Seminar 4: System Resilience

→ Warm up exercise!

→ Debrief from last seminar's Postcard Stories

→ Tips on drawing diagrams

→ Multi-loop feedback systems
  - Population and predator dynamics
  - Tipping Points in the Earth System

→ (if time) Brief intro to Chaos Theory

Postcard Stories

1. Tell the Story
   - What happened?
   - What surprised you?
2. Graph the Variables
3. Model the System Structure
4. Identify Lessons Learned

Drawing Causal Loop Diagrams

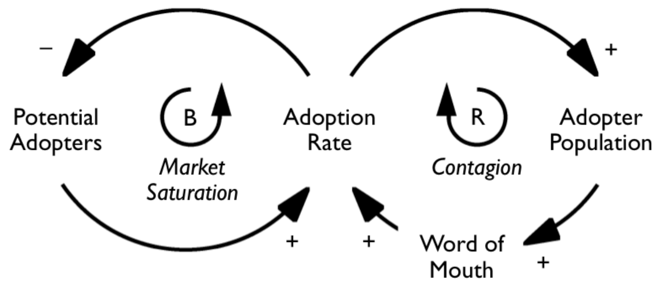
- Purpose:
  - Tell the story
  - What is the diagram for?
- Think about:
  - Time horizon
  - Boundary choices
  - Level of detail
  - Identify delays
  - Use nouns that represent quantities that change over time
  - Distinguish perceived and actual states
  - Distinguish short term and long term effects
  - Balancing loops are goal-seeking; identify the goal

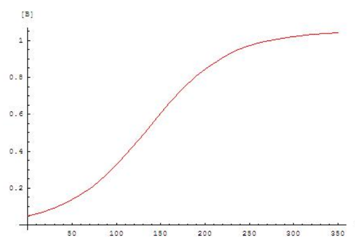
Source: Kim, "Guidelines for Drawing Causal Loop Diagrams"

Purpose of a System

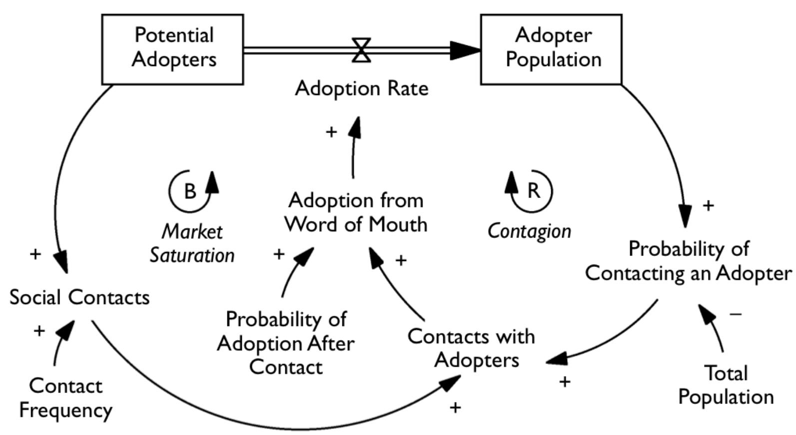
- State-maintaining
  - Reacts to changes in its environment to maintain a pre-determined state
  - E.g. thermostat, some ecosystems
- Goal-directed
  - Can respond differently to similar events in its environment; can act autonomously in an unchanging environment to achieve a pre-determined goal state
  - E.g. an autopilot, simple organisms
- Purposive
  - Has multiple goals; can choose how to pursue them; no choice over the goals themselves
  - E.g. computers, animals (?)
- Purposeful
  - System has multiple goals, and can choose to change its goals
  - E.g. people, governments, businesses, animals

Multi-loop systems



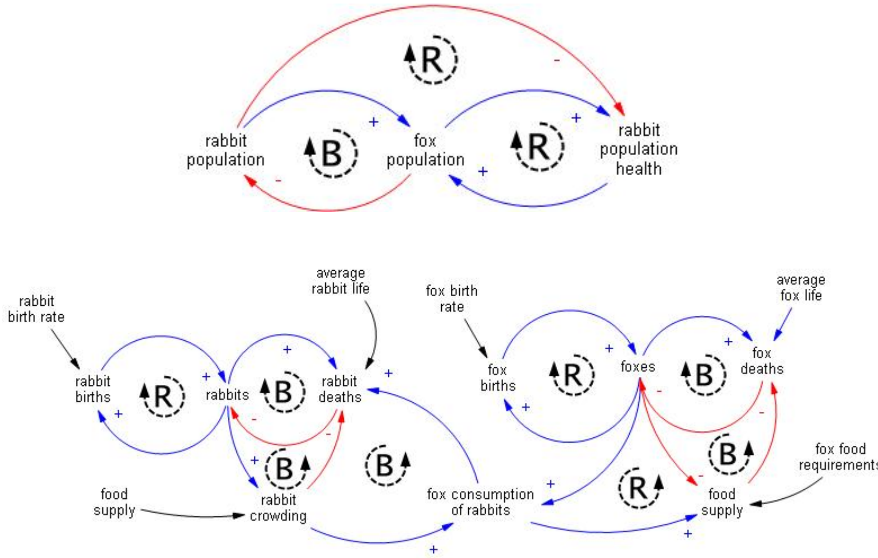


Causal Loops vs Stocks'n'Flows



Source: Sterman, "Systems Dynamics Modeling: Tools for Learning in a Complex World"

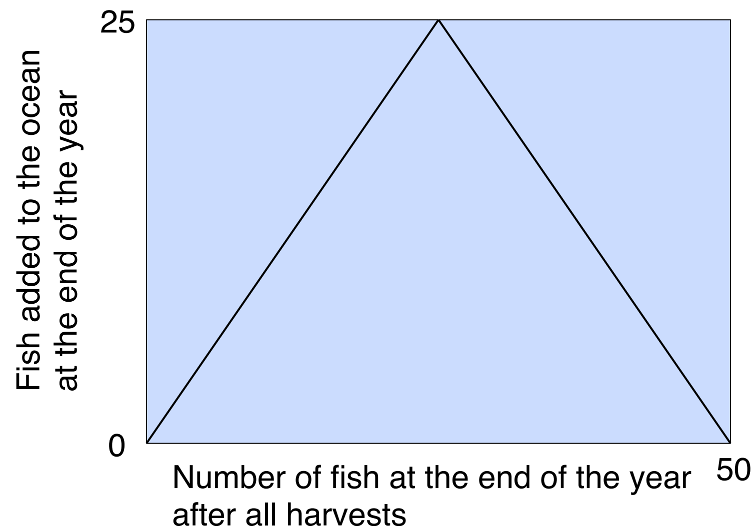
Predator – Prey models



Harvest (rules)

1. Each team owns a fishing boat. Your goal is to maximise your assets by the end of the game.
2. The ocean can support max 50 fish. Initially, between 25 and 50 fish in the ocean
3. We will play for 6 to 10 "years"
4. Each year you decide how many fish you will try and harvest. Place the "order" in your boat
5. I will fill your boats in a random order. If your order exceeds total remaining fish, you get nothing that year.
6. After all orders processed, fish will re-generate, according to the chart…

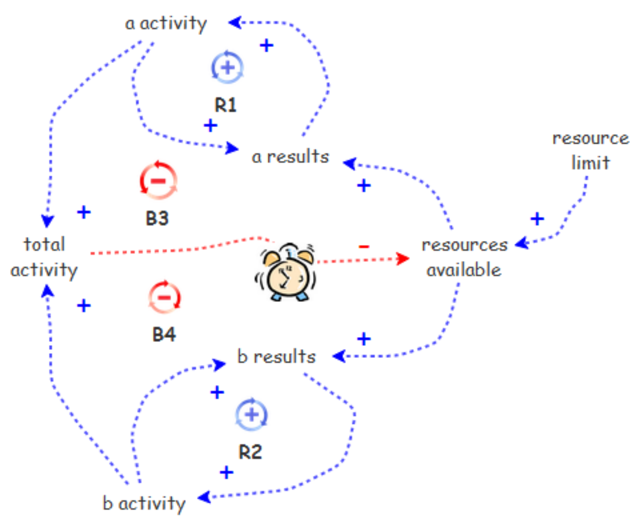
Fish Regeneration Model



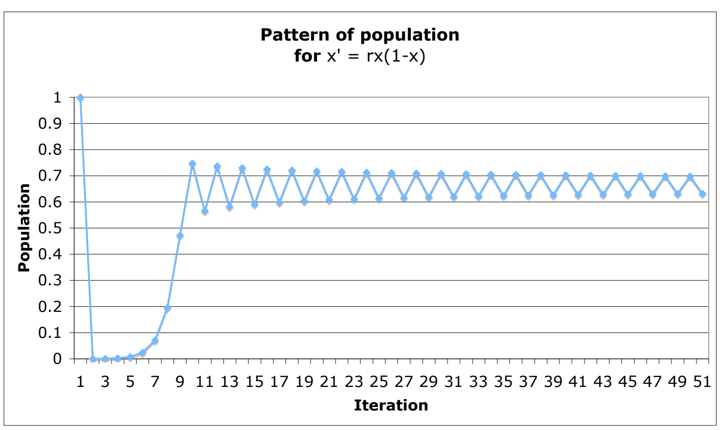
Steps of Play

1. Decide on your team's long-term strategy
2. In each decision round, select the number of fish you wish to harvest
3. Record the number of a slip of paper, insert the paper in the ship and pass it to me.
4. Harvest requests will be filled in a random order
5. Receive your ship back, remove the fish, and start the next round.

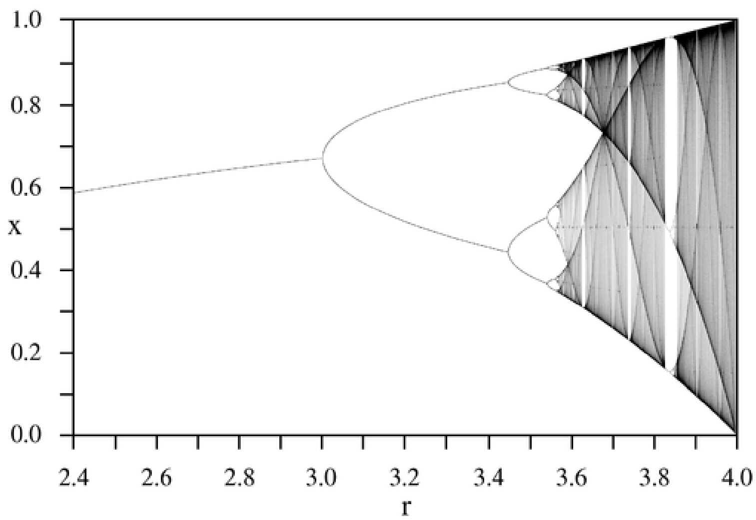
Tragedy of the Commons



Non-Linear Dynamical Systems

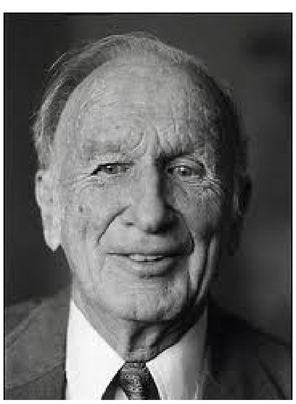


Bifurcation Diagram for x' = rx(1-x)



The discovery of Chaos

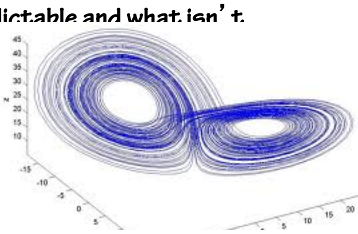
- **1950s: Edward Lorenz discovers non-linear effects in weather forecasting, develops Chaos Theory;**
  - **Basis for understanding what is predictable and what isn't.**

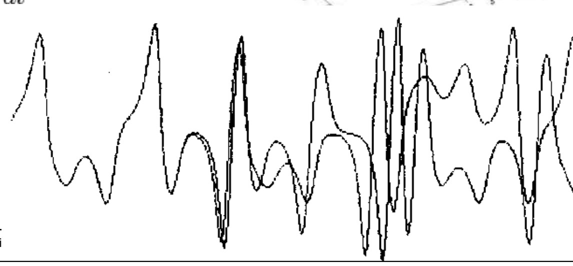


$$\frac{dx}{dt} = \sigma(y - x)$$

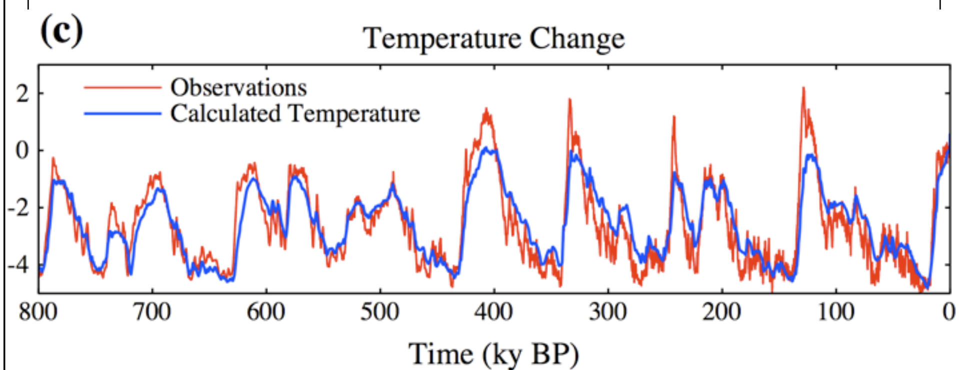
$$\frac{dy}{dt} = x(\rho - z) - y$$

$$\frac{dz}{dt} = xy - \beta z$$

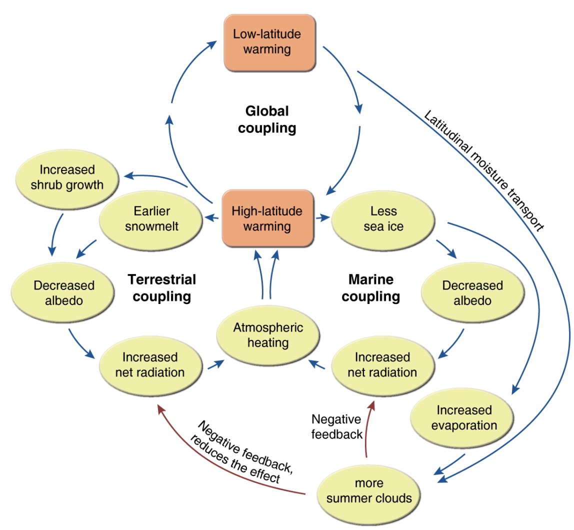




The ice ages



Feedbacks in the Earth System

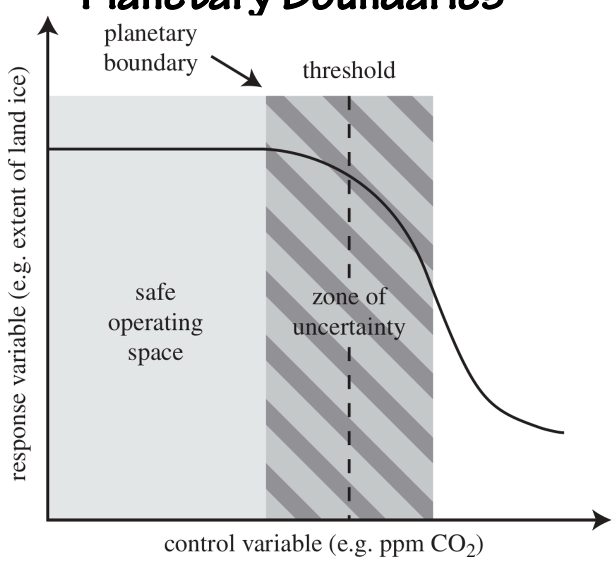


Tipping Points in the Earth System

Tipping element	Feature of system, F (direction of change)	Control parameter(s), ρ	Critical value(s),† ρ_{crit}	Global warming†‡	Transition timescale,† T	Key impacts
Arctic summer sea-ice	Areal extent (−)	Local ΔT_{air}, ocean heat transport	Unidentified§	+0.5–2°C	≈10 yr (rapid)	Amplified warming, ecosystem change
Greenland ice sheet (GIS)	Ice volume (−)	Local ΔT_{air}	+≈3°C	+1–2°C	>300 yr (slow)	Sea level +2–7 m
West Antarctic ice sheet (WAIS)	Ice volume (−)	Local ΔT_{air}, or less ΔT_{ocean}	+≈5–8°C	+3–5°C	>300 yr (slow)	Sea level +5 m
Atlantic thermohaline circulation (THC)	Overturning (−)	Freshwater input to N Atlantic	+0.1–0.5 Sv	+3–5°C	≈100 yr (gradual)	Regional cooling, sea level, ITCZ shift
El Niño–Southern Oscillation (ENSO)	Amplitude (+)	Thermocline depth, sharpness in EEP	Unidentified§	+3–6°C	≈100 yr (gradual)	Drought in SE Asia and elsewhere
Indian summer monsoon (ISM)	Rainfall (−)	Planetary albedo over India	0.5	N/A	≈1 yr (rapid)	Drought, decreased carrying capacity
Sahara/Sahel and West African monsoon (WAM)	Vegetation fraction (+)	Precipitation	100 mm/yr	+3–5°C	≈10 yr (rapid)	Increased carrying capacity
Amazon rainforest	Tree fraction (−)	Precipitation, dry season length	1,100 mm/yr	+3–4°C	≈50 yr (gradual)	Biodiversity loss, decreased rainfall
Boreal forest	Tree fraction (−)	Local ΔT_{air}	+≈7°C	+3–5°C	≈50 yr (gradual)	Biome switch
Antarctic Bottom Water (AABW)*	Formation (−)	Precipitation–Evaporation	+100 mm/yr	Unclear¶	≈100 yr (gradual)	Ocean circulation, carbon storage
Tundra*	Tree fraction (+)	Growing degree days above zero	Missing‖	—	≈100 yr (gradual)	Amplified warming, biome switch
Permafrost*	Volume (−)	$\Delta T_{permafrost}$	Missing‖	—	<100 yr (gradual)	CH_4 and CO_2 release
Marine methane hydrates*	Hydrate volume (−)	$\Delta T_{sediment}$	Unidentified§	Unclear¶	10^3 to 10^5 yr (>T_E)	Amplified global warming
Ocean anoxia*	Ocean anoxia (+)	Phosphorus input to ocean	+≈20%	Unclear¶	≈10^4 yr (>T_E)	Marine mass extinction
Arctic ozone*	Column depth (−)	Polar stratospheric cloud formation	195 K	Unclear¶	<1 yr (rapid)	Increased UV at surface

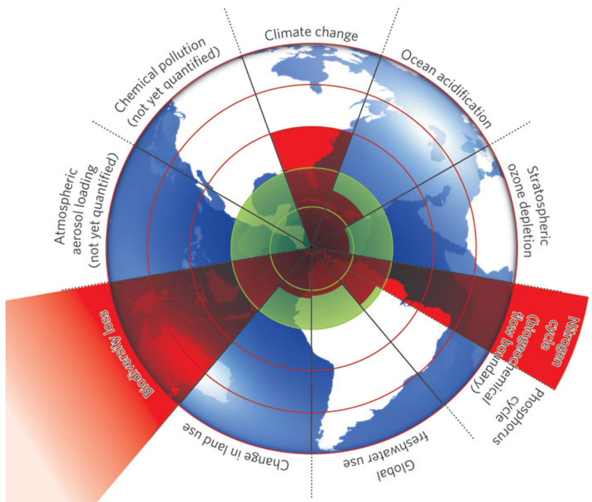
source: Lenton *et al.*, PNAS, vol 105 (6) 1786-1793, Feb 12, 2008

Planetary Boundaries



Source: Rockstrom et al, Planetary Boundaries

Planetary Boundaries



Resilience

1. Ability of a system to "bounce back" after a shock
2. Ability of a system to withstand & adapt to shocks