\Phi_0}{dL}\right|, \tag{1}$$

where λ is the mean-free path of the fluid, L_r is some global reference length, e.g. the spacing between plates or the cylinder diameter, and Φ_0 is any chosen quantity, e.g. the fluid density. The first definition in (1) represents a global Knudsen number, while the second can be used to represent a local Knudsen value. The mean-free path is the average distance a fluid particle travels between collisions with other particles. Larger Kn numbers indicate that particles travel further distances between collisions; thus, the fluid is said to be more rarefied.

Flows in which $Kn < 10^{-2}$ are said to be in the Hydrodynamic Range, where both the Euler and Navier-Stokes-Fourier (NSF) equations with traditional no-slip boundary conditions are valid. Flows for which $10^{-2} < Kn < 10^{-1}$ are said to be in the Slip Flow Regime, where the Euler equations are no longer valid and the NSF equation cannot be used with the traditional no-slip boundary conditions. Instead, velocity and temperature slips begin to occur as the Kn increases, i.e. the velocity and temperature of the fluid at the wall and that of the wall itself are not the same. Flows for which $10^{-1} < Kn < 10$ are said to be in the Transition Regime; here, the NSF equations are no longer valid. (CITE Burnett Equations as an example of what others do in this range?). Finally, flows for which $Kn > 10$ are said to be in the Free Molecular Flow Regime, where intermolecular collisions are so rare that they can be ignore; instead, only particle-wall interactions are important. The Direct Simulation Monte Carlo (DSMC) method is particularly powerful in this regime, since each particle can be considered independent of other particles in a flow. (CITE recent work with DSMC? Bird?) In contrast to other fluid flow equations, the Boltzmann Transport Equation (BTE) is valid across all these regimes, though a collision-less BTE is most appropriate for large Kn number flows.

This work seeks to expand on previous work in the Slip Flow Regime, where $Kn < 0.1$, by extending the use of the NSF equations by implementing slip boundary conditions and exploring the effect of the Kn number in topology optimization problems; this work will also explore the effect of the ghost penalization framework developed by (Villanueva?).

The Knudsen number can be given from the Reynolds and Mach numbers via:

$$Kn = \frac{Ma}{Re}\sqrt{\frac{\gamma\pi}{2}} \tag{2}$$

The incompressible Navier-Stokes are valid for $Ma < 0.3$; thus, for a given Kn number, the Re bound from above to satisfy the incompressibility constraint.

The new boundary condition introduced in this work requires the exact position and orientation of the fluid-solid interface, which is not realizable with density methods for optimization. Instead an immersed boundary method is used to describe the interface.

2 Optimization

2.1 Optimization Model

The optimization problems considered in this work are formulated with respect to an objective and one or more constraints for desired functionality. The objective and constraints are defined in terms of design criteria, such as

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Thesis Title: *Optimal Design for Fluidic Systems: Topology and Shape Optimization with the Lattice Boltzmann Method*
M.S. in Mechanical Engineering, Washington, University in St. Louis, MO 2004
Thesis Title: *Development of the Fast-Scanning-Electrical-Nanoparticle-Sizer*
B.A. in Mathematics and Physics, Samford University, Birmingham, AL 2003
B.S. in Mechanical Engineering, Washington, University in St. Louis, MO 2003

CERTIFICATIONS/LICENSES

Professional Engineer, Tennessee 2012
Graduate Teacher Certificate 2007
Preparing Future Faculty Professional Development Certificate 2007

PROFESSIONAL SOCIETY MEMBERSHIPS

American Society of Mechanical Engineers (ASME)
American Society of Engineering Education (ASEE)

RESEARCH INTERESTS

- Computational Engineering
- Computational Fluid Dynamics
- Kinetic Theory Approaches/Boltzmann Transport Equation
- Finite Element Methods
- Design Optimization/Topology Optimization
- Engineering Education

PUBLICATIONS:

Journals:

1. David Makhija, Kurt Maute, and **Georg Pingen**. *An Immersed Boundary Method for Fluids using XFEM and the Hydrodynamic Boltzmann Equation.* Computer Methods in Applied Mechanics and Engineering, vol 273, p. 37-55, May 2014.
2. David Makhija, Ronggui Yang, **Georg Pingen**, Kurt Maute. *Topology optimization of multi-component flows using a multi-relaxation time lattice Boltzmann method*, Computers and Fluids, vol 67, p. 104-114, 2012.
3. Sebastian Kreissl, **Georg Pingen**, Kurt Maute. *Topology Optimization for Unsteady Flow*, International Journal for Numerical Methods in Engineering, vol 87(13), p. 1229-1252, 2011.

4. Sebastian Kreissl, **Georg Pingen**, Anton Evgrafov, and Kurt Maute. *Topology Optimization of Flexible Micro-Fluidic Devices*, Structural and Multidisciplinary Optimization*, 2010, DOI: 10.1007/s00158-010-0526-6.*
5. Sebastian Kreissl, **Georg Pingen**, and Kurt Maute. *An explicit level-set approach for generalized shape optimization of fluids with the lattice Boltzmann method,* International Journal for Numerical Methods in Fluids, DOI: 10.1002/fld.2193, Oct. 2009.
6. **Georg Pingen** and Kurt Maute. *Optimal Design for non-Newtonian Flows using a Topology Optimization Approach*, Computers and Mathematics with Applications. DOI: 10.1016/j.camwa.2009.08.044, 2009.
7. **Georg Pingen**, Matthias Waidmann, Anton Evgrafov, and Kurt Maute. *A Parametric Level-Set Approach for Topology Optimization of Flow Domains*, Structural and Multidisciplinary Optimization, DOI: 10.1007/s00158-009-0405-1, 2009.
8. **Georg Pingen**, Anton Evgrafov, and Kurt Maute. *Adjoint Parameter Sensitivity Analysis for the Hydrodynamic Lattice Boltzmann Method with Applications to Design Optimization,* Computers and Fluids, Volume 38, No 4, p. 910-923, 2009.
9. **Georg Pingen**, Anton Evgrafov, and Kurt Maute. *A parallel Schur complement solver for the solution of the adjoint steady-state lattice Boltzmann equations: application to design optimization.* International Journal of Computational Fluid Dynamics, Volume 22, No. 7, p. 457-464, 2008.
10. Anton Evgrafov, **Georg Pingen**, and Kurt Maute. *Topology Optimization of Fluid Domains: Kinetic Theory Approach.* ZAMM, Volume 88, No. 2, p. 129-141, 2008.
11. **Georg Pingen**, Anton Evgrafov, and Kurt Maute. *Topology Optimization of Flow Domains using the Lattice Boltzmann Method,* Structural and Multidisciplinary Optimization, Volume 34, No. 6, p. 507-524, 2007.
12. Perry A. Tompkins and **Georg Pingen**. <u>The Physics Teacher</u>: *Real-Time Experimentation Across the Internet.* October 2002, Volume 40, Number 7.

<u>Conference Proceedings:</u>

1. **Georg Pingen**. *Team-Based Learning and Screencasts in the Undergraduate Thermal-Fluid Sciences Curriculum*. Proceedings of ASEE Annual Conference, June 23-26, 2013, Atlanta Georgia, Paper ID #6995 *(refereed)*
2. Caroline McConnell and **Georg Pingen.** *Multi-layer, pseudo 3D thermal topology optimization of heat sinks.* Proceedings of ASME International Mechanical Engineering Congress, Nov 9-15, 2012, Houston Texas, IMECE2012-93093. *(refereed)*
3. Andrew Kirk, Sebastian Kreissl, **Georg Pingen**, Kurt Maute. Lattice Boltzmann *Topology Optimization for Transient Flows.* Proceedings of the MAESC 2011 Conference, May 2011
4. Sebastian Kreissl, **Georg Pingen**, Kurt Maute. *Optimal Layout Design for Unsteady Flows.* 13th AIAA/ISSMO Multidisciplinary Analysis & Optimization Conference, 13-15 September, 2010, Fort Worth, TX *(refereed)*
5. **Georg Pingen** and David Meyer. *Design Optimization for Thermal Transport.* Proceedings of the ASME 2009 Fluids Engineering Summer Meeting, August 2-5, 2009, Vail, Colorado, FEDSM2009-78408. *(refereed)*
6. Sebastian Kreissl, **Georg Pingen**, Anton Evgrafov, and Kurt Maute. *Topology Optimization for Deformation-Sensitive Flow Problems*. Proceedings of 2009 NSF Engineering Research and Innovation Conference.

7. Sebastian Kreissl, **Georg Pingen**, Anton Evgrafov, and Kurt Maute. *Design of Deformation-Sensitive Flow Problems by Topology Optimization*. Proceedings of WCSMO2009, Lisbon, Portugal. *(refereed)*
8. **Georg Pingen**, Anton Evgrafov, and Kurt Maute. *A GMRES Schur Complement solution of the Lattice Boltzmann Sensitivity Equations for Large-Scale Topology Optimization.* Proceedings of 2008 NSF Engineering Research and Innovation Conference, Knoxville, TN
9. **Georg Pingen**, Matthias Waidmann, Anton Evgrafov, and Kurt Maute. *Application of a Parametric-Level-Set Approach to Topology Optimization of Fluids with the Navier-Stokes and Lattice Boltzmann Equations.* Proceedings of WCSMO2007. *(refereed)*
10. Anton Evgrafov, **Georg Pingen**, and Kurt Maute. *Topology Optimization of Fluid Domains: Kinetic Theory Approach.* Proceedings of WCSMO2007. *(refereed)*
11. **Georg Pingen**, Anton Evgrafov, and Kurt Maute. *3D Topology Optimization of Fluids by the Lattice Boltzmann Method.* AIAA-2006-7108. (Finalist, Best Student Paper Competition) *(refereed)*
12. **Georg Pingen**, Anton Evgrafov, and Kurt Maute. *Towards the Topology Optimization of Fluid-Structure Interaction Problems with Immersed Boundary Techniques*. Proceedings of 2006 NSF DMII Grantees Conference, St. Louis Missouri.
13. Anton Evgrafov, **Georg Pingen**, and Kurt Maute. *Topology Optimization of Fluid Problems by the Lattice Boltzmann Method*, IUTAM Symposium on Topological Design Optimization of Structures, Machines and Materials: Status and Perspectives, edited by M. P. Bendsøe, N. Olhoff, and O. Sigmund, Springer, Netherlands, 2006, pp. 559–568. *(refereed)*
14. Liu Z. Gerald, Da-Ren Chen, Nalin Perera, **Georg Pingen**, Edward M. Thurow, and Joseph C. Lincoln. <u>SAE</u>: *Transient Analysis of Engine Nano-Particles Using a Fast-Scanning Differential Mobility Particle Analyzer.* SAE International, 2004. No: 2004-01-0971.
15. **Georg Pingen**, Glen Hudson, and Perry A. Tompkins. *Internet Measurement of the Magnetic Field of a Long Straight Wire Using LabVIEW.* NI-week (National Instruments annual competition) 2001, Winner of the Education category.

PRESENTATIONS[1]:

<u>Conference:</u>

1. *Hydrodynamic Boltzmann Transport Equation: Finite Element Method for Moment Equations.* (Brief overview Presentation) Fields Institute Moment Method Workshop, Toronto, Canada, October 2014.
2. *Team-Based Learning and Screencasts in the Undergraduate Thermal-Fluid Sciences Curriculum.* ASEE Annual Conference in Atlanta, GA, June 25, 2013.
3. *Use of Screencasts to Enhance In-Class Student Participation.* Union University uTech Expo, Feb 28 – March 1, 2013.
4. *Transient Topology Optimization of Fluids*, presented at the Mid South Annual Engineering and Sciences Conference in Memphis, TN, May 3, 2011
5. *Design Optimization for Thermal Transport.* ASME 2009 Fluids Engineering Summer Meeting, Vail, Colorado, August 5, 2009.

[1] All listed presentations/posters have been personally presented

6. *Formal Design Approaches with the Lattice Boltzmann Method: Topology and Shape Optimization.* International Conference for Mesoscopic Methods in Engineering and Science, Amsterdam, Netherlands, June 18, 2008.
7. *A Parallel Schur Complement Solver for the Steady-State LBM Equations: Application to Design Optimization.* International Conference for Mesoscopic Methods in Engineering and Science, Munich, Germany, July 19, 2007.
8. *3D Topology Optimization of Fluids by the Lattice Boltzmann Method.* 11th AIAA/ISSMO Conference, Portsmouth, Virginia, Sep. 8, 2006.
9. *A Computational Framework for Parameter Sensitivity Analysis of Fluid-Structure Interaction Problems*. World Congress on Computational Mechanics, Los Angeles, California, July 19, 2006.

Invited:

1. *Flow Topology Optimization and Multi-Scale Flow Simulations: Boltzmann-Equation based Approaches*. Mechanical Engineering Seminar, Washington University in St. Louis, April 9th, 2015.
2. *Flipped Classroom, Team-Based Learning, and Real World Problems in Engineering.* Fall Faculty Workshop, Union University, August 15th, 2013.
3. *A Multi-disciplinary Graduate Research Experience: Kinetic Theory applied to Engineering Design*. EGR Seminar. Union University, Spring 2011.
4. *Kinetic Theory Approach to Computational Fluid Dynamics: Applications to Design Optimization, Modeling, and Analysis.* Research Seminar Series, Mechanical and Aerospace Engineering, University of Colorado, Colorado Springs, Colorado, October 17, 2008.
5. *Formal Approach to the Design of Fluidic Systems.* Faculty Interview, Mechanical and Aerospace Engineering, University of Colorado, Colorado Springs, Colorado, March 17, 2008.
6. *Optimal Design of Fluidic Systems with the Lattice Boltzmann Method: Topology Optimization.* Graduate Seminar Series, Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, September 12, 2007.
7. *The Lattice Boltzmann Method for Engineering Design Applications: Topology Optimization.* Technical University Munich, Bauingenieurwesen (civil/structural engineering), Munich, Germany, July 20, 2007.
8. *Design Optimization of Fluidic Systems*, Graduate Student Visitation, Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, March 8, 2007.
9. *Facilitation of Keynote Address Discussion* (Using Controversies in the Classroom to Help Prepare Future STEM Faculty for Teaching and Learning), Spring Conference, Graduate Teacher Program, Boulder, Colorado, January 12, 2007.
10. *Topology Optimization of Fluidic Systems: Use of the Lattice Boltzmann Method.* University of Braunschweig, Braunschweig, Germany, June 13, 2006.
11. *Design Optimization of Coupled-Multiphysics Problems*, Graduate Student Visitation, Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, March 9, 2006.

Poster:

1. *Having the Computer do the Design!* Georg Pingen, David Meyer, Sebastian Kreissl, and David Makhija. UCCS: Mountain Lion Research Day, Colorado Springs, Colorado, April 3, 2009.
2. *Thermal Lattice Boltzmann and Topology Optimization!* David Meyer and Georg Pingen. UCCS: Mountain Lion Research Day, Colorado Springs, Colorado, April 3, 2009.
3. *CAREER: A Biomimetic Approach to the Design of Shape-Controlled Systems.* Principal Investigator: Kurt Maute. NSF Design, Service and Manufacturing Grantees and Research Conference, St. Louis, Missouri, July 24-27, 2006.
4. *A Biomimetic Approach to the Design of Shape-Controlled Systems.* Principal Investigator: Kurt Maute. National Science Foundation, National Science Board Meeting, Boulder, Colorado, February 10, 2006.
5. *Development of A portable Nanometer Aerosol Size Analyzer (nASA)*, Nalin Perera, Georg Pingen, Da-Ren Chen, AAAR'03, Anaheim, California, Oct. 20-24, 2003.
6. *Numerical Modeling of a Nanoparticle Virtual Impactor*, Poshin Lee, Georg Pingen, Da-Ren Chen, AAAR'03, Anaheim, CA, Oct. 20-24, 2003.

TEACHING EXPERIENCE:

Union University:

- EGR 101, Intro to Engineering (co-instructor)
- EGR 210, Materials
- EGR 250 & 250L, Thermal-Fluid Sciences I
- EGR 320, Mechanics of Materials
- EGR 325, Computational Analysis of Structures
- EGR 342, Experimental Methods
- EGR 355 & 355L, Thermal-Fluid Sciences II
- EGR 391, Intro to Senior Projects
- EGR 456, Machine and Mechanism Theory and Design[2]
- EGR 498, Engineering Seminar

University of Colorado, Colorado Springs, CO:

- MAE 3201, Strength of Materials
- MAE 5131, Computational Fluid Dynamics (graduate)
- MAE 5310, Intermediate Heat Transfer (graduate)
- MAE 9510, Mechanics of Materials (graduate)

University of Colorado, Boulder, CO:

- ASEN 3111, Aerodynamics (teaching assistant)
- ASEN 4338, Computational Analysis of Structures (co-instructor)
- ASEN 4018, Senior Projects (assisted with CFD on 7 projects)
- Lead Graduate Teacher
- PowerFLOW Tutorial/Experiment Development

[2] Taught one month in Spring 2012 for Dr. Jay Bernheisel

RESEARCH ADVISING EXPERIENCE:

Undergraduate Students:

1. Matthew Owen (Union University, Fall 2016 – ongoing)
2. Chelsea Johnson (Union University, Fall 2014 – Spring 2016)
3. Dillon Lisk (Union University, Fall 2013 – Spring)
4. Zachary Benson (Union University, Fall 2013 – Spring 2014)
5. Phillip Johnson (Union University, Fall 2013 – Spring 2014)
6. Andrew Tan (Union University, Summer 2013 – Summer 2014)
7. Caroline McConnell (Union University, Spring 2011 – Spring 2013)
8. John Erickson (University of Colorado, Colorado Springs, Spring 2009 – Spring 2010)

Graduate Students:

University of Colorado at Colorado Springs

1. **David Meyer**, 2008-2010 **(M.S.)**
   Thesis Topic: Lattice Boltzmann based topology optimization for convective heat transfer applications.
2. **Andrew Kirk**, 2009-2010 **(M.S.)**
   Thesis Topic: Design Optimization under Transient Flow Conditions
   Co-Advisor: Dr. Rebecca Webb
3. **Joel Halpert**, 2009-2010 **(M.S.)**
   Thesis Topic: Simulation of Multi-Phase Flows in Cryogenically Cooled Channels
   Co-Advisor: Dr. Rebecca Webb

University of Colorado at Boulder, CO[3]

4. **Luis Negrete,** 2014-ongoing (**M.S.**)
   Thesis Topic: Moment Methods for the Hydrodynamic Boltzmann Equation.
5. **David Makhija,** 2008-2013 (**PhD**)
   Thesis Topic: Lattice Boltzmann based topology optimization for multi-phase/species and reacting flows.
6. **Sebastian Kreissl,** 2008-2011 (**PhD**)
   Thesis Topic: Topology optimization for Fluid-Structure Interaction Problems.
7. **Dominik Herrmann[4],** Universität Stuttgart, Diploma Thesis Research, 2007
   Thesis Title: A Study of the Suitability of PowerFLOW as an Educational Engineering Design Tool…
8. **Matthias Waidman[4],** Universität Stuttgart, Diploma Thesis Research, 2006/2007
   Thesis Title: A Pseudo-Level-Set Method for Topology Optimization of Flows based on Navier-Stokes and Lattice Boltzmann Solvers
9. **Sascha Ackerman[4],** Universität Stuttgart, Diploma Thesis Research, 2006
   Thesis Title: Time Coupling Methods for Explicit-Implicit FSI Schemes
10. **Thomas Gallinger[4],** Technische Universität München, Master's Research, 2005/2006
    Thesis Title: Lattice Boltzmann Method and Fluid-Structure Interaction Problems

HONORS & AWARDS

Visiting Scholar, Aerospace Engineering Sciences, CU Boulder, Summer 2016
Pew Research Grant, Union University, Fall 2013
Teaching and Learning Grant, Union University, Fall 2013
Honorable Mention, Newell Innovative Teaching Award, Union University, Spring 2013
Undergraduate Research Grant, Union University, 2011, 2013, 2014, 2015

[3] All have been co-advised with Dr. Kurt Maute
[4] Visiting International Student

Best Paper List, 7^{th} World Congress on Structural and Multidisciplinary Optimization
"Best Should Teach" Silver Award, Graduate Teacher Program, University of Colorado at Boulder
Finalist, Student Paper Competition 11^{th} AIAA/ISSMO Conference
University Fellowship, Aerospace Engineering, University of Colorado at Boulder
Gus Mesmer Academic Achievement Award, Mechanical Engineering, Washington University in St. Louis
Dual Degree Outstanding Senior Award, Mechanical Engineering, Washington University in St. Louis
Razek Prize for Outstanding Junior in ME, Mechanical Engineering, Washington University in St. Louis
First place, Freshmen Design Competition, Mechanical Engineering, Washington University in St. Louis
Tuition Scholarship to Washington University, Dual Degree Program, Samford University
First place, NI-week Educational Competition (2001), National Instruments

<u>Honorary Societies:</u>
Tau Beta Pi (National Engineering Honorary)
Pi Tau Sigma (Mechanical Engineering Honorary)
Phi Kappa Phi (Arts and Science Honorary)
Pi Mu Epsilon (Mathematics Honorary)

PROFESSIONAL SERVICE ACTIVITIES (RECENT)

Co-Leader of Engineering Fact Finding Trip, Orph. Emmanuel, Honduras, Sept. 2015
Faculty Forum President, Union University 2014/2015
Faculty Forum Vice President, Union University 2013/2014
Advisory Board Member, Project Lead the Way Northside High-School, 2013-2015
Faculty Forum Secretary, Union University 2011/2012/2013
Co-Leader of Humanitarian Engineering Trip to North Africa Spring 2011/2012
Reviewer (Applied Mathematical Modelling, Computer Methods in Applied Mechanics and Engineering, Computers and Mathematics with Applications, Mathematics & Computers in Simulation, Mathematical Methods in the Applied Sciences, Structural and Multidisciplinary Optimization, Journal of Computational Physics, Journal of Spacecraft and Rockets, ICMMES Conference Proceedings (2009), ASEE Conference Proceedings (2012, 2013, 2016))
Committee Member, Athletics Committee, Union University (Academic Year 2015/2016)
Committee Member, Institute for International and Intercultural Studies Committee, Union University (Academic Year 2011/2012 & 2013/2014)
Committee Member, +/- Grading Committee (2012), Union University, Jackson TN
Discipline Specific Honors Advisor, Union University, Jackson TN
Undergraduate Research Advisor, Union University, Jackson TN
PhD student Committees, University of Colorado at Boulder

PROFESSIONAL DEVELOPMENT (RECENT)

Fields Institute Moment Methods Workshop October 2014

ASEE Virtual Community of Practice

Thermodynamics Spring/Fall 2013

ASEE Congress June 2013

2013 ASEE Congress in Atlanta, Georgia

Collegium II Fall 2012/Spring 2013

Union University Faculty Development Program (Faith & Learning)

Team-Based Learning March 2012

2012 Conference/Workshop in St. Petersburg, FL

ASEE Congress June 2011

2011 ASEE Congress in Vancouver, Canada

Sustainable Assessment Processes Feb. 2011

1-day ABET workshop in Dallas, TX

Union University Dialogue Groups

Creating Significant Learning Experiences (Fall 2010), Generation iY (Spring 2011), Jesus Christ and the Life of the Mind (Fall 2011)

Creating Significant Learning Experiences

Faculty development workshop lead by Dee Fink November 2010

Effective College Teaching Workshop for Engineering February 2009

Two-day effective College Teaching Workshop given by Drs. Richard Felder and Rebecca Brent at the University of Colorado at Boulder.