Computational Sustainability:
Computational Methods for a Sustainable Environment, Economy, and Society

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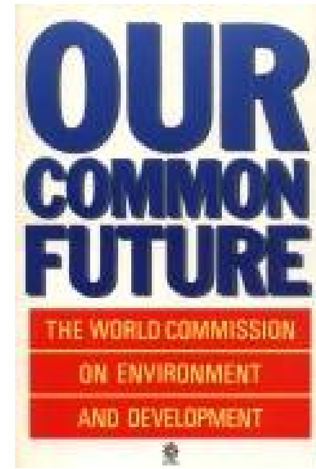
Sustainability and Sustainable Development

The 1987 UN report, “Our Common Future” (Brundtland Report):



- Raised serious concerns about the State of the Planet.
- Introduced the notion of sustainability and sustainable development:

> *Sustainable Development: “<u>development that meets the needs of the present without compromising the ability of future generations to meet their needs</u>.”*

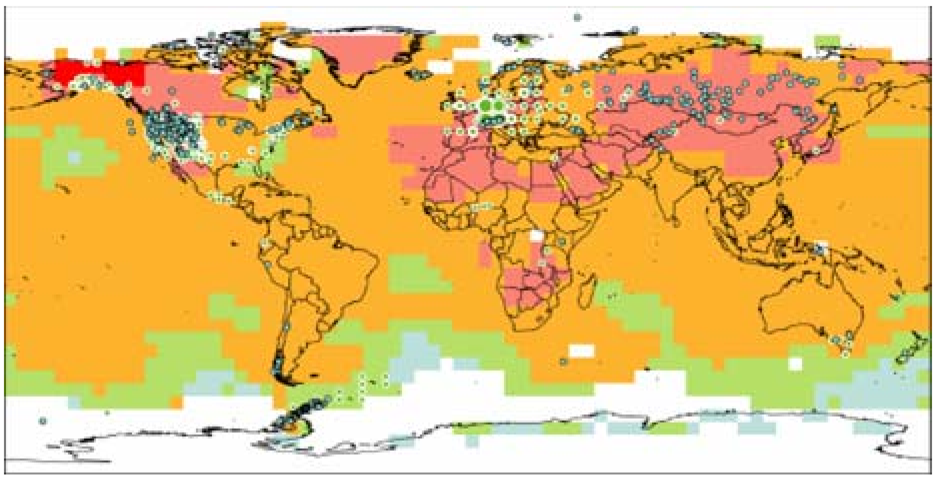
UNITED NATIONS

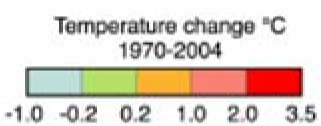
UN World Commission on Environment and Development,1987.

Gro Brundtland
Norwegian
Prime Minister
Chair of WCED

Follow-Up Reports:
Intergovernmental Panel on Climate Change (IPCC 07)
Global Environment Outlook Report (GEO 07)

"There are no major issues raised in Our Common Future for which the foreseeable trends are favourable."





Global Warming

Erosion of Biodiversity

Examples:

•The biomass of top marine predators is estimated to be 1/10 of what it was 50 years ago and is declining (Worm et al. 2006)

•At the current rates of human destruction of natural ecosystems, 50% of all species of life on earth will be extinct in 100 years.

+130 countries

WMO INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC) UNEP

[Nobel Prize with Gore 2007]

Policies for Sustainable Development

- The UN reports stressed the urgency of the adoption of policies for sustainable development.

- Key issues pertaining to the development of policies for sustainable development translate into decision and policy making problems concerning the management of our natural resources.

  – Often such problems involve significant computational challenges that fall into the realm of computing and information science, but in general they are not studied by computer scientists.

Vision

Computer scientists — can and should — play a key role in increasing the efficiency and effectiveness of the way we manage and allocate our natural resources.

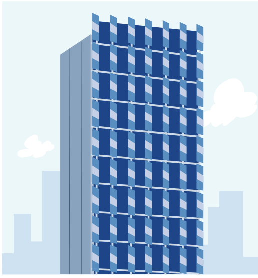
We need critical mass in the new field of
Computational Sustainability

Outline

- ❑Computational Sustainability Themes
  - ➢Conservation and Biodiversity
    - Wildlife Corridors and Reserve Design

  - ➢Natural Resource Management
    - Policies for harvesting renewable resources

  - ➢Energy
    - Energy efficiency and renewable energy



- ❑Conclusions

I Conservation and Biodiversity : Wildlife Corridors

Wildlife Corridors link core biological areas, allowing animal movement between areas.

Typically: low budgets to implement corridors.

Example:

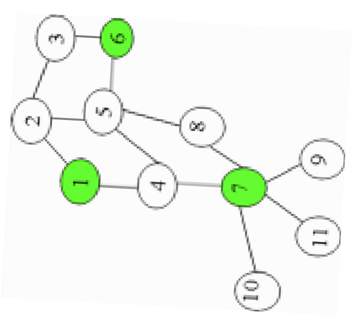
Goal: preserve grizzly bear populations in the Northern Rockies by creating wildlife corridors connecting 3 reserves:

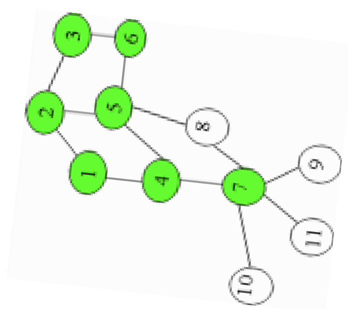
Yellowstone National Park;
Glacier Park and
Salmon-Selway Ecosystem

Conservation and Biodiversity: Wildlife Corridors
Challenges in Constraint Reasoning and Optimization:

Wildlife corridor design

Computational problem → **Connection Sub-graph Problem**





Connection Sub-Graph - NP-Hard

Worst Case Result --- Real-world problems possess hidden structure that can be exploited allowing scaling up of solutions→ Science of Computation.

Connection Sub-graph Problem

Given a graph G with a set of reserves:

Find a sub-graph of G that:

contains the reserves;
is fully connected;
with cost below a given budget;

and
with maximum utility

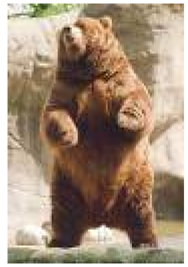
Conrad, G., van Hoeve, Sabharwal, Sutter 2007

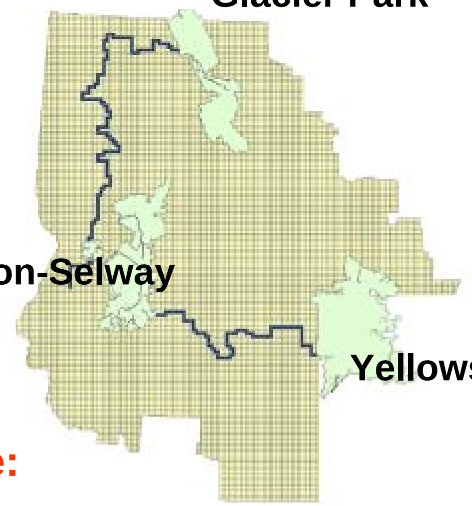
Real world instance:

Corridor for grizzly bears in the Northern Rockies, connecting:

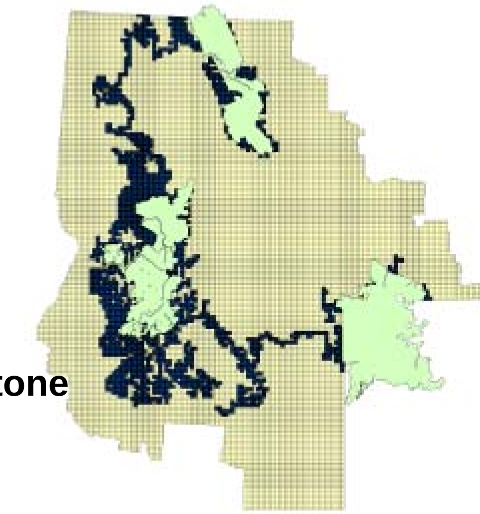
Yellowstone
Salmon-Selway Ecosystem
Glacier Park

(12788 nodes)





5 km grid
(12788 land parcels):
minimum cost solution



5 km grid
(12788 land parcels):
+1% of min. cost

Scaling up Solutions by Exploiting Structure:

Typical Case Analysis
Identification of Tractable Sub-problems
Exploiting structure with machine learning
Streamlining for Optimization
Static/Dynamic Pruning

Our approach allows us to handle large problems and reduce corridor cost dramatically compared to existing approaches.

Conrad, G., van Hoeve, Sabharwal, Sutter 2007

- Red Cockaded Woodpecker (RCW) is a federally endangered species

- Highly specific habitat – needs mature pine trees (80+ years old) infected with Red Heart fungus, in which it excavates nesting holes.

- Current population is estimated to be about 1% of original stable population (~12,500 birds)

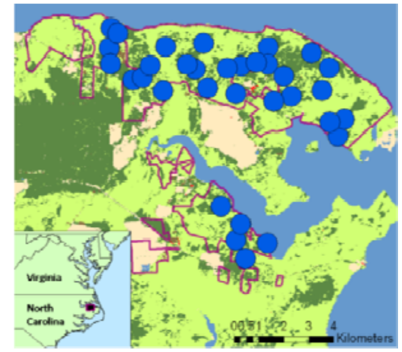
Red Cockaed Woodpecker (RCW)

Palmetto Peartree Preserve (3P), The Conservation Fund:

- 10,000 acres of wetland forest in North Carolina
- 32 active RCW territories (as of Sept 2008)

THE CONSERVATION FUND

America's Partner in Conservation



Goal: Increase population level

Management Decisions:

Prioritizing land acquisition adjacent to current RCW populations

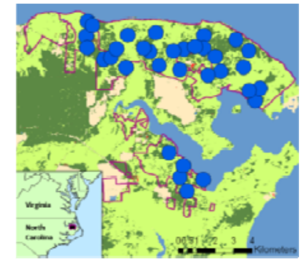
Building artificial cavities

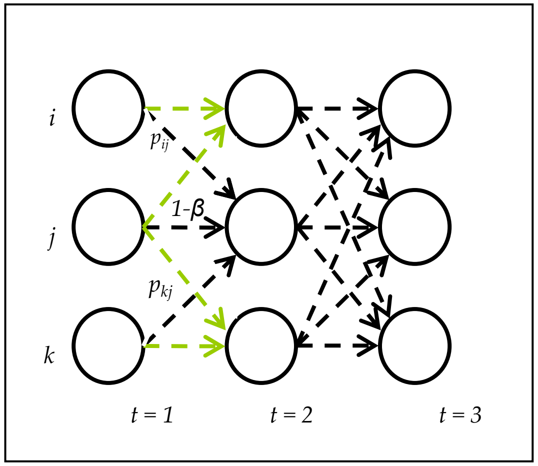
Translocation of birds

Need to explicitly consider interactions between the RCW biological and ecological processes and management decisions

Red Cockaded Biological and Ecological Model	⇄	Management Decisions: Land acquisition, Artificial cavities, Translocation of birds

Dilkina, B., Elmachtoub, A., Finseth, R., Sheldon, D., Conrad, J., Gomes, C., Shmoys, D., Amundsen, O., and Allen, W., 2009





$$\text{maximize } (1/K)\sum_{k=1}^{K}\sum_{i\in\mathcal{R}} x^k(i,T)$$

subject to

$$\begin{aligned}
\sum_{i\in\mathcal{R}}\sum_{t=1}^{T} b(i,t)y(i,t) &\leq B; \\
\sum_{t=1}^{T} y(i,t) &\leq 1 \quad \forall \text{ territories } i \in \mathcal{R}; \\
x^k(i,t) &\leq \sum_{s=1}^{t} y(i,s), \quad \forall \text{ scenarios } k, \text{ territories } i \in \mathcal{R}, \text{ and periods } t; \\
x^k(i,1) &\leq a^k(i,i,1), \quad \forall \text{ scenarios } k, \text{ territories } i \in \mathcal{R}; \\
x^k(j,t) &\leq \sum_{i\in\mathcal{R}} a^k(i,j,t)x^k(i,t-1), \quad \forall \text{ scenarios } k, \text{ territories } j \in \mathcal{R}, \text{ and periods } 2\ldots T; \\
x^k(i,t) &\geq 0, \quad \forall \text{ scenarios } k, \text{ territories } i \in \mathcal{R}, \text{ and periods } t; \\
y(i,t) &\in \{0,1\}, \quad \forall \text{ territories } i \in \mathcal{R} \text{ and periods } t;
\end{aligned}$$

Stochastic diffusion model (movement and survival patterns) in RCW populations

Stochastic optimization model
Decisions: where and when to acquire land parcels
Goal: Maximize expected number of surviving RCW

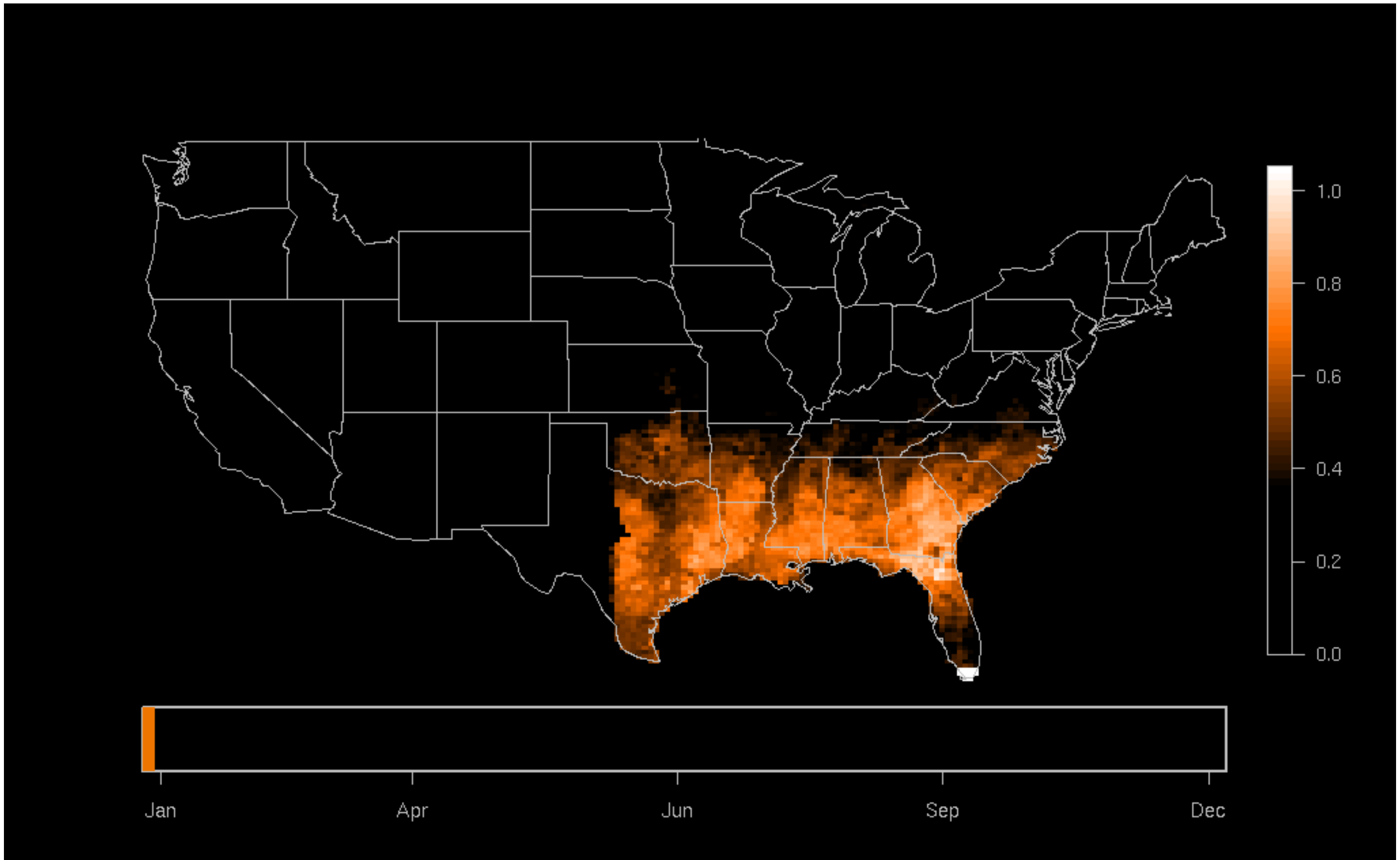
Computational Challenge: scaling up solutions for considering a large number of years
→ decomposition methods and exploiting structure

Dilkina, B., Elmachtoub, A., Finseth, R., Sheldon, D., Conrad, J., Gomes, C., Shmoys, D., Amundsen, O., and Allen, W., 2009

Additional Levels of Complexity: Stochasticity, Uncertainty, Large-Scale Data Modeling

- Multiple species (hundreds or thousands), with interactions (e.g. predator/prey).
- Spatially-explicit aspects within-species
- Different models of land conservation
  (e.g., purchase, conservation easements, auctions)
  typically over different time periods
- Movements and migrations;
- Climate change
- Other factors

Eastern Phoebe Migration



Source: Daniel Fink.

Information Sciences

Seasonal patterns of relative abundance for Eastern Phoebe, using eBird traveling counts less than 5 miles long (2004 – 2007) and considering local habitat characteristics controlling for variation in detection rates. The data are fit with **bagged decision tree models.** To account for habitat selectivity, remotely sensed habitat information compiled at a 15 x 15 km scale is included in the analysis. Variation in detection rates is modeled as a function of both effort spent watching birds and the length of the traveling count, Variation in availability for detection is modeled as a function of the observation time of day and date.

Daniel Fink,Wesley Hochachka, Art Munson, Mirek Riedewald, Ben Shaby, Giles Hooker, and Steve Kelling, 2009.

Wind Energy and Bird Conservation

Existing and proposed wind farms in US and MX (2008)

•26,000+ turbines, 1.5% of potential

• “Build-out” to reach potential would require >1.7 million turbines

•Areas with most favorable winds are also often associated with migratory pathways

Need *research* for establishing guidelines for locating wind farms

CORNELL LAB of ORNITHOLOGY

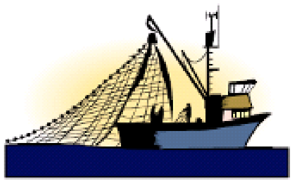
Andrew Farnsworth and Ken Rosenberg 2009

➢Natural Resource Management

Policies for fishery harvesting

II Natural Resource Management:
Policies for harvesting renewable resources

- The state of the world’s marine fisheries is alarming:
  - The biomass of top marine predators is estimated to be 1/10 of what it was 50 years ago and is declining (Worm et al. 2006).



- Researchers believe that the collapse of the world’s major fisheries is primarily the result of the mismanagement of fisheries (Clark 2006; Costello et al. 2008).

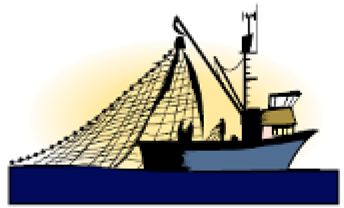
We need to find ways of managing fisheries in a sustainable manner.

II Natural Resource Management:
Policies for harvesting renewable resources

Economy

Y_t

Harvest of a Renewable Resource: Tuna



$$X_{t+1} - X_t = F(X_t) - Y_t$$

Empirical results Pacific Halibut in Alaska) suggest that periodic harvesting policies outperform standard constant escapement policies:

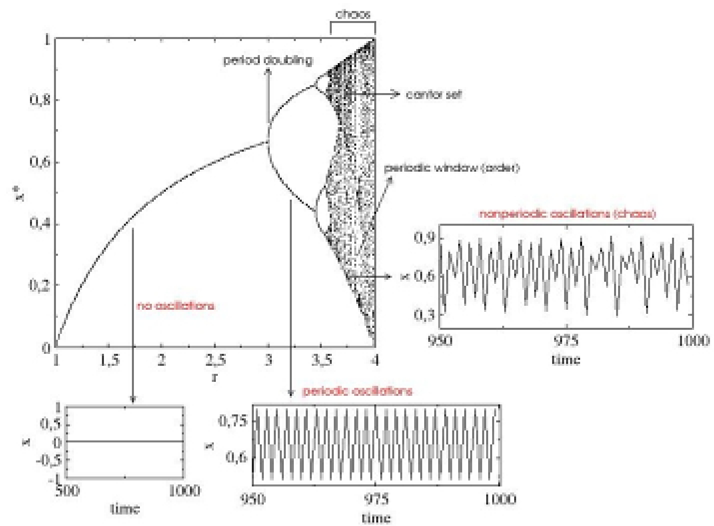
Under which conditions does it happen?

How to characterize and compute optimal periodic policies?

X_t = the fish stock (tuna)
Y_t = the rate of harvest
$F(X_t)$ = the net growth function

non-linear dynamics

Example of a Biological Growth Function F(x):
Logistic map: $x_{t+1} = r\, x_t\,(1 - x_t)$, r is the growth rate



Increasing Complexity: more complex models and multiple species interactions

We are interested in identifying policy decisions
(e.g. when to open/close a fishery ground over time).

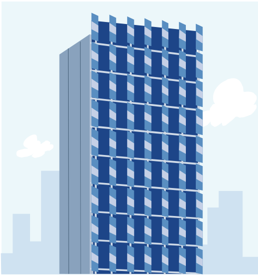
Uncharted territory: Combinatorial optimization problems with an underlying dynamical model.

Class of Computationally Hard Hybrid Dynamic Optimization Models

Clark 1976; Conrad 1999; Ang, Conrad, Just, 2009; Ermano, Li, Conrad, G., Zeeman 2009

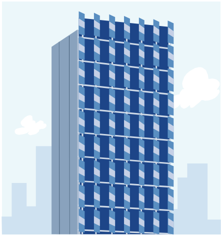
➢Energy

Energy efficiency and renewable energy



III Energy Efficiency and Renewable Energy

- Global warming and climate change concerns have led to major changes in energy policy in many industrial countries.



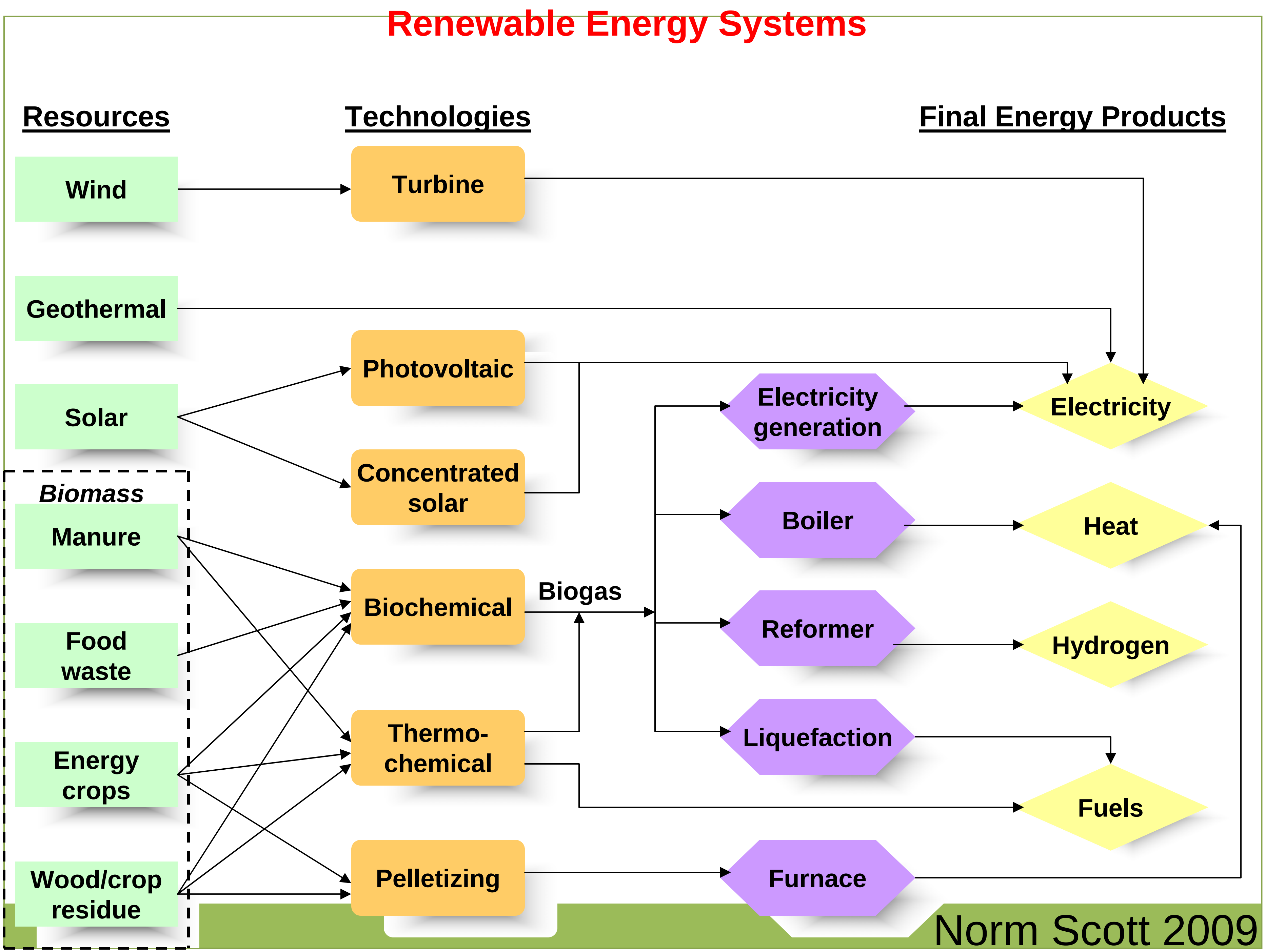
Smart buildings

- There are tremendous opportunities to increase energy efficiency, such as through the design of control systems for smart energy-efficient buildings, vehicles, and appliances.

- The development of renewable energy sources that are cleaner and generate little or no carbon can have an even greater environmental impact.

  – There has been considerable technological progress in the area of renewable energy sources, in part fostered by government incentives.

Renewable Energy

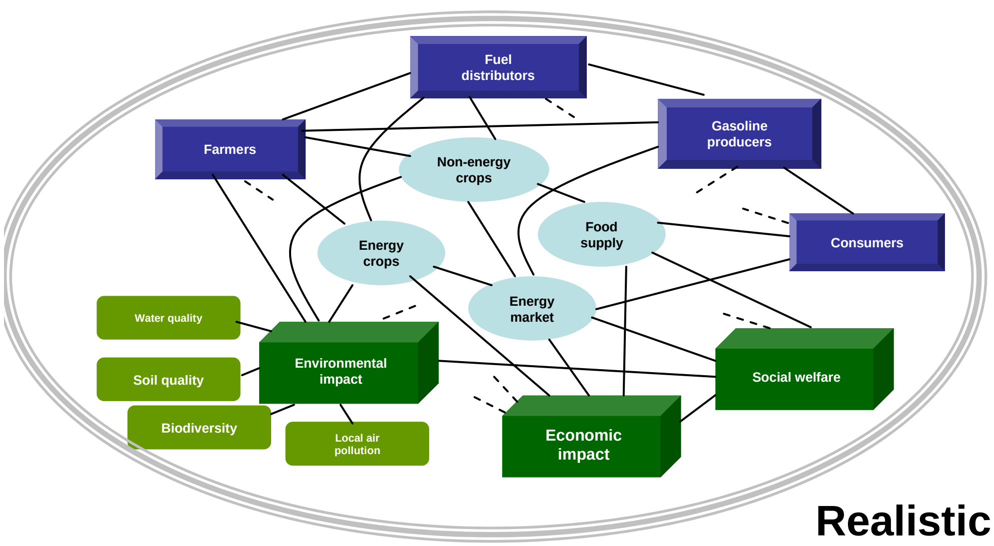

Renewable Energy Systems
Resources
Technologies
Final Energy Products
Wind
Turbine
Geothermal
Photovoltaic
Solar
Concentrated solar
Biomass
Manure
Food waste
Energy crops
Wood/crop residue
Biochemical
Biogas
Thermo-chemical
Pelletizing
Electricity generation
Boiler
Reformer
Liquefaction
Furnace
Electricity
Heat
Hydrogen
Fuels
Norm Scott 2009

III Energy Efficiency and Renewable Energy: Biofules

Energy Independence and Security Act

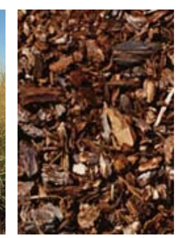
(Signed into law in Dec. 2007)

Ambitious mandatory goal of
36 billion gallons of renewable fuels by 2022
(five-fold increase from 2007 level)



First generation Biofuels

Advanced Biofuels ("*Cleaner*")
(non food crops and biomass)



Switchgrass Wood Waste Animal Waste Municipal Waste

Computational challenges:

Large Scale Logistics Planning
Realistic Computational Models to Evaluate Impact

III Energy Efficiency and Renewable Energy
Large Scale Logistics Planning for Biofuels

Large-scale investment in new technology provides exciting logistical planning and optimization challenges and opportunities

Feedstock Map

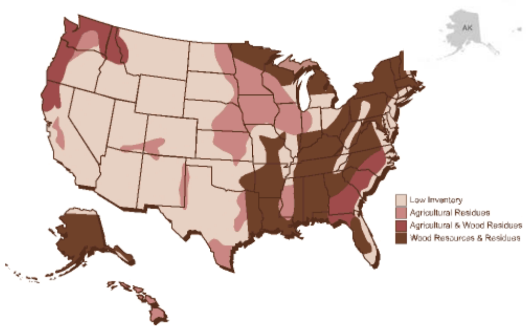
Transportation Network
(Roads, Rail, Marine)

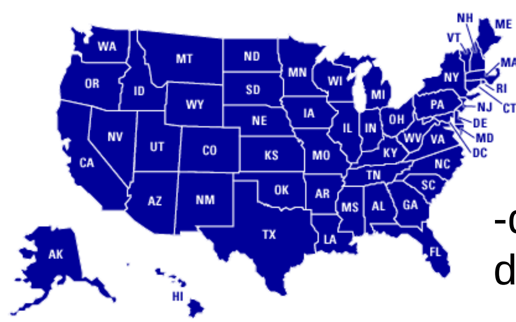
Resulting optimization models are beyond the scope of the current state of the art in several ways:

- -large-scale input;
- -stochastic nature (e.g.,feedstock and demand)
  - →new models to capture uncertainty
  - →new stochastic optimization algorithms;
- -dynamics of evolution of demand and capacity

Distribution Terminals and Inter-Modal Facilities to Transfer Liquid Fuel

Biomass Map





Potential biorefinery locations

Realistic Computational Economic Models to Study the Impact of Biofuels

Current approaches limited in scope and complexity

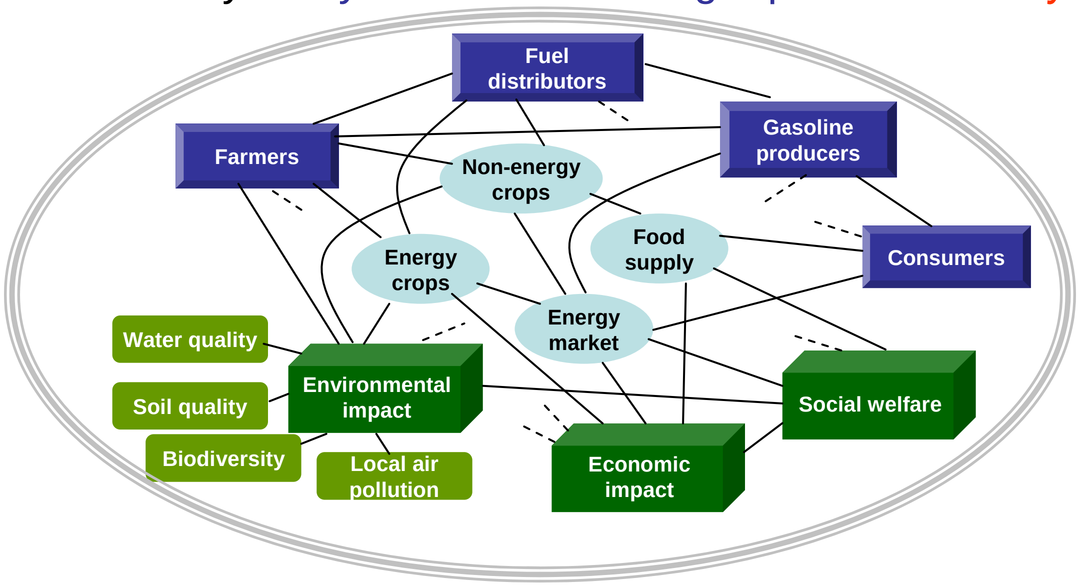
- E.g. based on *general equilibrium models* (e.g., Nash style)
- Strong convexity assumptions to keep the model simple enough for analytical, closed-form solutions (unrealistic scenarios)

  → *Limited computational thinking*

General Equilibrium Models for Biofuels

Transformative research directions

- More realistic computational models in which meaningful solutions can be computed
- Large-scale data, beyond state-of-the-art CS techniques
- Study of dynamics of reaching equilibrium — *key for adaptive policy making!*



How to measure risks/ predict rare events?

Impact of Biofuels: Dynamic Equilibrium Models

Impact of Land-use on Climate

Policies for a carbon cap and trade economy

Computational Research Areas and Themes

Deep Research Challenges posed by Sustainability

Key issues concerning policies for sustainable development translate into large-scale decision/optimization combining a mixture of discrete and continuous effects, in a highly dynamic and uncertain environment

→ increasing levels of complexity

Many highly interconnected components;

→ **From Centralized to Distributed Models**

Multiple scales (e.g., temporal, spatial, geographic)

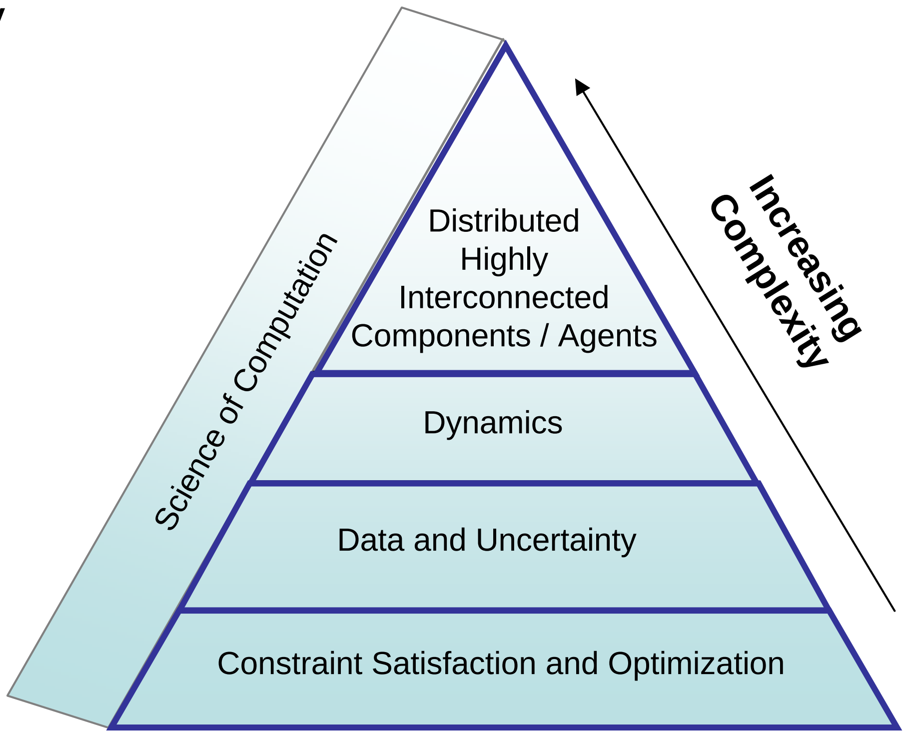
→ **Dynamic Models**

Large-scale data and uncertainty

→ **Machine Learning, Statistical Modeling, Stochastic Modeling**

Complex decision and optimization problems

→ **Constraint Reasoning and Optimization**



Complexity levels in Computational Sustainability Problems

Deep Research Challenges posed by Sustainability

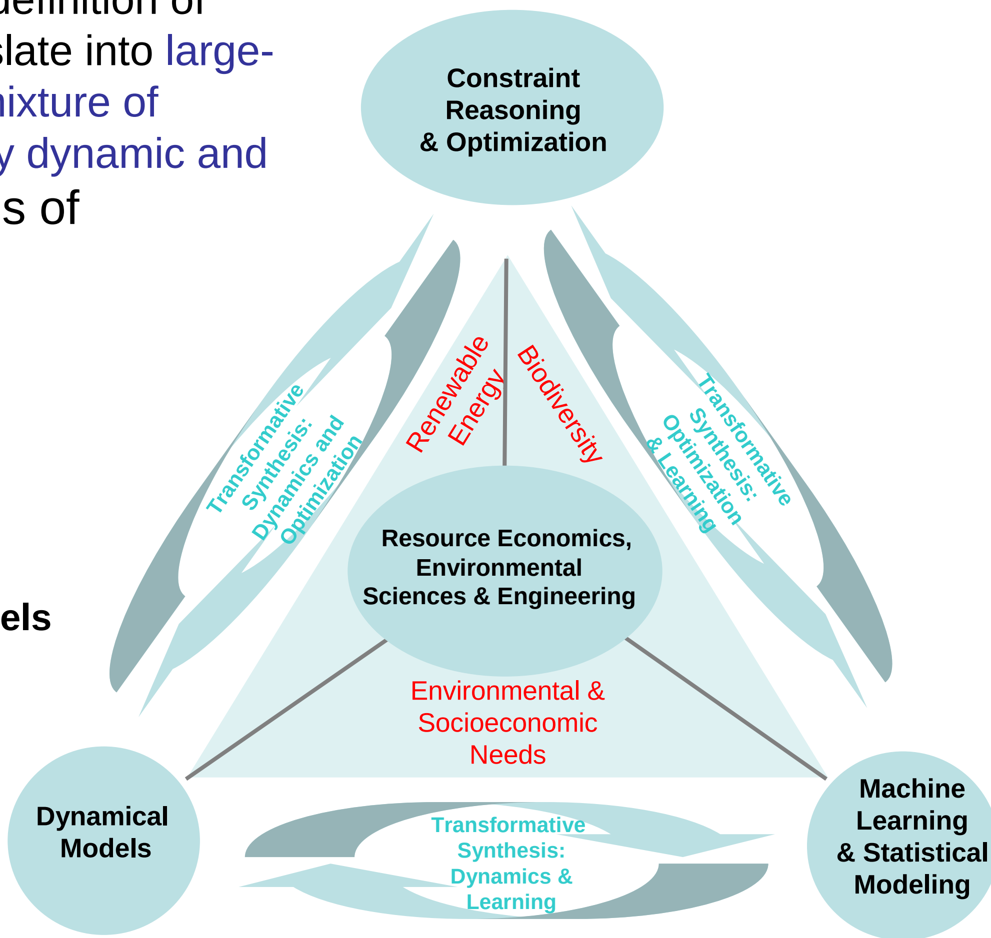
Key sustainability issues concerning the definition of policies for sustainable development translate into large-scale decision/optimization combining a mixture of discrete and continuous effects, in a highly dynamic and uncertain environment → different levels of complexity

Many highly interconnected components;
→ **From Centralized to Distributed Models**

Multiple scales (e.g., temporal, spatial, geographic)
→ **From Statics to Dynamics: Dynamic Models**

Large-scale data and uncertainty
→ **Machine Learning, Statistical Modeling, Stochastic Modeling**

Complex decision models
→ **Constraint Reasoning and Optimization**



- From a computational complexity point of view, computational sustainability problems are often NP-hard or worse, and problem size scales to several orders of magnitude.

- Traditional computer science approach is driven by worst-case analysis; Given the various sources of complexity of computational sustainability problems, different perspective is required.

Computational sustainability problems should be viewed as natural phenomena (instead of purely as mathematical abstractions) in which principled experimentation, to uncover hidden structure, is as important as formal analysis

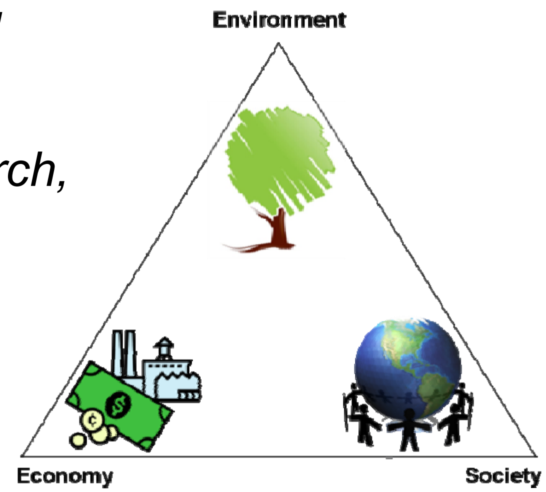
→ **Science of Computation**

Gomes and Selman 2007

Conclusions

Computational Sustainability

Computational Sustainability --- interdisciplinary field that aims to apply techniques from computer science, and related fields(information science, operations research, applied mathematics, and statistics) to help balance environmental, economic, and societal needs for sustainable development.



Focus:

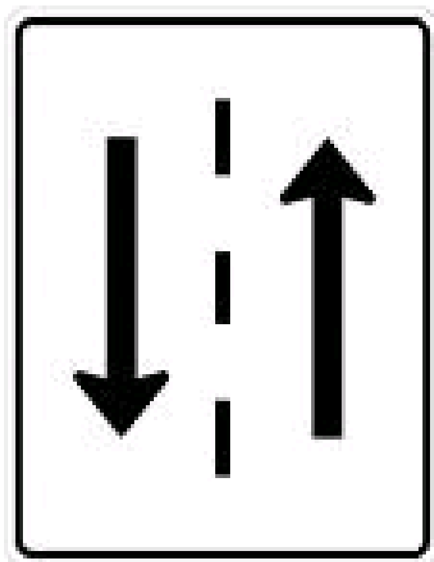
Developing computational models , methods , and tools for decision and policy making concerning the management and allocation of resources for sustainable development.

Computational Sustainability

Sustainability fields

New challenging applications

New methodologies
In Computer Science



Computational Thinking that will provide new insights into sustainability problems:

New methodologies
In Sustainability fields

Computer science and related fields

Analogywith Computational Biology

Computational Sustainability Community

- 1st International Conference on Computational Sustainability (June 8-11, 2009)

Over 225 international researchers from several disciplines and institutions (universities, labs, gov)

- 2nd International Conference on Computational Sustainability

MIT, June 2010

Summary

Computational Sustainability is a fundamentally new intellectual territory with great potential to advance the state of the art of computer science and related disciplines and with unique societal benefits!

Thank you ☺!

Thanks!

- ICS members and collaborators for their many contributions towards the development of a vision for Computational Sustainability, in particular:
  - Chris Barrett, Antonio Bento, Jon Conrad, Tom Dietterich, Bistra Dilkina, Stefano Ermano, Daniel Fink, John Gunckenheimer, Yunsong Guo, John Hopcroft, Steve Kelling, Nianpeng Li, Ken Rosenberg, Ashish Sabharwhal, Bart Selman, David Shmoys, Steve Strogatz, and Mary Lou Zeeman.
- Research support from:

NSF

Cornell University
Center for a Sustainable Future

More Information

For more information:

www.cs.cornell.edu/gomes

www.cis.cornell.edu/ics

www.computational-sustainability.org

Thank you ☺

www.computational-sustainability.org

Building a world-wide community of researchers, educators, policy makers, and students interested in Computational Sustainability

Getting involved

- Join computational-sustainability@yahoogroups.com
  Email list , calendar, polls, discussion, links
- Help with the creation of a ***community web portal***
  www.computational-sustainability.org
  - Benchmarks
  - Open-source tools, software
  - Catalog of challenge problems
  - Annotated bibliography
  - Announcements, news items
- Conferences, workshops, panels, publications
- Collaborative computational sustainability efforts
- Outreach activities

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