November 2022

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Director, Nuclear Safety and Regulatory Research Division

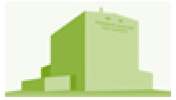
Nuclear Safety and Regulatory Research R&D

Talking Points

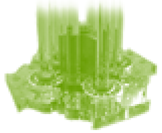
- Current R&D at INL in safety, risk, and reliability
- Technical focus
- Future directions

Current R&D at INL in Safety, Risk, and Reliability

Idaho National Laboratory – The U.S. Leading Nuclear Energy Laboratory


1959, Transient Reactor Test Facility (TREAT)

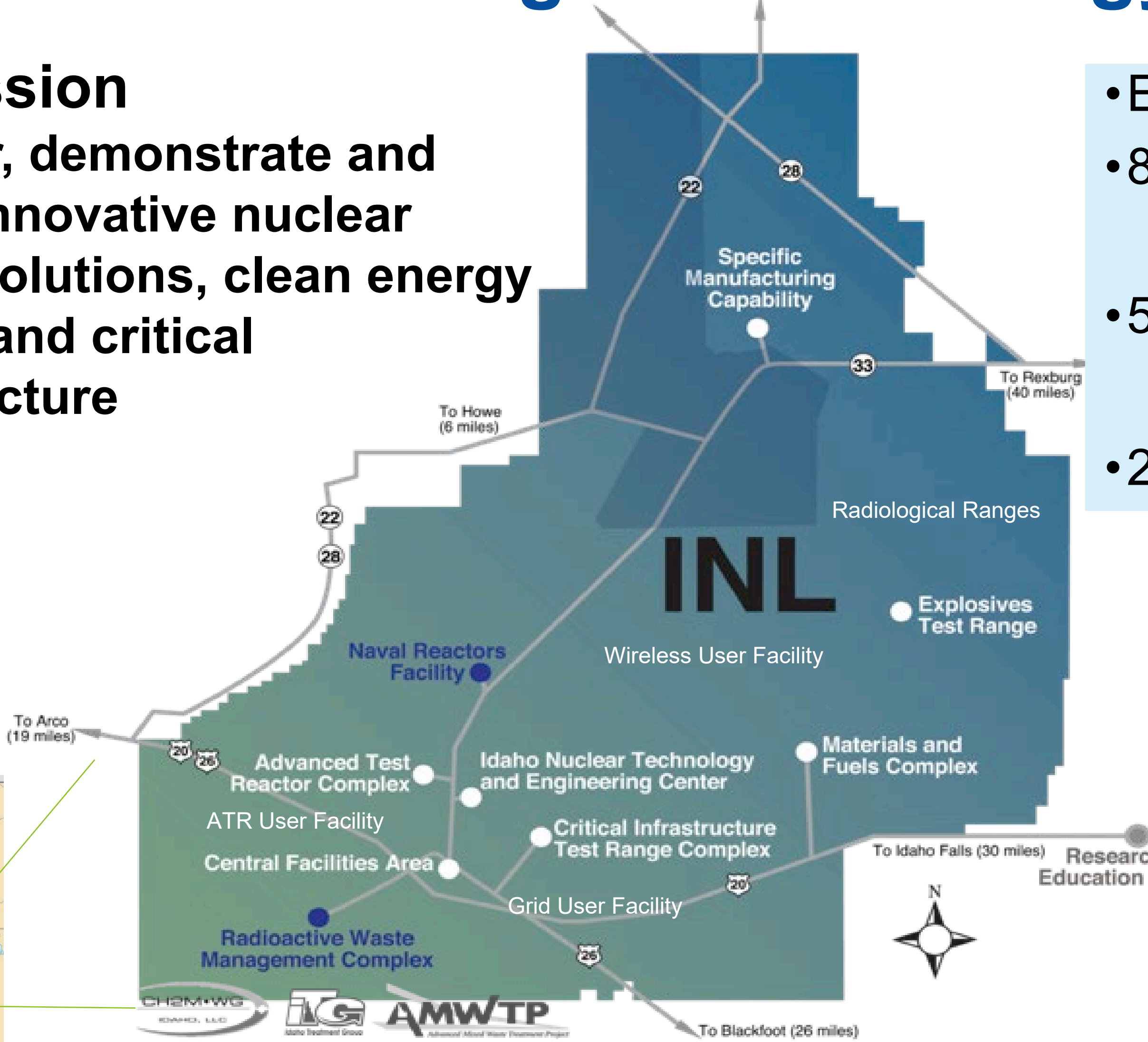

1963, Experimental Breeder Reactor-II (EBR-II) went critical

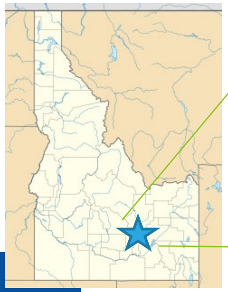

1967, Advanced Test Reactor (ATR) critical

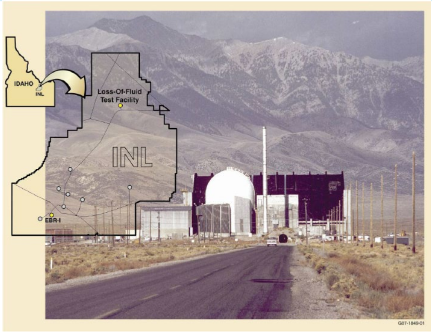
INL Mission

Discover, demonstrate and secure innovative nuclear energy solutions, clean energy options and critical infrastructure

- Established 1949
- 890 square miles (2,310 km^2)
  - 579 buildings
- 52 total reactors
  - 3 operating reactors
- 2 spent fuel pools







- Experimental Breeder Reactor I (EBR-I)

- Loss-of-Fluid Test Reactor (LOFT)

Nuclear R&D Team at INL

1400 staff working to revive, revitalize, and expand nuclear energy, enabled by unique research facilities, infrastructure & capabilities

Materials & Fuels Complex

Experiments and engineering that drive the world's nuclear energy future.

- Transient testing
- Space nuclear power and isotope technologies
- Analytical laboratories
- Fuel Fabrication
- Post-irradiation examination
- Advanced characterization

614 Employees

- 39 Ph.D.
- 65 Master
- 187 Bachelor
- 84 Associates

Nuclear Science & Technology

Change the world's energy future by advancing nuclear energy.

- Nuclear fuels and materials
- Nuclear systems design and analysis
- Fuel cycle science and technology
- Nuclear safety and regulatory research
- Advanced Scientific Computing

398 Employees

- 149 Ph.D.
- 90 Master
- 94 Bachelor
- 4 Associates
- 13 Postdocs

Advanced Test Reactor

Provide unique irradiation capabilities for nuclear technology research and development.

Steady-state neutron irradiation of materials and fuels

- Naval Nuclear Propulsion Program
- Industry
- National laboratories and universities

388 Employees

- 2 Ph.D.
- 36 Master
- 121 Bachelor
- 43 Associates

19-50373

Unique Research Facilities and Infrastructure/Foundational Enablers

Nuclear Safety and Regulatory Research (NSRR) Division

Our goal is to ensure the nation's safe, competitive, and sustainable use of engineered systems

in many domains by applying our capabilities to impactful issues

in risk, reliability, and operational performance

- Five Departments
  - Mike Calley → Regulatory Support
  - Nancy Lybeck → Instrumentation, Controls & Data Science
  - Shawn St. Germain → Reliability, Risk, and Resilience Sciences
  - Ron Boring → Human Factors and Reliability
  - TBD → Risk Phenomena Modeling

- Three Major Programs
  - Light Water Reactor Sustainability
  - Nuclear Energy Enabling Technologies
  - US Nuclear Regulatory Commission Support

Core Capabilities

- Dynamic risk analysis
- Risk assessment software and training
- Probabilistic risk assessment methods (PRA), models and applications
- Reactor licensing regulatory framework
- Operational experience data collection and analysis
- Image processing and pattern recognition
- Advanced wireless sensors and communication techniques
- Control and automation
- Machine learning/artificial intelligence (AI) and visualization/explainable AI
- Digital twins
- Bayesian statistics
- Stochastic modeling
- Uncertainty analysis and error propagation
- Grid resilience research
- Database design and development
- Reliability analysis, human reliability analysis (HRA), and simulation-based reliability tools
- Procedure development
- Human factors design and evaluation
- Human-system interface design and functional prototyping
- Workload evaluation
- Eye-tracking and 3D/ergonomic modeling
- Dynamic operations modeling

C200 Lab Capabilities

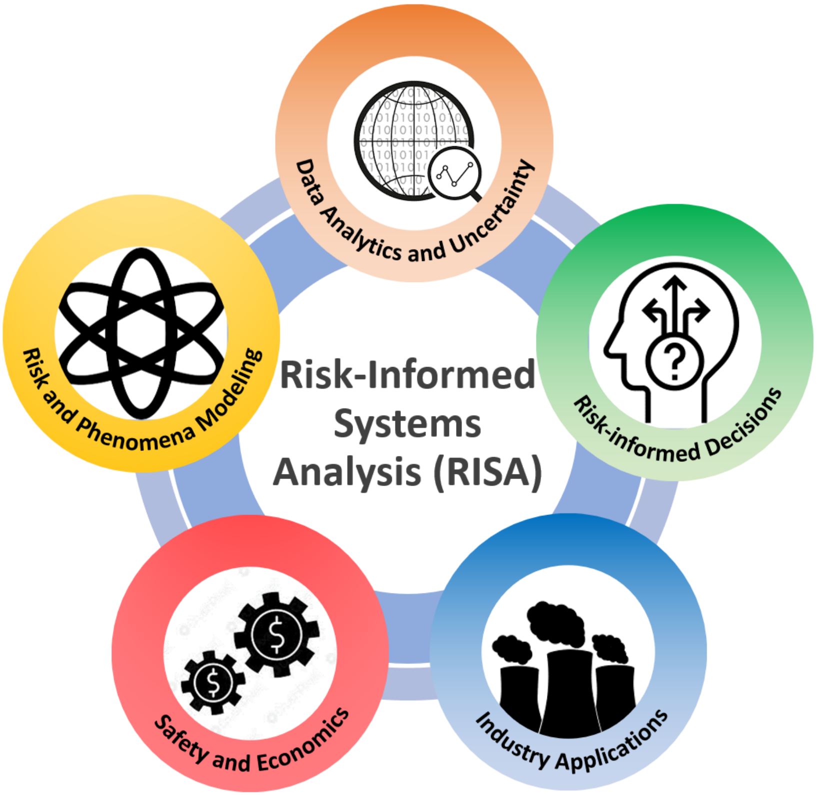
- Human Systems Simulation Laboratory (HSSL)
  - Digital control room simulator
- Monitoring, Diagnostics & Automation Lab (MDAL)
  - Data processing and visualization
  - Automation laboratory for instrumentation and controls testing, troubleshooting and hardware experiments
- Cognitive Modeling Lab
  - A laboratory for running cognition-based experiments

INL and Industry Collaborate to Help Make Nuclear Power Plants Even More Economically Efficient

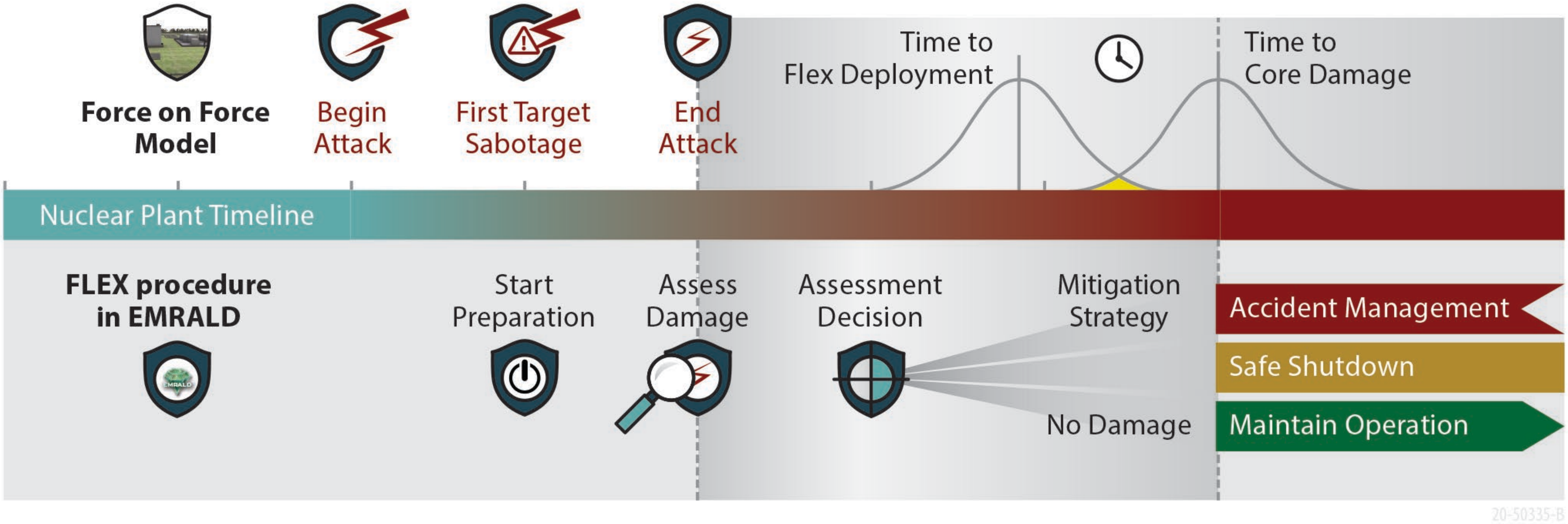
- **Improving the economic performance of nuclear power plants helps ensure continued access to clean energy.**
- **To assist in this effort, INL, Public Service Enterprise Service (PSEG) Nuclear, LLC and PKMJ Technical Services, LLC, developed methods for increased plant efficiency including:**
  - Natural language processing to automatically classify work orders into different categories
  - Machine learning diagnostic model using heterogeneous data
  - Reliability and survivability metrics using unstructured work orders and plant process data to support predictive maintenance
  - An economics model for initial cost-benefit analysis of predictive maintenance strategies.

Current Risk-Informed Systems Analysis (part of LWRS) R&D Activities

- **Enhanced Resilient Plant**
  - Support of accident tolerant fuel deployment by the LWR fleet
  - FLEX and portable equipment implementation at NPPs
  - Multi-criteria benefit evaluation (MCBE) methodology
  - Terry Turbine expanded operating band
- **Cost and Risk Categorization Applications**
  - Risk Informed plant health and asset management
- **Margin Recovery and Operating Cost Reduction**
  - Enhanced Fire PRA modeling (FRI3D, LiDAR)
  - Plant Reload Process Optimization
- **Supporting Projects**
  - Digital I&C Risk Assessment – support of digital instrumentation and controls upgrades at the LWR fleet
  - Dynamic PRA and dynamic HRA (HUNTER)
  - Legacy PRA Tools Enhancement
  - Best Estimate plus Uncertainty (BEPU) Methodology
  - RISA Toolkit V&V



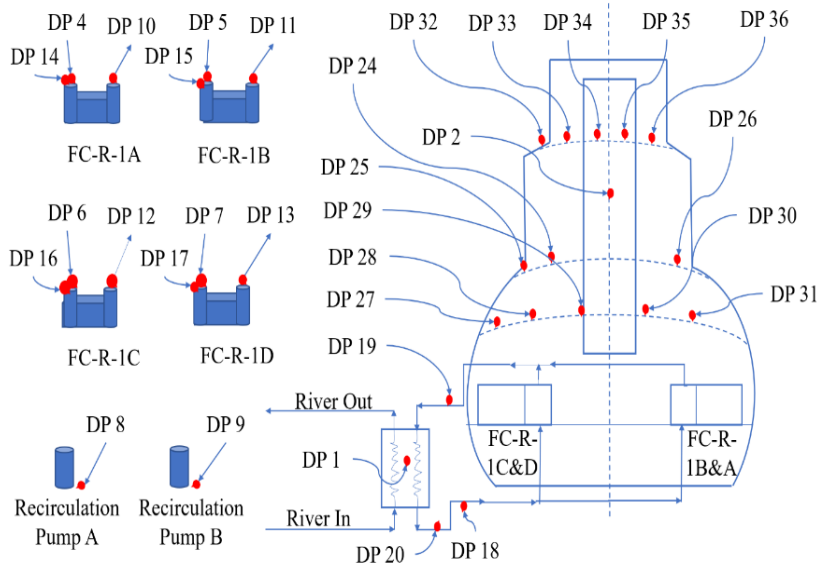
Security Modeling → Timeline Model

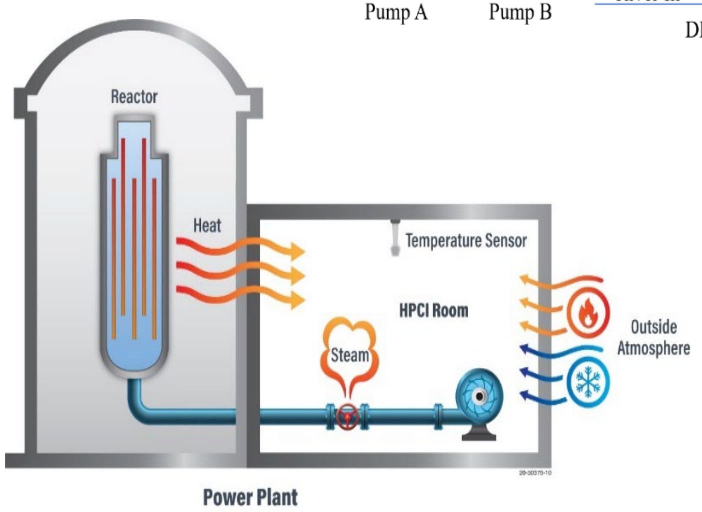


AI/ML Applications in Condition Monitoring

- **Unsupervised ML Methods**
  - Working with Nebraska Public Power District, Xcel Energy, Vistra Energy on the development of equipment-agnostic anomoly detection methods by holistic inference of process conditions.
- **Semi-Supervised ML Methods**
  - Working with NextEra Energy on the development of methods to couple text-mined information from sparse condition reports to equipment and process sensors data for equipment and process reliability analysis

Recurrent neural networks were used to predict dry well cooling fan failure using surrounding sensors





Clustering methods were used to detect High-Pressure Coolant Injection (HPCI) system steam leak

AI/ML Applications in Plant Automation

- **Computer Vision and Deep Learning Methods:**
  - Working with Talen Energy and NextEra Energy on automatically identifying a fire in a video stream to eliminate/reduce the need for fire watches.
  - Working with Western Services Corporation on automating manual logging of analog gauges (i.e., a method to recognize gauges in oblique angles and read their values)
  - Working with LPI Inc. on enabling drones to autonomously recognize and navigate their environment in a nuclear power plant.

Fire watch costs can exceed $1M per month in a nuclear power plant.

Automated gauge reading impacts a wide spectrum of activities in a plant including operator rounds, gauges calibration, and peer verification, and improves data fidelity for online monitoring.

Drones can automate several activities in a plant including operator and security rounds, and inspections of hazardous locations.

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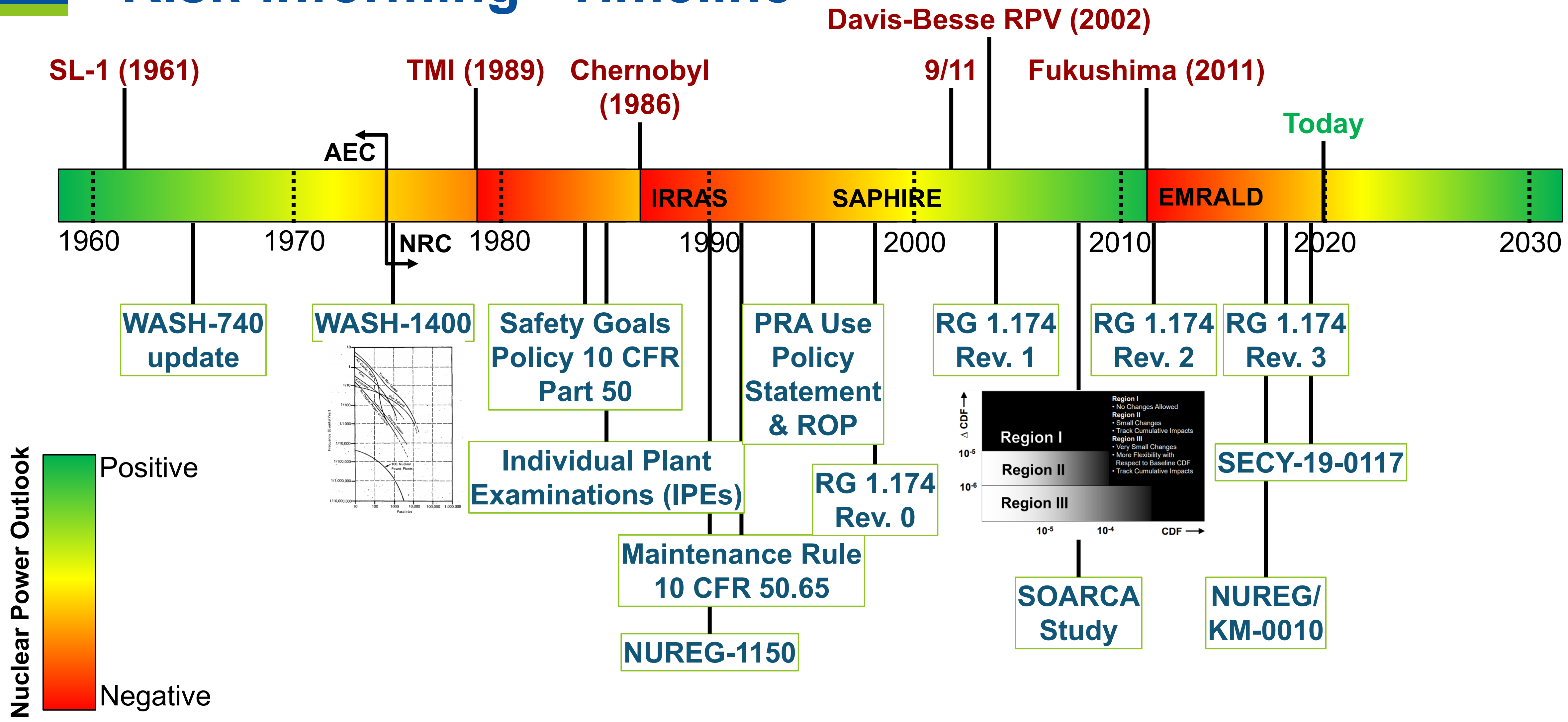
Recent examples of C200 Accomplishments & Impact

- R&D 100 Winner Machine Intelligence for Review and Analysis of Condition Logs and Entries (MIRACLE) – Ahmad Al Rashdan
- Idaho Woman of the Year Award – Johanna Oxstrand
- Laboratory Director's Outstanding Impact Award – Wayne Moe, Mark Holbrook
- Laboratory Director’s Lifetime Achievement in Science and Technology Award – Robert Youngblood
- 33 active projects being conducted for the Nuclear Regulatory Commission
- Award for the American Nuclear Society (ANS) 2022 Special Award for Outstanding Contributions to Retaining the Operations and Lifetime of Zero-Carbon Nuclear Reactors – Bruce Hallbert
- MeV Summer School in 2020 including publication of first MeV School Textbook “Risk-informed Methods & Applications in Nuclear and Energy Engineering” – Curtis Smith, Katya Le Blanc, and Diego Mandelli
- Multiple staff responsibilities for ANS service (Human Factors, Instrumentation and Controls Division, Nuclear Installations Safety Division, Joint Committee on Nuclear Risk Management)
- DiversityMBA's Top 100 Under 50 Emerging Leaders– Katya Le Blanc
- For last two years, C200 Interns (Blake Cecil, Roger Boza, and Saeed Alhadhrami) have won the Best Poster for Nuclear Operations at INL’s Interns Awards event
- Program funding awards for multiple new customers (Nuclear Safety Research and Development, State Department, CAES, NNSA International Nuclear Security, DHS Countering Weapons of Mass Destruction Office)
- ANS Theos J. ("Tommy") Thompson Award For Reactor Safety – Robert Youngblood

Technical Focus

I am working to transform the application safety and reliability for complex systems by deploying next-generation methods, data, and tools through knowledge transfer, design, operations, and regulatory applications

“Risk-informing” Timeline



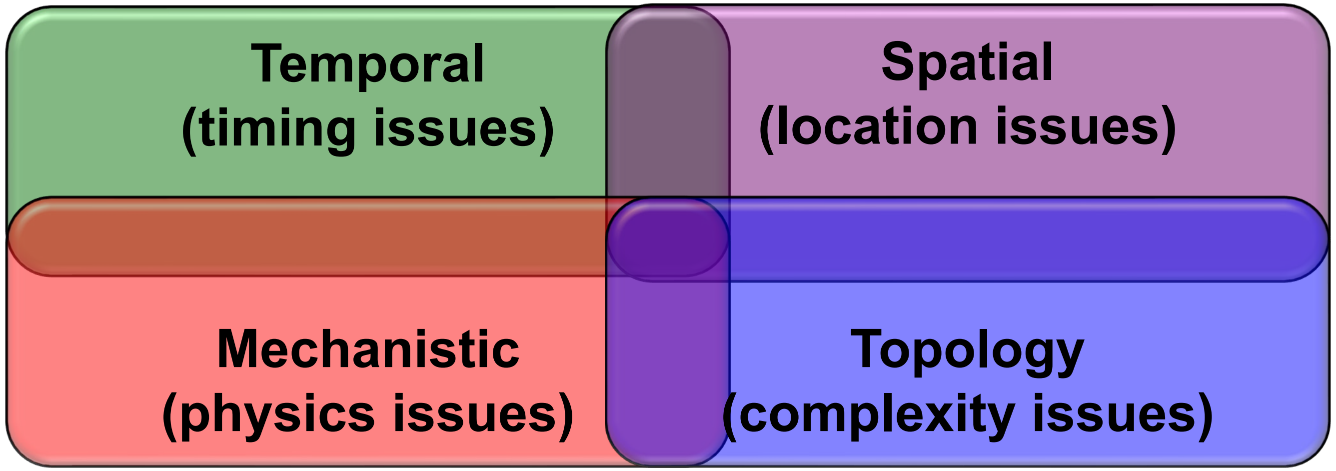
Computational Risk Assessment (CRA)

- **Computational Risk Assessment is a focus of current research and development**
- **CRA is a combination of**
  - Probabilistic (i.e., dynamic) scenario creation where scenarios unfold and are not defined a priori
  - Mechanistic analysis representing physics of the unfolding scenarios
- **CRA relies on the availability of computational tools**
  - Processors (hardware)
  - Methods (software)
- **CRA is not simply solving traditional PRA models faster or with higher precision**
  - It is a different way of thinking about the safety problem

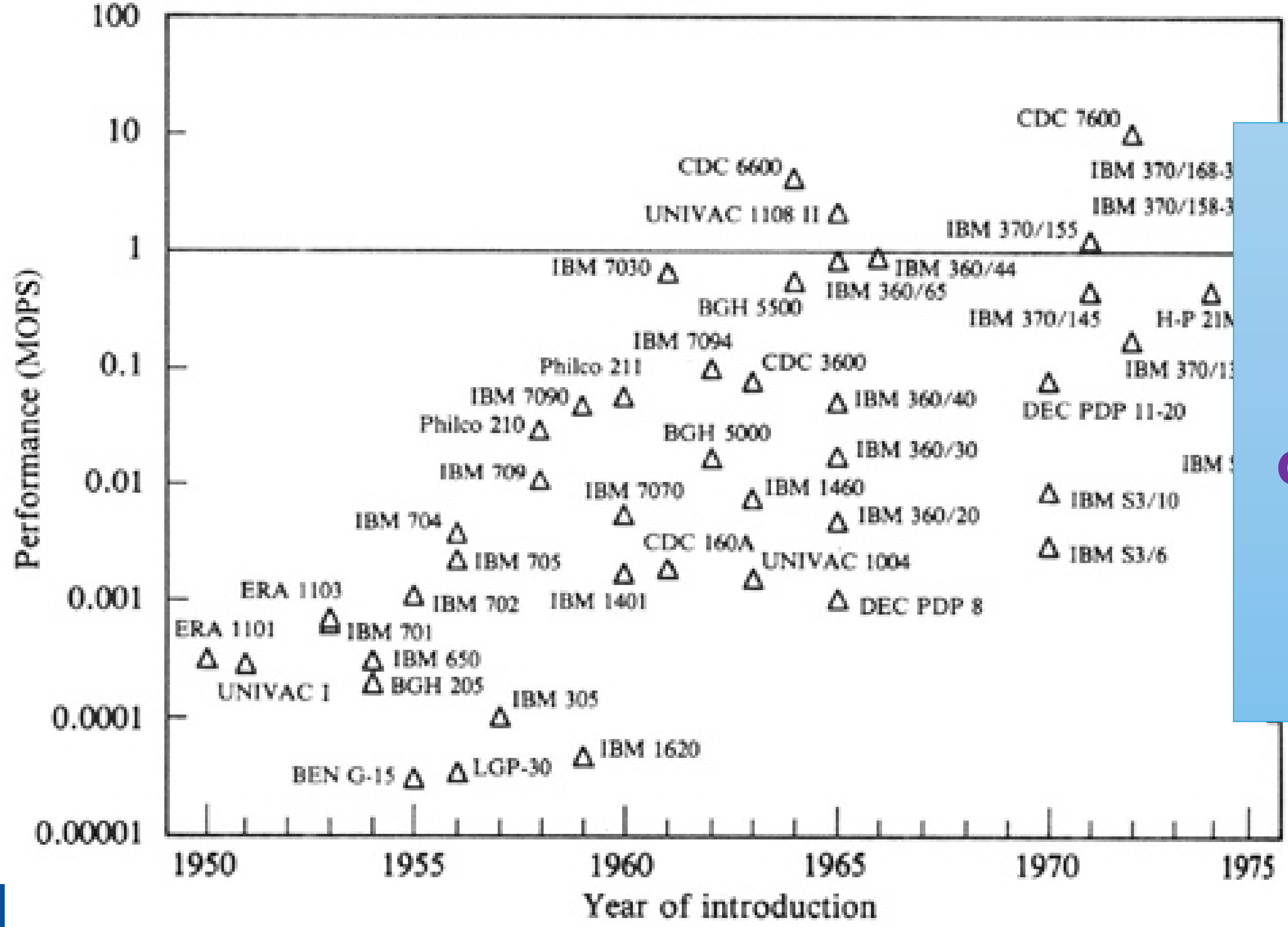
Integrating the worlds of physics and probability leads us to predictions based upon an approach called "computational risk assessment"

CRA driving factors

- **Computers are improving**
- **Software is improving**
  - And much of it is free
- **Analysis characteristics including**



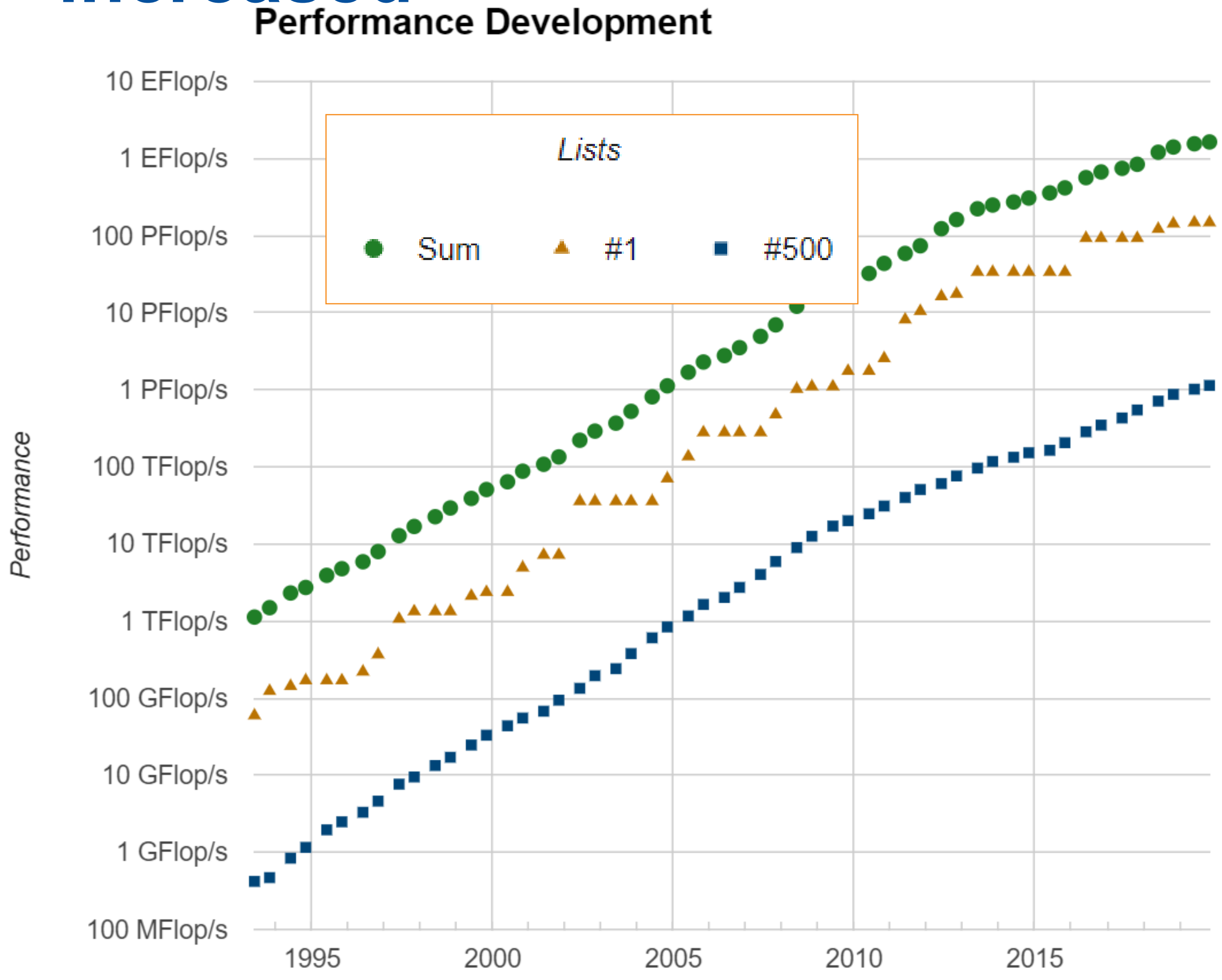
Computational performance @ dawn of risk and reliability analysis



MOPS = millions of operations per second

https://www.nap.edu/read/11148/chapter/5#31

Computational performance over time has steadily increased



Notes:

1 EFlop/s = one exaFLOPS, or a billion billion calculations per second (10^{18})

1 MOPS does not even appear on this plot.

https://www.top500.org/statistics/perfdevel/

Risk Analysis Steps for Scenario Generation

Enabling Conditions → Initiating Event → Plant SSC Response to Initiator → SSC Failures & Successes → Scenario Simulation

3D Models for the Facility including Systems, Structures, & Component (SSC)

Computational Layers Used for the Analysis

Probabilistic events **These tend to be stochastic models (but could be load/capacity)**

Seismic

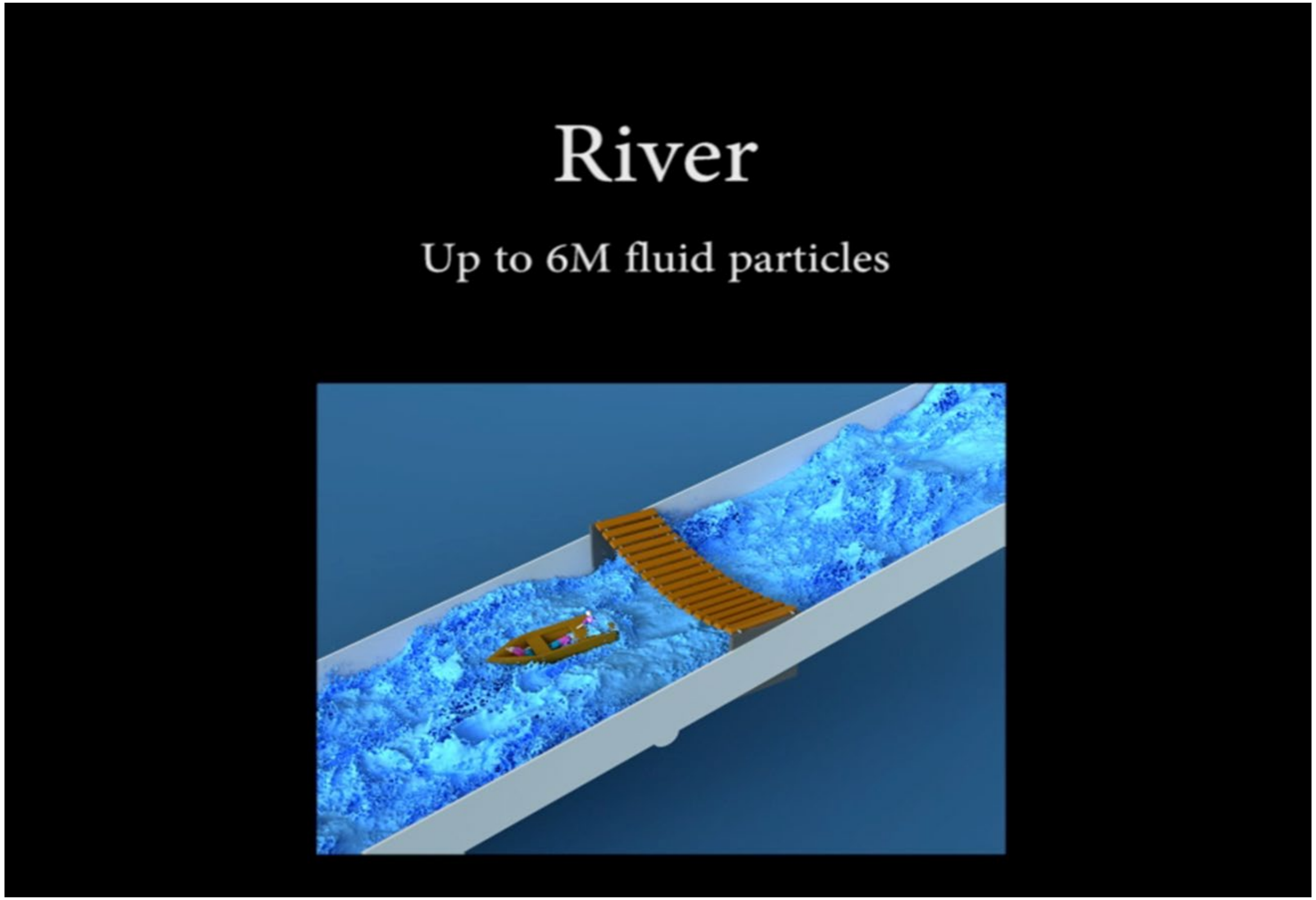
Flooding

. . .

Thermal-hydraulics

These tend to be physics models

Example of a fluid solver (physics representation)



SPH as a fluids solver

- **Fluid is composed of many discrete particles (mesh-free)**
  - Lagrangian method

Smoothed Particle Hydrodynamics (SPH)

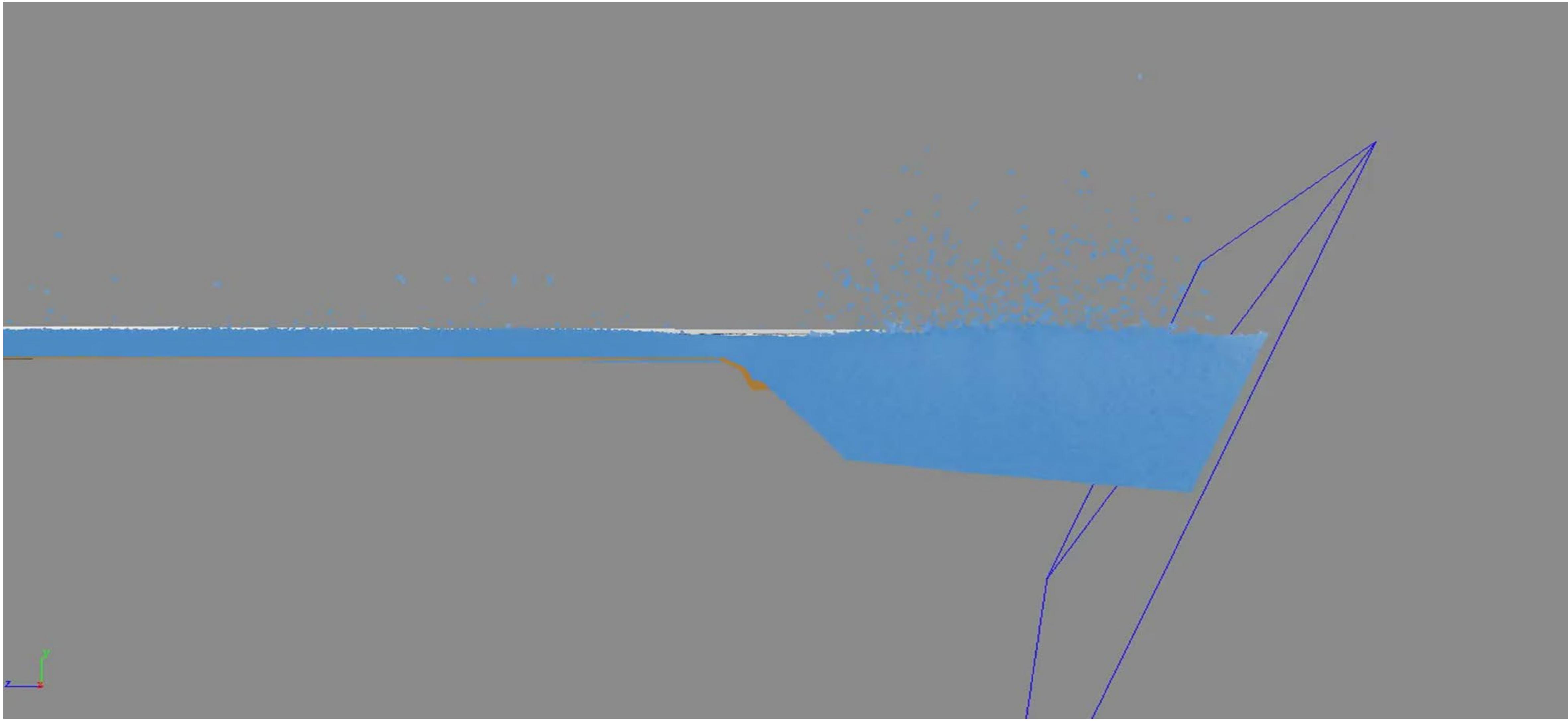
Some particle properties are determined by taking an average over neighboring particles

The fluid is represented by a particle system

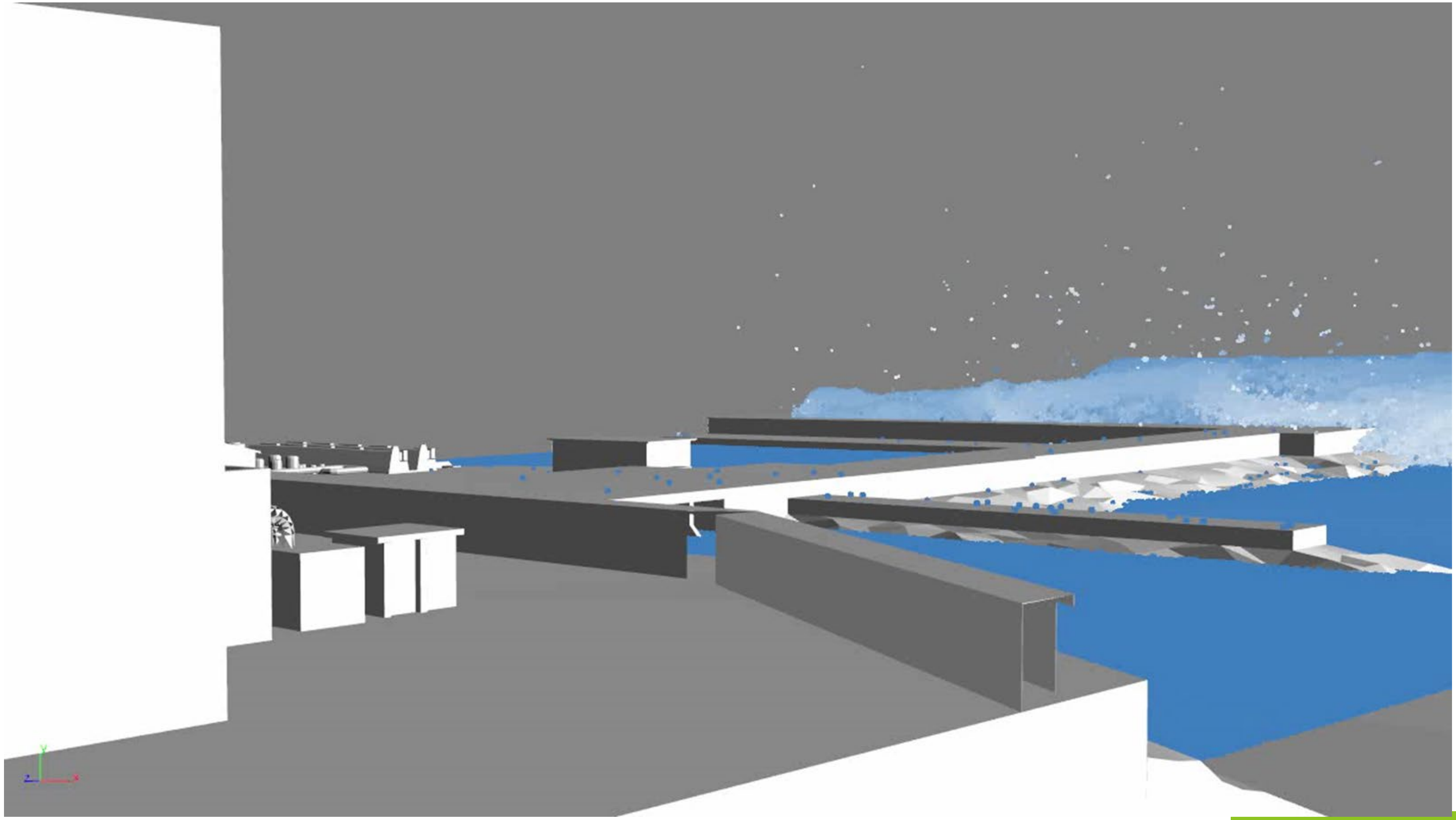
Fluid dynamics

- **Each particle has certain velocity, density, thermal energy, and fixed mass**
- **Global conservation of mass fulfilled**

Making a wave CRA style (water physics)



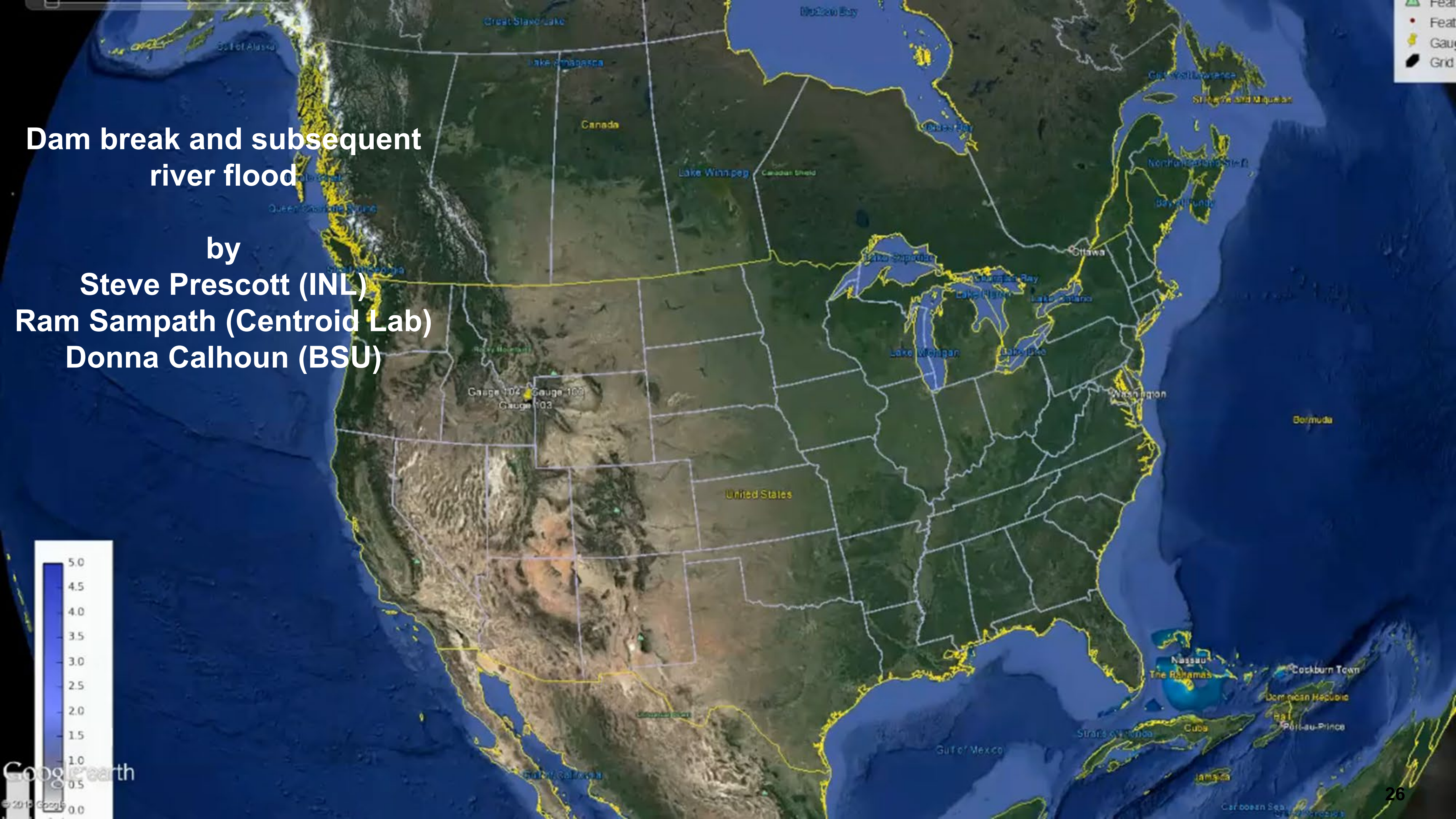
Physics (water) + facility model + probabilistic failures = CRA



Dam break and subsequent river flood

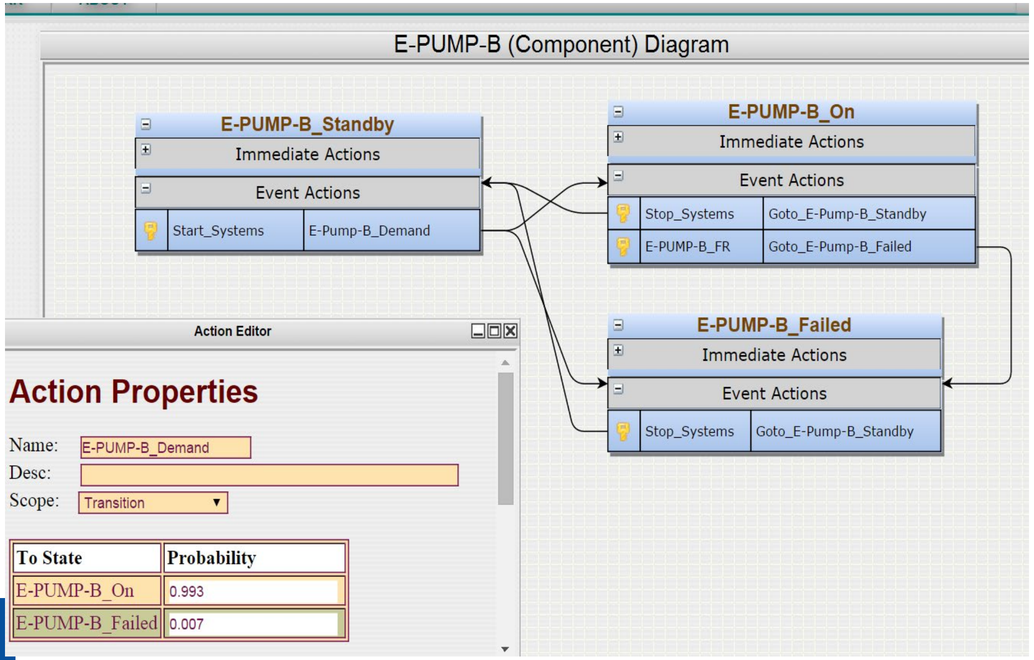
by

Steve Prescott (INL)
Ram Sampath (Centroid Lab)
Donna Calhoun (BSU)

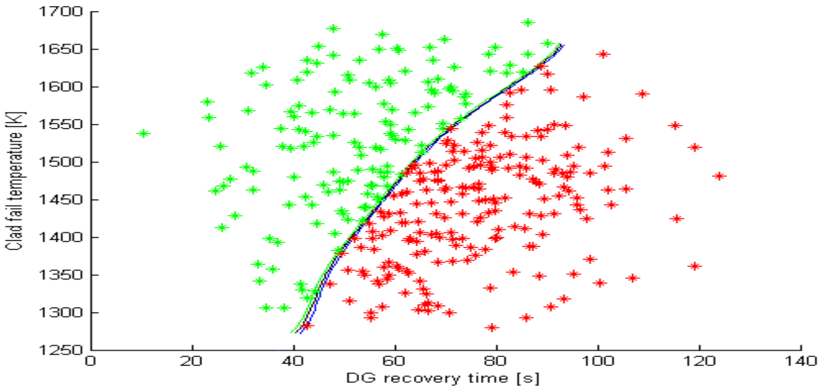


Next-Generation Risk Analysis Tools

- **Event Model Risk Assessment using Linked Diagrams → EMRALD**
- **Dynamic probabilistic risk assessment (PRA) model based on state-based simulation**
- **Graphical user interface to represent states and logic corresponding to traditional methods**



- **Risk Analysis in a Virtual Environment → RAVEN**
  - **RAVEN.inl.gov**
- **High performance computing to provide advanced algorithms to analyze complex system**
- **Modular construction including**
  - **Job handing for analysis tasks**
  - **Sampling strategies for efficient simulation**
  - **Flexible model construct**
    - **Script-based models**
    - **Reduced order models (emulators)**
    - **External models**



Future Directions

AI/ML Strategic Plan at INL

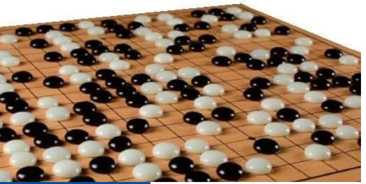
- The INL AI/ML **goals** are focused through five aspects
    1. **Methods** Using AI/ML, INL will challenge existing research gaps
    2. **Data** Through its unique data sources and expertise, INL will leverage AI/ML for new insights
    3. **Tools** INL will innovate an agile AI/ML computing infrastructure
    4. **People** INL will develop and mature researcher’s AI/ML capabilities
    5. **Security** INL will ensure trustworthy AI/ML that is explainable to end users and decision makers
- We have developed objectives behind each of the goals above as part of the **INL AI/ML Strategic Plan**
- Pursing these objectives will allow INL to successfully implement our AI/ML aspirations

Examples of current ML and AI applications

- **Symbolic reasoning to differentiate & integrate math expressions**
  - Neural network used 80 million examples of first- and second-order differential equations and 20 million examples of expressions integrated by parts
  - How well does it work?
    - Significantly outperforms Mathematica (on integration, close to 100% accuracy)
      - Mathematica reaches 85%, Maple and Matlab not as good performance
      - In many cases, conventional solvers unable to find a solution in 30 seconds
      - The neural net takes about a second to find its solutions
  - https://www.technologyreview.com/s/614929/facebook-has-a-neural-network-that-can-do-advanced-math/

$$y' = \frac{16x^3 - 42x^2 + 2x}{(-16x^8 + 112x^7 - 204x^6 + 28x^5 - x^4 + 1)^{1/2}}$$

- **AlphaGo and AlphaGo Zero to play Go**
  - AlphaGo defeated 18-time world champion Lee Sedol 4 games to 1
    - Used game tree search, neural network trained on expert human games, second neural network for board positions, and additional Monte Carlo rules
  - AlphaGo Zero used same tree search algorithm, but then single neural network trained without any human games
    - AlphaGo Zero defeated AlphaGo 100 games to 0
    - https://medium.com/ww-engineering/alphago-zero-a-brief-summary-dcff16ba3064



Discussion of Future Applications (1 of 2)

- **CRA to produce "data" for ML**
  - ML requires training data – however risk and reliability applications have a small set of "failure" data
  - Advanced computational methodologies (e.g., CRA) can be used to produce very large set of synthetic data
    - Use this data to train ML models
- **Digital twin**
  - Advance applications such as CRA and autonomous control requires virtual representation of complex systems
  - "Operating" these facilities complete with potential hazards provides robust understanding
- **Digital regulator**
  - Agent-based systems can be created to accomplish difficult real-world tasks such as oversight of construction and operations
  - CRA combined with real-world sensors can facilitate next-generation of regulation
    - Technology to keep a digital presence in complex systems to enable real-time independent oversight

Discussion of Future Applications (2 of 2)

- **System abstraction**
  - Ability to describe systems using an integrated approach is vital to cost-effective analysis
  - SysML is an open modeling language being increasing used for engineering applications
    - Standard that can describe system specifications (e.g., what is a system), containing details of system geometry, material properties, dependencies, & operational rules
- **RI construction**
  - Tailor construction (e.g., 3D printing) of complex systems to focus on facility characteristics that minimize hazards and construction costs
- **RI design**
  - Develop risk analysis to focus on community infrastructures, with special emphases on the impacts of changing climate
  - For example, make systems and components more resilient to flood hazards
- **Autonomous operation**
  - To lower the cost of complex systems, AI will need to combine sensing, computational engineering, and advanced algorithms to achieve heightened state-space awareness
  - These AI strategies will provide economical, resilient operations

Conclusions

- Demonstrating a next-generation uncertainty and risk-assessment approach that supports decision-making
- Combines mechanistic physics-based models with probabilistic analysis → CRA
  - Uncertainty analysis can be built upon and supported for next-generation methods and tools
    - Provides an opportunity to greatly enhance the realism in our risk models
      - Also provides solutions to many of the vexing issues found in current risk analysis applications

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Thank you!

Idaho National Laboratory