Advancing Reactors with Advanced Solvers and Innovative Programs

Prof. Rachel Slaybaugh
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EPRI
Palo Alto, CA

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What if?

We could have a world

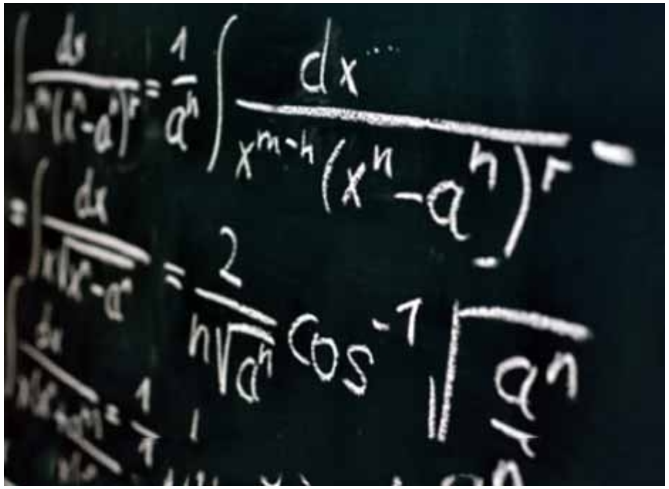
- Free from air pollution?
- Free from energy poverty?

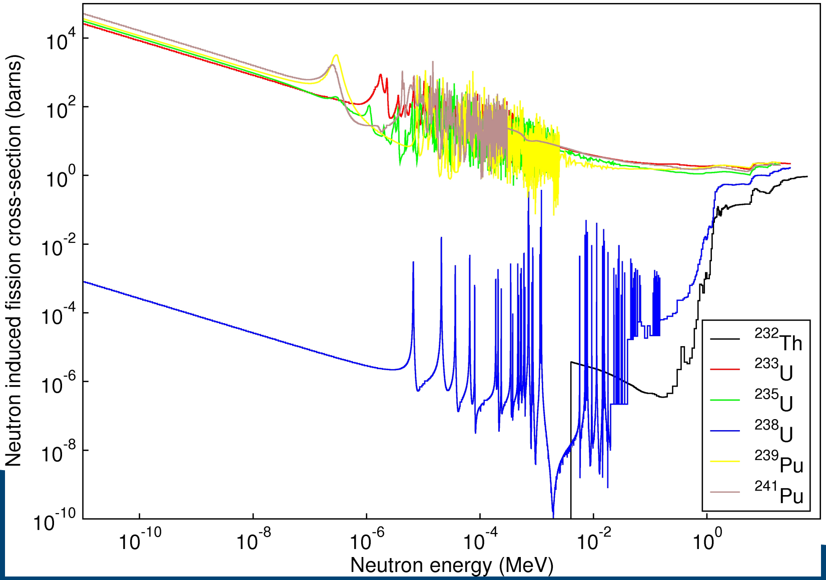
What if the U.S. could lead the way in developing and deploying advanced energy technologies to make that happen?

My Contribution: Numerical Methods

To facilitate nuclear innovation, we need *predictive simulation*

- I build tools (translate applied math into code) used to design and analyze nuclear systems
- I focus on high performance computing
- and inform algorithm development with physics of problems of interest





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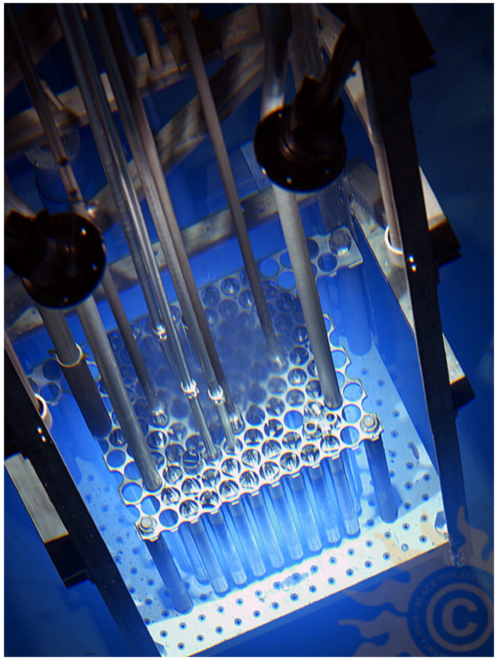
Outline

- Background
  - What exactly are you solving? Why is it hard? What is the current state?
- New hybrid method algorithms
  - Space and energy self-shielding
  - Anisotropies in angular flux
- Beyond Computation
  - What else do we need?
  - How might we get there?



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Finding All of the Neutrons

$$[\hat{\Omega} \cdot \nabla + \Sigma(\vec{r}, E)]\psi(\vec{r}, \hat{\Omega}, E) =$$
$$\int dE' \int d\hat{\Omega}' \, \Sigma_s(\vec{r}, E' \rightarrow E, \hat{\Omega}' \cdot \hat{\Omega})\psi(\vec{r}, \hat{\Omega}', E')$$
$$+ \frac{\chi(E)}{k} \int dE' \, \nu\Sigma_f(\vec{r}, E') \int d\hat{\Omega}' \, \psi(\vec{r}, \hat{\Omega}', E')$$

- $\psi(\vec{r}, \widehat{\Omega}, E)$: eigenvector; angular neutron flux (n / cm^2–steradian)
- *k:* dominant eigenvalue; governs steady–state system behavior
- $\Sigma(\vec{r}, E)$: probability of neutrons interacting with a material (cm^{-1})

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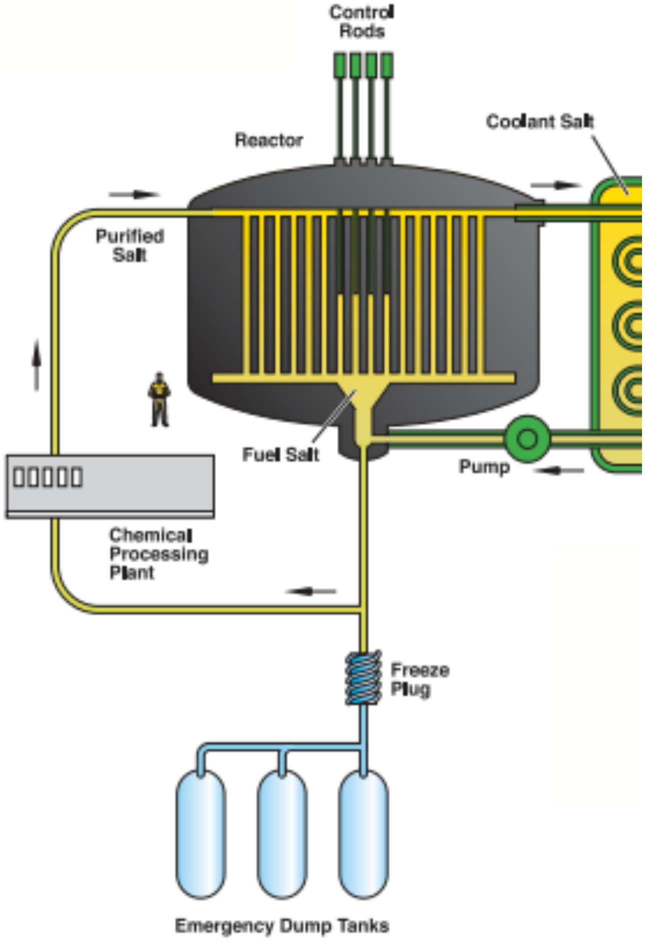
Accurately is Hard

- 6-D phase space: location (3-D), direction (2-D), energy (1-D)
- Can be geometrically large and/or physically complex and/or coupled to other physics
- The physics data is *Complicated*
- Strategies: Deterministic, Monte Carlo, Hybrid



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What is the Current State?

- Existing tools can predict what we already know, but not necessarily new things (e.g. advanced reactors)
  - We need increased accuracy, resolution, and confidence in our solutions
- Some calculations are still hard to do
  - We need strategies for specific physics
- Some calculations still take a very long time
  - We need to continue focusing on speedup

Improved algorithms can help

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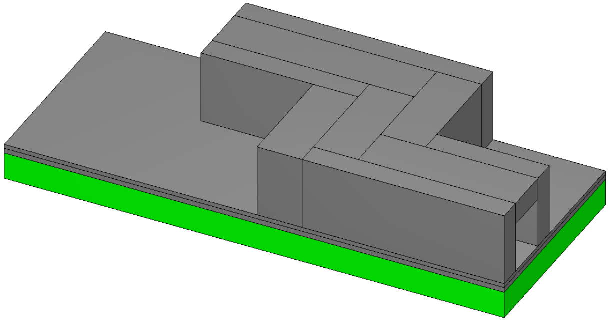
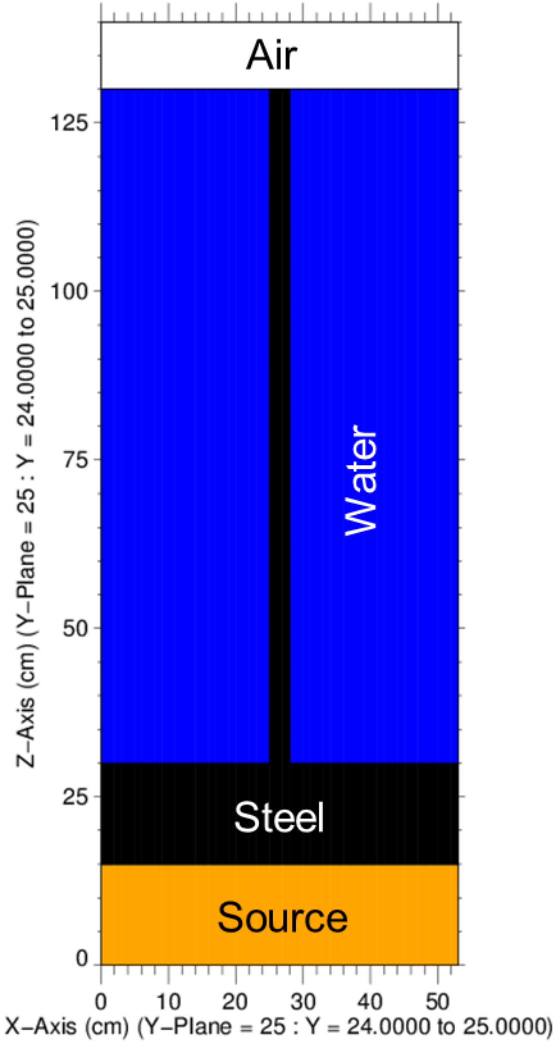
Specific Challenges



- Space and energy self-shielding

- Strong directional dependence



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Quick Brief: Hybrid Methods

- Monte Carlo: highly accurate, can be slow
  - Physics expressed continuously; solution has statistical error
- Deterministic methods: usually fast, can be inaccurate
  - Discretize phase space; solution equally valid everywhere
- Hybrid methods use deterministic solutions to create variance reduction parameters for MC
  - Particles are assigned weights that map to impact
  - Set how to update weights
  - Set how to bias the source

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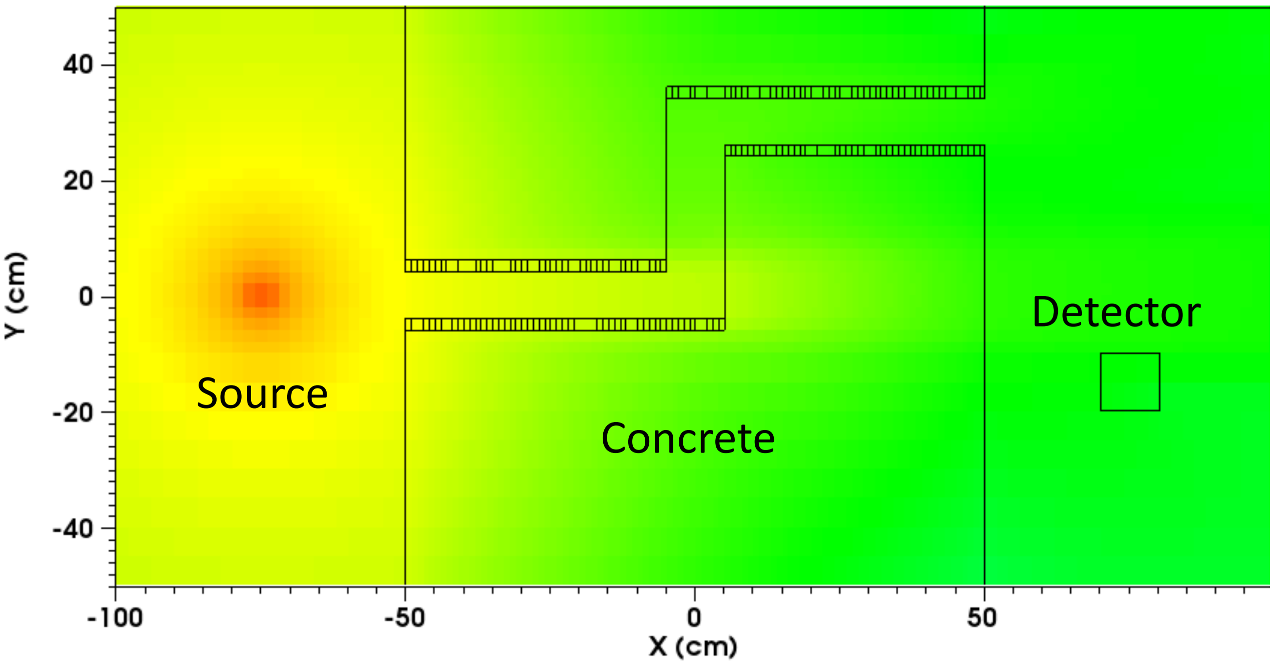
Start with Importance

- Many hybrid methods use the adjoint: the importance of a source particle to the solution



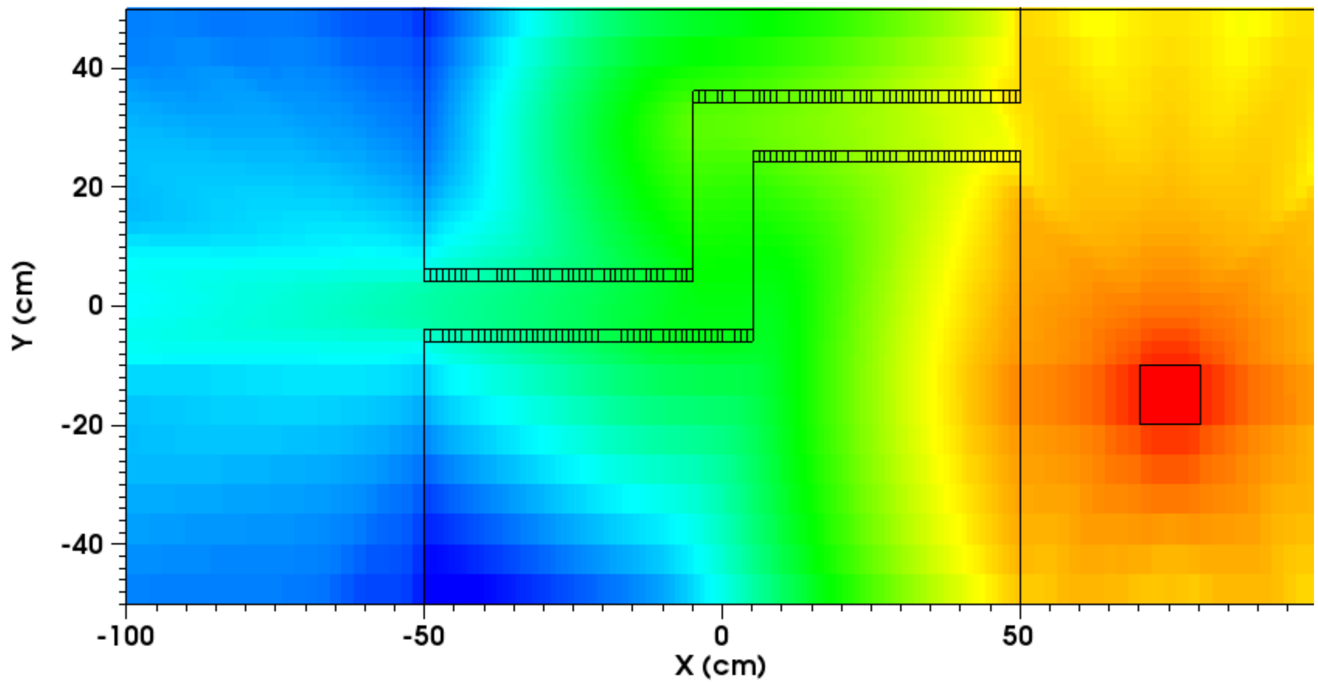
Neutrons in the forward problem will flow from the source to the detector

Start with Importance

- Many hybrid methods use the adjoint: the importance of a source particle to the solution

Adjoint measures how each part of phase space contributes to the solution:

importance map



And a Good Method

- The state of the art in current space-energy methods is called FW/CADIS
- It uses importance information that is only a function of space and energy

$$\phi^{+}(\vec{r},E) = \int \psi^{+}\left(\vec{r},E,\widehat{\Omega}\right) d\widehat{\Omega}$$

to set Variance Reduction parameters

- It has been successful in many problems
- But doesn't do well with space and energy self-shielding

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Update to Capture More Information

- We've modified FW/CADIS to include more physics information without changing the method's end use
- Background cross section, σ_0, captures the effect of cross sections of other materials
- Augment source to include impact

$$q^{+}(\vec{r},E) = \left(\frac{\phi_{res(\sigma_0)}(\vec{r},E)}{\phi_{dilute\,(\sigma_0)}(\vec{r},E)}\right)^{M} q^{+}{}_{FWC}(\vec{r},E)$$

M is a problem-dependent constant

$\phi_{res(\sigma_0)}(\vec{r},E)$ is forward flux with impact of resonances

$\phi_{dilute\,(\sigma_0)}(\vec{r},E)$ is forward flux without resonance impact

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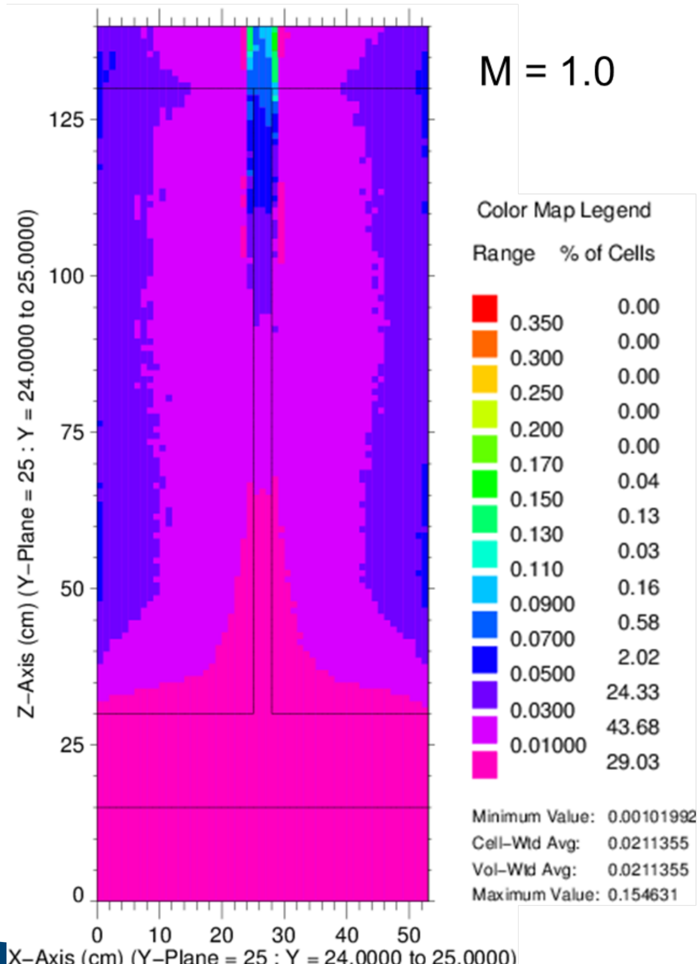
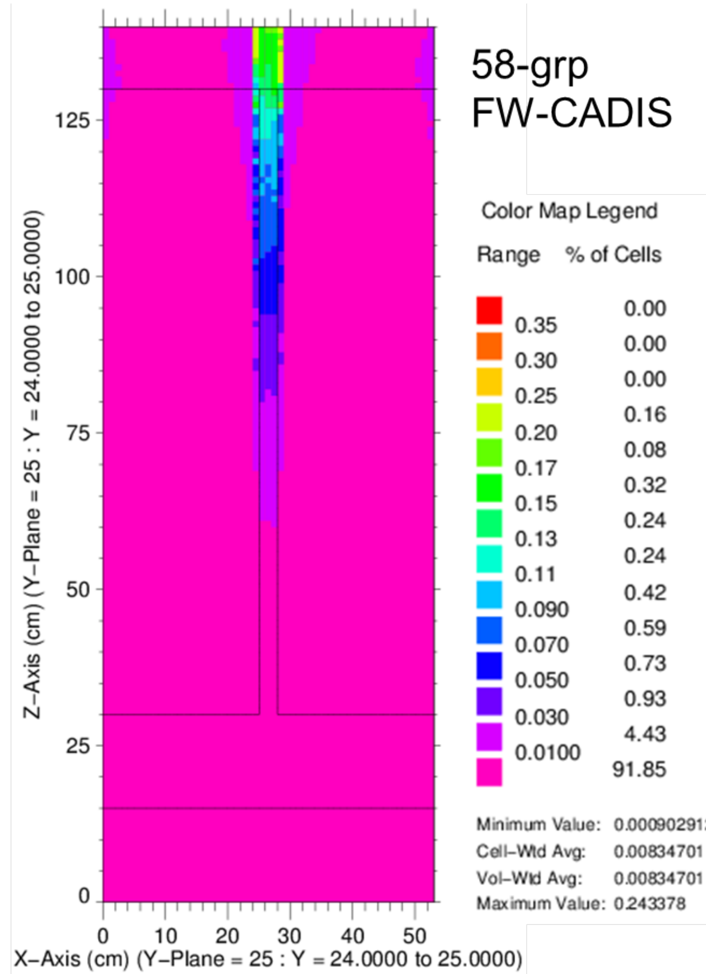
Much Better Results





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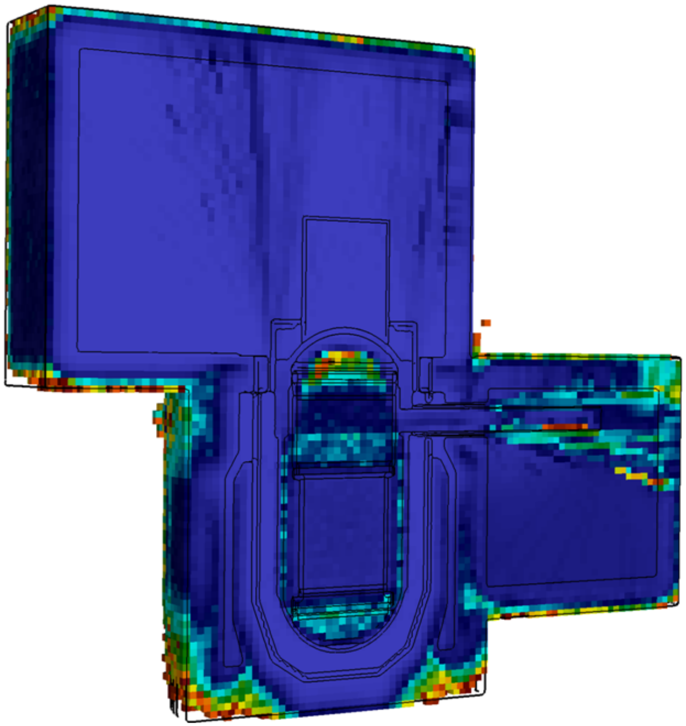
S.C. Wilson and R.N. Slaybaugh. *Improved Monte Carlo Variance Reduction for Space and Energy Self-Shielding*. Nuclear Science and Engineering, **179** 1-20 (2015).

Angle-Informed Methods

- Radiation shielding is a tough problem, especially when there are strong angular anisotropies
- Hybrid methods currently only include space and energy information
- Including angle explicitly is too costly
- Other attempts haven't worked well
- But we are having trouble…



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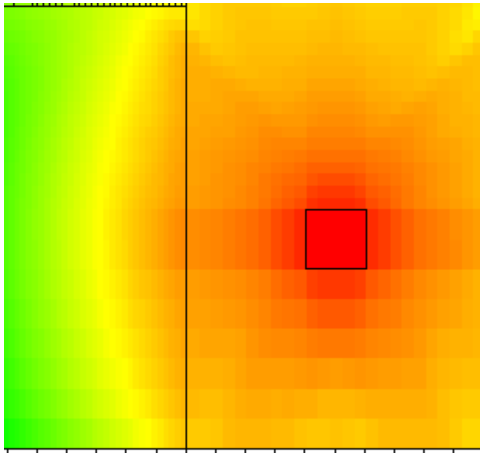
Update to Capture More Information

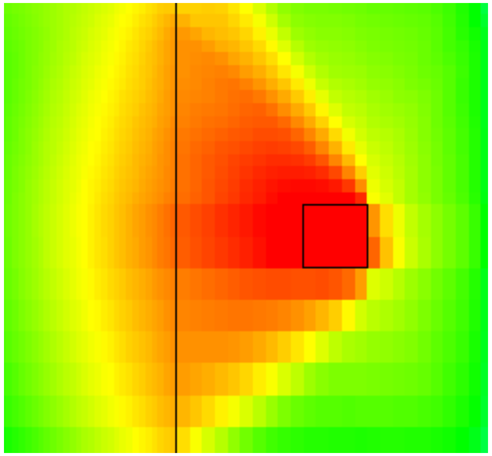
- Include anisotropy explicitly to get the impact of angular behavior

$$\phi^{+}(\vec{r},E)=\frac{\int \psi^{+}(\vec{r},E,\widehat{\Omega})\psi(\vec{r},E,\widehat{\Omega})d\widehat{\Omega}}{\int \psi(\vec{r},E,\widehat{\Omega})d\widehat{\Omega}}$$

- Enabled by ability to write and store $\psi^{+}(\vec{r},E,\widehat{\Omega})$



Original Method



Our Method

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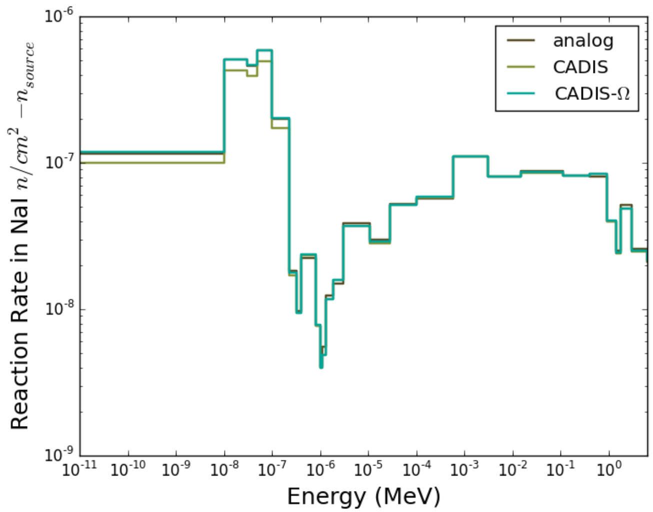
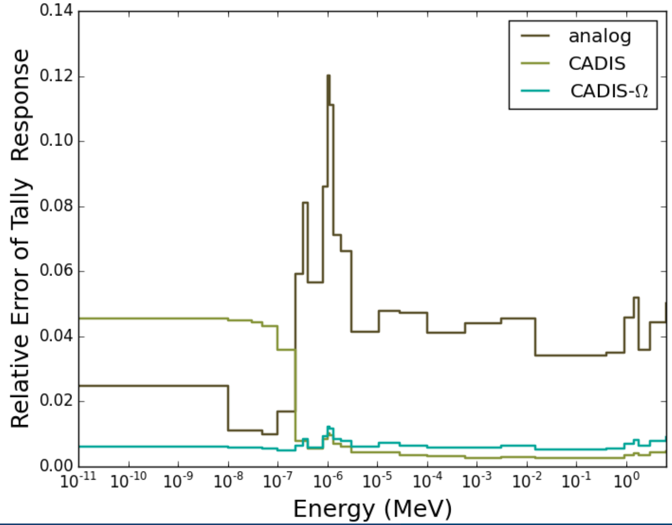
Good Initial Results





	T (min)	FOM
CADIS	524.9	5.1
CADIS-Ω	491.9	145.0

Adjusted CADIS has:

- A relatively uniform uncertainty distribution
- Much better FOM

$$\text{FOM}= \frac{\text{Time}}{\text{Rel Err}^2}$$

M. Munk, et al., “An Angle-Informed Hybrid Method for CADIS and FW-CADIS.” Proceedings of the PHYSOR 2016 Meeting in Sun Valley, ID, May 2016.

Part 1 Summary

- We need nuclear innovation to help solve some of the world's biggest challenges
- Predictive simulation is required, but how do we get there?
- Develop algorithms that take advantage of more or a problem's physics
- We can improve computational ability for many tough problems… However,

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Computation Isn’t Enough

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Barrier Roundup

Physical Environment

- High radiation
- High temperatures
- Corrosive (often)
- Pressure (often)

Cost

- Construction
- O&M
- Implementing changes

Licensing

- Things need to last decades
- Get new ideas approved
- Build anything
- Uncertainty

Lack of Policy Direction

Conventional Wisdom

What Do We Need To Achieve?

1. Cost-competitive with natural gas
   = 50% capital cost reduction
   = 50% reduction in O&M cost

2. New ideas can be implemented and deployed in a reasonable fashion

3. Setup for mass adoption of resilient, clean energy systems

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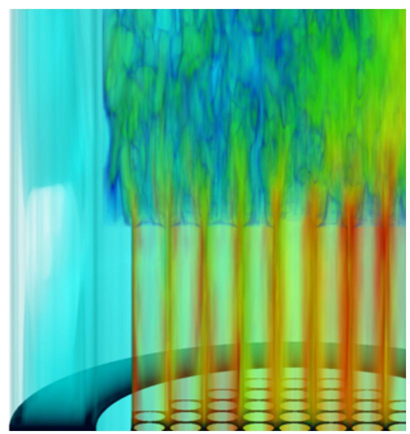
How Do We Achieve It?



Idea: Replaceable Components

Design systems to be entirely replaceable

- "Vessel, turbine, major valves, anything that requires major welding"
- "A replaceable core (from a materials degradation perspective)"
- "Any type of turbomachinery, pump, or valve; things that wear out easily due to cyclic fatigue issues"
- "The entire reactor vessel and internals"

Why Replaceable Components?

- Don’t need 40/60/80 year lifetime components
- Can incorporate new ideas more quickly
- Configuring Management framework consistent with industry push:
  - “The IAEA Incident Reporting System (IRS) shows that on average 25% of recorded events could be caused by configuration errors or deficiencies.”
- Like-in-kind issues become easy
- Easier to address issues that arise

Benefit of Replaceable Components

Savings

- Shorten licensing time; lower cost up front
- Allow for less expensive materials
- NRC makes larger number of small decisions
- Reduce supply chain issues

"This would dramatically reduce costs and enable nuclear plants to operate indefinitely."

What's Needed?

Advanced Robotics

- Robots that can execute component replacements and maintenance
- Electronics and Cameras that can withstand radiation, heat, corrosive environments
- Can also help in construction and O&M

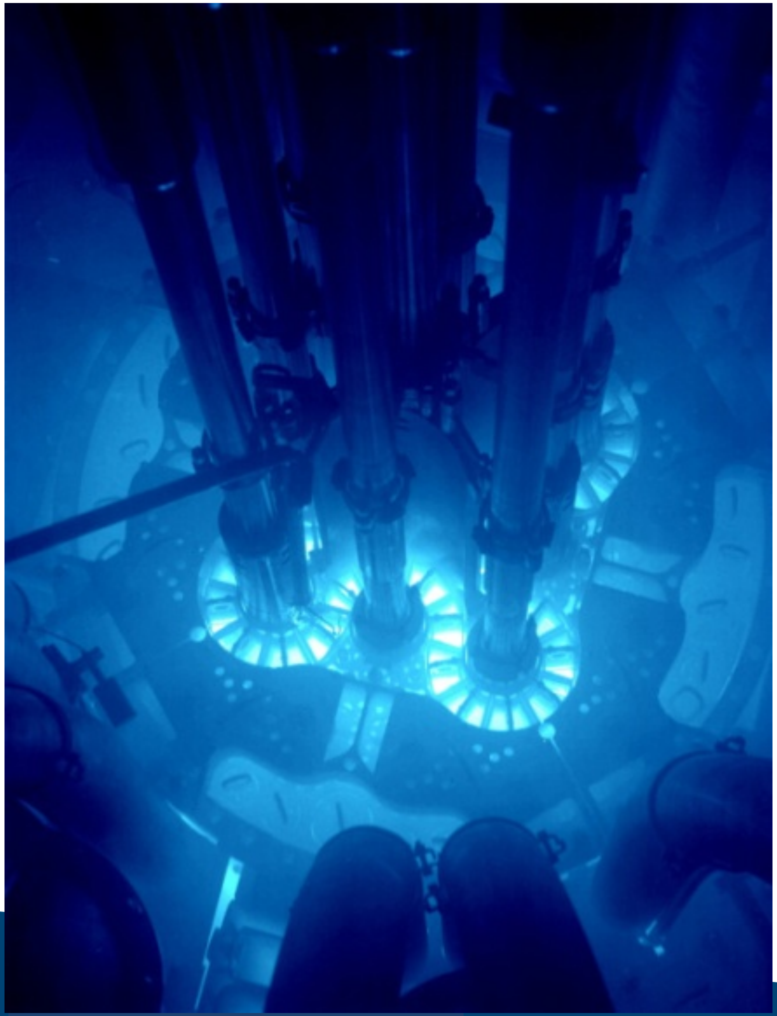
Sensoring and Analytics

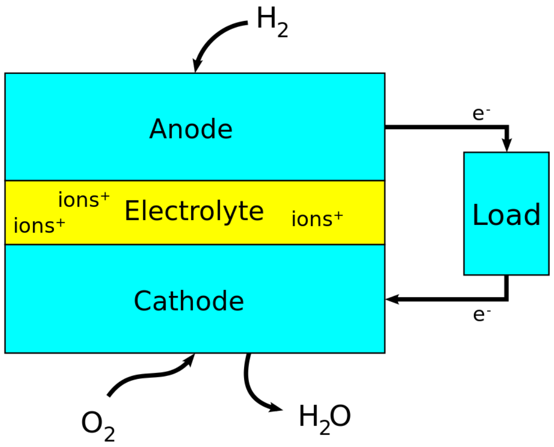
- Better and more sensors to know when to replace components
- Ability to real-time integrate more data streams across systems
- Ability to compare noisy measurements with predictive calculations
- Can also help in construction and O&M

Leveraging Research

- Developments also useful outside of nuclear
- Taps knowledge base outside the nuclear community
- Could help existing nuclear fleet (and existing fleet can serve for testing)

Clean, Affordable Energy





We would accomplish many more things if we did not think of them as impossible.

– Vince Lombardi

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Nuclear Innovation Bootcamp

http://nuclearbootcamp.berkeley.edu/

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[F] @NulcearInnovationBootcamp
[I] @NulcearBootcamp

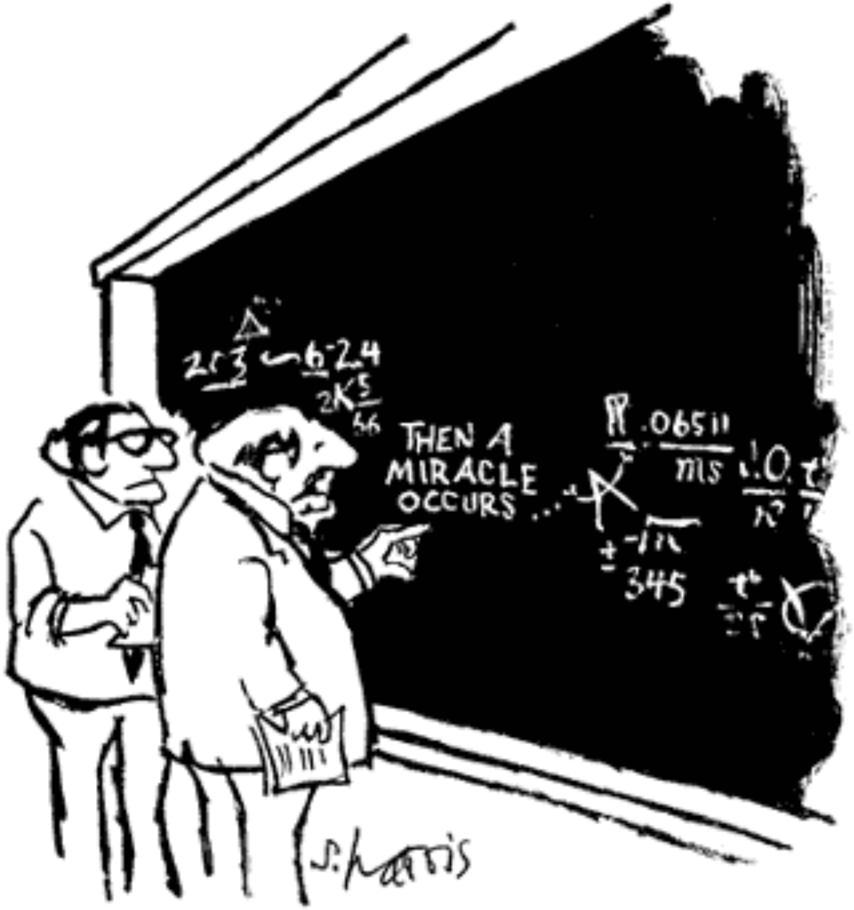
- Pilot program held at UC Berkeley August 1–12, 2016
- Team design projects:
  - Entrepreneurship
  - Nuclear aspects
  - Non-traditional material
- Large company involvement
- Experts teach and mentor
- 2017: *July 16–29, 2017*
- Expanding to include professionals

Abdalla Abou Jaoude • Adam Scheider • Adriana Ureche • Advanced Reactor Concepts, LLC • Advanced Reactor Solutions • Alan Bolind • Alex Cheung • Alex Polonsky • Alphabet Energy • Alyse Scurlock • American Nuclear Society • Andrea Saltos • Andres Alvarez • Andrew Greenop • Andrew Worrall • Andy Klein • April Novak • Argonne National Laboratory • Aries Loumis • Arun Khuttan • August Fern • August Fern Consulting LLC • Bala Ramamurthy • Bart Roe • Behnam Taebi • Ben Reinke • Beth Zotter • Bipartisan Policy Center • Boris Hombourger • Breakthrough Institute • Brenden Heidrich • Brett Rampal • Canadian Nuclear Laboratories • Canon Bryan • Caroline Hughes • Center for Financial Services Innovation • Chris Comfort • Chris Poresky • Christina Castellanos • Cindy Rodriguez • Cyclotron Road • Daine L. Danielson • Dan Yurman • Darby Kimball • Dave Pointer • David Charpie • David Matthews • Delft University • Dennis Hussey • Dishcraft Robotics • Doug Crawford • Dr Atambir RAO • Duke Energy • Ed Blanford • Edward Kee • Ehud Greenspan • Electric Power Research Institute • Elizabeth McAndrew-Benavides • Emily Nichols • Eric Fettner • Exelon • Fran Bolger • Frank Rahn • Gaetan Bonhomme • Garon Morgan • GE Hitachi Nuclear Energy • GE Power & Water • General Fusion • Georgia Institute of Technology • Gigi Wang • Gil Brown • Gilbert Brown • Haas School of Business • Harvard Business School • Ian Hamilton • Idaho National Laboratory • Igor Bolotnov • Ilan Gur • Institute of Nuclear Power Operations • Irfan Ali • Ivan Maldonado • Jacob DeWitte • Jacopo Buongiorno • James Kendrick • James Lim • Jared Friedman • Jeremy Conrad • Jessica Chow • Jessica Lovering • Jing Hu • Joe Lassiter • Joey Kabel • John Jackson • John Kotek • Karl van Bibber • Kathryn Yates • Kathy Shield • Kurion Veolia • Kyle Brumback • Lara Pierpiont • Lars Jorgensen • Lawrence Berkeley National Laboratory • Lemnos Labs • Leslie Dewan • Lightbridge Corporation • Linda Pouliot • Lindsay Dempsey • Linsday Miller • Lin-wen Hu • Lucas Davis • Lydia Sohn • Marissa Zweig • Marius Stan • Mark Mawdsley • Markus Piro • Massachusetts Institute of Technology • Massimiliano Fratoni • Matt Thompson • Matthew A. Hertel • Matthew C. Thompson • Megan Casper • Michael Martin • Michael Trinh • Michael Van Loy • Mike Kurzeja • Mike Laufer • Mike Safyan • Milos Atz • Mintz Levin • Mitch Negus • Modeste Tchakoua • Morgan, Lewis & Bockius LLP • Nathan Gilliland • Nathan Gold • Nick Touran • Nikhil Bharadwaj • Nnaemeka Nnamani • North Carolina State University • Nuclear Economics Consulting Group • Nuclear Energy Consultants, Inc. • Nuclear Energy Institute • Nuclear Innovation Alliance • Nuclear Technology Innovation Laboratory • NuScale Power • Oak Ridge National Laboratory • Oklo • Ondrej Chvala • Oregon State University • Oscar Espinoza • Out Educated • Paul Lorenzini • Pavel Tsvetkov • Per Peterson • Peter Hosemann • Peter Secor • Phil Hildebrandt • Phil Russell • Planet • Positron Dynamics • Rachel Slaybaugh • Raluca Scarlat • Ray Rothrock • RedSeal, Inc. • Richard Pearson • Richard Vasques • Robert J. Budnitz • Robert Petroski • Roe Energy Consulting LLC • Ronald Horn • Ryan Falvey • Sam Brinton • Sama Bilbao y Leon • Samuel Brinton • SAP • Sara Harmon • Sarah Stevenson • SC Moatti • Sebastian Lounis • Senate Energy Committee • Seth Grae • Shane Johnson • Shannon Yee • Shrey Satpathy • Shyam Dwaraknath • Southern Company • Southern Nuclear • Stephen Clement • Stephen R. Booker • Steve Herring • Sutardja Center for Entrepreneurship & Technology • Suzy Baker • TerraPower • Terrestrial Energy • Texas A&M University • The Demo Coach • Third Way • ThorCon • ThreeBridges Ventures • Timothy Crook • Todd Allen • Tom Isaacs • Transatomic • Tri Alpha Energy • U.S. Department of Energy • UC Berkeley College of Engineering • UC Berkeley Department of Nuclear Engineering • University of California, Davis • University of Massachusetts, Lowell • University of New Mexico • University of Tennessee, Knoxville • University of Wisconsin, Madison • Virginia Commonwealth University • Walter Howes • Wendolyn Holland • Whitekoat, Inc. • Whitney Research Services • Will Boyd • Y Combinator • Yishu Qiu

Summary

- We need nuclear innovation to help solve some of the world's biggest challenges
- Better computation, moving towards predictive simulation, is an important component
- We need to truly rethink approaches to make nuclear a "no-brainer" electricity choice
  - Cost reduction
  - Implementation of new ideas
  - Enable mass adoption

Questions?



"I think you should be more explicit here in step two."

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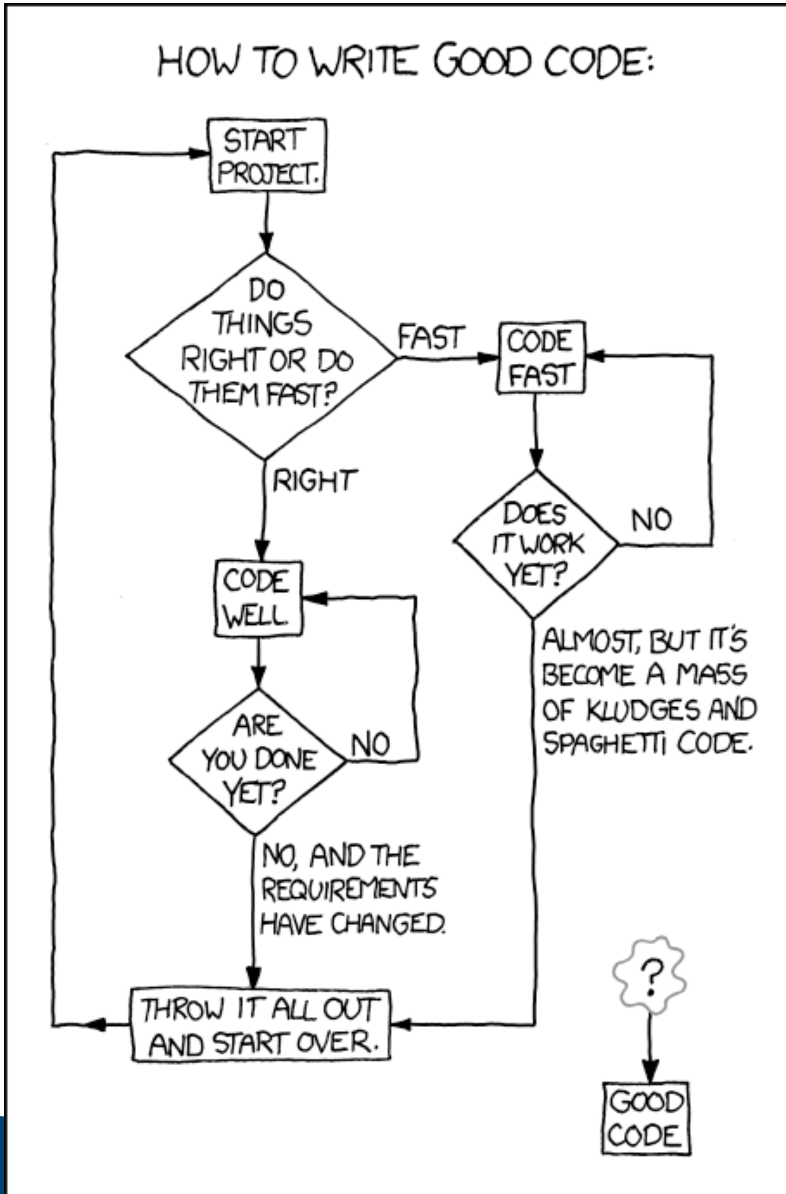

P.S. quality software required

THW

software carpentry

PyNE

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