**Mitigating Climate Change**

Sources and sinks of atmospheric CO2
- Emissions trading
- Historical and projected CO2 emissions
- Climate wedges
- Alternative energy

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**The Global Carbon Cycle**

- **Atmosphere**
  - 775 + 4 GtC/yr
  - ~90
  - ~120

- **Ocean**
  - 38,000

- **Land**
  - 2000

- **Humans**
  - 8 GtC/yr

*About half the CO2 released by humans is absorbed by oceans and land*

*“Missing” carbon is hard to find among large natural fluxes*

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**Variable Sinks**

- **El Niño years**
- **Fossil fuel emissions**
- **Accumulation rate in ocean and on land**
- **Accumulation rate in atmosphere**

- **Half the CO2, “goes away!”**

- Some years almost all the fossil carbon goes into the atmosphere, some years almost none
- Interannual variability in sink activity is much greater than in fossil fuel emissions
- Sink strength is related to El Niño. Why? How?
European "cap-and-trade" market set up as described in Kyoto Protocol (http://www.europeanclimateexchange.com)

- 7/10/2009 price €16.19/ton of CO$_2$ emitted 12/2012 = $83.25/ton of Carbon
- Supply and demand!

Where Has All the Carbon Gone?

- Into the oceans
  - Solubility pump (CO$_2$ very soluble in cold water, but rates are limited by slow physical mixing)
  - Biological pump (slow "rain" of organic debris)

- Into the land
  - CO$_2$ Fertilization (plants eat CO$_2$ ... is more better?)
  - Nutrient fertilization (N-deposition and fertilizers)
  - Land-use change (forest regrowth, fire suppression, woody encroachment ... but what about Wal-Marts?)
  - Response to changing climate (e.g., Boreal warming)

Present Value of Carbon Sinks

- Terrestrial and marine exchanges currently remove more than 4 GtC per year from the atmosphere
- This free service provided by the planet constitutes an effective 50% emissions reduction, worth about $325 Billion per year at today's price on the ECX!
- Carbon cycle science is currently unable to quantitatively account for
  - The locations at which these sinks operate
  - The mechanisms involved
  - How long the carbon will remain stored
  - How long the sinks will continue to operate
  - Whether there is anything we can do to make them work better or for a longer time

Coupled Carbon-Climate Modeling

- "Earth System" Climate Models
  - Atmospheric GCM
  - Ocean GCM with biology and chemistry
  - Land biophysics, biogeochemistry, biogeography
- Prescribe fossil fuel emissions, rather than CO$_2$ concentration as usually done
- Integrate model from 1850–2100, predicting both CO$_2$ and climate as they evolve
- Oceans, plants, and soils exchange CO$_2$ with model atmosphere
- Climate affects ocean circulation and terrestrial biology, thus feeds back to carbon cycle
Coupled simulations of climate and the carbon cycle.
Given nearly identical human emissions, different models project dramatically different futures!

Emission Scenarios

- A1: Globalized, with very rapid economic growth, low population growth, rapid introduction of more efficient technologies.
- A2: Very heterogeneous world, with self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, resulting in high population growth.
- B1: Convergent world with the same low population growth as in A1, but with rapid changes in economic structures toward a service and information economy, reductions in material intensity, introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, without additional climate initiatives.
- B2: Local solutions to economic, social, and environmental sustainability. Moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than in B1 and A1.

Each "storyline" used to generate 10 different scenarios of population, technological & economic development.

Carbon intensity of the world economy fell steadily for 30 years.

Actual emissions are above even the highest IPCC scenarios.
Dramatic contrast - history versus future

CO$_2$ "Budget" of the Atmosphere

How Far Do We Choose to Go?

Historical Emissions
The "Stabilization Triangle"

- Billions of Tons Carbon Emitted per Year
- Historical emissions
- Flat path → Stabilization Triangle
- Interim Goal

The Stabilization Triangle

- Billions of Tons Carbon Emitted per Year
- Current path = "ramp"
- Easier CO₂ target ~850 ppm
- Interim Goal

The "Stabilization Wedges"

- Billions of Tons Carbon Emitted per Year
- 16 GtC/yr
- Eight "wedges"
- Goal: In 50 years, same global emissions as today

What is a "Wedge"?

A "wedge" is a strategy to reduce carbon emissions that grows in 50 years from zero to 1.0 GtC/yr. The strategy has already been commercialized at scale somewhere.

1 GtC/yr

Cumulatively, a wedge redirects the flow of 25 GtC in its first 50 years. This is 2.5 trillion dollars at $100/tC.

A "solution" to the CO₂ problem should provide at least one wedge.
Fifteen Wedges in 4 Categories

Energy Efficiency & Conservation (4)

Stabilization Triangle

Renewable Fuels & Electricity (4)

Forest and Soil Storage (2)

Fuel Switching (1)

CO₂ Capture & Storage (3)

Nuclear Fission (1)

Efficiency

Double the fuel efficiency of the world’s cars or halve miles traveled

Average coal plant efficiency is 32% today

Produce today’s electric capacity with double today’s efficiency

Use best efficiency practices in all residential and commercial buildings

Replacing all the world’s incandescent bulbs with CFL’s would provide 1/4 of one wedge

There are about 600 million cars today, with 2 billion projected for 2055

Average coal plant efficiency is 32% today

Double the fuel efficiency of the world’s cars or halve miles traveled

Efficiency

Fuel Switching

Substitute 1400 natural gas electric plants for an equal number of coal-fired facilities

Fuel Switching

Carbon Capture & Storage

Implement CCS at

- 800 GW coal electric plants
- 1600 GW natural gas electric plants
- 180 coal synfuels plants
- 10 times today’s capacity of hydrogen plants

There are currently three storage projects that each inject 1 million tons of CO₂ per year – by 2055 need 3500.
Nuclear Electricity

Triple the world's nuclear electricity capacity by 2055

The rate of installation required for a wedge from electricity is equal to the global rate of nuclear expansion from 1975-1990.

Wind Electricity

Install 1 million 2 MW windmills to replace coal-based electricity,
OR
Use 2 million windmills to produce hydrogen fuel

A wedge worth of wind electricity will require increasing current capacity by a factor of 30

Solar Electricity

Install 20,000 square kilometers for dedicated use by 2054

A wedge of solar electricity would mean increasing current capacity 700 times

Imagine it's 1800, and you're in charge...

Somebody presents you with a grand idea for transforming the world economy:

- Dig 8 billion tons of carbon out of the ground every year
- Build a system of pipelines, supertankers, railroads, highways, and trucks to deliver it to every street corner on the planet
- Build millions of cars every year, and millions of miles of roads to drive them on
- Generate and pipe enough electricity to every house to power lights & stereos & plasma TVs

... "and here's the itemized bill ..."
Thinking about Costs

- Our global society built that very system
- We didn’t go broke building it …
- We got rich beyond the avarice of kings!
- Now we have to do it again!
- How?

Putting a Price on Carbon Emissions

- A new industrial revolution won’t happen because people want to "do the right thing"
- The government can’t just pass a law and create a new global energy economy, any more than they could 200 years ago
- If low-carbon-footprint goods and services cost less than "dirtier" ones, people will buy them
- The role of policy is to provide incentives, to put a price on carbon!

A Policy Spectrum

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<thead>
<tr>
<th>&quot;command and control&quot;</th>
<th>&quot;market capitalism&quot;</th>
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<tbody>
<tr>
<td>direct subsidy</td>
<td>“cap and trade”</td>
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Conclusions

- Rising levels of CO₂ will cause significant climate change in the 21st century and far beyond
- The only way to mitigate these changes is to stop burning coal, oil, and gas
- This can feasibly be done using today’s technology, but requires tremendous will
- Solving the climate problem will lead to a new industrial revolution, and huge wealth creation
- Dealing with this problem will be a major theme of history for centuries to come
We choose to do these things not because they are easy, but because they’re hard!

President John F. Kennedy
Rice University
September 12, 1962