Introduction to System Dynamics Modeling

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Course Website: http://todd.bendor.org/datamatters

Today’s Syllabus

- **Morning (10-11:15, 11:30-12:45)**
  - Introduction to Modeling
  - Stocks and Flows
  - Lab #1 – learning to model with Vensim
- **Afternoon (2:00-3:15, 3:30-4:45)**
  - Dynamic Equilibrium and System Archetypes
  - Introduction to Feedback
  - Oscillations
- Course Website: http://todd.bendor.org/datamatters

Goals for today

- Understand basic system dynamics modeling (SD)
  - Concepts and terminology
  - History
  - Theory (e.g. stocks, flows, feedback, numerical analysis)
  - Software platforms

- Understand the advantages and dis-advantages of SD modeling
- Understand the limitations of SD modeling relative to relative to other modeling techniques (e.g. agent-based modeling)

- Learn some fundamentals of the Vensim modeling platform

- Learn about the best practices for system dynamics modeling construction

What today is NOT…

- An in-depth SD course
  - See: WPI System dynamics masters degree
  - Mastering SD takes a LOT longer than two days
- An in-depth course in STELLA or other modeling platforms
  - See resources on the course website

- All modeling efforts are unique and confront unique challenges.
- Fortunately, most can be overcome with patience, perseverance, and attention to good modeling practices.

Who am I?

- Associate Professor of City and Regional Planning
- BS/MS in **system dynamics** modeling/environmental science
- PhD focused on land use modeling based on cellular automata/agent-based modeling concepts
- Experience with system dynamics applications towards…
  - auto emissions policies
  - wetland restoration
  - spatial-dynamic modeling
  - invasive species spread
  - park planning in cities
  - brownfield restoration
  - endangered species policy

Assumptions I will make

- Computer literacy

- Comfort with general modeling concepts and impetus behind modeling systems or problems in our world

[I]t is often more important to clarify the deeper causes behind a given problem and its consequences than to describe the symptoms of the problem and how frequently they occur.

– Bent Flyvbjerg (2006, Pg. 229)

Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful.

– George Box and Norman Draper (1987, Pg. 74)

Overview

- What is a model?
- Why model?
- System dynamics modeling
- Components of feedback in systems
- Modeling environmental and urban systems

Modeling

- Lots of definitions:
  - "A model is a picture of reality" – *Wittgenstein*
  - A representation or substitute for a real system

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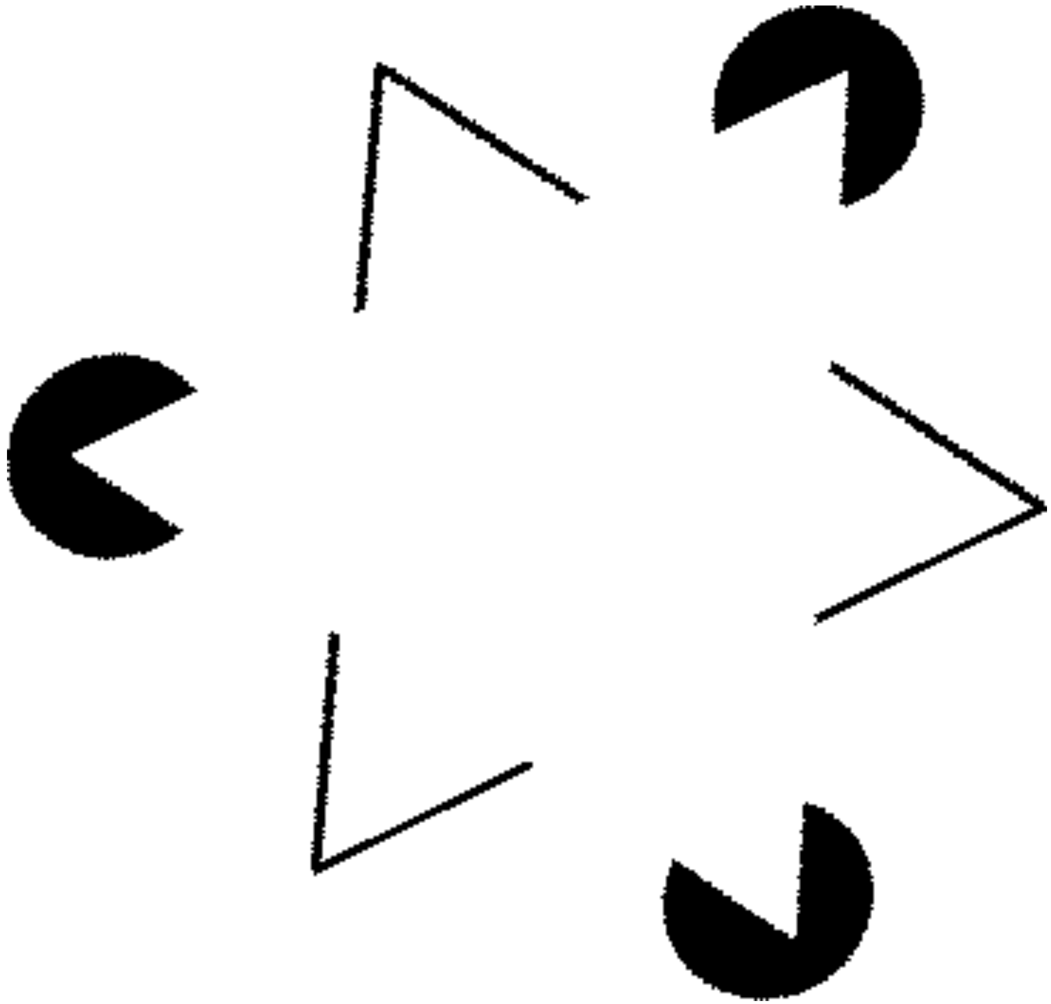
– George Box and Norman Draper (1987, Pg. 74.)

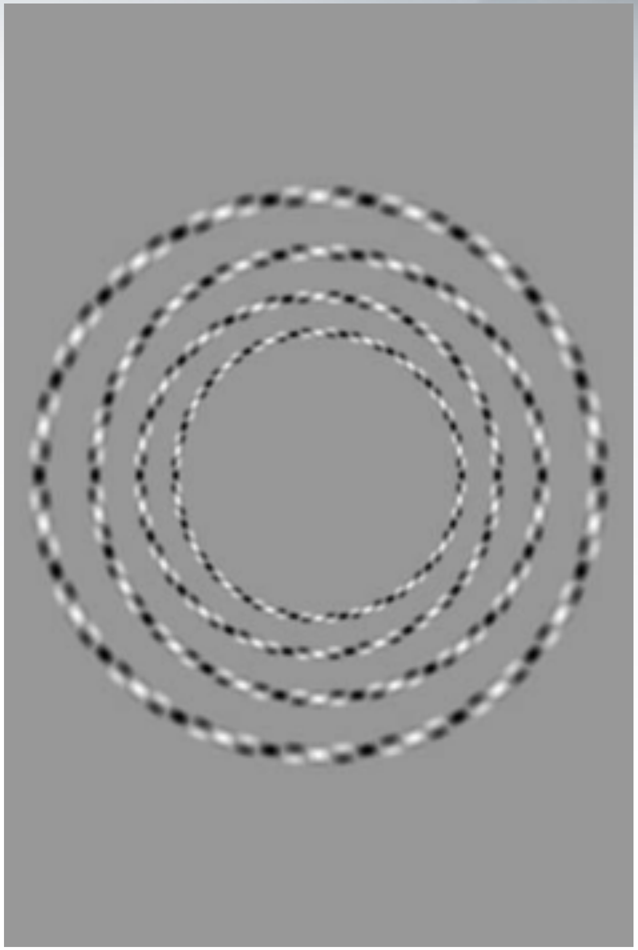
- We use them all the time
  - Blueprints, graphs, maps, and wind tunnels are all models
- Rigorous forms
  - Econometric / statistical regression models, mathematical models representations of reality

What Do You See?



Why Model?

- We already do it
  - Human cognitive processes
  - How do we know that a cow is a cow?
- Informal models – mental "maps"
  - Help us understand and interpret the world around us
- Formalized modeling also helps us to understand the world around us
  - Make our mental models of the world explicit



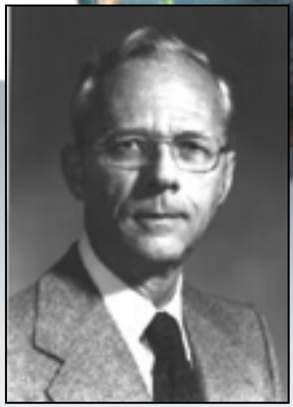
Premise of System Dynamics

- We may be clever when thinking about geometric shapes
- But we are often baffled when thinking about dynamic problems and the environment
- Models give us a chance to practice and to learn
- Models give others a chance to build from our work

System Dynamics Definition

An approach to understanding the behavior of complex systems over time. It deals with internal feedback loops and time delays that affect the behavior of the entire system. What makes system dynamics different from other approaches to studying complex systems is the use of feedback loops and **stocks and flows**.

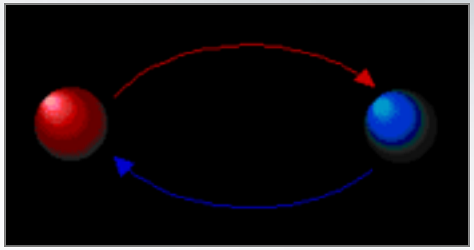
System Dynamics



- Developed in 1950’s by Jay Forrester and colleagues at MIT
  - Based on electrical engineering control theory
    - Electrical circuits exhibit great examples of feedback
- Scientific process for understanding and modeling ‘**systems**’ as they are represented ‘**dynamically**’
- Urban Dynamics
- Industrial Dynamics

System

- System – A set of interacting components that influence or affect each other



- Environmental system
  - Ecosystems – interacting biotic and abiotic components
- Urban system
  - Set of interacting social systems (social networks, communities, cultures, economies) and physical systems (air, land, water, environment, transport)

Dynamics

- Change over time

- Bathtub – Faucet and drain
  - Flows in and flows out
  - Accumulation of water
- Bank Account – receipts and expenditures
  - Accumulation of money in account

System Dynamics Modeling

- Tools for representing changing interactions of system components
- Based on three fundamental ideas
  - Flows – change or movement of information or material
  - Stocks – accumulations of information of materials (system states)
  - Feedback – representation of relationships between components

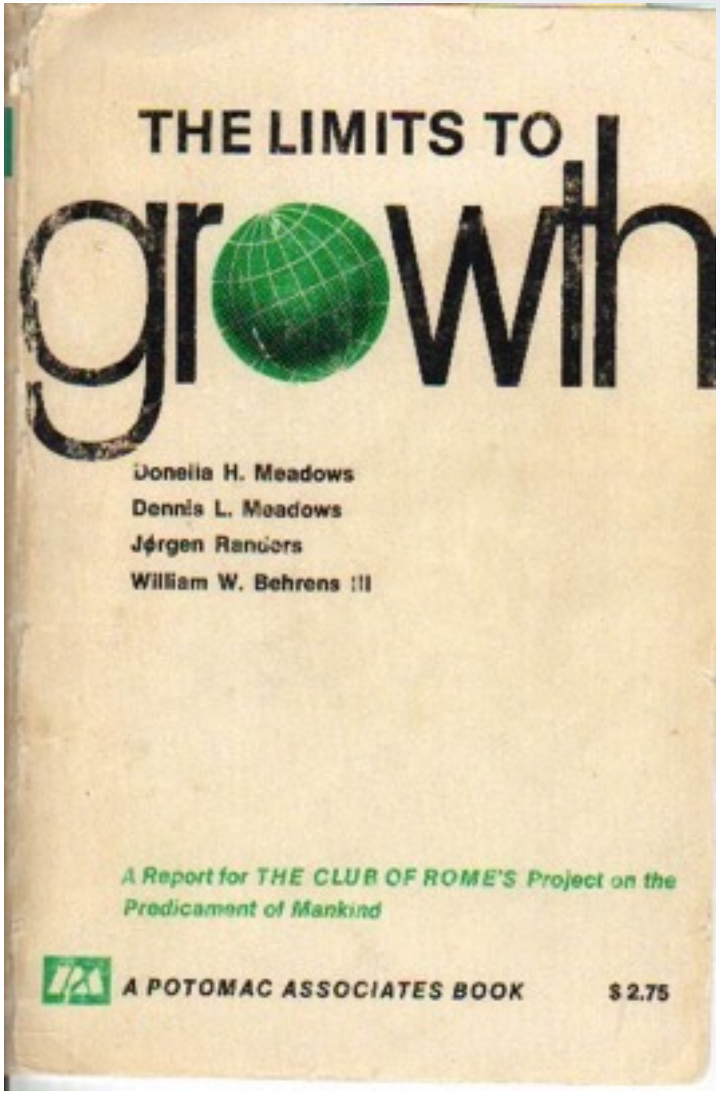
What about the math?

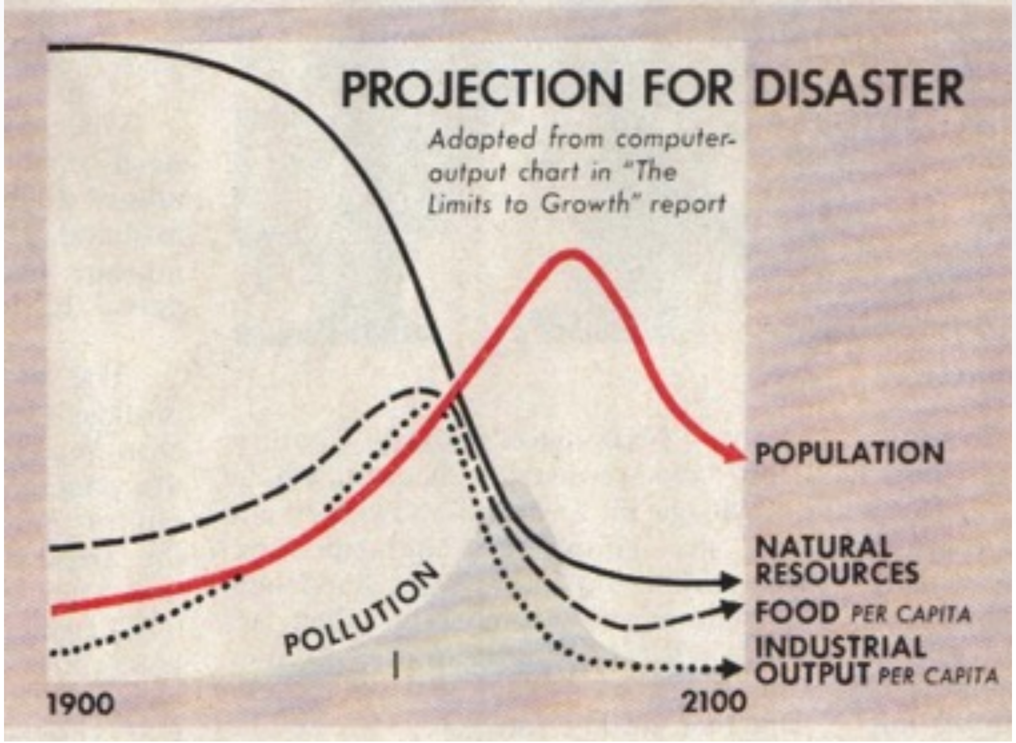
- Common issue: you haven't studied differential equations or your memory of calculus has faded over time
- SD is designed to eliminate common simulation modeling barriers
  - No need to study calculus to understand systems, change, or system dynamics (even in great depth)
- SD methods assume you have learned introductory algebra and that you know how to read and interpret graphs
- SD premised on representing interactions between system elements in simple mathematical terms
  - E.g. If I give you distance and speed: What is time traveled?

So how does this all fit together?…

- We build system dynamics models in a visual manner on the computer.
- Your job is to concentrate on the structure of the model
  - Tedious job of numerical simulation will be left to the computer.
- For those of you with calculus experience:
  - The software is integrating the effect of flows over time.
- Those of you that have taken differential equations
  - Models are equivalent to a set of coupled, first-order differential equations.
- The great leveler for varied math experience:
  - The equations are almost always highly nonlinear, so there is little hope of finding an analytical solution.
  - The software will find a numerical solution

The Most Widely Read Book using System Dynamics?



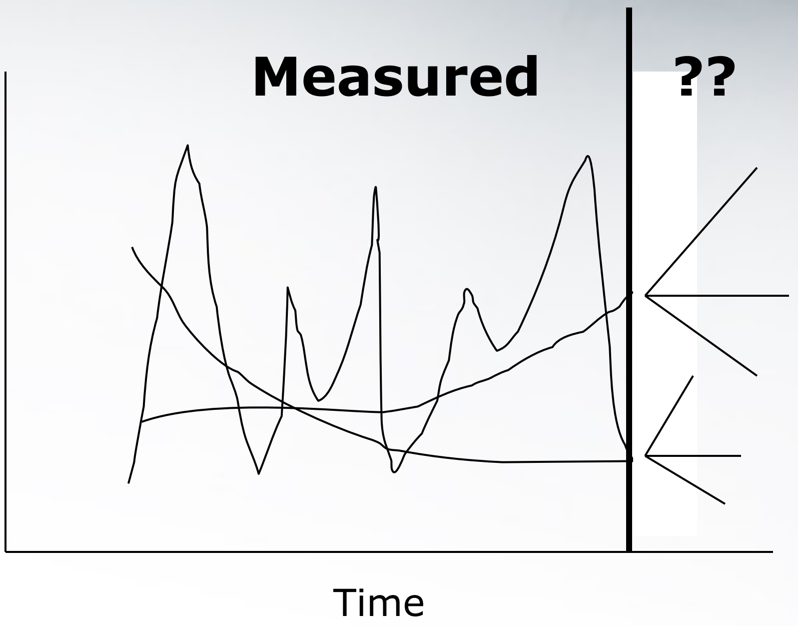


Scientific Process of System Dynamics

1. “Reference Mode” - Understanding past behavior

   – Graphical
     - Population dynamics over time
     - Employment over time
     - Automobile Adoption
     - Wildlife population
       – Bee dieoff
       – Kaibab Plateau deer

   – Use to understand system ***structure***
     - Structure vs. Behavior



Scientific Process of System Dynamics

2. The “dynamic hypothesis”
   - Use reference mode to understand causal linkages
   - Based on systemic archetypes
     - Basic:
       - Linear growth, decline
       - Exponential growth, decline
       - Oscillation
     - Combinations
       - Logistic growth
       - Growth with limit cycle (oscillation)
       - Overshoot and collapse

Scientific Process of System Dynamics

3. Simulation Modeling
   - Using dynamic hypothesis, create quantitative, dynamic model
     - Stocks and flows
     - Bathtub example
   - Test model
     - Replication of past data – “Validation”
     - Policy ‘levers’
       - How does policy affect a system?
         - Land use policies
         - Economic growth policies
         - Transportation policies
     - Projections based on a series of scenarios
       - Forecast – most likely scenario
   - Problems? - Iterative process!!
     - Go back to reference mode

$$Stock = \int_0^t \left(Inflow - Outflow \right)$$

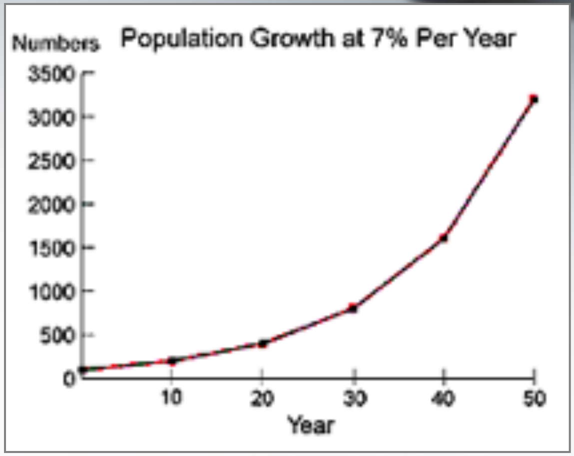
Feedback

- Feedback controls how rates change
- Accumulations themselves determine how quickly they change!

- Bathtub and bank account examples – no feedback!

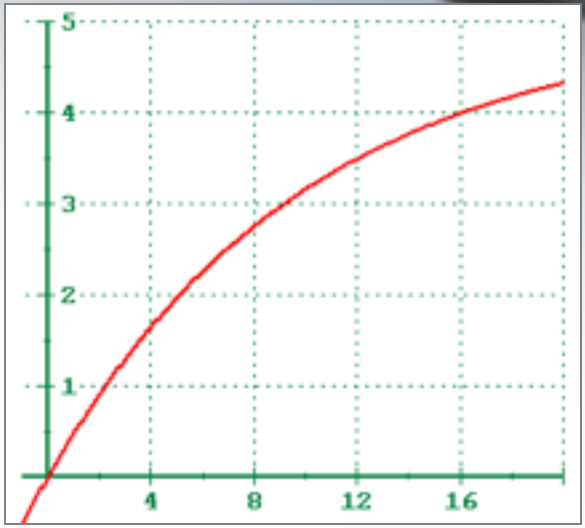
Positive feedback

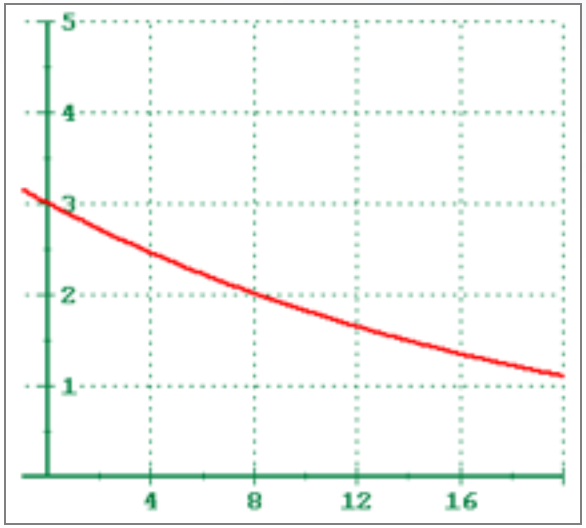
- Exponential growth
  - More begets more
  - Less begets less
- The "vicious cycle"
- Snowball rolling down a hill
- Bank account interest
- Unlimited population growth
- Tribbles in Star Trek
- "Broken window" theory
  - Blight begets more blight



Negative feedback

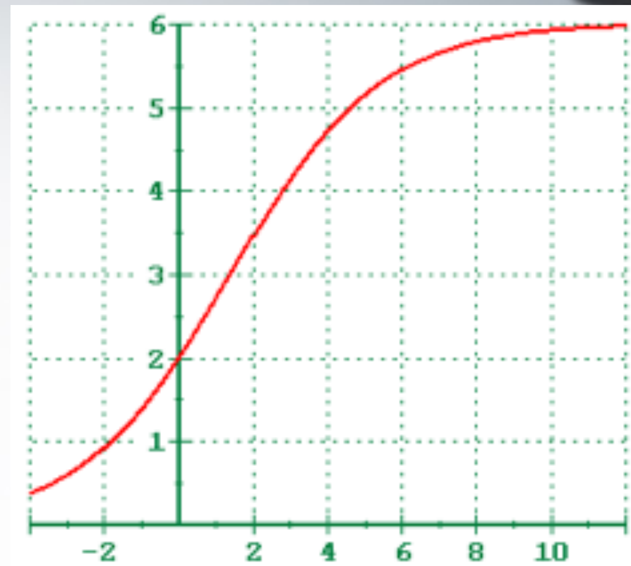
- Goal seeking behavior
- Pouring water into a glass
- Chickens crossing a road
  - Lower chicken population
  - Less chickens to cross road

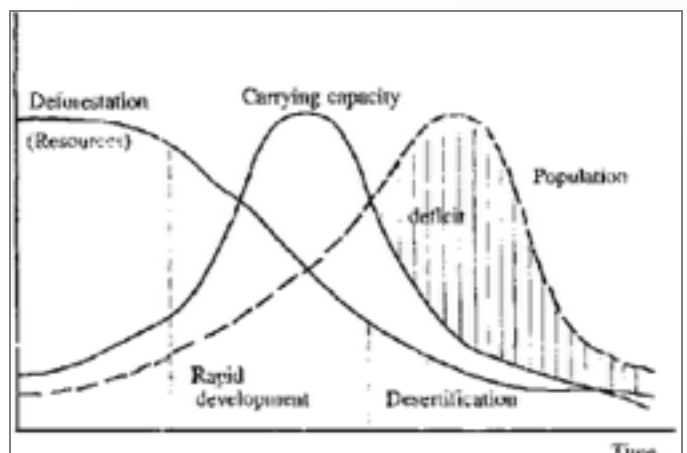




Environmental and Urban Dynamics

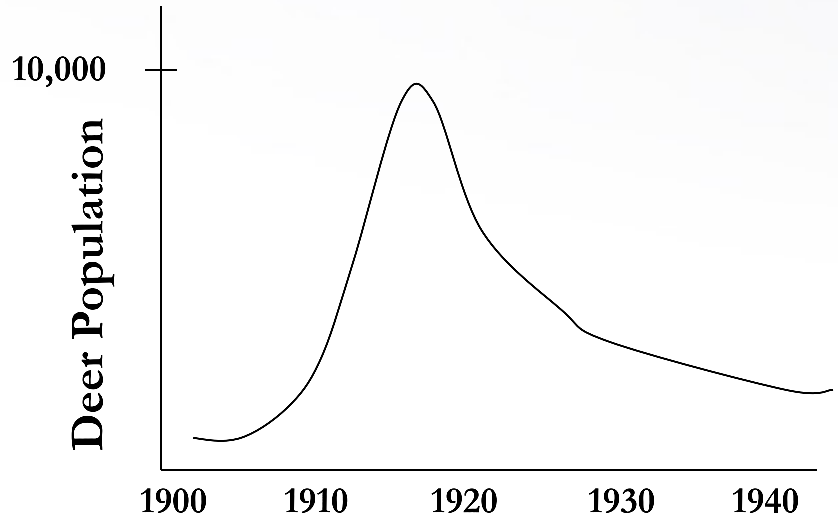
- Environmental and urban systems often combine feedbacks
  - Growth and limitation
- Urban Dynamics (1969)
  - Overshoot and collapse of cities
- Populations
  - Overshoot and collapse
  - Oscillation





Application to Wildlife Management

- Kaibab Plateau in Arizona
  - 1920s pressure from ranchers
    - Government-led control of coyotes, “wildcats,” and mountain lions
  - Deer population skyrockets…and collapses
- System structure
  - Destroyed forage
  - No new forage



Core System Dynamics Concepts

- Simple processes can generate complicated behavior
- System dynamics provides unified approach for understanding problems
- Assists with your own mental models by making dynamic problems explicit
  - Accumulations (Stocks), Change (Flows), Feedback (interactions between the two)
- From my field: urban problems involve **LOTS** of feedback
  - Complicated by lots of interacting factors!

Modeling for Learning

- Learn from comparing simulations
- Irreversibility of real-world actions
  - Value of digital laboratory
- We will reach for understanding and for good management “rules of thumb”
  - Initially difficult in context with statistical forecasting models