Musings of a Meandering Mathematician

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Outline

• The Big Picture
  – What can I do with a math/physics degree?

• Academia/Research Centers/National Labs:
  – My experiences and reflections

• If more education is what you desire…
  – How can I best prepare for graduate school?
  – Tips and advice: courtesy of hindsight
The Big Picture

- What can I do with a math/physics degree? *Anything!*
  - Industrial research and development
    - Energy, transportation, telecommunication, defense...
  - Finance
    - Wall Street, hedge funds, investment banking, quant...
  - Software development and IT
  - High-school teaching
    - College and university teaching
    - Government and academic research
      - National laboratories and universities
    - Even politics!
  - Graduate degree required
Why Math?

• Inherent honesty
  – Objective: no “schools of thought”
  – Security in consistency

• Inherent beauty
  – Inter-connectedness

• Universal language of science and nature
  “The laws of nature are but the mathematical thoughts of God.”
  – Euclid

• Finally:
  “Physics is becoming too difficult for the physicists.”
  – David Hilbert
My Meandering Path

BS, Math & CS  
Liberty University

PhD, Applied Math  
Florida State University

Postdoc,  
Dept. of Physics  
Northern Illinois University

Postdoc,  
Dept. of Astronomy  
University of Florida

Scientist, CASA  
Jefferson Lab

?
Undergraduate Preparations at Liberty

• Set from the start: always knew that I’d be a scientist
• For me, math came alive when used to solve a physical problem
• Most interesting physical problems that can be solved with pen & paper were already solved: *computers to the rescue!*
• Computer training:
  – Mathematical software: Mathematica, Maple, Matlab...
  – Programming: C, Fortran
  – Numerical analysis
• Honor’s project on *neural networks*:
  – *Taught a computer to play a game*
    2 players taking turns, 15 coins, each player must take 1-3 coins, taker of the last coin loses
    *Computer won!*
Chaos in Grad School at Florida State

- **Chaos:** *Exponential sensitivity to initial conditions*
- Discovered by Poincaré in 1880s, but came to life after the advent of computers
  - Edward Lorenz and weather prediction “Butterfly effect”
- Chaos is an *intrinsic* property of all nonlinear systems:
  - Weather prediction
  - Population dynamics
  - Celestial mechanics: solar system, stellar orbits
- **Common misconception:** chaotic = random. **No!** chaotic ≠ random
  *Chaos limits our ability to quantitatively predict the future after a point* (weather few days, planets few million years...)
Chaos in Grad School at Florida State

• My PhD thesis investigated manifestations of chaos in galactic dynamics:
  – *Elliptical galaxies* have dense centers and often supermassive central black holes, which induce chaos in stellar orbits
  – This limits the shapes of elliptical galaxies (Explains why very flat ellipticals have never been observed)

• Theoretical connection between chaos in a conservative physical system and Riemannian geometry
  – Geodesics in Riemannian manifold + metric *are equivalent to* orbits in a Hamiltonian system
  – Established analogies between fields to enable *cross-fertilization*
More Chaos & Black Holes at UF as a Postdoc

• More chaos theory: quantifying chaos in low-dimensional systems using statistical and differential-geometric approach

• I continued studying the role of chaos in galaxies:  
  – Chaotic motion leads to rapid settling of early stages of galaxies toward equilibrium (chaos as a conduit for “violent relaxation”)
  – How chaotic motion caused by the central black hole binary acts as a “galactic blender” and vacates the galaxy center

• Developed a new family of models for:  
  (dwarf & giant) elliptical galaxies, DM halos, central bulges in spirals...
  – Flexed math muscles in creatively inverting Abel integral (projected ↔ deprojected quantities)
Postdoc at Northern Illinois: A Career Change

• **Sobering realization:**
  – Theoretical astrophysics is underfunded \(\rightarrow\) job prospects bleak
  – Mathematics education made me flexible by providing me with a useful set of skills:
    
    *Use them elsewhere, make it a career! Math is math!*

• Accepted an offer to switch to accelerator physics at NIU rather than continue in theoretical astrophysics
  – My postdoc mentor was also a “recovering astrophysicist”
  – I relegated astrophysics to a hobby

• **No regrets**
  – Accelerator physics is as dynamic and versatile field, every bit as much in need of mathematical prowess as astrophysics
Postdoc at Northern Illinois: Wavelets

- **Wavelets**: orthogonal basis of functions $\varphi^k(x) = 2^{k/2} \varphi(2^k x - i)$

  
  
  ![Wavelet Functions](image)

  
  
  Compact support: finite non-zero domain

  Hierarchy of frequencies: $2^{k/2}$

  Fast Wavelet Transform available

- **Why wavelets?**
  - Simultaneous localization in frequencies and space
  - Good correlation with various signal types (irregular): *data compression*
    
    *FBI fingerprint file is compressed in using wavelets*
  
  
  - Preserves hierarchy of scales
  
  
  - Wavelet space is advantageous for solving some PDEs (preconditioner)
  
  
  - **Wavelet denoising**: removal of numerical noise by coefficient thresholding
Postdoc at Northern Illinois: Wavelets

Illustrative example of wavelet denoising: Monte-Carlo realization
Analytic distribution sampled by N point particles, deposited on the 256x256 grid
Signal-to-Noise Ratio (SNR): quality of representation (SNR ~ N^{1/2})

**ANALYTICAL**

![Analytical wavelet denoising example](image)
Illustrative example of wavelet denoising: Monte-Carlo realization Analytic distribution sampled by $N$ point particles, deposited on the 256x256 grid Signal-to-Noise Ratio ($SNR$): quality of representation ($SNR \sim N^{\frac{1}{2}}$)
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Denoising by wavelet thresholding: if $|c_{ij}| < T$, then $c_{ij}=0$
More physics out of the simulation:
  Increase SNR by $A$, equivalent to representation with $A^2$ particles
Compression: Distribution compactly stored in wavelet space (79/65536 coeffs)
Postdoc at Northern Illinois: Wavelets

• Developed a code for N-body simulations of charged particle beams in accelerators based on wavelet methodology
  – Nifty mathematical “trick” led to substantial improvements
  – Opened an avenue for further use of wavelets in accelerators
  – Established a “theme” for many of my future projects

• Mentored a Master’ degree student to an award-winning thesis based on wavelets and their use in solving elliptical PDEs

• Made a transition into accelerator physics

• All the while, kept the astrophysics as a “hobby”:
  – Mentored students in astrophysical projects
  – Taught a graduate class in astrophysics and cosmology
**Scientist at Jefferson Lab**

- **The night is darkest before the dawn**
  
  Before Jefferson Lab offered me a permanent position, I was:
  
  – Unemployed (“soft money” turned into mush!)
  
  – Mailing out hundreds of job applications to no avail
    (Bad job climate: many faculty searches were cancelled)
  
  – Interviewing for a quant jobs
    (My inside voice screaming “What are you doing?! You’re a scientist!!”)

- **The dawn is brilliant!**
  
  – Virginia is a nice change from Illinois!
  
  – Permanent position – finally can grow roots!
  
  – Work is very interesting:
    
    • Plenty of problems for *math muscle flexing*
    
    • On-site supercomputer (CPUs and GPUs)
    
    • Brilliant group of scientist in my group and at JLab in general
Jefferson Lab: The Big Picture

- Jefferson Lab’s next big project: electron-ion collider
  - Particles are collided at high energy to study their constituents
- We are developing a design to compete with Brookhaven NL
- On the order of a billion $ project!
- Part of the design:
  - Numerical simulations of collisions at IP
  - Executed in parallel on JLab’s supercomputer
Jefferson Lab: Evolutionary Algorithm

- Motion of particles in the ring: oscillatory around design orbit in both x- and y-directions
- In a collider, frequencies (tunes) of each beam should be kept away from resonances (they destroy the beam)
- Problem:
  Find an optimal working point (tunes for each beam) with minimal number of function evaluations (expensive!)
- Problem-solving tool: Evolutionary algorithm
  - Optimizes a non-linear function using natural selection/recombination
  - Independent variables: 4 tunes (2 for each beam)
  - Objective function: collider’s luminosity
Collider Optimization With Evolutionary Algorithm

- Resonances occur when $m_x v_x + m_y v_y = n$
  $m_x$, $m_y$, $m_s$ and $n$ are integers
- Green lines: difference resonances (stable)
- Black lines: sum resonances (unstable)
- Restrict search to a group of small regions along diagonal devoid of black resonance lines
- Found an excellent working point near half-integer resonance
  e-beam: $v_x = 0.53$, $v_y = 0.548456$
  p-beam: $v_x = 0.501184$, $v_y = 0.526639$
- Luminosity about 33% above design value in only ~300 simulations
- Main point: have a reliable and streamlined way to find optimal working point
If Academia Is Your Choice...

• Continuing education is always a good choice, because *graduate degrees give you more options*
  – For instance: college teaching, research, quantitative analyst

• During slow economic times, continuing education is even a wiser choice, because you can *wait out the market*

• Having established that academia is your choice, how do you put yourself in a position to succeed?

• Prepare
  – Before you start graduate school
  – Applying to graduate school
  – While in graduate school
  – After you get your degree
Prepare: Before Graduate School

• Major evaluation criteria for admittance to graduate school:
  – Grades
    • High GPA is a must
    • Strong & diverse curriculum
      Computer programming proficiency for applied math/physics grads
  – GRE: required standardized entrance exam
    • General: analytic, verbal & quantitative
    • Sometime specialized subject test is required as well
  – Activities
    • Internships, undergraduate research, summer schools...
  – Recommendation letters
    • Professors’ words carry weight
Prepare: Applying to Graduate School

- **Tiered approach**
  Pick at least 3 tiers of schools to which to apply
  - **Tier 1:** Top schools – Why not? Dreaming is free!
  - **Tier 2:** Near-the-top schools – Decent chance, but no sure thing!
  - **Tier 3:** Good schools – Excellent chance, not a bad option

- **Get all the paperwork in order and on time**
  - Admission committee does not like to hunt around for your stuff
  - You want to make it easy for them to like you
  - The shape of your application is the direct reflection of you

- **Familiarize yourself with professors and their research**
  - However, you don’t have to have all the answers at the start
Prepare: While in Graduate School

• **Commit**
  – *Don’t look back:* second-guessing degrades your resolve
  – *Minimize distractions:* rally family support; no side jobs
  – *Go full-time:* part-time *may* be possible for MS, never for PhD
    • *Tuition and assistantship are paid for by the school through teaching and research assistantships (TA/RA)*

• **Explore**
  – Shop around for an interesting MS/PhD project
  – Approach professors and ask them about their research
  – Ask older graduate students

• **Pick your advisor wisely**
  – Your success and happiness will directly depend on your advisor
  – Before you sign up, look at your advisor’s track record
Prepare: After You Get Your Degree

• Graduate degree = more options

• What now?
  – Research career: postdoc, publications, professorship
  – Teaching: teaching professorship
  – Make money: Wall Street, quantitative analyst...

• By the end of your studies, things will be clearer
  – You will develop ideas about the future
  – Your graduate experience will shape your life and show the path forward
Virginia is Not Only For Lovers...

• ...it’s for scholars too – there are fine graduate schools nearby:
  – University of Virginia, College of William and Mary, Hampton University, University of Richmond, Old Dominion University...

• Strengthened by their proximity to JLab and NASA Langley
  – Focus on nuclear physics, accelerator science & material science

• My group, Center for Advanced Studies of Accelerators (CASA) teamed up with ODU to create Center for Accelerator Science [http://www.jlab.org/accelerator-center.html](http://www.jlab.org/accelerator-center.html)

• Also at Jefferson Lab:
  – Internships: [http://www.jlab.org/div_dept/admin/HR/jobline/student.html](http://www.jlab.org/div_dept/admin/HR/jobline/student.html)

• All the info you need is online, so look around!
Summary

• Getting a degree in math/physics is empowering!
  – Analytical and problem-solving skills will always be in demand
  – Opportunities are nearly endless
  – Graduate education opens even more opportunities

• My personal path:
  – What drew me to academia and math
  – Math education afforded me flexibility to meander through different fields of physics

• If grad school is what you want – benefit from my hindsight
  – Tips and thoughts on how to give yourself a best chance to succeed
  – Take charge – Be a tailor of your own destiny!