Mathematics of Planet Earth (MPE): Education for the Planet Earth of Tomorrow

Fred Roberts
Rutgers University

The MPE Challenge

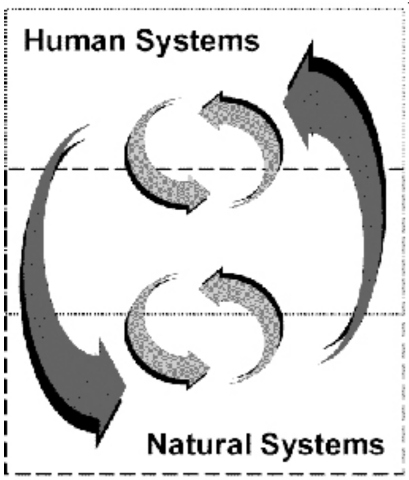
- Learning to live sustainably on Earth is going to require enormous advances in our understanding of the natural world, the human world, and their inter-relationships.
- To acquire that understanding, progress in the mathematical sciences is essential.

The MPE Challenge

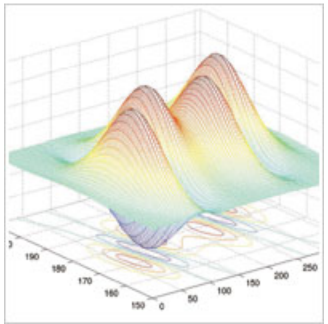
- The human population is swelling toward 10 billion.
- All of these people need food, clean water, housing, energy, health care, safety, (jobs), etc.
- To stay within the planet's carrying capacity, we are going to have to be extraordinarily clever about how we use the earth's resources and human resources.

Deepwater Horizon
Oil Spill

The MPE Challenge



- Need to understand
  - Impact of our actions on environment
  - How natural world functions
  - How human processes function
  - How we can deal with inevitable changes coming
- Doing so requires answering extremely complex, multidisciplinary questions in the emerging "science of sustainability."
- That science requires the precise insights that the mathematical sciences provide.



Why Mathematics?

- The world of science is becoming highly multi-disciplinary.
- Especially true of issues facing the planet.
- Leads to need for teams from different disciplines.
- Mathematics the language of science.
- Key role for mathematical scientists in addressing the problems of the planet.
- But what are the best ways mathematical scientists can help?

Mathematics of Planet Earth 2013

- A joint effort initiated by North American Math Institutes: **MPE2013**
- But the problems of the planet are world-wide problems.
- More than 100 partner institutes, societies, and organizations in UK, France, South Africa, Japan, and all over the world
- www.mpe2013.org

Mathematics of Planet Earth 2013

- Activities world-wide throughout 2013
- Sponsorship by UNESCO
- Support from Simons Foundation
- Workshops, tutorials, competitions, distinguished lectures, educational programs

Research Themes of MPE2013+

- ***MPE continues beyond 2013: MPE2013+***
- ***Themes:***
  - ***Global Change***
  - ***Sustainable Human Environments***
  - ***Natural Disasters***
  - ***Management of Natural Resources***
  - ***Data-aware Energy Use***

Research Themes of MPE2013+

- ***Themes:***
  - ***Global Change***
  - ***Sustainable Human Environments***
  - ***Natural Disasters***
  - ***Management of Natural Resources***
  - ***Data-aware Energy Use***
- **Corresponding to each research theme is a "cluster" of activities.**
  - **Start with a workshop**
  - **Continue with smaller, more focused workshops, meetings, etc. – being developed**

Theme 1: Global Change

- The planet is constantly changing.
- But the pace of change has accelerated as a result of human activity:
  - Construction and deforestation change habitats
  - Over-fishing reduces wild populations
  - Fossil fuel combustion leads to atmospheric greenhouse gas buildup
  - Commerce and transport introduce non-native species.

Global Change

- We need to:
  - Monitor global change to understand processes leading to change
  - Learn how to mitigate and adapt to its effects
  - Determine if we are meeting goals for our planet
  - Get early warning of dangerous trends

Global Change

- ***The Age of Observation***:
  - The unprecedented amount of data about health of the planet provides great opportunities but also poses immense challenges
  - How do we choose what to observe and what data to save?
  - What are appropriate sampling and monitoring designs?

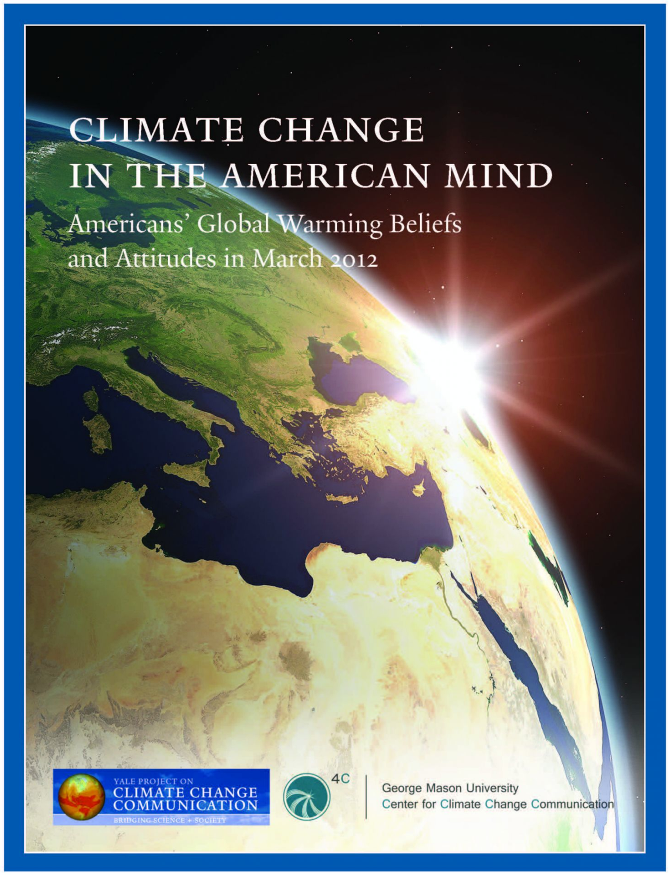
  - How to reconcile so many different variables with so many different spatiotemporal characteristics?

Global Change

- ***Effects of Global Change***:
  - Goal is not so much to describe the many effects of global change as to understand:
    - Interface between change in one sector on another – e.g., to understand Lyme Disease spread into Canada, need understand tick life cycles, bird migrations, climate change
    - Risk-based comparison of alternative adaptation and mitigation strategies – e.g., for control of invasive species or for more severe weather.

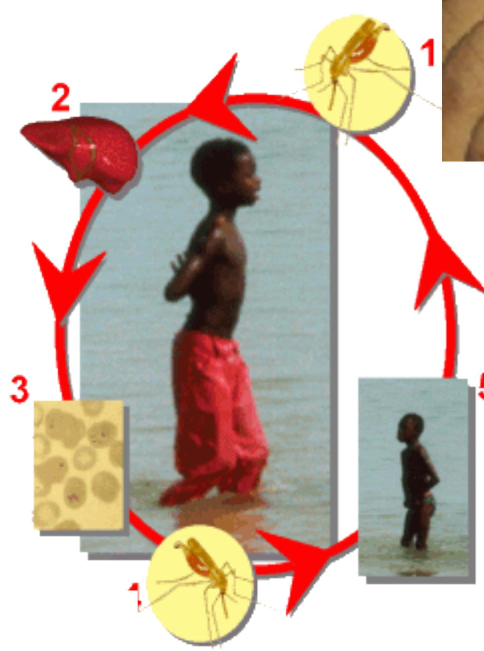
Global Change

- ***Communicating Global Change***:
  - How better to communicate the evidence for Global Change and get more people to take it seriously.



Climate and Health

- Some early warning signs:
  - Malaria in the African Highlands
  - Dengue epidemics along the Rio Grande & in Brazil



Dengue Fever

Climate and Health

- Some early warning signs:
  - Cholera affected by sea surface temperature
  - Increase in Lyme disease in Canada
  - St. Louis Encephalitis (Florida outbreak)
  - Animal and plant diseases too

–Complex interaction among climate, life cycle of hosts and vectors, migration patterns, etc.

Tick carrying Lyme Disease

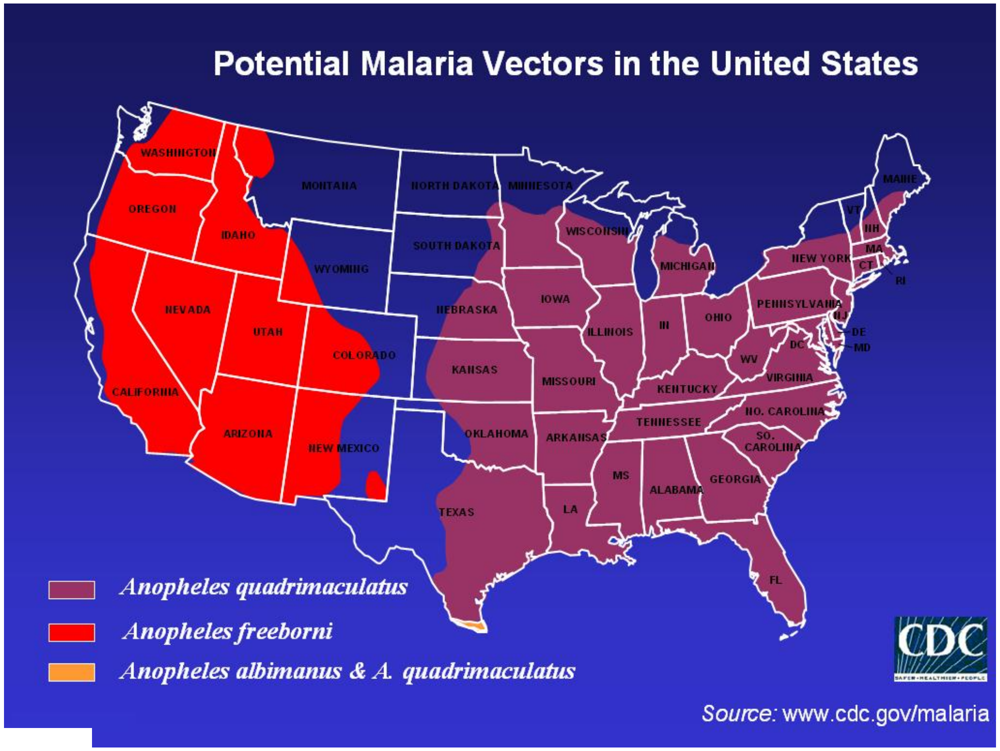
cholera

Malaria

- The challenge of climate change: Malaria springs up in areas it wasn't in before.
- Highlands of Kenya
- Potential for Malaria in the US – Texas, Florida, Washington, …
- A key role for modelers:

Aid in early warning:

Surveillance.



Theme 2: Sustainable Human Environments

- In 1900, only 13% of the world's population lived in cities.
- By 2050, it is predicted that 70% will.

http://citadel.sjfc.edu/students/rnr00577/e-port/msti260/urban.htm

Sustainable Human Environments

- Rapidly growing urban environments present new and evolving challenges:
  - Growing needs for energy and water
  - Impacts on greenhouse gases
  - Public Health
  - Safety
  - Security

- As rapid city expansion continues, mathematical scientists can play key roles in shaping sustainable living environments – in collaboration with scientists from many fields

Sustainable Human Environments

- Four themes for this research cluster's activities (so far):

1. The Role of Data in "Smart Cities"
2. Anthropogenic Biomes
3. Security
4. Urban Planning for a Changing Environment

Example: The Role of Data in "Smart Cities"

"With recent advances in technology, we can infuse our existing infrastructures with new intelligence, … digitizing and connecting … [to] sense, analyze and integrate data, and respond intelligently to the needs of their jurisdictions. In short, we can revitalize them so they can become smarter and more efficient."

IBM SmarterPlanet. http://www.ibm.com/smarterplanet/us/en/?ca=v_smarterplanet, 2012.

The Role of Data in "Smart Cities"

- Challenge: Find ways to use data to:
  - Make smarter, more livable cities
  - Understand patterns driving human behavior
  - Understand causes of the state of the urban environment
  - Learn how to optimize our choices.

The Role of Data in Smart Cities

- ***The Role of Data In Smart Cities: Math Science Challenges:***
  - Smart systems to reduce congestion and pollution thru traffic prediction and optimization
  - Real-time rerouting of commuting passengers
  - Vehicle sharing systems
  - Energy Management
  - Water Management
  - Health care allocation in emergencies
  - Keeping citizens informed of municipal services (especially during disasters)

Sustainable Urban Environments

- ***One Example: Safety and Security***
- ***Math Science Challenges:***
  - Understanding crime patterns and deploying police
  - Modeling evacuations from large gathering places (stadiums, transportation hubs)
  - Inspection procedures for people entering restaurants, stores, stadiums, transportation hubs
  - Location and optimization of new security initiatives: cameras, barricades, street closures
  - Role of randomization
  - Interface between security and commerce

Theme 3: Natural Disasters

- ***No part of the world is impervious to natural disasters***
  - Epidemics
  - Earthquakes
  - Floods
  - Hurricanes
  - Tornadoes
  - Wildfires
  - Tsunamis
  - Extreme temperatures
  - Drought
  - Oil spills
- ***Mathematical sciences can help in predicting, monitoring, and responding to such events, and mitigating their effects.***

Nepal 2015: www.circleofblue.org

Extreme Heat Events

- A key CDC concern
- One response to such events: evacuation of most vulnerable individuals to climate controlled environments.

- Modeling challenges:
  - Where to locate the evacuation centers?
  - Whom to send where?
  - Goals include minimizing travel time, keeping facilities to their maximum capacity, etc.
  - All involve tools of Operations Research: location theory, assignment problem, etc.
  - Long-term goal in “smart cities”: Utilize real-time information to update plans

Floods

- Which flood mitigation projects to invest in?
  - Buyouts
  - Better flood warning systems
  - "Green infrastructure" (cisterns & rain barrels)
  - Pervious concrete
  - Etc.

Raritan River flood
Bound Brook, NJ
August 2011

Floods

- This requires data-driven/Model-driven Decision Support
- Data-driven. Assemble data about:
  - Precipitation (duration, amount)
  - Antecedent conditions (soil moisture content, ground cover, seasonality)
  - River gage levels
  - Flood maps
  - Property damage data – FEMA payouts

Disease Events

•Newly emerging diseases can threaten the health of millions of people.

•The 1918 influenza epidemic killed 50 million people around the world; WW I killed 16 million

•Great concern about the potential for a new influenza outbreak of similar proportions

Source: Dartmouth Medicine 2006

Disease Events

- Modern transportation systems make it much easier for diseases to spread around the world – e.g., Ebola
- Deliberate introduction of diseases by bioterrorists is a serious concern
- Climate change leads to diseases appearing in places the have not appeared in before – e.g., malaria in the highlands of Kenya & potential for malaria in the US

Oil Spills

- With climate change, more vessel traffic in the Arctic and possibility of offshore oil drilling
- Increased risk of spills
- Arctic challenges: resource allocation in advance in case of oil spill
  - Necessary because of long transit times, lack of infrastructure, remote locations, lack of roads, distant airlift

Response teams start their cleanup work at the Refugio State Beach oil spill in California.

Photo credit: USCG

US Coast Guard Cutter Healy parked in an ice floe for a 2011 scientific expedition in the Chukchi Sea.

Photo credit: NASA, Flickr Creative Commons

Oil Spills

- Of special interest to the Coast Guard: Arctic resource allocation a persistent and complex challenge in many Coast Guard missions

"The lack of infrastructure and oil spill response equipment in the U.S. Arctic is a significant liability in the event of a large oil spill" (National Academies, 2014).

United States Coast Guard
U.S. Department of Homeland Security

Hurricanes

- Using mathematical modeling, simulation, and algorithmic methods of risk assessment to plan for the future:
  - What subways will be flooded?
  - How can we protect against such flooding?

Hurricanes

•Using mathematical modeling, simulation, and algorithmic methods of risk assessment to plan for the future:

– What power plants or other facilities on shore areas will be flooded?
– Do we have to move them?

Hurricanes

- Using mathematical modeling, simulation, and algorithmic methods of risk assessment to plan for the future:
  - How can we get early warning to citizens that they need to evacuate?
  - How can we plan such evacuations effectively?

Hurricanes

- Using mathematical modeling, simulation, and algorithmic methods of risk assessment to plan for the future:
  - –How can we plan placement of utility lines to minimize down time?

My street and neighborhood after hurricane Sandy

Hurricanes

- Using mathematical modeling, simulation, and algorithmic methods of risk assessment to plan for the future:
  - How can we plan for getting people back on line after a storm?

Bringing in help from out of state

Hurricanes

- Using mathematical modeling, simulation, and algorithmic methods of risk assessment to plan for the future:
  - –How can we set priorities for cleanup?

Theme 4: Management of Natural Resources

- Natural resources affect the health of our planet
- They provide materials for buildings, food, and other essentials for our way of life
- How do we protect them for future generations?

Management of Natural Resources

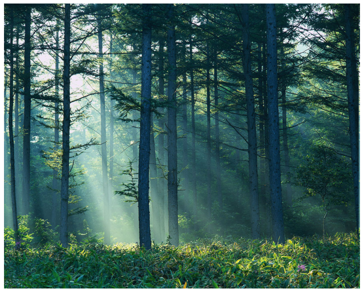
- Major themes:
  - Forests
  - Water
  - Food
  - Animals, Plants, Ecosystems
- But all of the themes of MPE2013+ are relevant.
- Example: Big emphasis nowadays on the nexus of food, energy, water, and climate.
- ***"When we try to pick out anything by itself in nature, we find it hitched to everything else in the universe."*** – John Muir, 1911

The Nexus of Food, Energy, Water, and Climate

- It takes water (lots of water) to produce food and energy
- Energy is needed to treat water
- Energy is needed to produce food
- Food crops can be used as a source of energy
- Production of energy affects the climate
- Climate change affects crops
- And so on.

Forests

- Research about environmental health often requires merging datasets produced at different times for different purposes.
- Many different government agencies and others collect data that is relevant to understanding the health of forests:
  - The Forest Service does an inventory of plots around the country every five to ten years that assesses the trees, the ground vegetation, the soils, and the air quality;
  - EPA assesses water quality around the country;
  - Private groups assess at-risk species
- Understanding the true state of our forests and the threats to them requires integrating this data coherently. A data fusion research challenge.



Food

- Fish a major source of food in the world
- Management of fish populations a subject of a great deal of mathematical modeling
- Complex interactions of human and ecological systems

Water Quality

- Need contamination warning systems
- Early warning of accidental or deliberate contamination of a water supply system
- Complex because water systems have many components:
  - Pipes and constructed conveyances, physical barriers, water collection, pretreatment, treatment, storage and distribution facilities

Source: www.leesburgva.gov

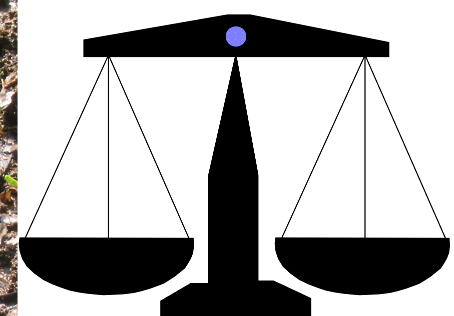
Source: www.thehindu.com

Water Quality

- One approach: locate water quality sensors throughout the system.
- But where?
- Sensor placement can be automated with optimization methods that computationally search for a sensor configuration that minimizes contamination risks.

Source: www.wager-quality-sensors.com

Ecosystems



Measurement of Biodiversity

•Evidence about the health of ecosystems is often obtained by measuring the "biodiversity."

•***An index of biodiversity allows us to set specific goals and measure progress toward them.***

Dimensions of Biodiversity

- But what is biodiversity?
- 100s of papers trying to define it
- ***Biodiversity is a multidimensional concept.***
- Some components of it are:
  - –Species diversity
  - –Genetic diversity within species
  - –Ecosystem diversity
  - –Ecosystem services and processes

Measurement of Biodiversity

- Only by putting the measurement of biodiversity on a firm mathematical foundation can we be confident that we are capturing the true diversity in nature.

Cicada images courtesy
of Nina Fefferman

Management of BioReserves

- I saw this baby rhino at the Mohololo Animal Refugee Reserve in South Africa
- It was rescued from dried mud in a waterhole where its mother had perished

Management of BioReserves

- We were studying management of biological reserves.
- Some of the mathematical sciences issues:
  - How large should the reserve be?
  - How do you measure whether it is successful in preserving the "biodiversity"?
  - Should we treat animals for illness/injury?

Management of BioReserves

Management of BioReserves

- Some other issues:
  - Should one manage the water supply? Or let nature take its course?
  - Should one vaccinate animals?
  - Should one have taken the baby rhino from the reserve?

Theme 5: Data Aware Energy Use

- Need to make good choices about energy future
- Data can help
- Themes include:
  - Sensor networks and data acquisition.
  - Data mining
    - E.g., understand state of the power grid
  - Optimization and control
    - Real-time precision in operations and control of energy systems

Theme: Data Aware Energy Use

- Themes include:
  - Smart grid
    - To help customers be more efficient and operators to respond in real time or better
  - Smart buildings
    - Real-time usage information to occupants and building managers
  - Electric vehicles

UCSD CSE building – a lab for studying real-time energy use

Source: cse.ucsd.edu

Today’s Electric Power Grid

- Today’s electric power systems have grown up incrementally and haphazardly – they were not designed from scratch
- They form *complex systems* that are in constant change:
  - Loads change
  - Breakers go out
  - There are unexpected disturbances
  - They are at the mercy of uncontrollable influences such as weather

Today's Electric Power Grid

- Today's electric power systems operate under considerable uncertainty
- Cascading failures can have dramatic consequences.

ROCHESTER
Democrat and Chronicle

Huge power failures
Parts of eight states and Canada left dark; cause remains in dispute.
Story below

Six pages of coverage
A roundup of blackout stories from around the region and nation.
Pages 10A-15A

No delays for PGA
Today's second round of the PG Championship will not be affect
Story below

BLACKOUT

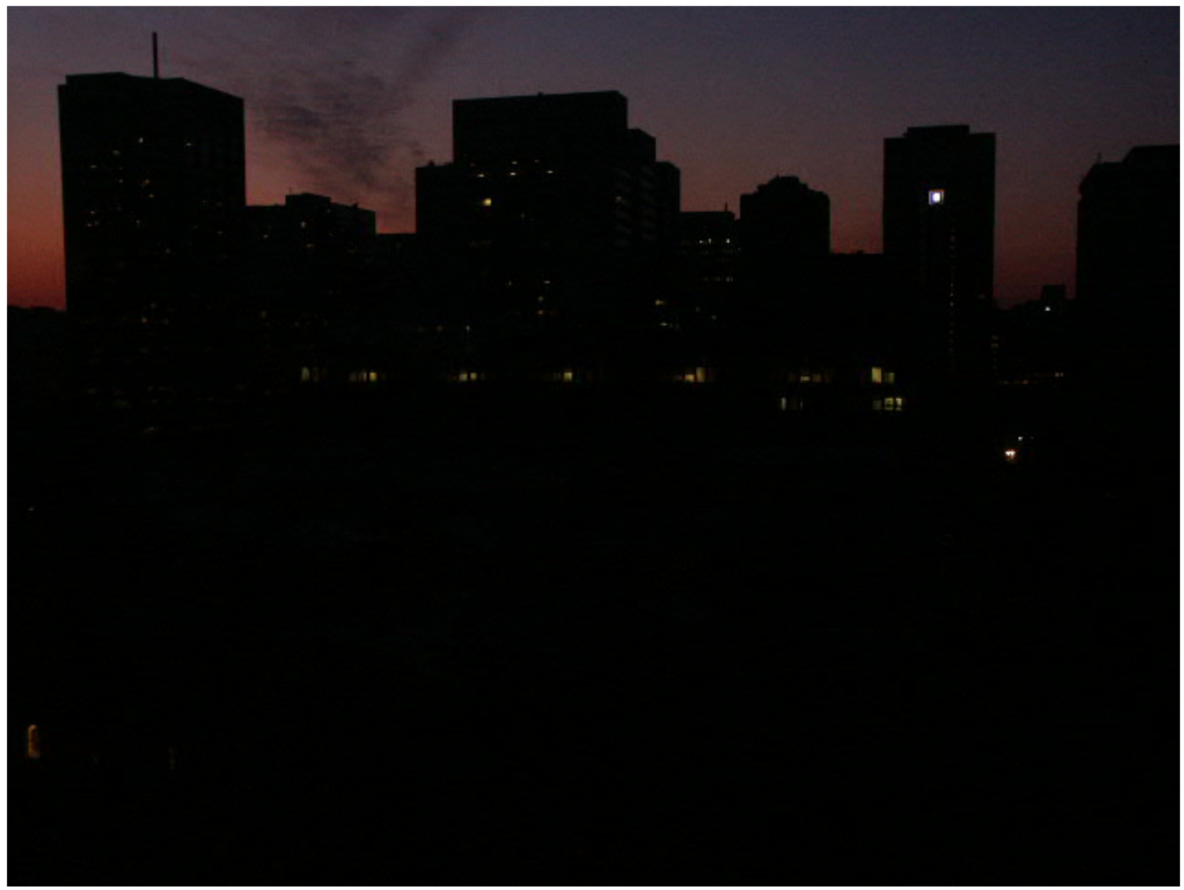
As the blackout rolled across vast portions of the northeastern United States and southeastern Canada, officials estimated that it affected as many as 50 million people. Gov. George Pataki said

BLACKOUT, PAGE 10A

Emergency declared in Monroe, Livingston

Affected cities across the Northeast
Shortly after 4 p.m. power outages spread across the northeastern United States and parts of Ontario, Canada.

Some parts of these states or provinces were affected.



Today's Electric Power Grid

- Challenges include:
  - Huge number of customers, uncontrolled demand
  - Changing supply mix system not designed for complexity of the grid
  - Operating close to the edge and thus vulnerable to failures

Today's Electric Power Grid

- Challenges include:
  - –Interdependencies of electrical systems create vulnerabilities
  - –Managed through large parallel computers/ supercomputers with the system not set up for this type of management

The Need for a "Smart Grid"

- Massoud Amin defines the "smart grid" this way:

The term "smart grid" refers to the use of computer, communication, sensing and control technology which operates in parallel with an electric power grid for the purpose of enhancing the reliability of electric power delivery, minimizing the cost of electric energy to consumers, improving security, quality, resilience, robustness, and facilitating the interconnection of new generating sources to the grid.

The Need for a Smart Grid

Why do we need a smart grid?

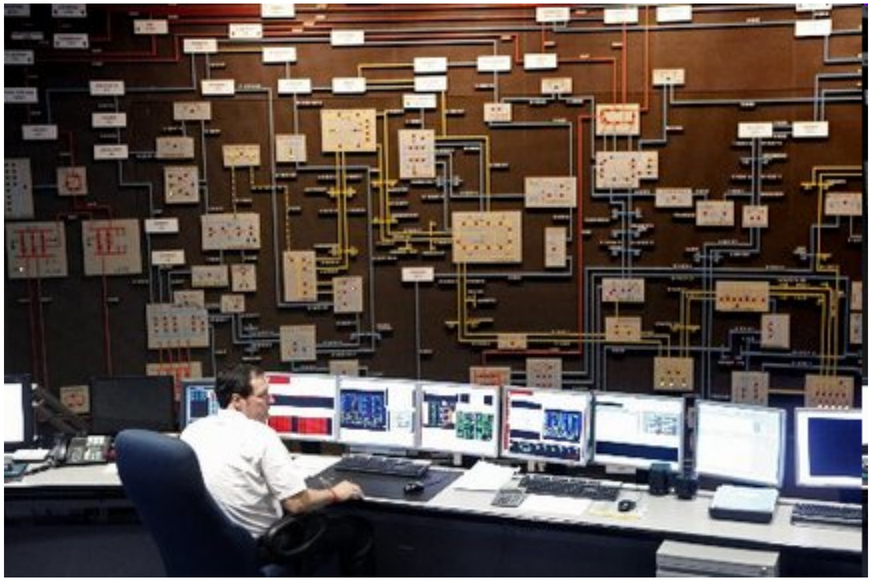
- The electric grid is a massive, complex system.
- With sufficient information to determine what is happening in real time, grid operators would be able to contain a cascading outage or perhaps prevent one altogether.
- However:
  - The grid has hundreds of thousands of miles of transmission lines
  - Decisions have to be made really fast – in real time or faster

Acknowledgement: Article by Sara Robinson, SIAM News, Oct. 2003

The Need for a Smart Grid

Why do we need a smart grid?

•Power grid operators need to see several moves ahead, sorting through millions of possible scenarios, to choose an appropriate response.



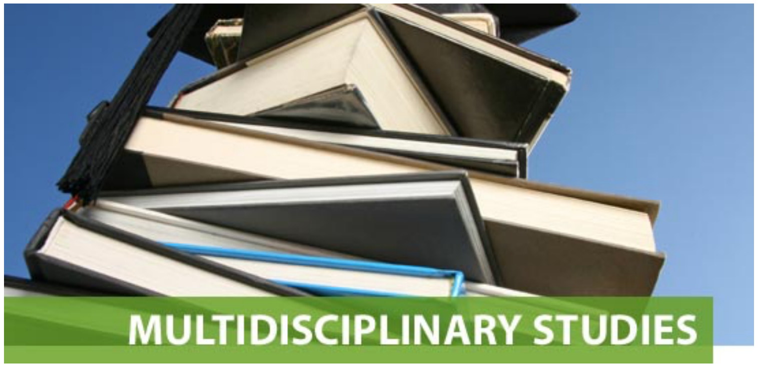
The Need for a Smart Grid

Why do we need a smart grid?

- It could be that humans just can't respond that quickly or calculate that fast.
- Either we give them some tools to aid them or we put the decision making into the hands of machines.
- This calls for the tools of "algorithmic decision theory."
- What is called for is a new complex, adaptive system that has self-healing properties.
- Need mathematical scientists to help design such a system.

Education for the Planet Earth of Tomorrow: This Workshop

- Issues facing the planet call for a new type of workforce:
  - Trained in multidisciplinary and multi-national communication and collaboration.
- Math students will need to:
  - Appreciate concepts at the interface between their discipline and others
  - Comprehend ways disciplines interact
  - Understand new educational and career opportunities in an increasingly multidisciplinary world



Source: sienaheights.edu

Education for the Planet Earth of Tomorrow

- Students from non-mathematical disciplines will benefit from observing the importance of mathematical sciences tools for their discipline.
- A crucial time to train next generation of scientists, engineers, and decision makers to be able to think broadly across disciplines.
  - Multidisciplinary education should start at young age
  - There are the beginnings of materials and approaches at the K-12 level (see e.g., DIMACS Interdisciplinary Math-Bio – just one example)
  - There are opportunities for postdoctoral programs and mid-career programs.

Education for the Planet Earth of Tomorrow

- This workshop will explore all these ideas.
- Major emphasis at the undergraduate and beginning graduate levels, but also K-12, community colleges, and postdoc and mid-career education
- Discussion of existing materials for MPE, e.g., for undergraduate and beginning graduate education e.g., the Earth Math Project and the MPE Sustainable Planet Education Project (DIMACS)

Challenges for this Workshop

- How do we connect mathematical sciences with other disciplines?
  - Multidisciplinary courses?
  - Inject multidisciplinary topics into existing curricula?
  - Case study courses?
  - More emphasis on multidisciplinary projects as part of existing courses?
  - Does it matter what the "other" discipline is, or is some multidisciplinary experience sufficient?

Challenges for this Workshop

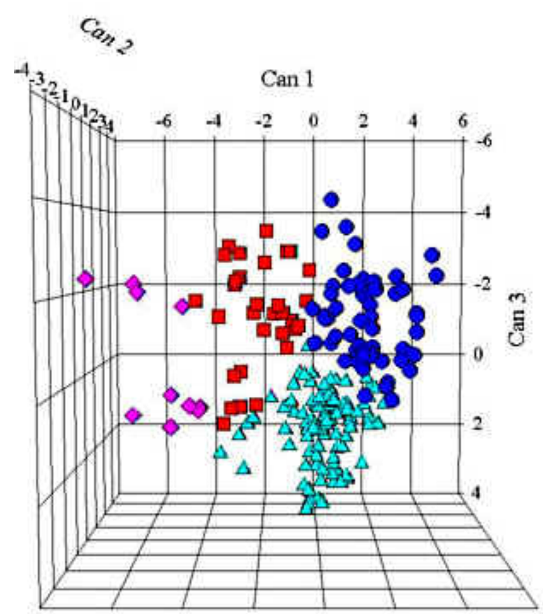
- How do we prepare mathematical sciences students to work in disciplines that they might not encounter until later in their careers?
  - What is the role of team experiences?
  - Could increasing emphasis on MPE topics early in undergraduate education improve retention of STEM majors?
  - Do MPE topics provide opportunities for involvement of undergraduates in research?

Challenges for this Workshop

•How do we prepare faculty for multidisciplinary education in MPE topics?
•Given that problems facing the planet do not stop at national borders, do international experiences play a role?

Connection to MPE2013+ Research Clusters

- Each MPE 2013+ research workshop had an education session.
- Can we develop recommendations for new programs and new initiatives with specific cluster themes in mind?.



Workforce Development

- Workforce development should be a primary focus at the workshop.
  - Are there MPE-related jobs requiring either an associate degree, a four-year degree, or graduate education?
  - What is the role of "green jobs"?
  - How can graduate schools be responsive to applicants with MPE backgrounds and multidisciplinary interests?

Source: cwdb.ca.gov

Working Groups and White Papers

- The workshop will have five working groups.
- Goal of each group: prepare a white paper that:
  - Provides a roadmap for education and communication for teachers at all levels, policy leaders, and others
  - Highlights the role of the mathematical sciences in understanding and sustaining the planet.
- White papers will be disseminated through a report shared with the wider mathematical sciences community and those interested in undergraduate education and in other ways paper authors recommend.

Working Groups and White Papers

The Five White Paper Topics:

1. Best ways for teachers at all levels to communicate issues related to planet earth.

2. Effective ways to inform the public about the essential role of the mathematical sciences in understanding issues related to planet earth.

3. Ways to infuse mathematics related to planet earth in undergraduate courses, as well as develop their communication skills.

4. Ways to infuse mathematics related to planet earth at the high school and community college level.

5. Effective ways to encourage graduate students, post-docs, and early career researchers to pursue research areas related to sustainability of planet earth.

Thanks

- National Science Foundation
- DIMACS Staff
- NIMBioS Staff
- Organizing Committee
  - Carlos Castillo-Chavez
  - Midge Cozzens
  - Gene Fiorini
  - Holly Gaff
  - Suzanne Lenhart
  - Kelly Sterner

CCICADA
Command, Control, and Interoperability Center for Advanced Data Analysis
A Department of Homeland Security Center of Excellence


Tim Killeen, Assistant Director, NSF
•"It is the challenge of the century: How do we live sustainably on the planet? We all have to contribute."