Earth Systems Engineering and Management: A Geoengineering Perspective
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Failure Mode: Heidegger

“So long as we do not, through thinking, experience what is, we can never belong to what will be.”

“The flight into tradition, out of a combination of humility and presumption, can bring about nothing in itself other than self deception and blindness in relation to the historical moment.”

Lest We Forget: The Power of Technology Systems – Railroad Example

- Railroad technology is a network that must co-evolve with uniform, precise system of time and network scale communication systems
  - Railroads encouraged evolution of “industrial time” and associated culture
  - Telegraph
- Size of network requires large, geographically distributed firm
  - Co-evolution of modern managerial capitalism (modern accounting, planning, and administration systems)
  - Trend: division of labor from blue collar (e.g., Adam Smith’s pin factory) to white collar jobs
Lest We Forget: The Power of Technology Systems – Railroad Example

• Size of capital requirements leads to co-evolution of modern capital and financial markets
  – Railroad construction was the single most important stimulus to industrial growth in Western Europe by 1840s

• As technology integrated into economy and society, railroads transformed landscapes at all scales
  – Chicago existed, and structured the Midwest economically and environmentally, because of railroads.
Railroad Technology Implications

- Enabled qualitative change in US economic and power structures
  - From local/regional business concentrations to trusts
  - Scale economies of national markets
  - Enabled international trade at global scale
  - Opened up continental interiors to development and economic growth

- Co-evolved with fundamental shift in US culture from Edenic Jeffersonian agrarianism to technology-driven New Jerusalem
  - Note this same cultural conflict being played out in the current geoengineering debates
The Five Horsemen

- Nanotechnology
- Biotechnology
- Robotics
- Information and communication technology
- Applied cognitive science
Dialectic

• Technological evolution increasingly makes comfortable assumptions contingent.
• We conceptualize ecosystems as somehow separable from human systems, but does this reflect a disciplinary bias, or the reality of the Anthropocene?
• And does it matter if ecosystems become another engineered system? And are we engineering ecosystems, or earth systems?
A Few Implications

• Ecology as design space
  – From evolved biodiversity to designed biodiversity
  – Geoengineering
  – Integrated human/natural/built system design (from terraforming Earth to terraforming Mars)

• Design at all scale, from nano to genetic to landscape to global systems (C, N cycles as products of design)
A Few Implications

• The human as design space
  – Radical life extension
  – Augcog – human cognition as network function – from military to Ford and GM
  – Human component design
    • Infrared vision
    • Ratbot – to human brains? What is human?
    • Redesign of evolutionary psychology
Why Earth Systems Engineering?

• Age of human impact on global systems:
  – Global climate change
  – Nitrogen
  – Biodiversity
  – Economy
  – Technology systems
  – Social and cultural behavior (mass consumption)
  – Water
Why Earth Systems Engineering?

• These Earth systems are difficult in themselves, but because they are foundational, they are coupled to each other, and to many others.

• They integrate human, natural and built components, and cannot be understood, designed, and managed using just information from one of those domains.
  – Ecosystem services is not an environmental category; it is an engineering category.
Water as Earth System

- Biodiversity
- Human Health
- Nitrogen Cycle
- Phosphorous Cycle
- Carbon Cycle
- Agriculture
- Global Trade
- Culture/Law
- Efficient Use Options
- Recycling Technologies
- Production Technologies
- Treatment Technologies
- OTHER TECHNOLOGY SYSTEMS
- WATER ECONOMICS
- WATER SYSTEMS

Usual Focus of WATER POLICY

Earth Systems

Arizona State University
## Global Freshwater Use 1700 - 2000

<table>
<thead>
<tr>
<th>Year</th>
<th>Withdrawals (km³)</th>
<th>Withdrawals (per capita)</th>
<th>Irrigation</th>
<th>Use (in percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1700</td>
<td>110</td>
<td>0.17</td>
<td>90</td>
<td>2</td>
</tr>
<tr>
<td>1800</td>
<td>243</td>
<td>0.27</td>
<td>90</td>
<td>3</td>
</tr>
<tr>
<td>1900</td>
<td>580</td>
<td>0.36</td>
<td>90</td>
<td>6</td>
</tr>
<tr>
<td>1950</td>
<td>1,360</td>
<td>0.54</td>
<td>83</td>
<td>13</td>
</tr>
<tr>
<td>1970</td>
<td>2,590</td>
<td>0.70</td>
<td>72</td>
<td>22</td>
</tr>
<tr>
<td>1990</td>
<td>4,130</td>
<td>0.78</td>
<td>66</td>
<td>24</td>
</tr>
<tr>
<td>2000 (est.)</td>
<td>5,190</td>
<td>0.87&lt;sup&gt;1&lt;/sup&gt;</td>
<td>64</td>
<td>25</td>
</tr>
</tbody>
</table>

<sup>1</sup> In richer countries, water use stabilized after the 1970’s. In the U.S., total water use peaked around 1980 and had declined by a tenth as of 1995, despite simultaneous addition of some 40 million people.

Source: Based on J. R. McNeill, 2000, Something New Under the Sun (New York: W. W. Norton & Company), Table 5.1, p. 121, and sources cited therein.
Water as Earth System

• It is a material
• It is a commodity (a material that can be owned)
• It is a legal construct – “water rights”
• It is a cultural construct – “water as human right”
• It is a technological construct (technology makes “potable water” from “sewage”)

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Water as Earth System

• It is transport network (and thus prerequisite for development if other infrastructure is lacking)
• It is energy
• It is political power (cf. water wars)
• Essential for life (critical environmentally)
• It is something that can be used, but not used up (form and quality matter)
Water as Earth System

• Availability in a particular circumstance is a matter of pricepoint, infrastructure and power, not “natural” constraints.
• It is provided, traded, and sold both as a material (“water”) and as embedded in other products (“virtual water”)
• Traditional definitions fail (e.g., factory beef from stem cells as “water technology”)
## Embedded Water Content of Selected Items

<table>
<thead>
<tr>
<th>Product</th>
<th>Embedded water content (liters)</th>
<th>Embedded Water Content, liters per gram</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 microchip (2 g)</td>
<td>32</td>
<td>16</td>
</tr>
<tr>
<td>1 sheet of A4-size paper (80 g/m²)</td>
<td>10</td>
<td>.125 (liters/m²)</td>
</tr>
<tr>
<td>1 slice of bread (30 g)</td>
<td>40</td>
<td>1.33</td>
</tr>
<tr>
<td>1 potato (100 g)</td>
<td>25</td>
<td>.25</td>
</tr>
<tr>
<td>1 cup of coffee (125 ml)</td>
<td>140</td>
<td>1.12 (l/ml)</td>
</tr>
<tr>
<td>1 bag of potato crisps (190 g)</td>
<td>185</td>
<td>.97</td>
</tr>
<tr>
<td>1 hamburger (150 g)</td>
<td>2,400</td>
<td>16</td>
</tr>
</tbody>
</table>

Embedded Water

- 80% of embedded water in global trade is in agricultural goods
  - $\frac{3}{4}$ in crops
  - $\frac{1}{4}$ in animal products
- But beef is single largest component of virtual water flow at 13% of global VW, compared with 11% for soybeans and 9% for wheat
  . . . because
Embedded Water

• To produce:
  – 1 ton of vegetables requires about 1,000 cubic meters of water
  – 1 ton of wheat requires about 1,450 cubic meters
  – 1 ton of beef requires 42,500 cubic meters
Policy Implications

• Ecosystem services need to be conceptualized as earth systems engineering and management
Policy Implications

• Technology is rendering many assumptions underlying current frameworks obsolete – ecosystems services are not an ecological or environmental category, but an engineering category
• Policy solutions are not found in familiar domains (e.g., to help manage water for ecosystems services, manage trade to enable efficient use of embedded water)
Earth Systems Engineering and Management: Climate Change - Carbon Cycle Schematic

- **Nitrogen, phosphorus, sulfur cycles**
- **Hydrologic cycle**
- **Other cycles**
- **Carbon cycle**
- **Atmosphere and Oceanic Systems**
- **Biosphere**
- **Human systems: economic, cultural, religious, etc**

**Geoengineering options**
- Genetic engineering and biotechnology
- Information technology and services (e.g., telework)
- Other Technology systems

**Energy system**
- Fossil fuel industry, etc.
- Fish farming, etc.

**Ocean fertilization**
- Biomass agriculture

**Other options**
- Organic chemical industry, etc.

**Implementation at firm, facility, technology and process level**

**Engineering/Management of Earth system relationships**
- Earth System Engineering
  - Engineering/Management of carbon cycle
  - Scope of traditional engineering disciplines
What Is Geoengineering?

- Geoengineering is “deliberate large-scale intervention in the Earth’s climate system, in order to moderate global warming.” (from the 2009 Royal Society report, Geoengineering the Climate).

- Two basic geoengineering classes:
  - Techniques that remove carbon dioxide from the atmosphere (CDR, or carbon dioxide removal)
  - Techniques that reflect incoming solar radiation back into space (SRM, or solar radiation management)
Examples of CDR Techniques

• Land use management to absorb CO2
• Biomass carbon sequestration
• Engineered ambient air carbon sequestration
• Ocean fertilization
• Enhancement of natural weathering
Examples of SRM Techniques

• Enhance marine cloud reflectivity by, e.g., ships spewing water droplets into atmosphere
• Increase reflectivity of planet (e.g., paint roofs white, plant reflective crops, or put reflective material across deserts)
• Inject sulfate aerosols
• Upper atmosphere or space reflectors, including balloons, shields, or other devices
What Do the Kyoto Treaty and Traditional Geoengineering Projects Have in Common?

• They assume simple systems dynamics when the underlying systems are complex adaptive systems.

• They apply reductionist paradigms beyond the boundaries within which they are effective.
What Do the Kyoto Treaty and Traditional Geoengineering Projects Have in Common?

• They show little understanding of the dynamics and characteristics of technological evolution
• They are ad hoc, inadequate and increasingly dysfunctional responses
• They assume climate change is a “problem” to be “fixed” rather than a condition to be managed
Geoengineering Technologies: Historical

• Railroad
• Electrification
• Automobile mass production/consumption
• Nuclear
  – “Now I am become Death, destroyer of worlds.” (Vishnu, Bhagavad Gita, Robert Oppenheimer at Trinity Test, 1945, White Sands, New Mexico)
Geoengineering Technologies: Future

• Factory meat production
  – Cows and pigs are environmentally inefficient ways to make beef and pork

• ICT/ virtual reality, rather than automobiles, as iconic technology of freedom (GM seeking MTV help in reaching young)

• Redesign of human
  – Extended life issues
  – Differentiation of labor as source of efficiency extended to design of human varietals
The Five Horsemen: The Real Geoengineering

• Nanotechnology
  – End of 2,500 year long project to extend human design to limits of material world
  – Potent enabling technology

• Biotechnology
  – “Biodiversity crisis” is cusp to designed biology (biology as economic science)
  – Human as design space
  – Radical human life extension
The Five Horsemen: The Real Geoengineering

• Robotics
  – Rapid technological evolution: Iraq (0 ground robots at invasion time; 150 by end 2004; 2,400 end of 2005; 5,000 end of 2006; 12,000 end of 2008)
  
  – “Lethal autonomous robots”
  
  – Integrated hardware/software: rat neural systems integrated into robots
The Five Horsemen: The Real Geoengineering

– Ethics of robotics now under serious development (based on scifi – Azimov’s Three Laws)

• A robot may not injure a human being or, through inaction, allow a human being to come to harm.

• A robot must obey orders given to it by human beings, except where such orders would conflict with the First Law.

• A robot must protect its own existence as long as such protection does not conflict with the First or Second Law
The Five Horsemen: The Real Geoengineering

- Information and communication technology
  - Facebook is only 6 years old; Second Life only 7 (launched June 23, 2003); Twitter only 3.
  - Potential for fundamental communication shifts (from verbal to integrated telepathic packages) – have you watched what the Net did to English?
The Five Horsemen: The Real Geoengineering

- Cognitive science
  - Augcog: the human bandwidth is systems limiting in complex adaptive systems
    - In Iraq and Afghanistan, the diffusion of cognition across technologies to enable mission performance in complex environment
    - GM and others with autonomous vehicles
What is to be done?

• Stop UNFCCC and geoengineering processes?
  – No: culturally and psychologically locked-in at this point.
  – No: helps keep underlying system evolving.

• Pretend that UNFCCC and geoengineering processes will work? No; they are profoundly over-simplistic approaches to a complex situation.
What is to be Done?

• Work around existing processes while initiating a new, more sophisticated effort to understand how to ethically, rationally, and responsibly manage the complex, adaptive, integrated human/built/natural systems that characterize the Anthropocene

• Explicitly create large portfolio of technologies with climate change implications, to achieve resilience in face of unpredictable and uncertain future

• Identify and support promising new technologies while not being naïve about costs and benefits
“He, only, merits freedom and existence who wins them every day anew.”

(Goethe, 1833, *Faust*, lines 11,575-76)
BACK-UP SLIDES
Earth Systems Engineering and Management Principles: Theory

- Only intervene when and to the extent required: humility when facing complexity.

- At the level of earth systems engineering and management (ESEM), projects and programs are not just technical and scientific in nature, but unavoidably have powerful cultural, ethical, and religious dimensions.

- Unnecessary conflict surrounding ESEM projects and programs can be reduced by separating social engineering from technical engineering dimensions.

- ESEM requires a focus on systems as systems, rather than as just constituent artifacts; a dynamic, rather than static, mental model of underlying phenomenon.

- Boundaries around ESEM projects and programs should reflect real world couplings and linkages through time, rather than disciplinary or ideological simplicity.

- Major shifts in technologies and technological systems should be evaluated before, rather than after, implementation.
Earth Systems Engineering and Management Principles: Design and Engineering

◆ ESEM initiatives should all be characterized by explicit and transparent objectives or desired performance criteria, with quantitative metrics which permit continuous evaluation of system evolution (and signal when problematic system states may be increasingly likely).

◆ ESEM initiatives should not be based on implicit or explicit models of centralized control. The ESEM professional is an integral component of the system, co-evolving with it. This will require a completely different psychology of engineering.

◆ ESEM projects should be incremental and reversible to the extent possible.

◆ ESEM should aim for resiliency, not just redundancy, in systems design. A resilient system resists degradation and, when it must, degrades gracefully even under unanticipated assaults; a redundant system may have a backup mechanisms, but still may be subject to unpredicted catastrophic failures.

◆ ESEM should aim for inherently safe, rather than engineered safe, design. An inherently safe system fails in a non-catastrophic way; an engineered safe system is designed to reduce the risk of a particular catastrophic failure mode, but there is still a finite probability that such a failure may occur.
Earth Systems Engineering and Management Principles: Governance

◆ ESEM initiatives by definition raise important scientific, technical, economic, political, ethical, theological and cultural issues, requiring a governance model which is democratic, transparent, and accountable.

◆ ESEM governance mechanisms should foster inclusive, multicultural dialog.

◆ ESEM governance models apply to complex adaptive systems that are inherently unpredictable and uncertain. Thus, ESEM policy development and implementation is a dialog with the relevant systems, rather than finding a “solution” to a “problem”.

◆ ESEM governance systems should accordingly place a premium on flexibility and the ability to evolve in response to changes in system state.

◆ The ESEM environment and the complexity of the systems at issue require explicit mechanisms for assuring continual learning by ESEM professional and stakeholders alike.

◆ There must be adequate resources available to support both the immediate ESEM project and the science and technology research and development necessary to ensure that the responses of the relevant systems are understood.