Computation and Sustainability: Beyond Green IT

Alan Mackworth

Growth of Awareness of Sustainability

- *An Essay on the Principle of Population*, Malthus (1798)

  "This natural inequality of the two powers, of population, and of production of the earth, and that great law of our nature which must constantly keep their effects equal, form the great difficulty …."

- *Silent Spring*, Carson (1962)
- Club of Rome (1968)
- Greenpeace (1971)
- *Limits to Growth*, Meadows et al. (1972)
- *Our Common Future,* Brundtland Report (1987)
- Intergovernmental Panel on Climate Change (IPCC, 1988)
- *Climate Change 2007*, IPCC (2007)
- *Global Environment Outlook GEO-4,* UNEP (2007)
- *The Limits to Growth Revisited,* Bardi (2011)
- *Climate Change 2013: The Physical Science Basis* (IPCC, 2013)

Sustainable Development

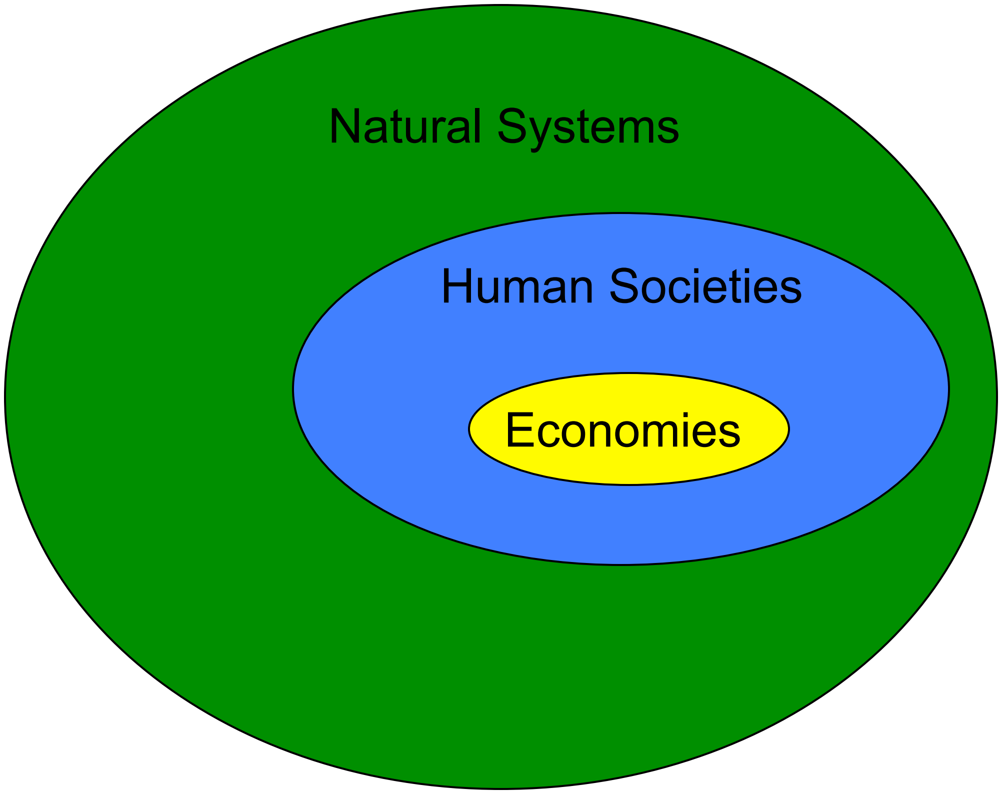
Our Common Future, Brundtland Report (1987)

Sustainable development meets the needs of the present without compromising the ability of future generations to meet their needs.

Sustainable development requires satisfying environmental, societal, and economic constraints.

Environmental, social and economic issues are intertwined.

Nature, Society and Economy



An economy only exists in the context of a society, and both social and economic activity are constrained by the earth's natural systems and resources.

Sustainability

Sustainability The ability to maintain the balance of a process in a system

Ecological Sustainability The ability of an ecosystem to maintain ecological processes, functions, biodiversity and productivity into the future

Human Sustainability The ability to meet the needs of the present without compromising the ability of future generations to meet their own needs

Resilience

Ecosystem resilience: the capacity of an ecosystem to tolerate disturbance without collapsing into a qualitatively different state. Resilience in social systems has the added capacity of humans to anticipate and plan for the future. (Holling, 1973)

"Resilience" as applied to ecosystems, or to integrated systems of people and the natural environment, has three defining characteristics:

1. The amount of change the system can undergo and still retain the same controls on function and structure
2. The degree to which the system is capable of self-organization
3. The ability to build and increase the capacity for learning and adaptation

[Source: www.resalliance.org]

Computation

- Basic power growing exponentially: ~100x each decade
- Similar growth in sensing, actuators, big data and communications networks
- Huge software systems for commerce, supply chains, search engines, financial & logistic systems, cloud computing, …
- Next, ubiquitous computing: computers disappear, the Internet of things, smart matter, smart personal transit, …
- Computer science is surfing the wave of innovation

Computer Science

- Early days, make computers more efficient, easier to program: OS, compilers, prog. languages, complexity theory (inward looking)
- Then, make computers smarter, easier to interact with: AI, machine learning, HCI, robotics, …
- Now mobile ecosystems, social networks, smart buildings, automatic translation, speech understanding, self-driving cars, household robots, …
- Computational thinking pervasive
- CS was peripheral, now central to the intellect & the university

> $\forall x\, \exists y$ *(y = 'Computational x')*
>
> $x \in$ *{Science, Physics, Astronomy, Biology, Chemistry, Music, Economics, Psychology, Linguistics, Sustainability, …}*

- Computation transforming society and the economy

Green IT

Sustainability meets computation.

Green IT: “designing, manufacturing, using, and disposing of computers, servers, and associated subsystems [...] efficiently and effectively with minimal or no impact on the environment.” [Source: Wikipedia]

- Lifecycle design
- Modular, replaceable, recyclable systems
- Low power chips and programming
- Cloud computing
- Server farm design
- Load balancing
- Green renewable energy supplies

E-Waste: not-so-green IT

Computation & Dematerialization

***Computation has, at its core, an inherent sustainable dynamic: dematerialization - from atoms to bits*.**

- Physical mail displaced by email and texting
- Paper books by e-books
- Analog photography, film and video by digital
- Planes and cars by Skype, Facebook and Twitter
- ….

Green IT is worthwhile and important, but dematerialization is much more significant.

Computational Sustainability

Computational Sustainability is an interdisciplinary field that applies techniques from computer science, information science, operations research, applied mathematics, and statistics for balancing environmental, societal and economic needs for sustainable development. (Gomes *et al.*)

Two main themes:

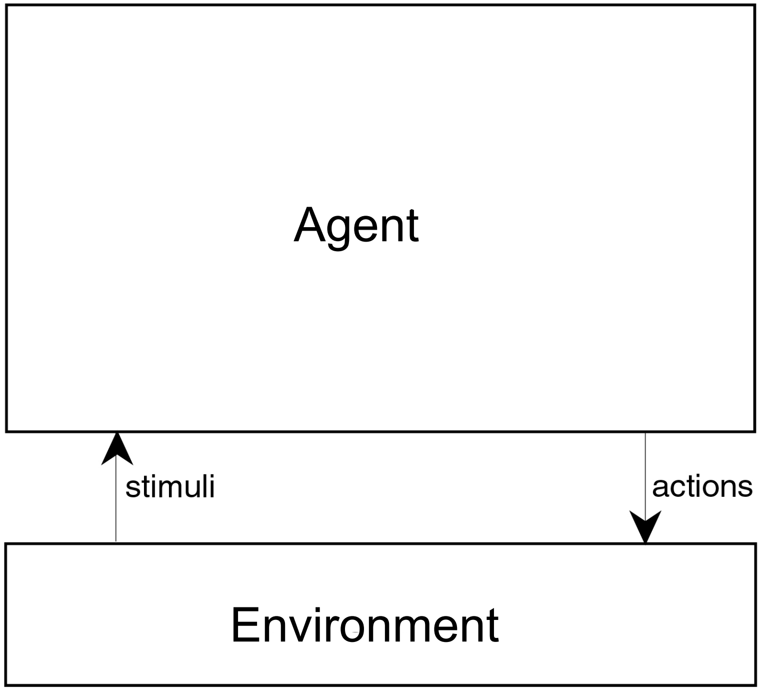
1. Developing computational models and methods for decision making for the management and allocation of ecosystem resources
2. Developing computational modules embedded directly in ecosystem monitoring, management and control systems

Constraint satisfaction is at the core of computational sustainability.

Designing Constraint-Based Agents

- The evolution of the pivotal role of constraints in intelligent systems: from static to dynamic constraints
- Theory of constraint-based agent design and experiments in robot architecture for soccer etc. (Mackworth et al.)
- Our collective failure to recognize and satisfy various constraints explains why many of the worlds we live in are unsustainable - out of kilter.

An Agent in the World



Constraints on an Agent

An agent could be a robot, a bacterium, a human or humankind.

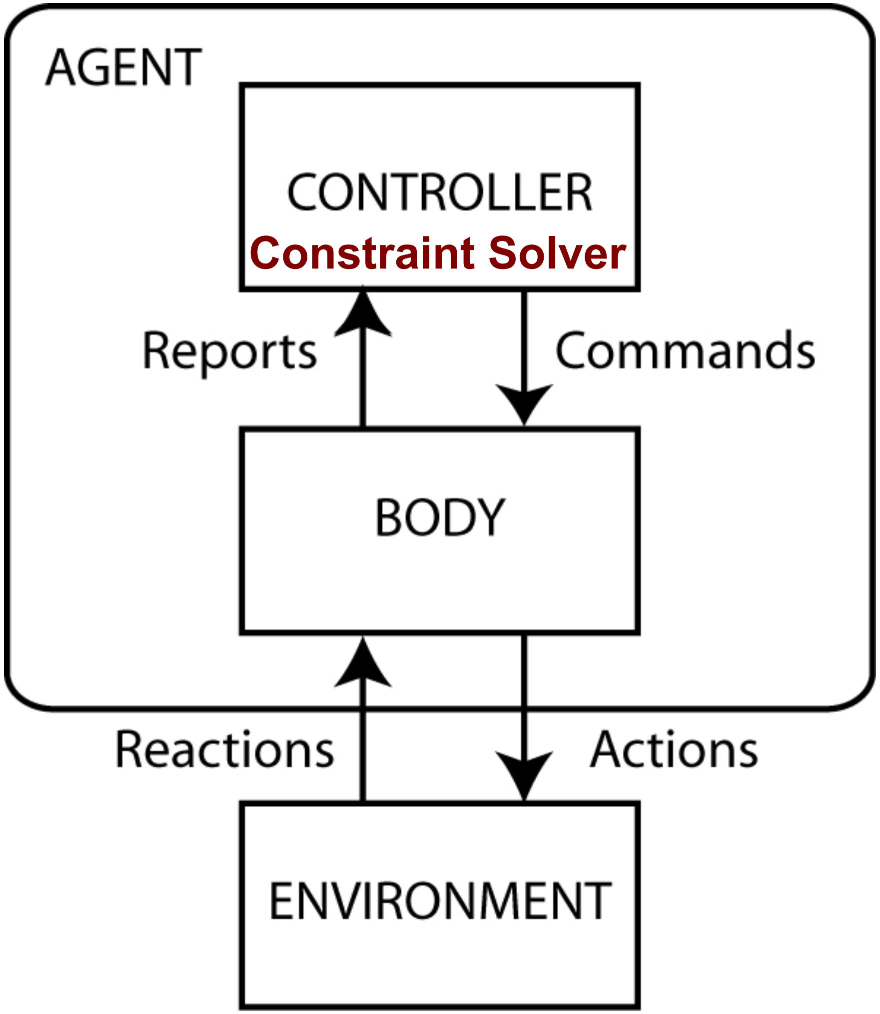
To thrive, an agent must satisfy dynamic constraints deriving from four sources:

A. Its internal structure
B. Its goals and preferences
C. Its external environment
D. The coupling between its internal and external worlds

The life of any agent who does not respect and satisfy those constraints will be out of balance.

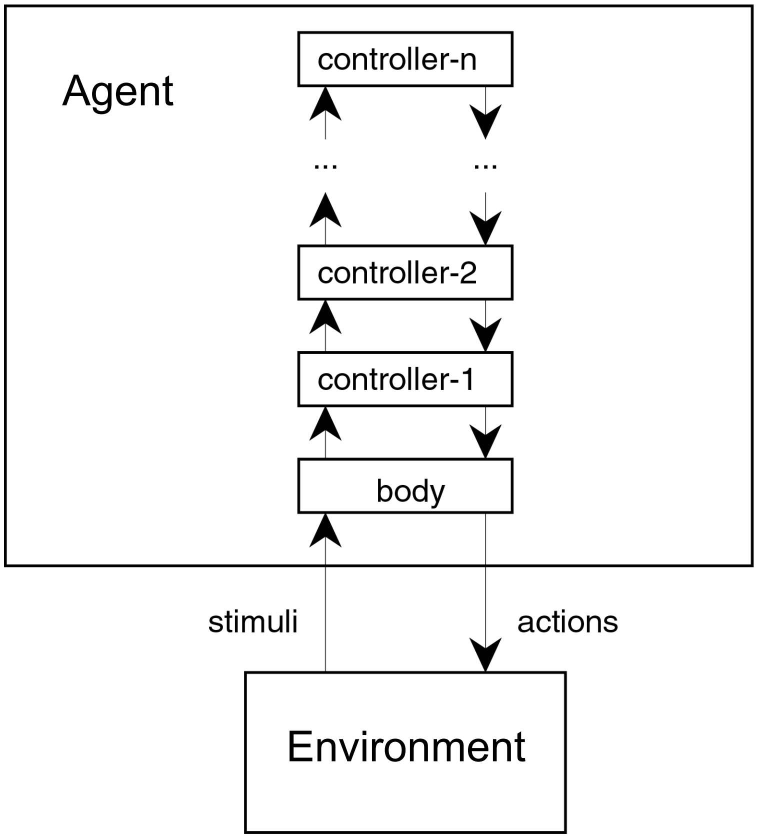
A Constraint-Based Agent

- **Situated Agents**
- **Constraint Satisfaction**
- **Prioritized Constraints**
  e.g. Asimov's laws



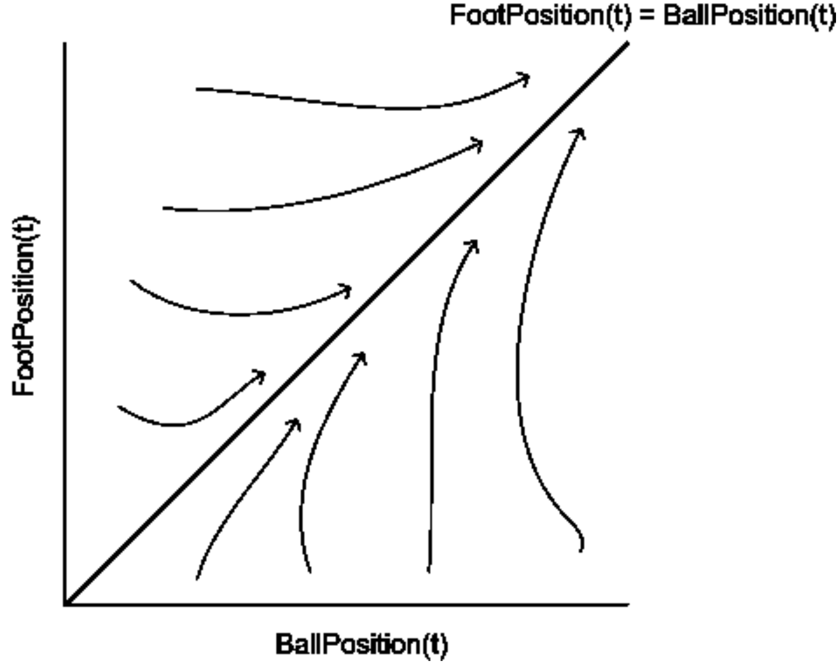
CBA Structure

Vertical Architecture



(Albus, Brooks, Zhang & Mackworth, …)

Dynamic Constraint Satisfaction



We say the coupled agent-environment system *satisfies a constraint* if the constraint's solution set, in the phase space of the coupled hybrid dynamical system, is an attractor of the system, as it evolves.

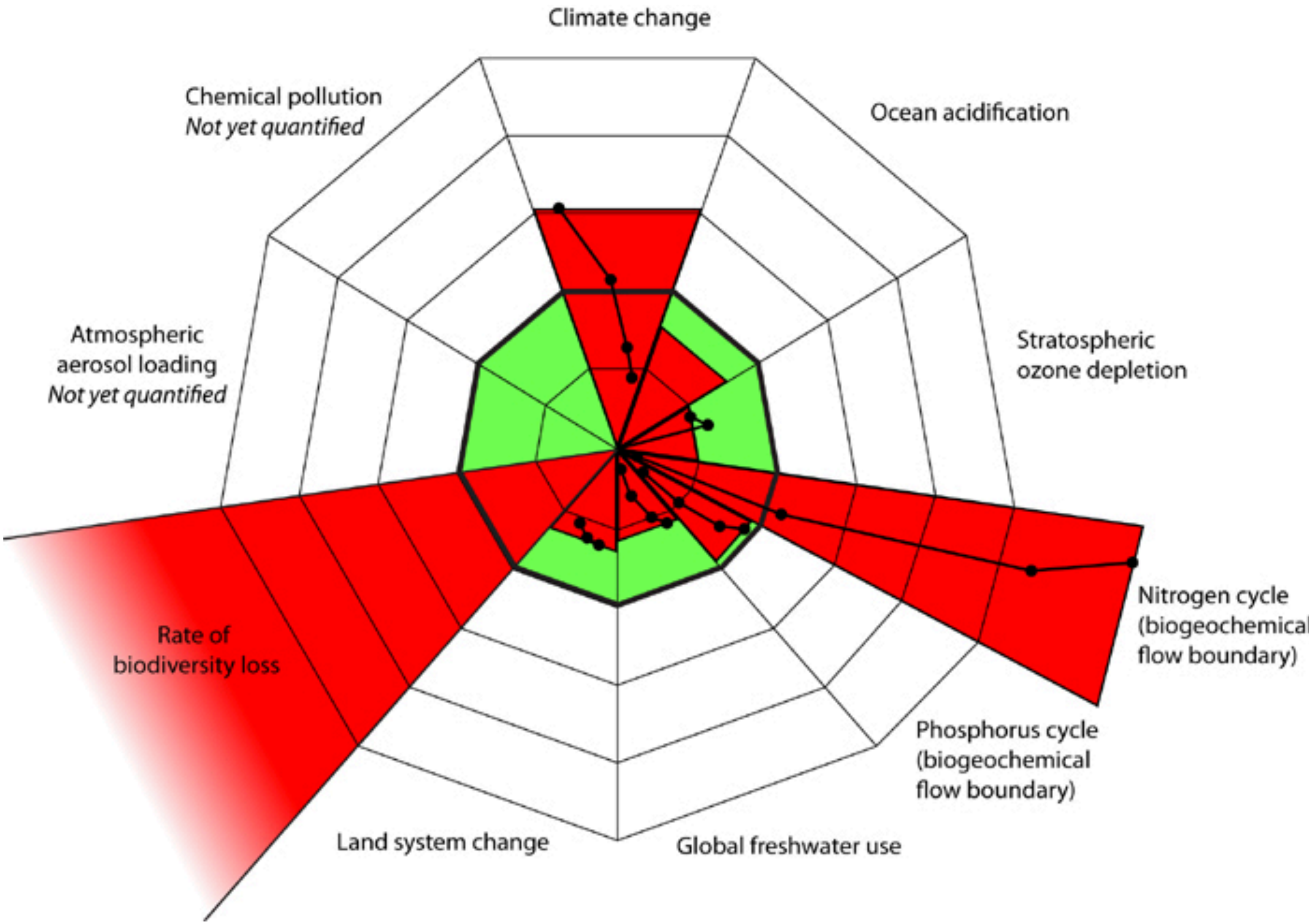
Constraint-based Sustainability

Sustainable systems must satisfy physical, chemical, biological, psychological, social and economic constraints.

Consider constraints involving energy supply, waste management, GHG, ocean acidity, climate, ecological footprint, biodiversity, habitat, harvesting, food supply, population size and global equity.

Sustainability = Constraint Satisfaction

Planetary Boundaries as Constraints

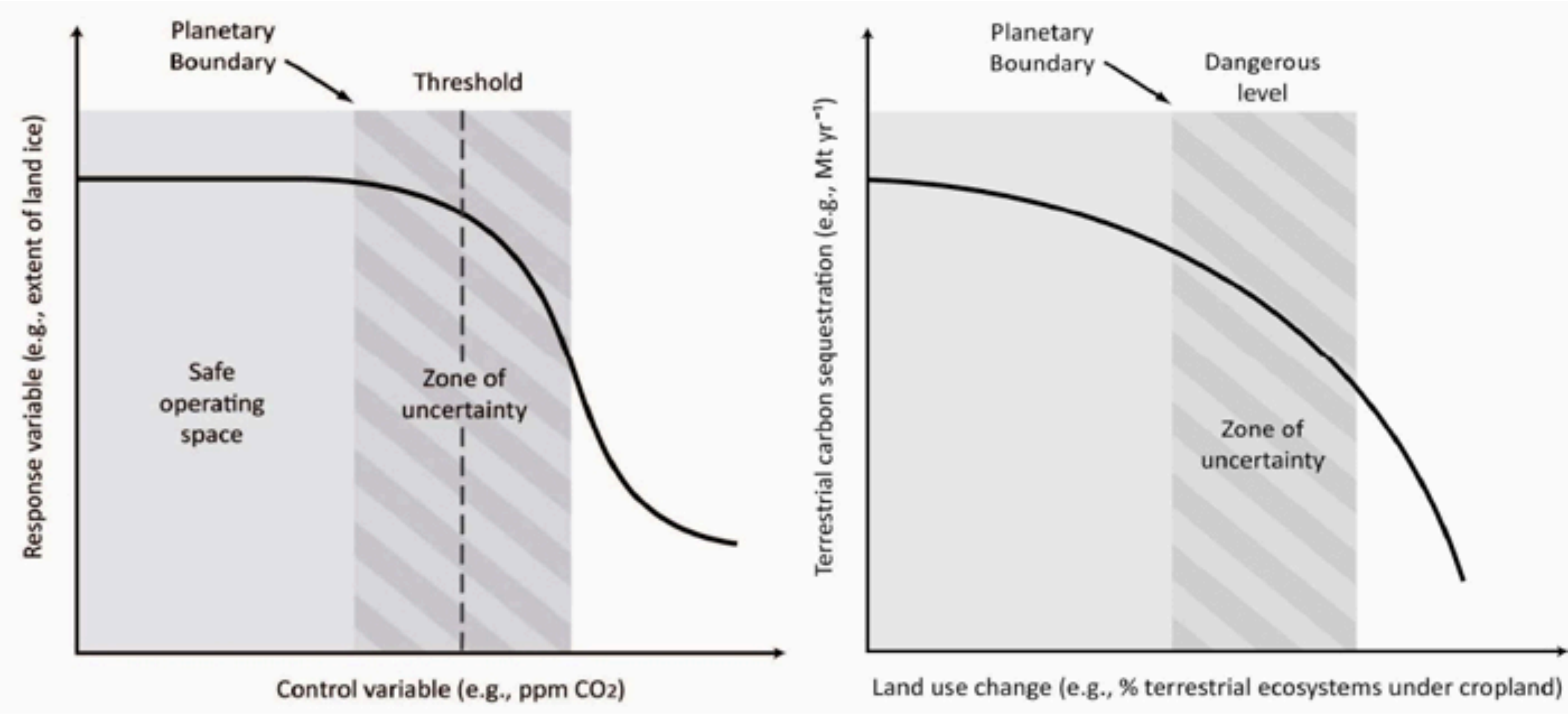


[Source: “Planetary Boundaries: Exploring the Safe Operating Space for Humanity”, (Rockström *et al.*, 2009)]

Safe Operating Space

- Simple conceptual model: 10-dimensional phase space for the planetary dynamical system.
- The safe operating space is defined by an envelope within which those biophysical constraints ($x < x_{limit}$) are all satisfied.
- Many of the subsystems display resilience in that they resist movement away from homeostasis, moving back to an equilibrium - Gaia principle, Daisy World (Lovelock).
- But disturbance beyond the resilient limit can tip the system into a new basin of attraction which may represent abrupt environmental change e.g. collapse.

Setting the Constraint Boundaries

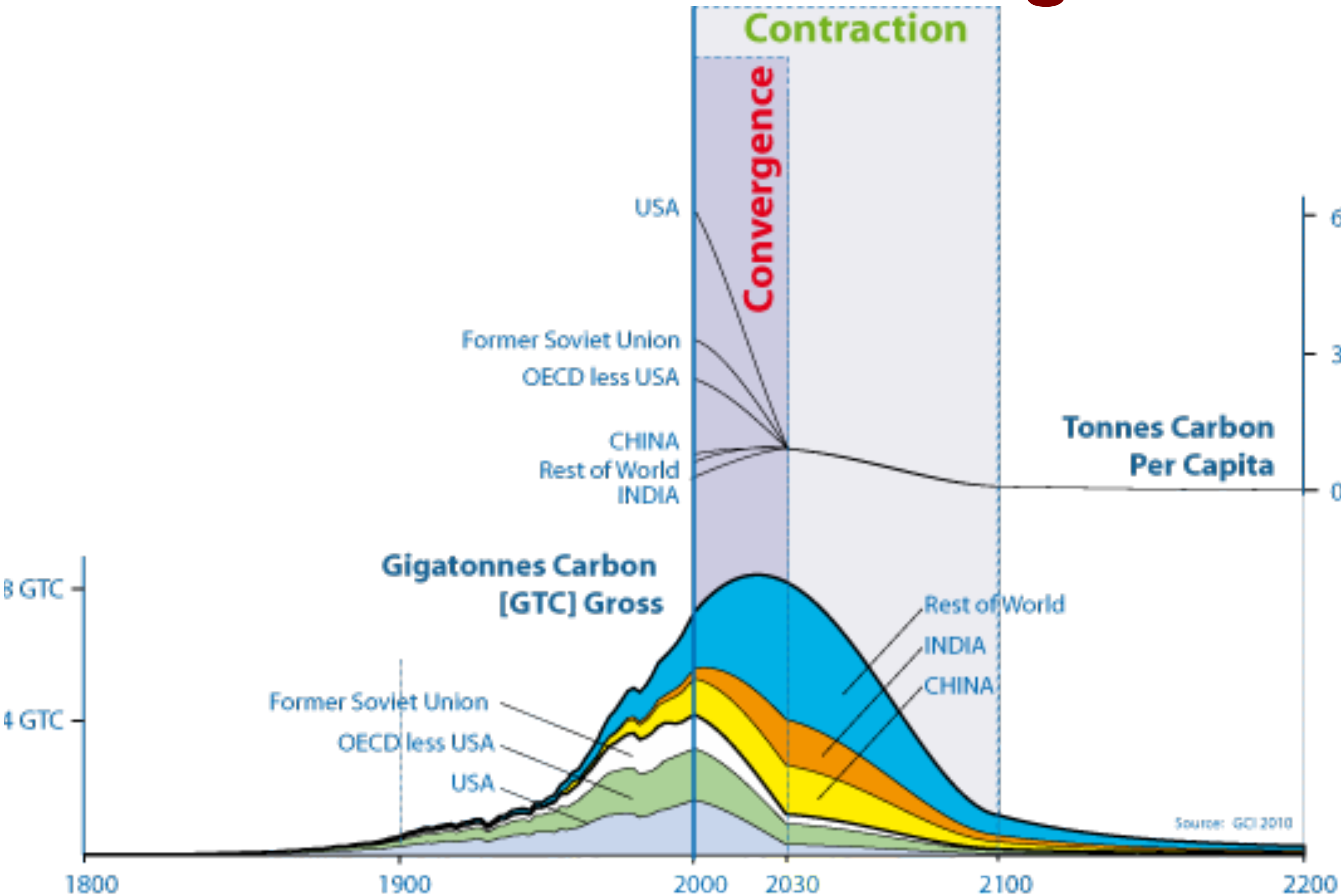


[Source: "Planetary Boundaries: Exploring the Safe Operating Space for Humanity", Rockström *et al.*, *Ecology and Society* (2009)]

The Carbon Constraint: One Trillion Tonnes

- Copenhagen (2009): limit global warming < 2° C
- IPCC (2013) **total** cumulative carbon emissions < 1 trillion tonnes
- To date 574 billion tonnes emitted www.trillionthtonne.org
- Trends say 1 trillion tonnes emitted by 2040
- How to allocate the 426 billion tonnes available in the cap?
- About one trillion tonnes in viable fossil fuels available
- Global equity: USA used its per capita share by 1936.
- Political issue: setting the starting point – ignore the past?
- Assumptions: other GHGs, ocean & terrestrial capture (~50%), permafrost, carbon capture and storage, geo-engineering, ….

Satisfying the carbon constraint: contraction and convergence



[Global Commons Institute www.gci.org.uk]

Design Space for Computational Sustainability Systems

Five dimensions:

1. *Level*

   Primary level that constraints operate at: *biophysical, biological, social* or *economic*. Note that most systems operate with constraints at several levels.

2. *Domain*

   Application sphere: *climate, ocean, fisheries, energy, agriculture, transportation, urban design, education, healthcare, ...*

3. *Type*

   Role: *model* or *embedded*

4. *Spatial Scale*

   From *nano (10^{-9}m)* to *global (10^{7}m)*

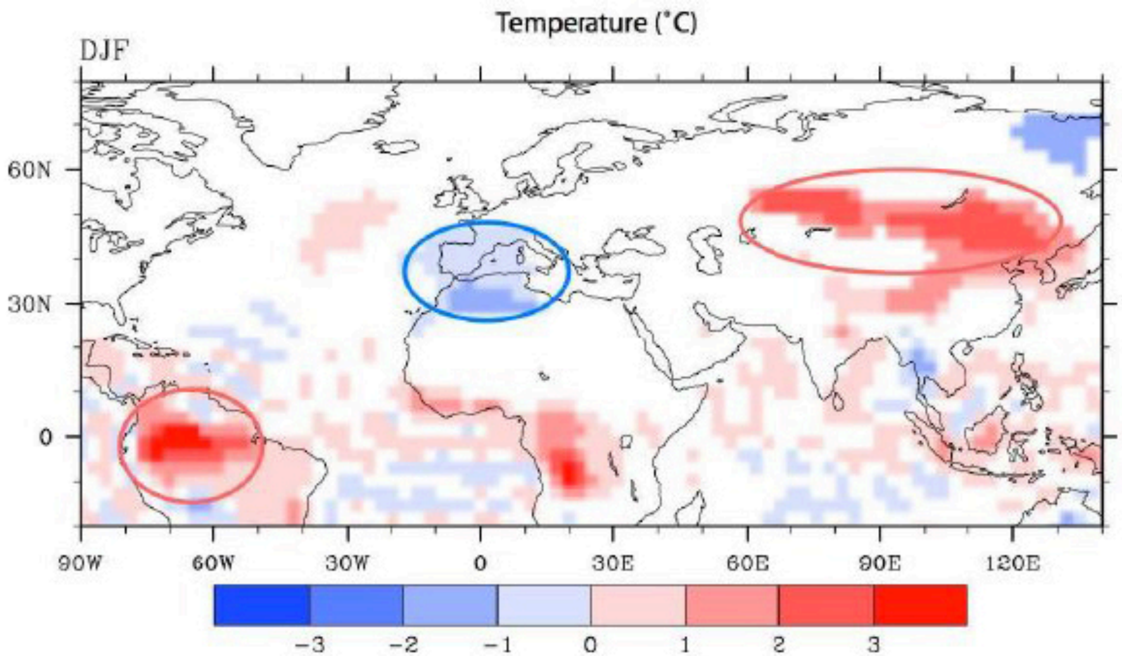
5. *Temporal Scale*

   From *fast (10^{-3}s)* to *slow (10^{9}s)*

Climate Models

Level: biophysical; Domain: climate; Type: model

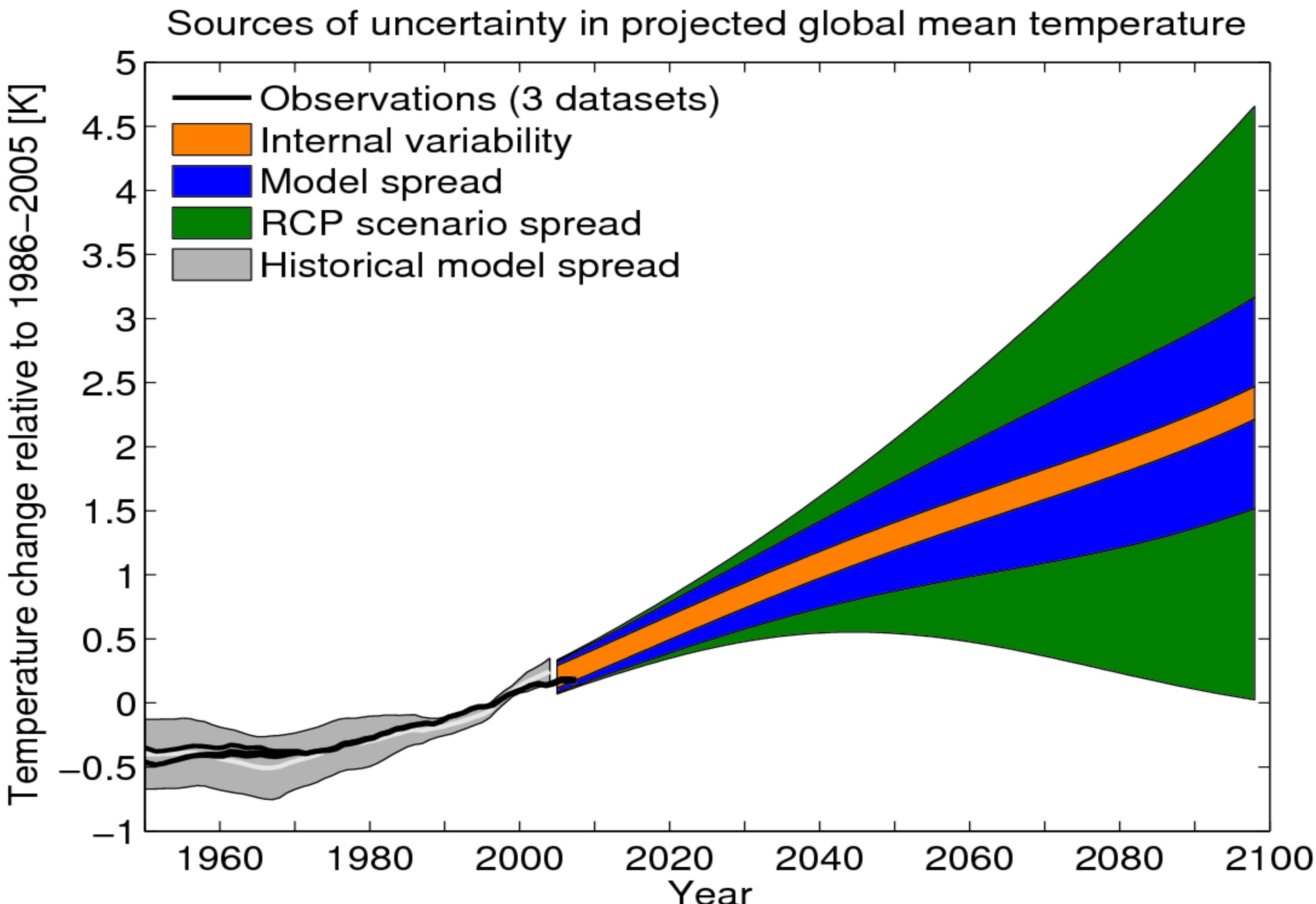
IPCC models



Simulated global surface temperature changes as a result of converting the tropical forest basins of the Amazon, Africa, and the Indian archipelago from rainforest to bare ground.

This simulation was performed by the CCM3 climate model, coupled to the IBIS land Surface/ecosystem model (Snyder et al., 2004a,b) [Source: (Rockström *et al.*, 2009)]

Sources of Uncertainty



[IPCC AR5 (2013)]

Climate change threatens outdoor hockey in Canada

Outdoor hockey season already shortened.

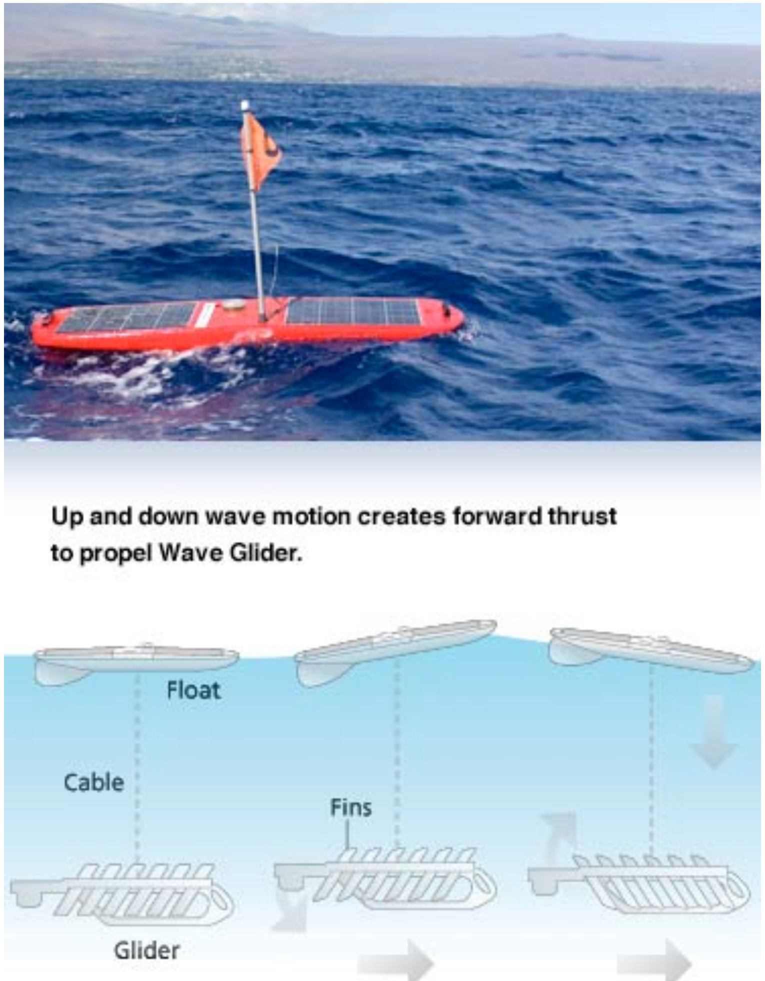
“If we extend the trends into the future, there could be no outdoor skating rinks with global warming taking place”

(Mysak et al., 2011)

[Source: Globe and Mail, March 4, 2011]

Oceanographic Monitoring

Level: biophysical; Domain: ocean; Type: embedded



Liquid Robotics' PacX Challenge Wave Gliders break world record for distance by an unmanned wave powered vehicle, surviving gale force winds to reach Hawaii from San Francisco.

Wave Gliders use ocean wave energy for propulsion, solar energy to power sensors and transmitters to satellites.

"Liquid Robotics tackles a rocket science problem that does good for the world and is incurably cool. ….
It involves a large data problem and a large-scale control problem, both of which … have been passions of mine for years."

James Gosling, Chief Software Architect

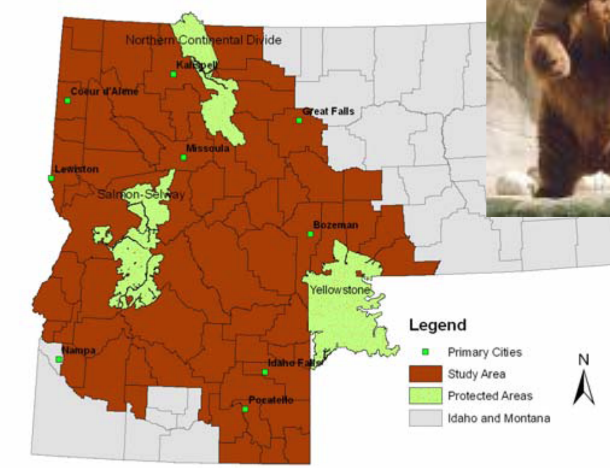
[Source: liquidr.com]

Wildlife Corridor Design

Level: biological; Domain: mammal habitat; Type: model

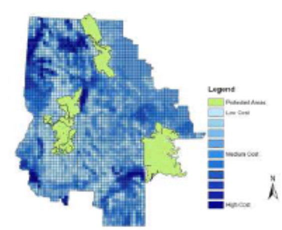
Wildlife Corridors link core biological areas, allowing animal movement between areas. Design resilience against climate change.

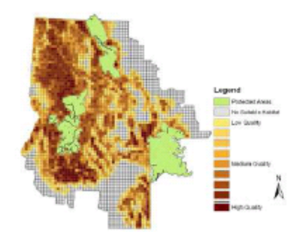
Constraint Optimization:
Maximize resilience, minimize cost.



Preserve grizzly bear populations in the U.S. Northern Rockies by creating wildlife corridors connecting 3 reserves.

Related projects: migratory bird flyways.





[Sources: Conrad, Dilkina, Gomes, van Hoeve, Sabharwal, Sutter (2007-2010)]

Computational Insights into the Social Life of Zebras

Level: biological; Domain: mammal habitat; Type: embedded

Zebra dynamic social network analysis

Zebra bar codes

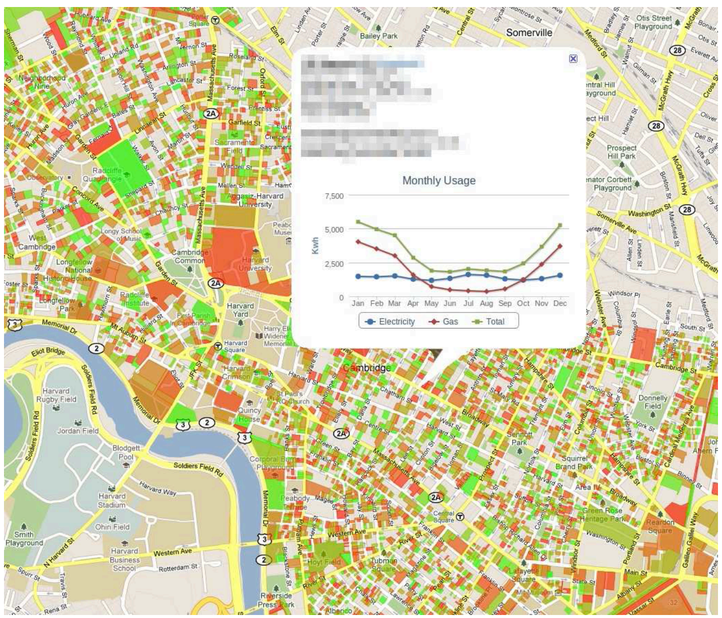
[Image: Tim Flach/Getty]

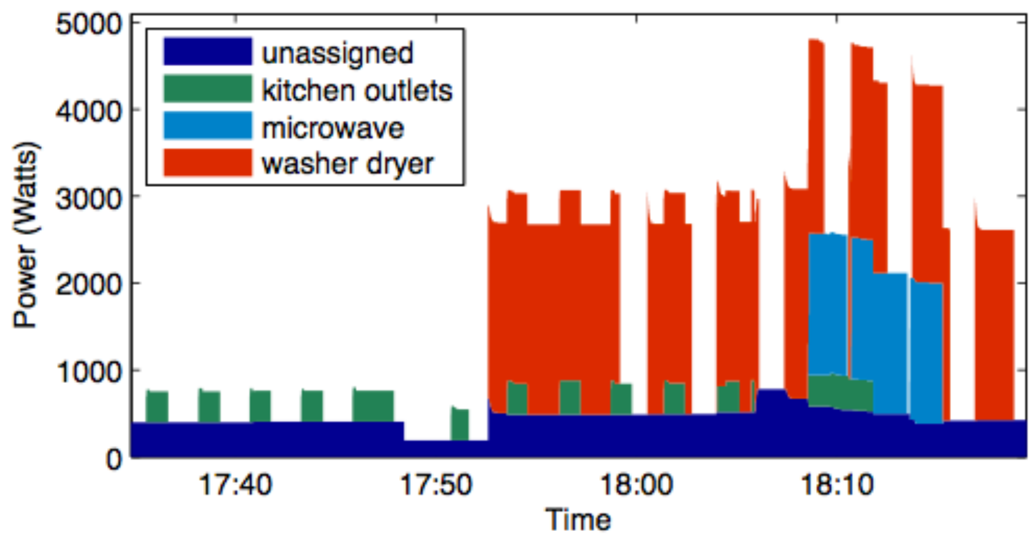
[Sources: Berger-Wolf *et al.* (2010, 2011)]

Energy Management

Level: social; Domain: energy; Type: embedded

Smart grid, smart meters, disaggregation, adaptive pricing and demand, smart batteries, ….





[Sources: Kolter et al. (2011, 2012)]

Smart Buildings

Level: social; Domain: architecture; Type: embedded

UBC Centre for Interactive Research in Sustainability

The UBC Living Lab project

[Images: Don Erhardt]

RoboCars

Level: social; Domain: transportation; Type: embedded

"Junior"
(Stanford Racing Team, 2007)

"Boss"
(CMU-GM Tartan Racing Team, 2007)

DARPA Urban Challenge

Smart Cars

Level: social; Domain: transportation; Type: embedded

Social sustainability consequences:

- Auto, pedestrian and cyclist safety
- (Human) driver can relax
- Increase in road capacity: fewer roads
- Fuel efficiency, platooning
- Shared cars, less material waste
- Fewer parking lots
- Truly self parking auto-taxis
- Inter-vehicular communication and coordination
- Intersections: no stop signs or traffic lights, 2-3x capacity increase?
- Autonomous traffic control: autonomous intersection management protocol (AIM) avoids deadlock (gridlock) and livelock (Stone *et al.*, 2004-12)

Google self-driving Prius

Urban Design

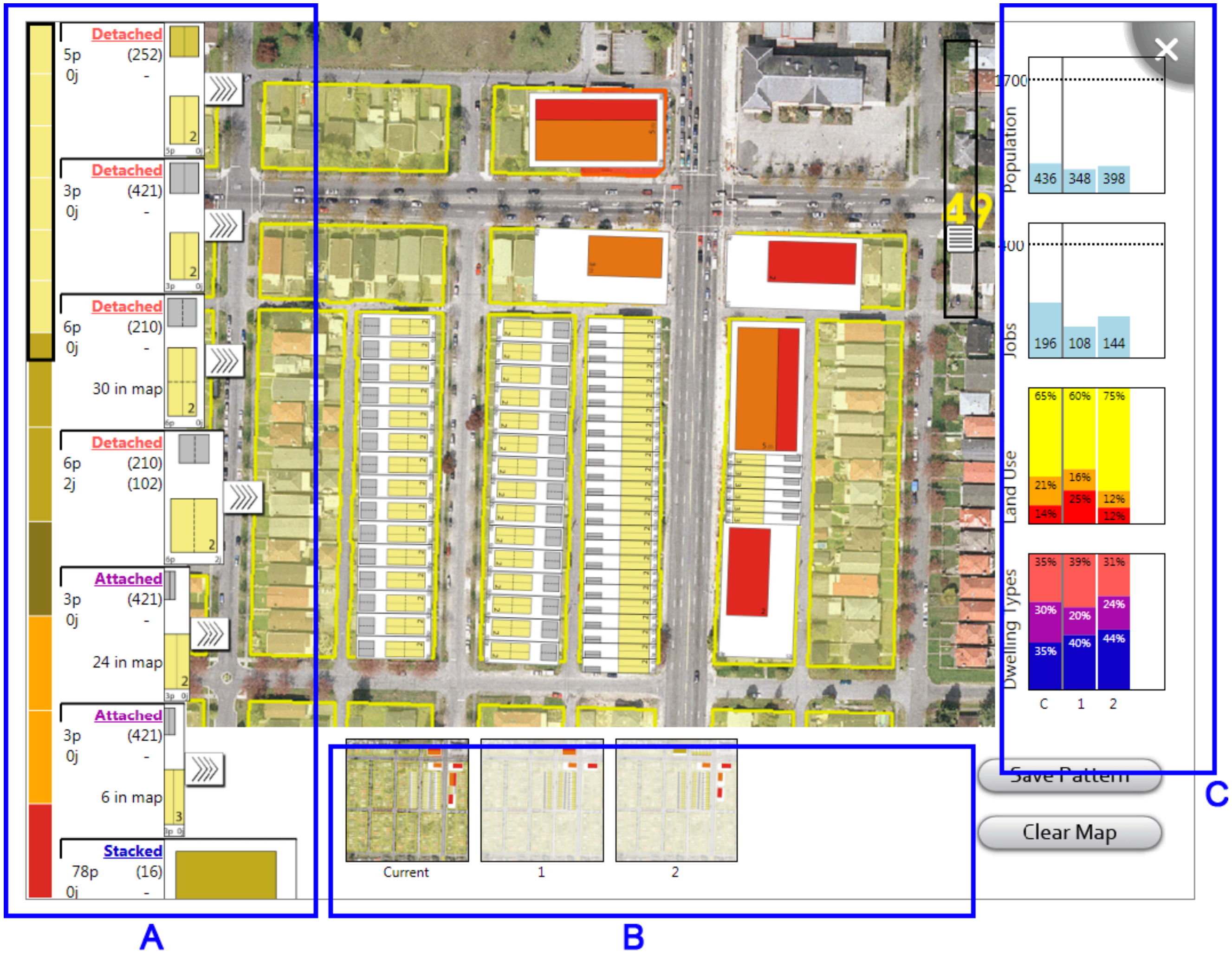
Urban design sustainability principles (constraints)

1. *Jobs*: Job sites located within communities reduce time spent travelling to work.
2. *Corridors*: High density commercial and residential corridors focus growth along transit routes
3. *Walkability*: Interconnected street systems link residents with the services they need.
4. *Green space*: Green spaces provide recreation opportunities and connect people with natural systems.
5. *Infrastructure*: Integrating natural systems reduces infrastructure costs and environmental impact.
6. *Housing*: A range of housing types allows residents of differing economic situations to live in the same neighbourhood and have access to the same services.

[Source: *Sustainability by Design: A Vision for a Region of 4 Million*. Design Centre for Sustainability (2007)]

Urban Design

Level: social; Domain: urban planning; Type: model



A Collaborative Planning Support System for a Multi-Touch Tabletop

[Source: Fernquist (2010)]

Educational Equity

Level: social; Domain: education; Type: embedded

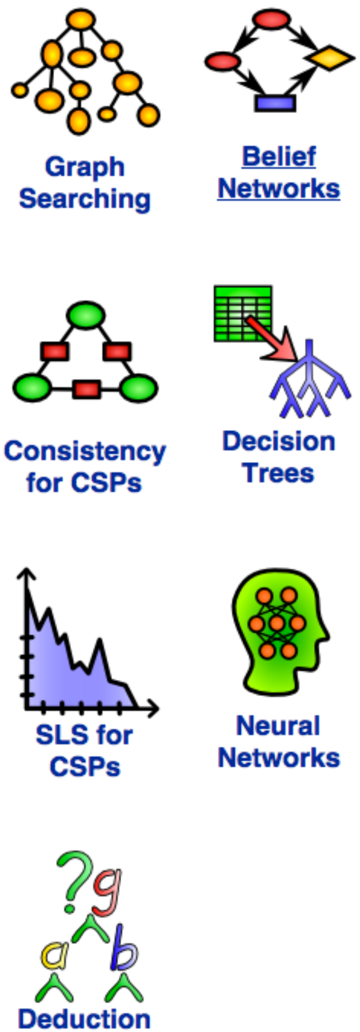
- Khan Academy: khanacademy.org
- Massive open online courses (MOOCS):
  coursera.org, udacity.com
- Learn to code web courses: codeyear.com
- AIspace: aispace.org

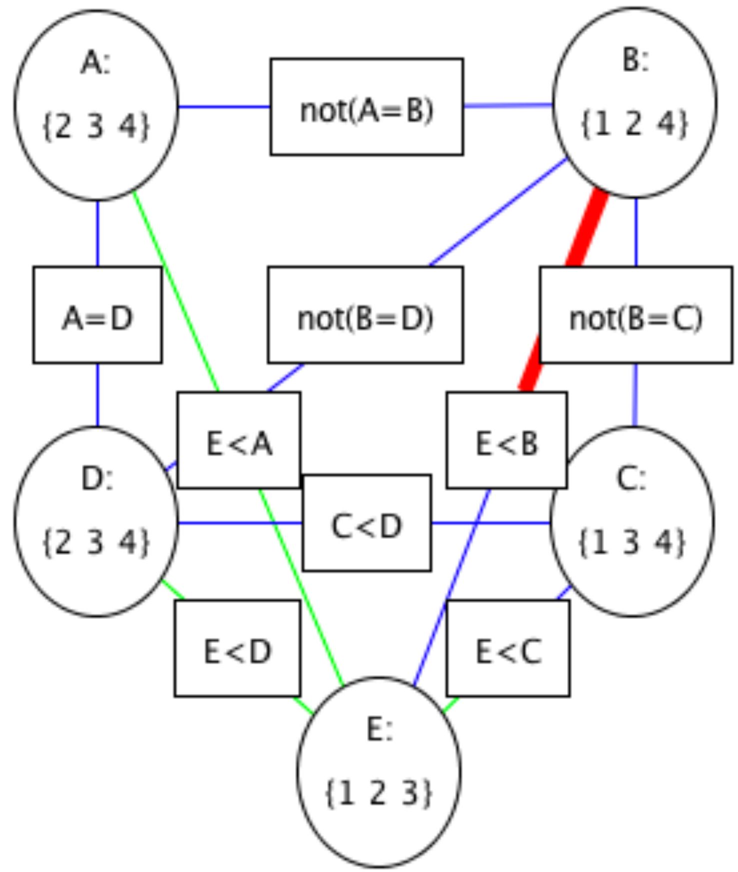
"I am **against** education that is only available to the top 1% of all students. …. I want to **empower** the 99%. …. Education should be **free**. Accessible for **all, everywhere, and any time**."

Sebastian Thrun [Source: robots.stanford.edu]

Educational Equity:

Level: social; Domain: education; Type: embedded





Consistency-based Constraint Satisfaction Problem Solver

[Source: www.aispace.org]

Wheelchair Mobility

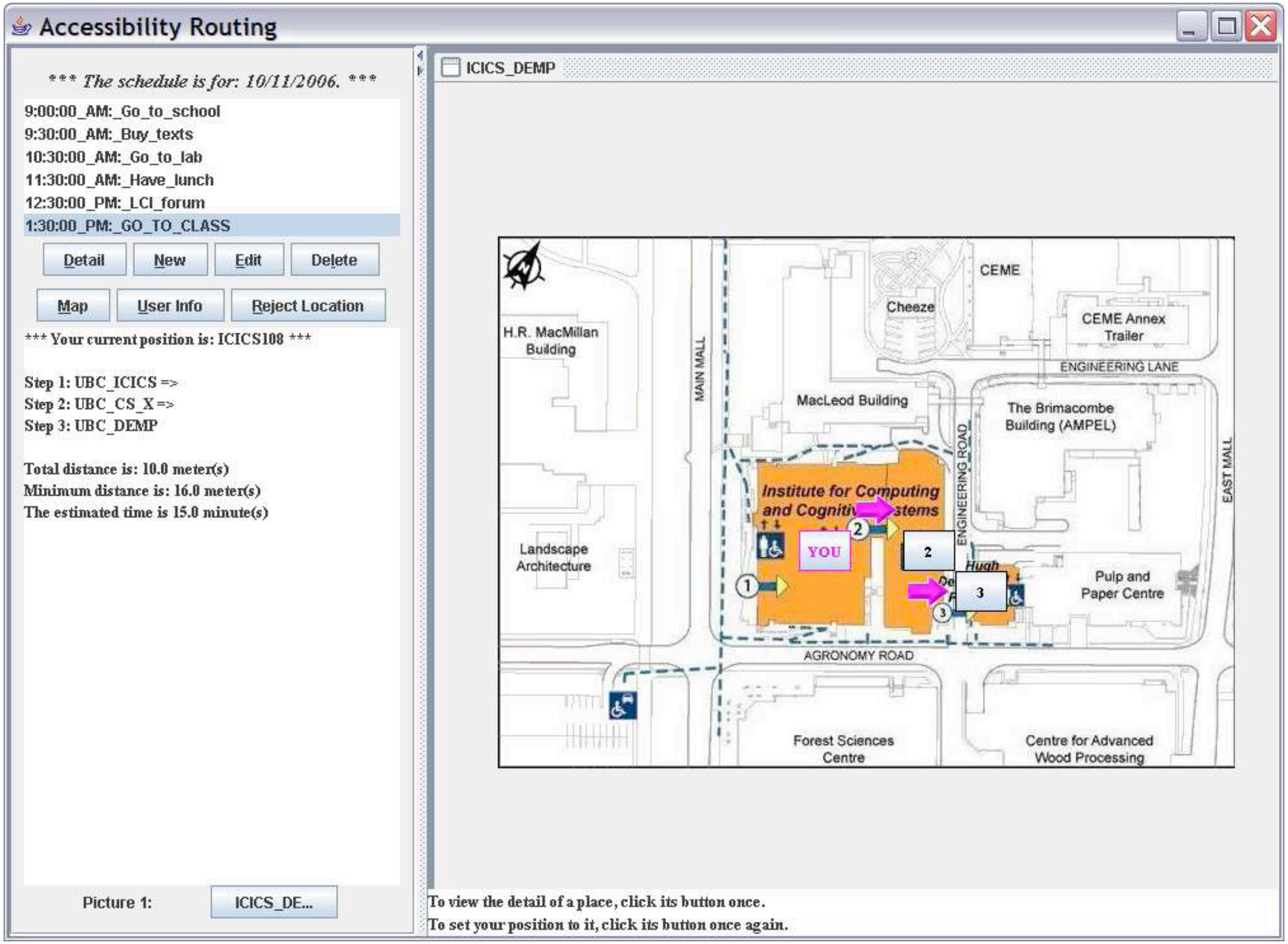
Level: social; Domain: health; Type: embedded

The design of two assistive technology prototypes for people with physical and mental disabilities who are living with significant additional constraints:

- Wayfinding in a chair
- Aging sustainably

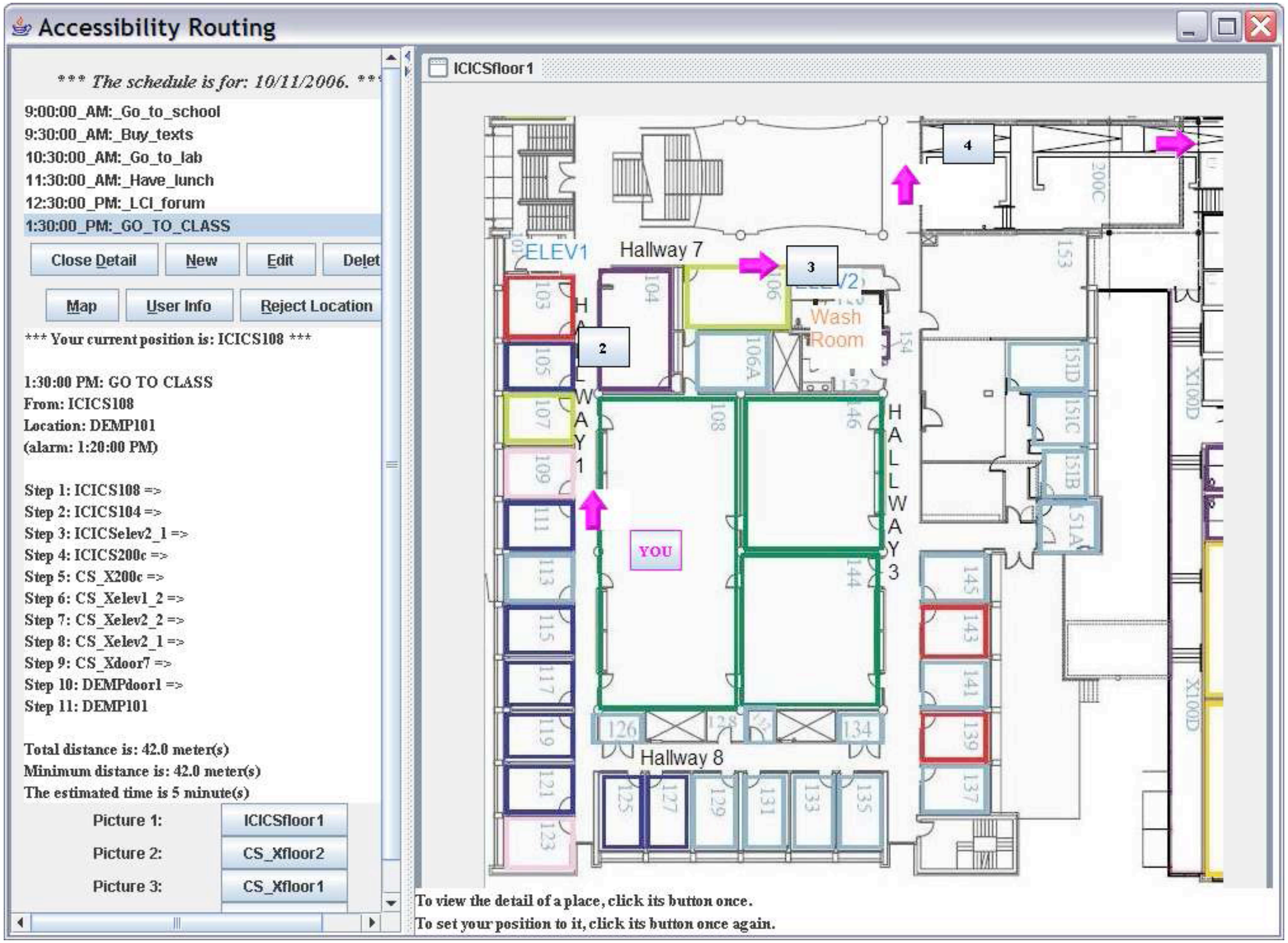
Intelligent wheelchair: mild dementia, nursing homes, acute care, aging in place, …

Wayfinding for Wheelchair Users



(Yang & Mackworth, 2007)

Wayfinding in a Building



(Yang and Mackworth, 2007)

Satisfying Mobility Constraints in NOAH

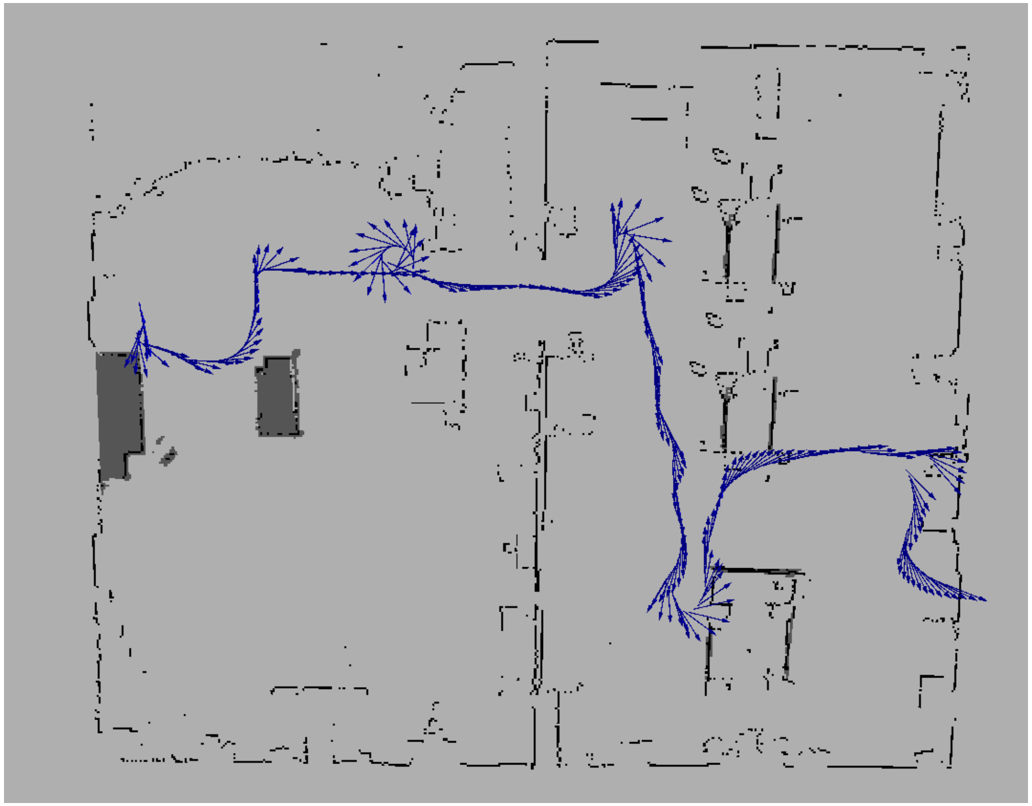
Navigation and obstacle avoidance help (NOAH) in a collaboratively controlled smart wheelchair

[Sources: Viswanathan *et al.*(2009-2012)]

Satisfying Mobility Constraints in NOAH

Navigation and obstacle avoidance in a collaboratively controlled smart wheelchair

[Sources: Viswanathan *et al.*(2009-2012)]



Crop Disease Monitoring

Level: economic; Domain: agriculture; Type: embedded

Crop Disease Monitor

Automated diagnosis and mapping of crop disease in Uganda

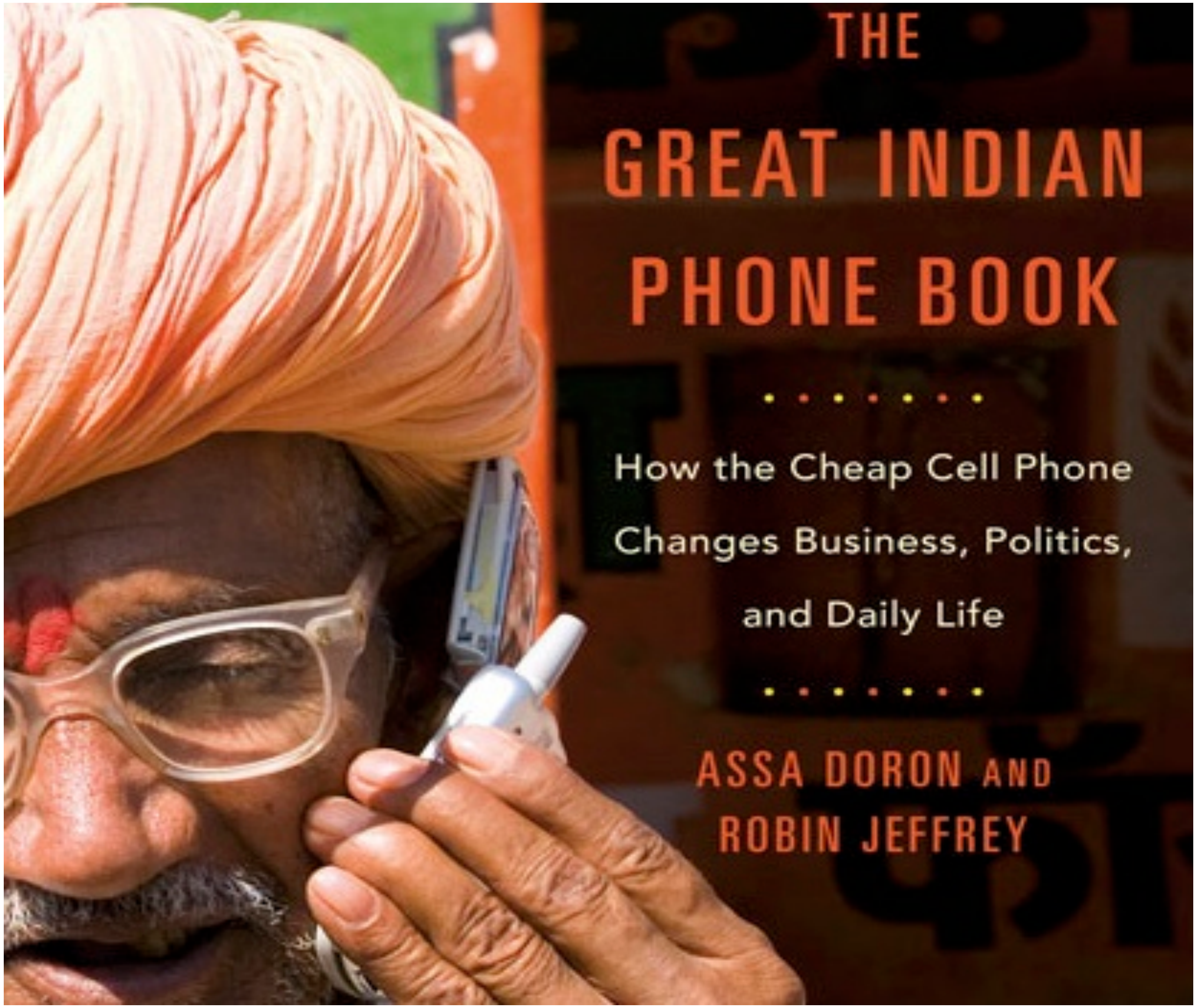
Healthy and Diseased Cassava

[Source: “Modeling and Monitoring Crop Disease in Developing Countries” (Quinn, Leyton-Brown & Mwebaze, 2011)]

Crop Disease Monitoring

[Source: cropmonitoring.appspot.com]

Disruptive IT



Livestock Insurance

Level: economic; Domain: agriculture; Type: embedded

- Satellite-based vegetation data combined with household-level herd data to create a livelihood-focused contract that minimizes basis risk

- In the midst of a drought-induced food crisis affecting millions in the Horn of Africa, an innovative insurance program for poor livestock keepers made its first payouts Oct. 21, 2011 providing compensation to some 650 insured herders who have lost up to a third of their animals in northern Kenya's vast Marsabit District.

- Index Based Livestock Insurance payouts triggered when satellite images show that grazing lands in the region have deteriorated to the point that herders are expected to lose more than 15 percent of their herd. Readings for which indemnities paid in 2011 show that between 18 and 33 percent of livestock were lost to drought that season.

[Source: “Designing Index Based Livestock Insurance for Managing Asset Risk in Northern Kenya” (Chantarat *et al.*, 2011)]

Livestock Insurance

Local livestock owners gather to receive payouts for a unique livestock insurance scheme
[Source: Cornell Chronicle]

How Can We Help?

- CS and computation in service to people and our planet
- Global crises of poverty and inequity, overdevelopment, climate change, health, education, aging, …
- Teaching and learning tools for CS & AI: games, …
- Sustainability: smart cars, smart traffic control, scenario modeling, auctions for carbon credits, smart energy controllers, distributed sensors, smart communication systems, teleconferencing, …
- Assistive technology: assisted perception, cognition and action for seniors and disabled, smart wheelchairs, companions, nurse assistants, …
- Every area of CS needed: Machine Learning, AI, Graphics Database, HCI, HRI, Systems, Scientific Computing, Algorithms, Theory, …

Thanks

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Learn more: www.cs.ubc.ca/~mack/ComputationalSustainabilityResources

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