Welcome to System Dynamics

15.871 and 15.873(1)

Fall 2022

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MIT MANAGEMENT SLOAN SCHOOL

Your TAs

Alex
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Jason
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Celia
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Administrative Matters

- **Syllabus, FAQs, other key info on Canvas**
- **Registration (waitlist, cross-registration, timing of approval)**
- **15.871 (H1, 6 units) vs. 15.873 (full semester, 9 units)**
- **Heavy assignments, but no final exam, and lenient final grading!**
- **Assignment 1: due Wed 14 Sep, Noon. On MITx**
  - Get started ASAP; contact TAs if you can't access MITx (sd-ta-fall22@mit.edu).
  - Get started (and perhaps finish) in recitation this Friday
- **Start forming teams for assignment 2 (871 or 873 only; can cross sections)**
  - Canvas > People: https://canvas.mit.edu/courses/17238/groups
- **Textbook and readings**
  - **For Monday: BD 3.1-3.4**

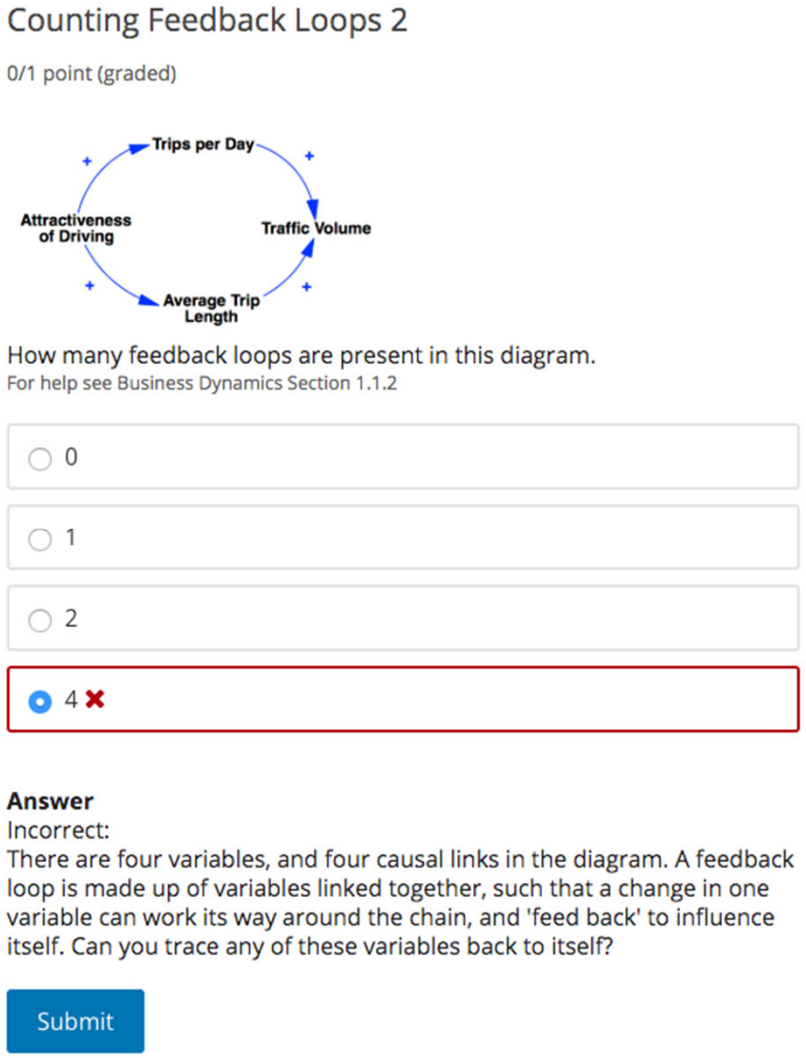
Friday Recitations

- 10:00-11:30 (E51-315) and 2:30-4:00 (E51-335).

  DIFFERENT LOCATION THIS WEEK: E62-223
- You only need to attend one each week; no need to match your section.
- This Friday: Installing Vensim, getting started on assignment 1
- Join with a laptop
- Don’t worry if you can’t make it

Online Learning Materials on MITx

- Assignments 1 & 3
- Weekly reviews: Questions designed to give you instant feedback.
  - Required, but not graded.
- Access:
  - You should have access if registered or on waiting list with MIT email
  - If you need MIT email, email TAs ASAP

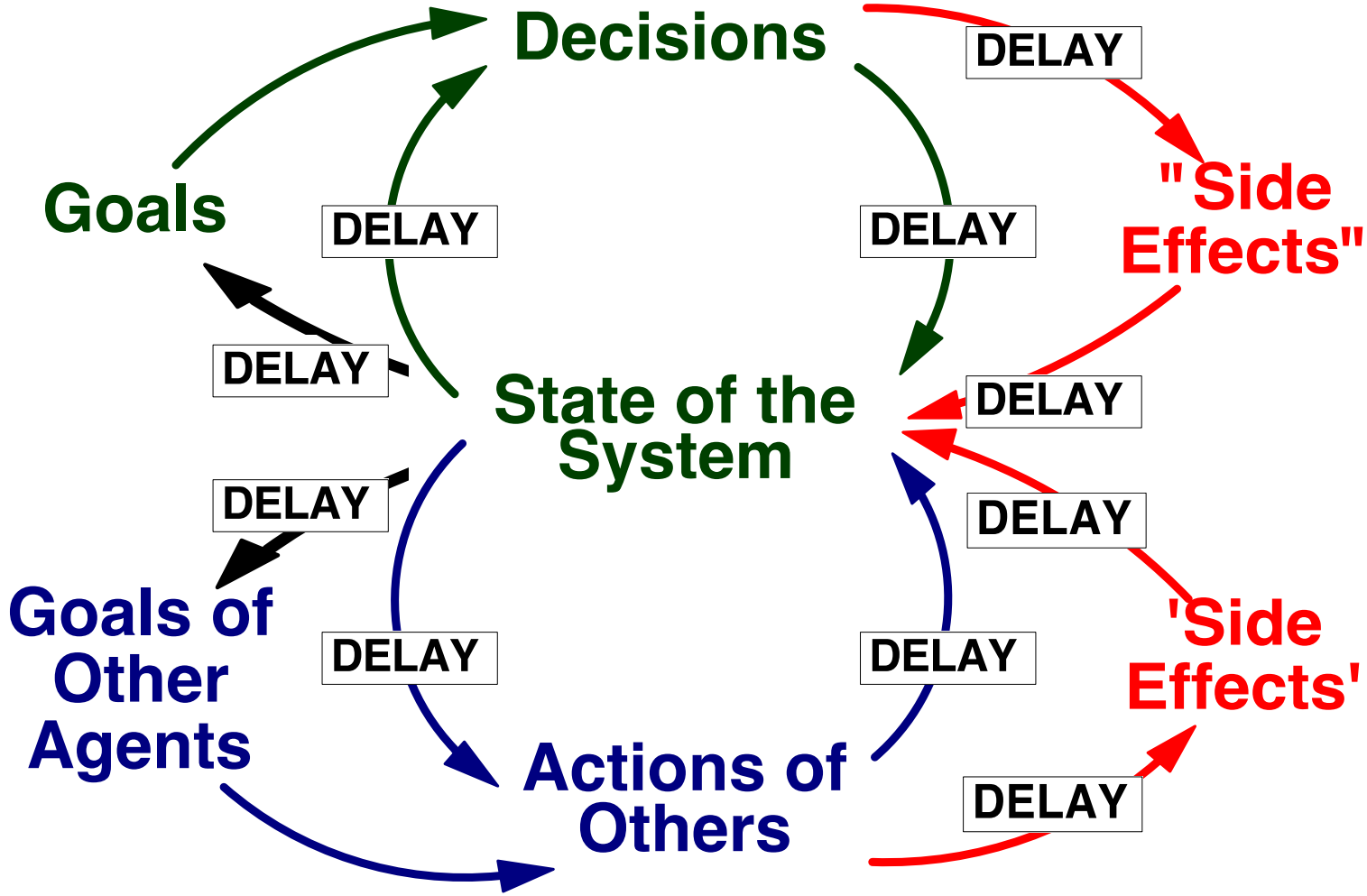


Policy Resistance

- Forest fire suppression
- Road building
- Health care
- Mergers and acquisitions
- Process improvement programs
- Projects: Late, Expensive and Wrong
- Antibiotic/pesticide resistance
- Economic growth and well being

NYTimes: McKinney Fire Becomes California's Largest of 2022

We are embedded in a larger system



Learning Goals

- **1) Systems Thinking** skills for making sense of and structuring complex, policy resistant problems
- **2)** Build a mental library of **archetypal dynamics** in management and public policy that you can quickly draw on for new problems
- **3) System Dynamics** tools for modeling and analyzing complex problems and designing better organizations and policies
- **4)** Become a **better consumer of models**

Models

- Human action often based on models, mostly **mental models**
- **Strength:**
  - Tremendous store of information
  - Versatile, and does not give up easily
- **Weakness**:
  - Can't handle large amounts of quantitative data➔ Value of statistical and machine learning methods
  - Misses feedbacks not salient in our daily experience
  - Unreliable in handling dynamic complexity

Value of Dynamic Models

The Iceberg Metaphor for Systems Thinking

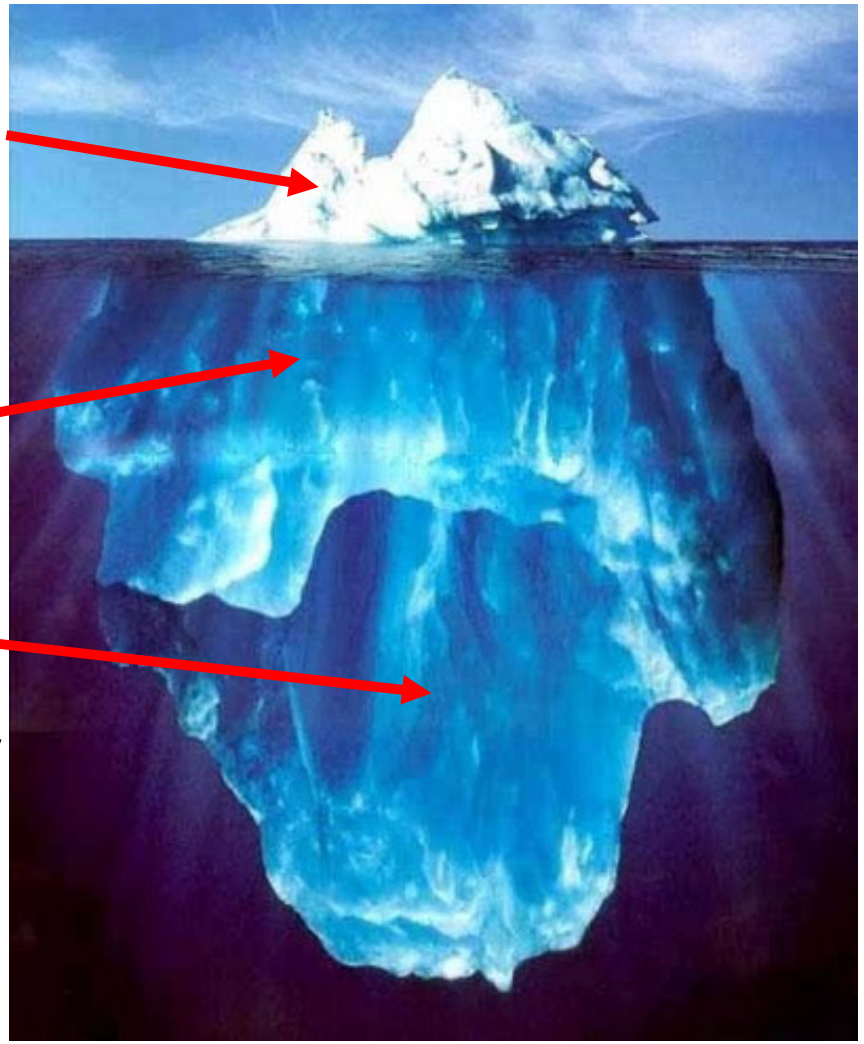
Events: Salient & compelling, but noisy, short-term, ephemeral

Patterns of behavior: Harder to detect. Require long time horizon and more data

System Structure:

- System physics
- Information availability & quality
- Incentives
- Relationships
- Mental Models/Perceptions/ neurobiological reactions

More Leverage



Policy Resistance:
a hallmark of dynamic complexity

- Actions meant to solve a problem cause unanticipated "side effects"
- The system responds to our actions in ways that delay, dilute, or defeat them
- Actions designed to solve the problem actually make it *worse*

Learning Goals

- **1) Systems Thinking** skills for making sense of and structuring complex, policy resistant problems
  - Moving from events to trends and underlying structures
  - Surfacing implicit mental models
  - Tools for building qualitative models
  - Using these models to engage diverse stake-holders and help change entrenched mental models

2) System archetypes

- Build a mental library of **archetypal dynamics** in management and public policy that you can quickly apply to new problems. Examples include:
  - **Diffusion** of new ideas, diseases, and products
  - **Overshoot and collapse** dynamics in startups and societies
  - (Mis-)**managing stocks**, from inventories to housing bubbles
  - Cost and schedule overruns in **projects**
  - Goal adjustment and **quality erosion** in services
  - **Resource allocation** and capability traps
  - …

3) System Dynamics

- Tools for modeling and analyzing complex problems and designing better organizations and policies
  - Stocks and flows
  - Standard formulations
    - Natural and physical processes
    - Organizational decision making
    - Financial accounting
    - Modeling human resources
    - …
  - Iterative modeling process
  - Engaging stakeholders
  - Use of quantitative data with models

4) Becoming a savvy model consumer

- You may not be building formal models regularly but you are likely to be a consumer of others' models at work and personal life.
- Having done modeling allows you to better:
  - Challenge the boundary of model
  - Identify missing feedback loops
  - Assess robustness to extreme conditions
  - Assess the appropriate use of data and potential abuses
  - Design better policies
  - Enhance the modeling process and its transparency

Course Structure: Learning through **cases** and **hands on exercises**

- **H1 (871 and 873)**
  - Epidemics
  - New product adoption
  - Climate change
  - Growth dynamics
  - Strategy design
- **H2 (873 only)**
  - Managing supply chains
  - Instability in markets
  - Forecasting
  - Service operations
  - Global sustainability
  - Platform markets
  - Dynamics of privilege
  - Project dynamics
  - Capability traps
  - Process improvement

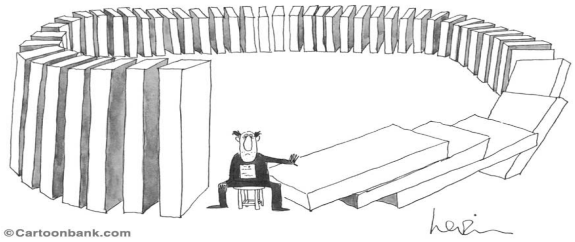
Systems Thinking: Foundations

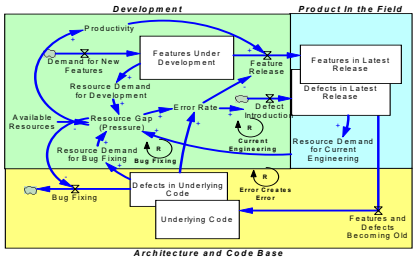
- **Structure generates behavior**
  - Dynamics emerge from the interaction of:
    - Physics
    - Information availability
    - Decision rules
- **Mental models matter (a lot).**
  - It is not enough to change physical structure, information, and incentives
- **The Fundamental Attribution Error**
  - Our first instinct is to blame the people in the system. Almost always a low-leverage response.

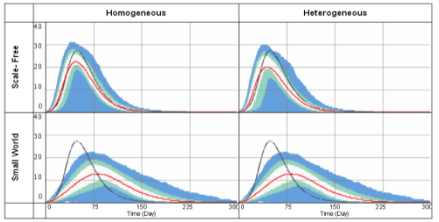
An Overview of the System Dynamics Process: Understanding COVID-19

15.871 & 15.873 System Dynamics

Hazhir Rahmandad







Administrative

- **Use Name cards; No laptop/cellphone**
- **Waitlist; Class Videos; TAs' office hours**
- **Assignment 1 due Wed 11:59 AM EST**
- **Teams of 3 for Assignment 2 and later**
  - Teams can cross sections
  - Teams should not cross 871 vs. 873; we will fix changes due to class switch later
  - Get into a team ASAP; use Canvas and the spreadsheet
- **Readings for Wed: BD 5.1-5.4**
- **Do MITx Weekly review for Week 1**

The Iceberg Metaphor for Systems Thinking

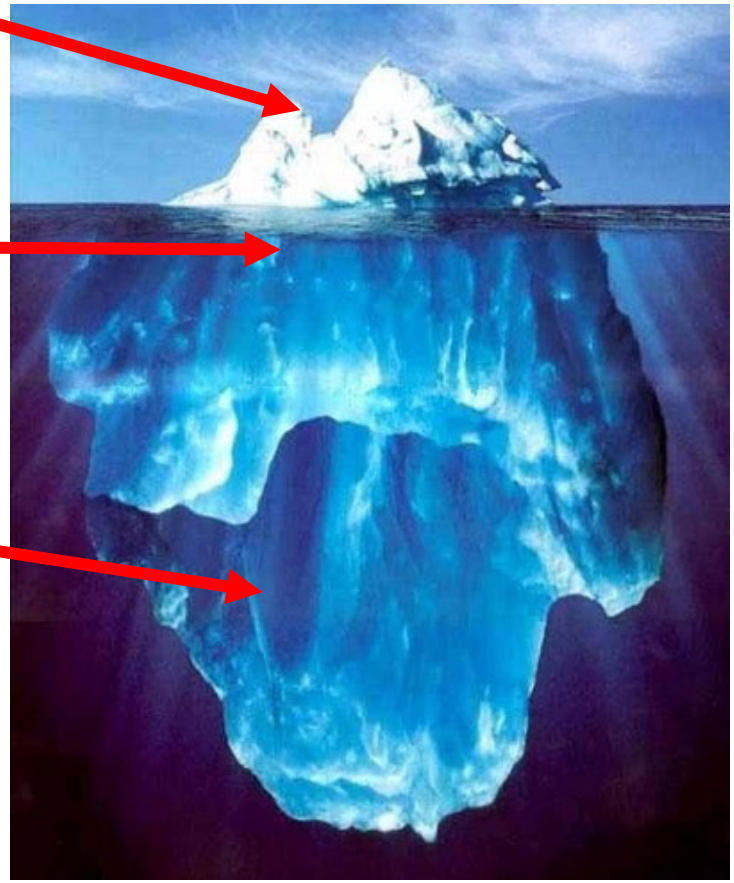
Events: Salient & compelling, but noisy, short-term, ephemeral

Patterns of behavior: Harder to detect. Require long time horizon and more data

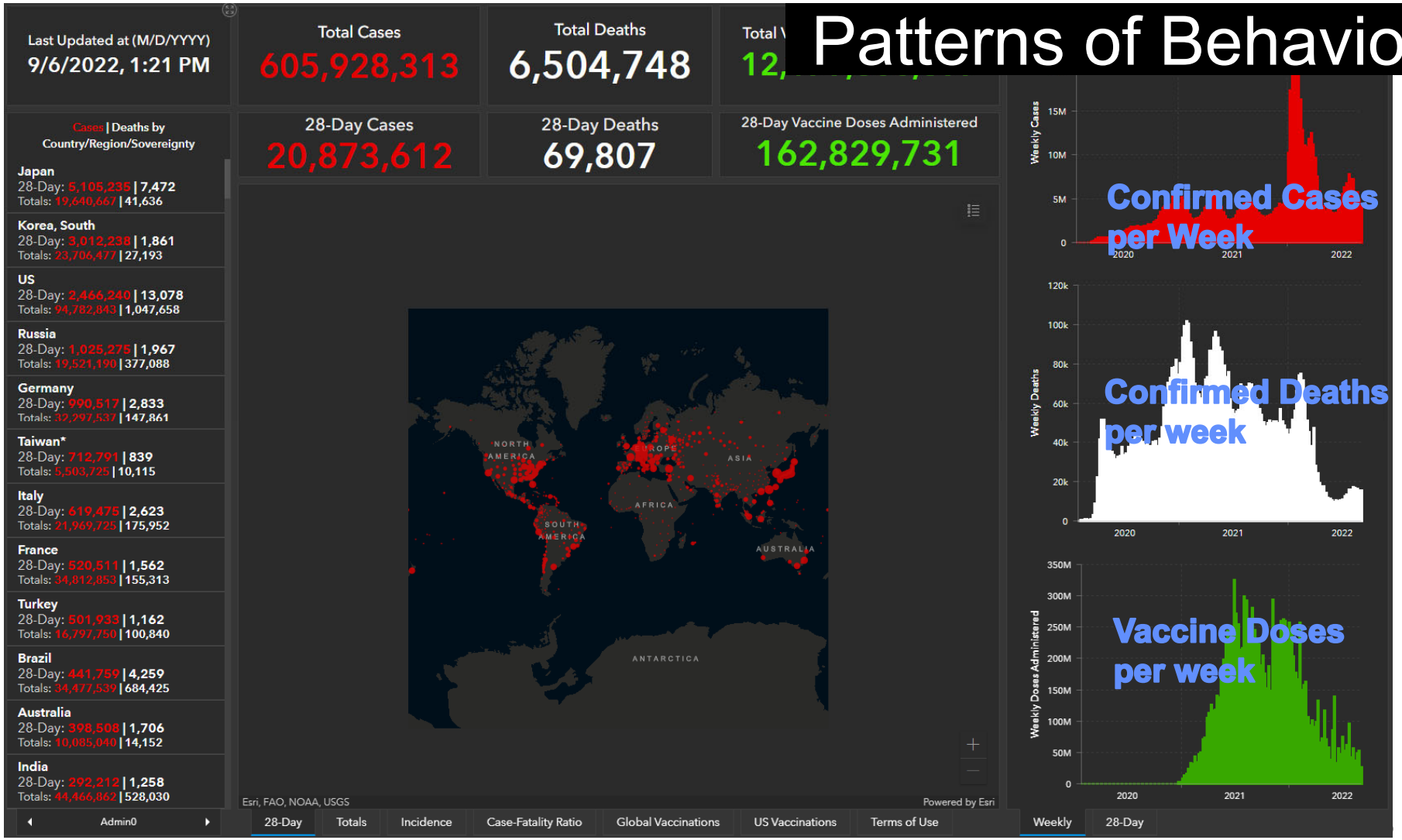
System Structure:

- **System physics**
- **Information availability & quality**
- **Incentives**
- **Relationships**
- **Mental models/perceptions/ neurobiological reactions**

More Leverage



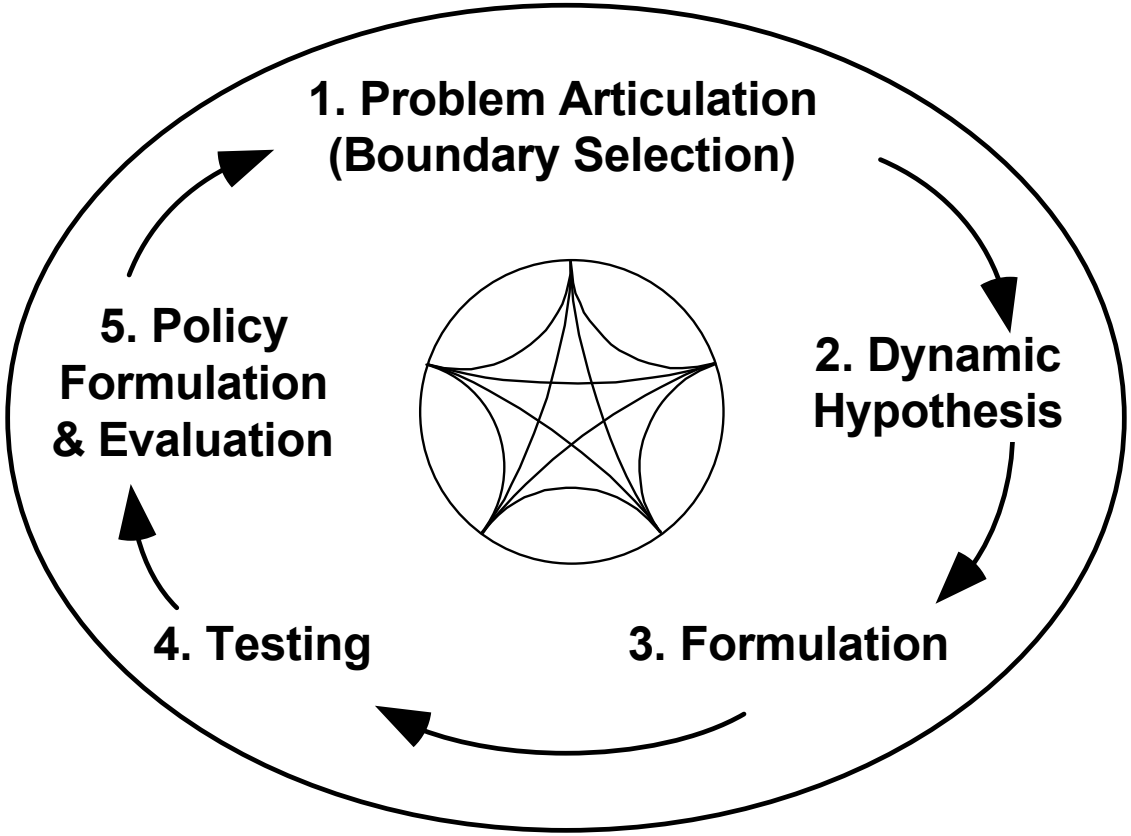
Patterns of Behavior



The System Dynamics Process

- **Problem Articulation**
- **Mapping a Dynamic Hypothesis**
  - Operational (causal) thinking
  - The feedback perspective
  - Stocks and flows
- **Model Formulation**
- **Model Testing**
- **Policy Design and Evaluation**

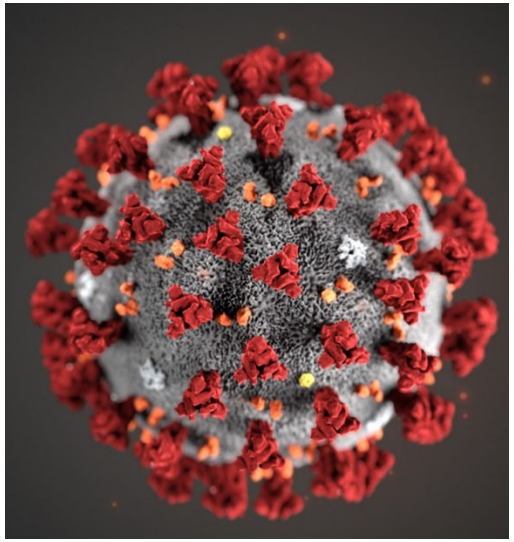
Modeling is highly iterative



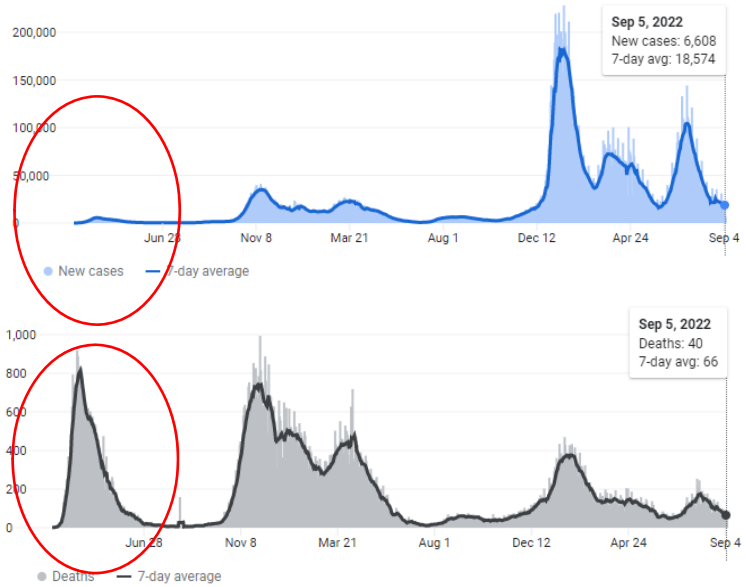
Source: *Business Dynamics*

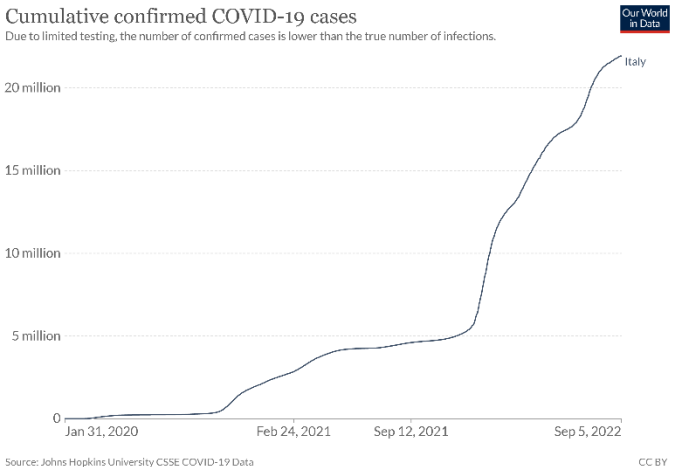
The Problem

- **New infectious diseases emerging with greater frequency (HIV/AIDS, Ebola, Avian Flu, Zika, MERS, others)**
- **COVID-19**
  - Emerged in late 2019
  - Pandemic by March 2020
  - Official toll as of today (2 Feb 2022):
    - >605 Million infected
    - >6.5 Million deaths
    - Significant undercount in official data
  - Severe economic and social harm



Management and Policy Issue: ***What should government officials do to halt the spread of infectious diseases?***





COVID-19, Italy

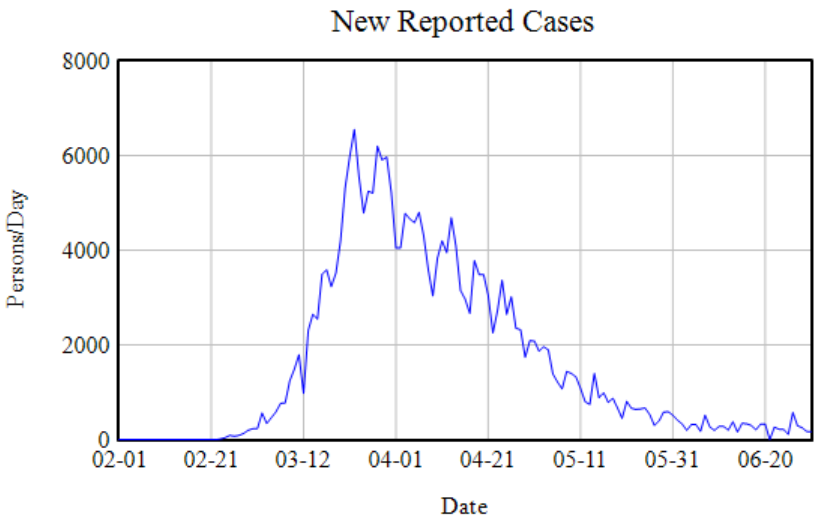
As of 6 Sep 2022:

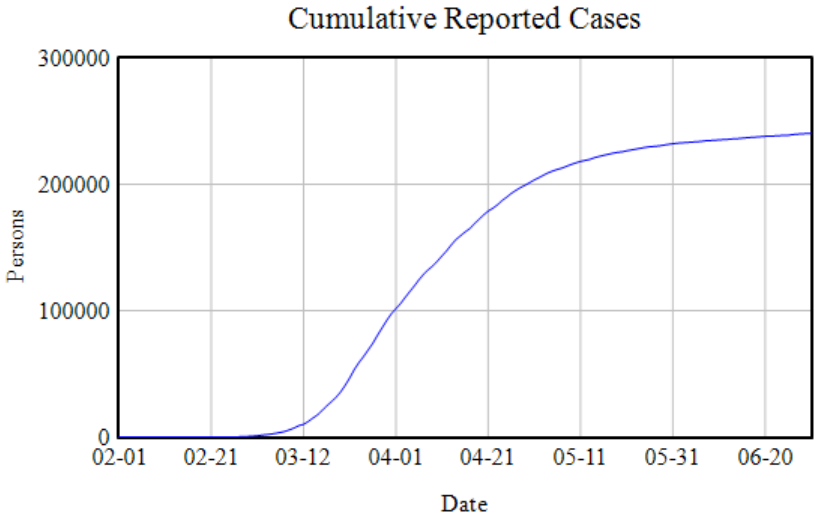
Official Cum. Cases: 21.9 Million

Official Cum. Deaths: 176K

JHU Data dashboard
Cases are underreported

https://coronavirus.jhu.edu/map.html





Trends: COVID-19, Italy

First Wave: February – June 2020

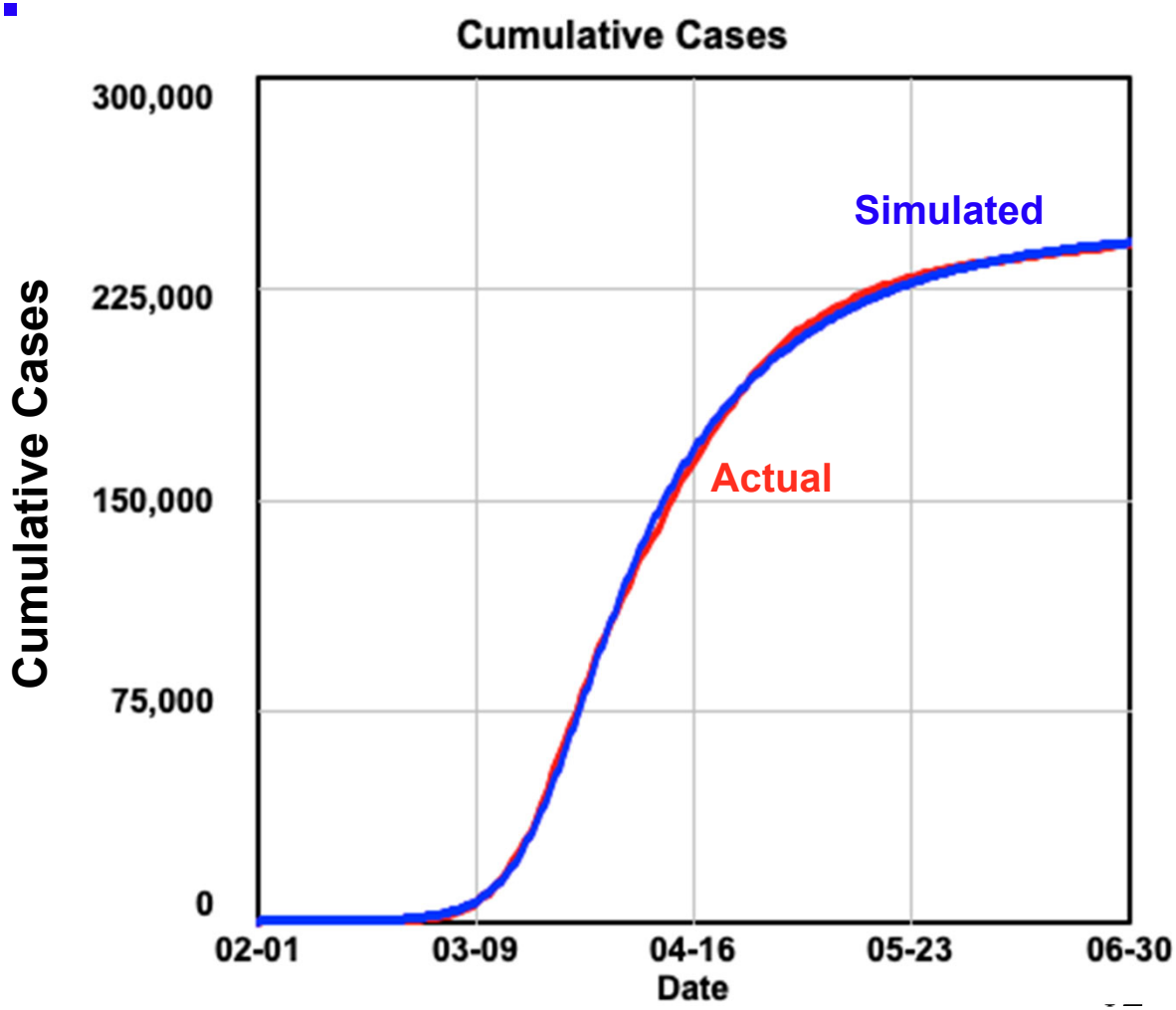
Source: JHU Data dashboard
Cases are underreported

https://coronavirus.jhu.edu/map.html

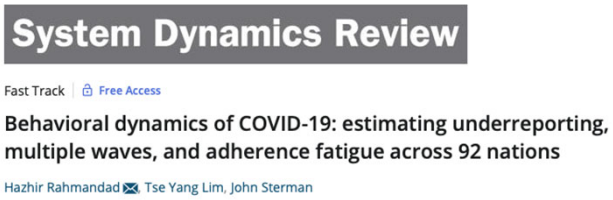
SEIR Model vs. Data, Italy

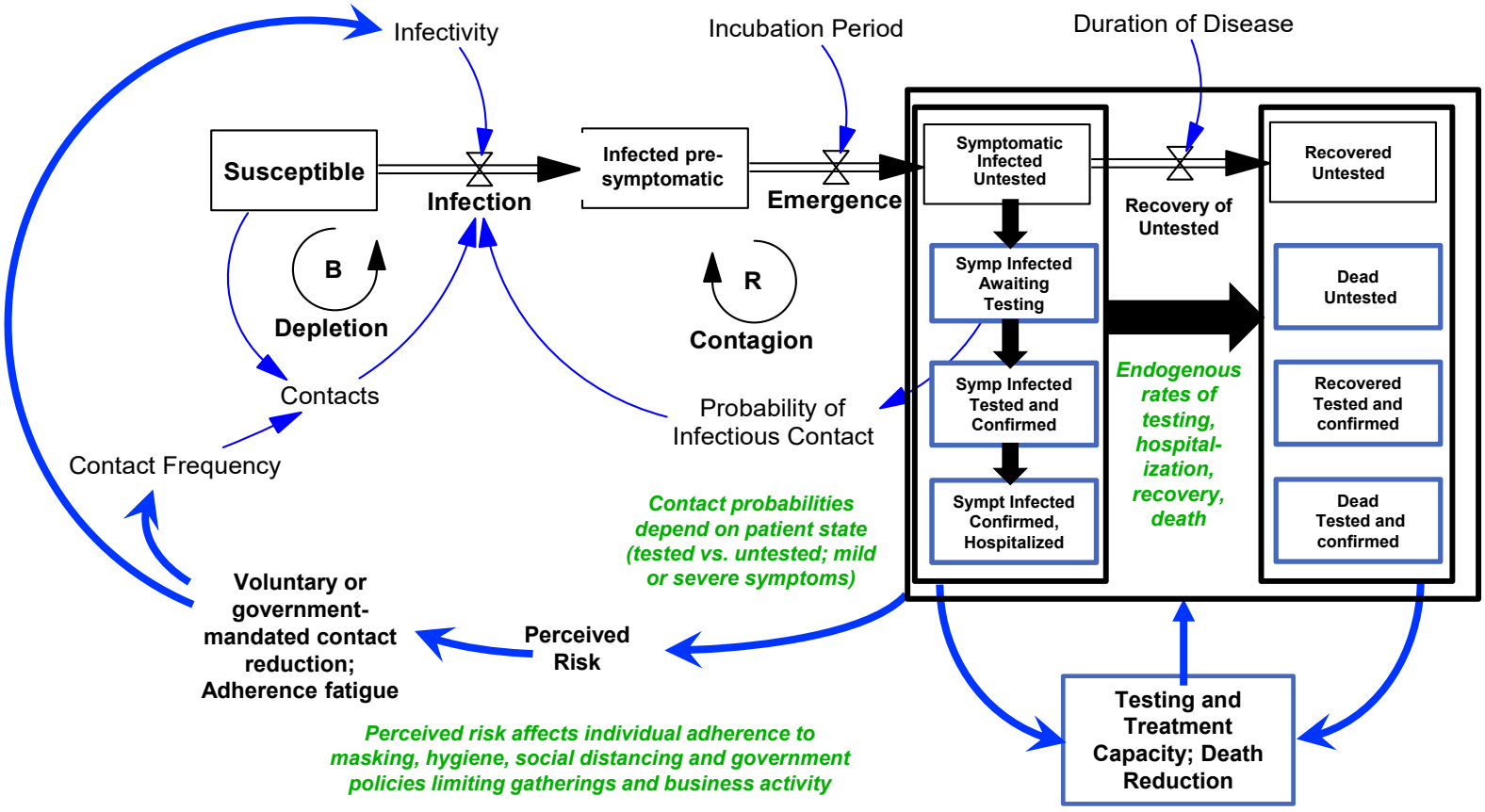
With Policies and Behavioral Feedback

Max Effectiveness of Policies and Behavior Change = 0.80



Model Overview

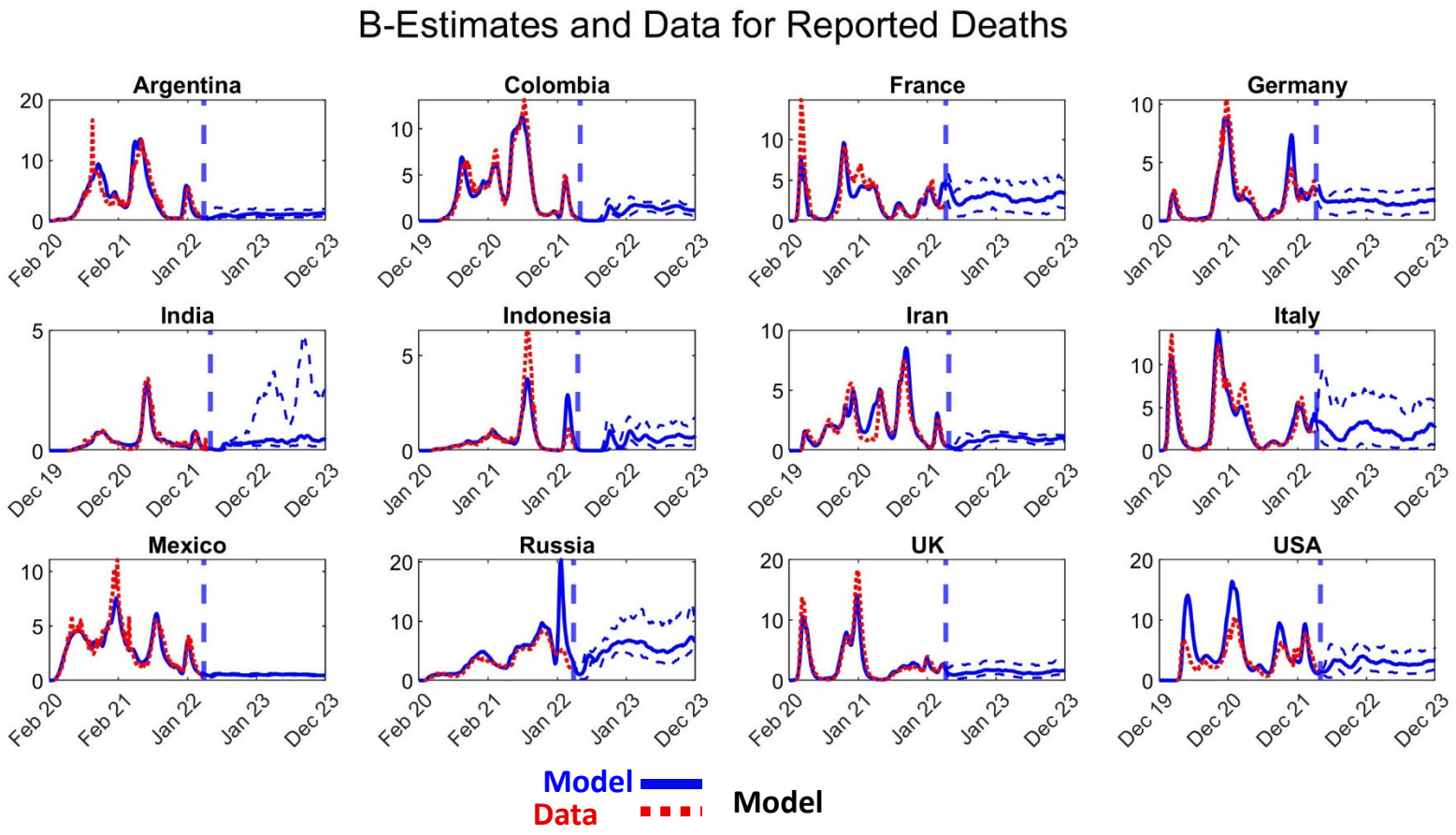




- **Disaggregated by nation** (92 countries)
- **Data:** cases, deaths, testing, vaccination
- Used to estimate **parameters**, e.g.:
  - **Disease**: R_0, asymptomatic fraction, morbidity & mortality, etc.
  - **Behavior**: risk perception and impact, testing and treatment decisions, impact of health care capacity, adherence fatigue, etc.

Model Fit & Projections

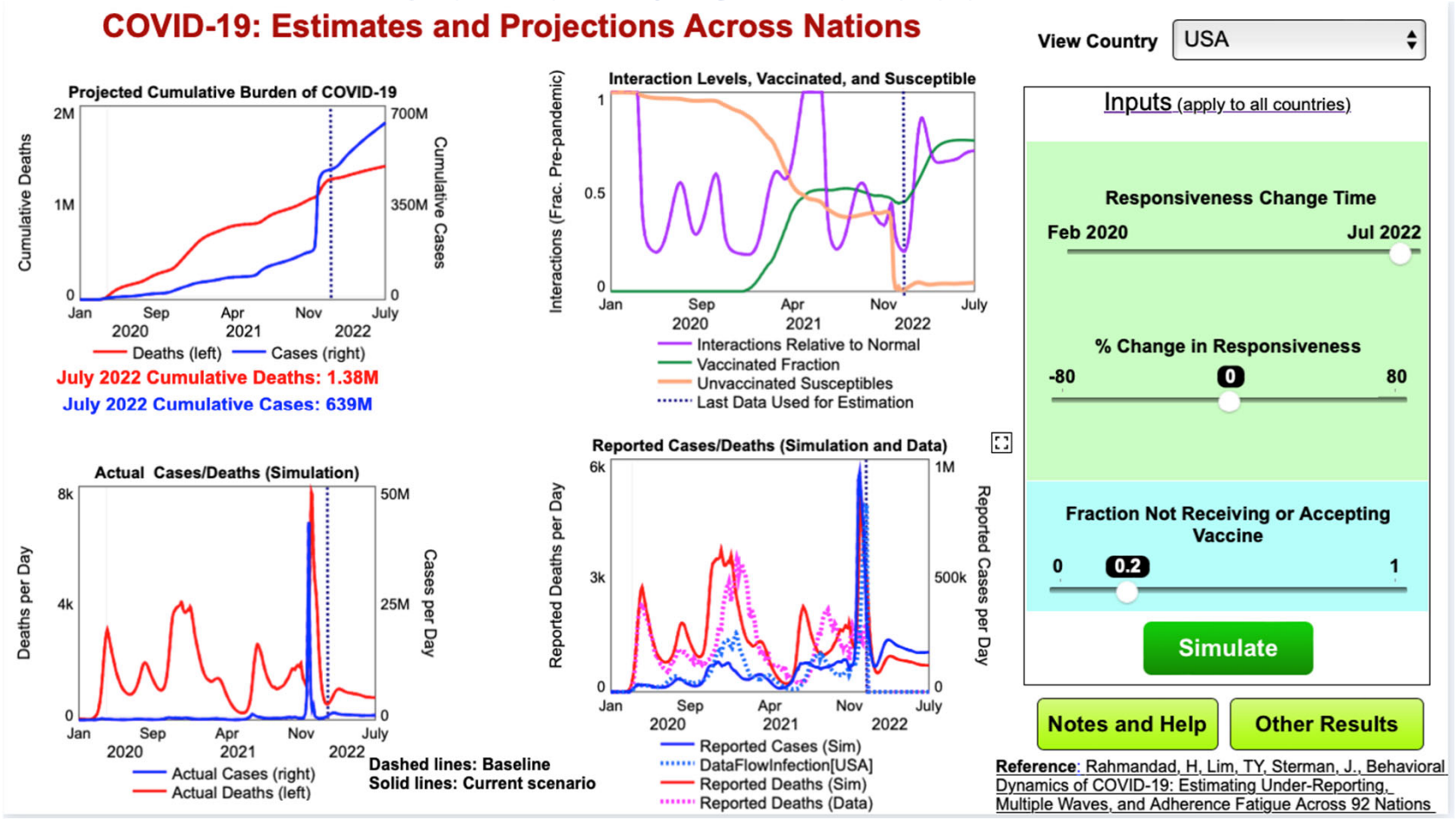
deaths per million people/day



Validation:

- ✓ **Extensive sensitivity analysis**
- ✓ **Out-of-sample prediction test**
- ✓ **Estimation on synthetic data**
- ✓ **Comparison with seroprevalence data**

Covid-19 Simulator



https://tinyurl.com/CovidVacSim

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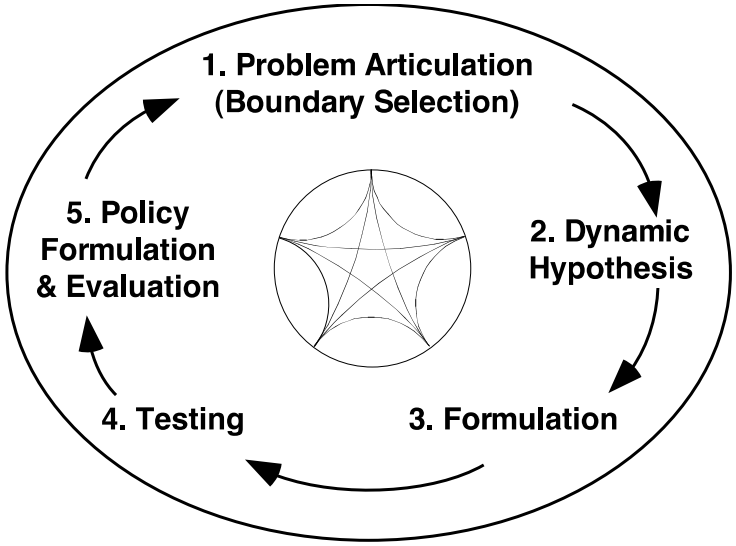
Models and Epidemic Response

- **Response policies based on SD models like SEIR**
- **Level of detail depends on purpose**
  - **Aggregate models with few stocks**
    - fast and cheap to run and carry out sensitivity analysis; Rapidly adjusted to new data
  - **Detailed, "agent-based" models with explicit individual interactions or global travel network**
    - Capture network of interactions among actors, more detailed treatment of interventions, but slow and costly to change; limited sensitivity analysis
- **Used by CDC, NIH, White House, states, WHO, other nations**
  - Scenario analysis
  - Planning and optimizing outbreak response
  - Vaccine allocation and other preventive measures
- **Regularly applied to flu, SARS, MERS, Polio, Ebola, HIV/AIDS, computer viruses & malware**

Models and COVID-19 Response

- **≈740,000 Google Scholar results for "Covid-19" and "Simulation." Models applied to:**
  - Estimating features of disease (infectivity, fatality, association with age and co-morbidities)
  - Estimating true magnitude
  - Assessing alternative policies
    - Masking, lockdowns, isolation, distancing, air flow, vaccines, variants, …
  - Designing clinical trials
  - …many others

Key Ideas: All Models are Wrong; Some are Useful



- Reference Modes
- Causal Loop Diagrams
- Stocks and Flows
- Equation Formulation
- Dimensional Analysis
- Simulation
- Sensitivity Analysis
- Policy Testing

Good modelers:

Focus on an important problem
Follow scientific method
Start with a broad model boundary
Add detail as necessary
Iterate!

System Dynamics
15.871 and 15.873
Fall 2022

Problem Definition and Causal Mapping

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Administrative

- **Those not part of a team on canvas by 5pm today will be assigned to one**
- **Assignment 2 out now; due *Monday Sep 26***
- **Readings for Monday: BD 5.6, 6.1, 6.2, 7.1**
- **Start Weekly Review 2 on MITx**

Agenda

- **Perspective**
  - Structure generates behavior
- **Tools for Systems Thinking**
  - Fundamental modes and generative structures
  - Dynamic problem definition
  - Causal loop diagrams: rules and syntax
- **Mini Case**
  - The petroleum industry

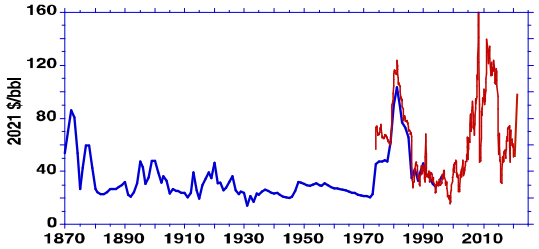
Structure Generates Behavior

Events

- "The world's oil glut is much worse than it looks" (9/8/19)
- "Oil ends higher on the back of a third weekly decline in US oil-drilling rigs" (MarketWatch, 9/7/19)
- "Crude Oil Prices Crater as Saudi Arabia Kicks Off a Price War" (Motley Fool, 3/9/20)
- "Oil prices rise on signs an industrial recovery is underway" (World Oil, 9/15/20)
- "US oil prices turn negative as demand dries up" (BBC, 4/21/20)
- "Gulf markets ride high on upbeat oil prices" (Reuters, 9/12/22)
- "Drunk trader caused a spike in oil prices" (NY Post, 2012)

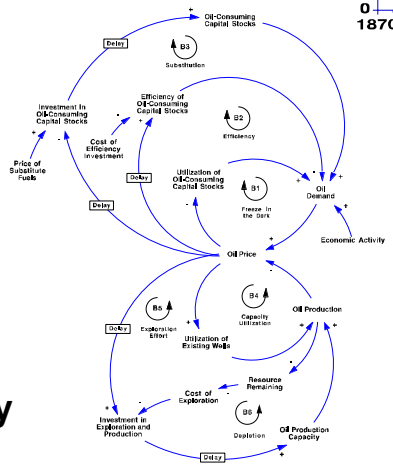
Patterns of Behavior

- Chronic boom and bust cycles
- Real Prices rising on average
- Growing Pressure from climate change



Structure

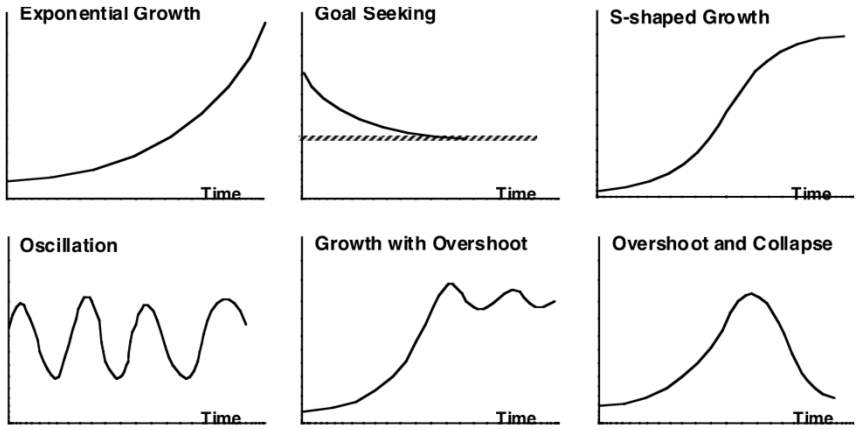
- **Physical structure:**
  - Feedback processes
  - Stocks and flows
  - Time delays
- **Information availability**
  - Delays, biases, error, gaps
  - Access & transparency
- **Mental Models**
  - Actor goals and incentives
  - Time horizon, model boundary
  - Misperceptions of feedback



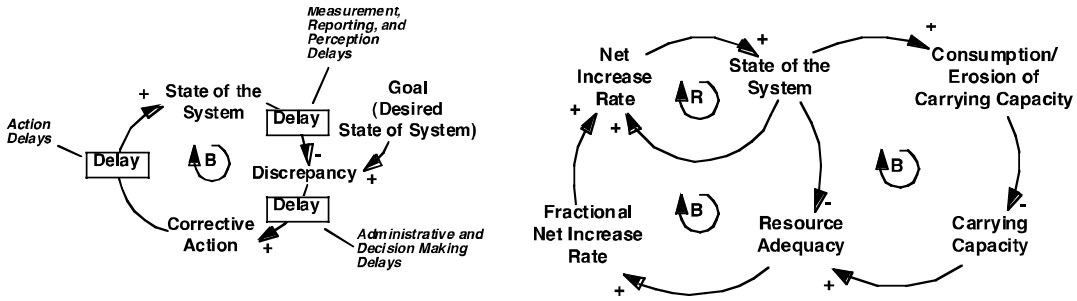
Events

Volatile Oil Prices
COVID Vaccine, new variants, mask mandates, lockdowns
Record cold hits Texas

Patterns of Behavior

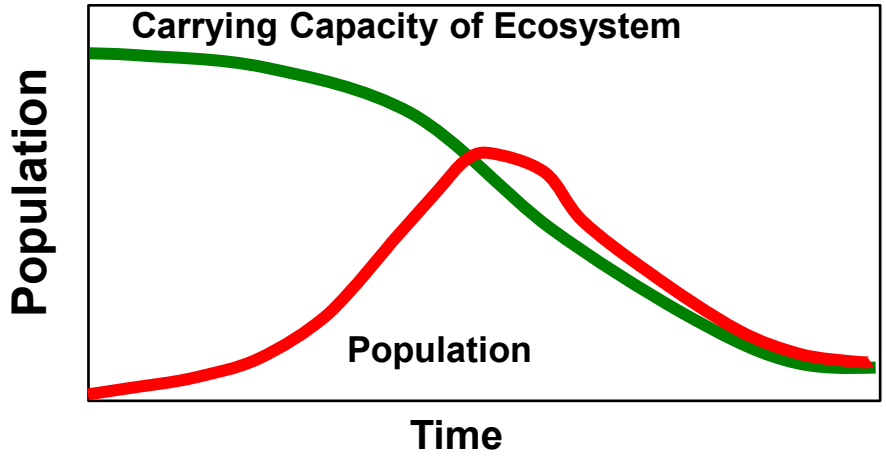


Structure

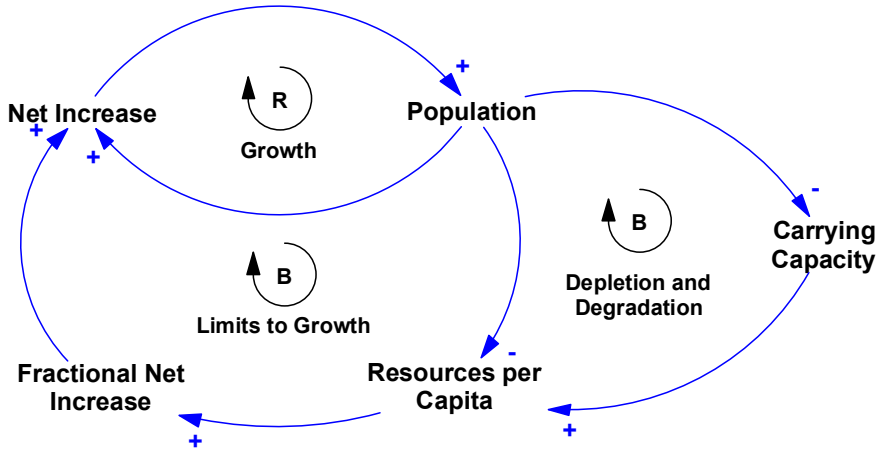


Overshoot and Collapse

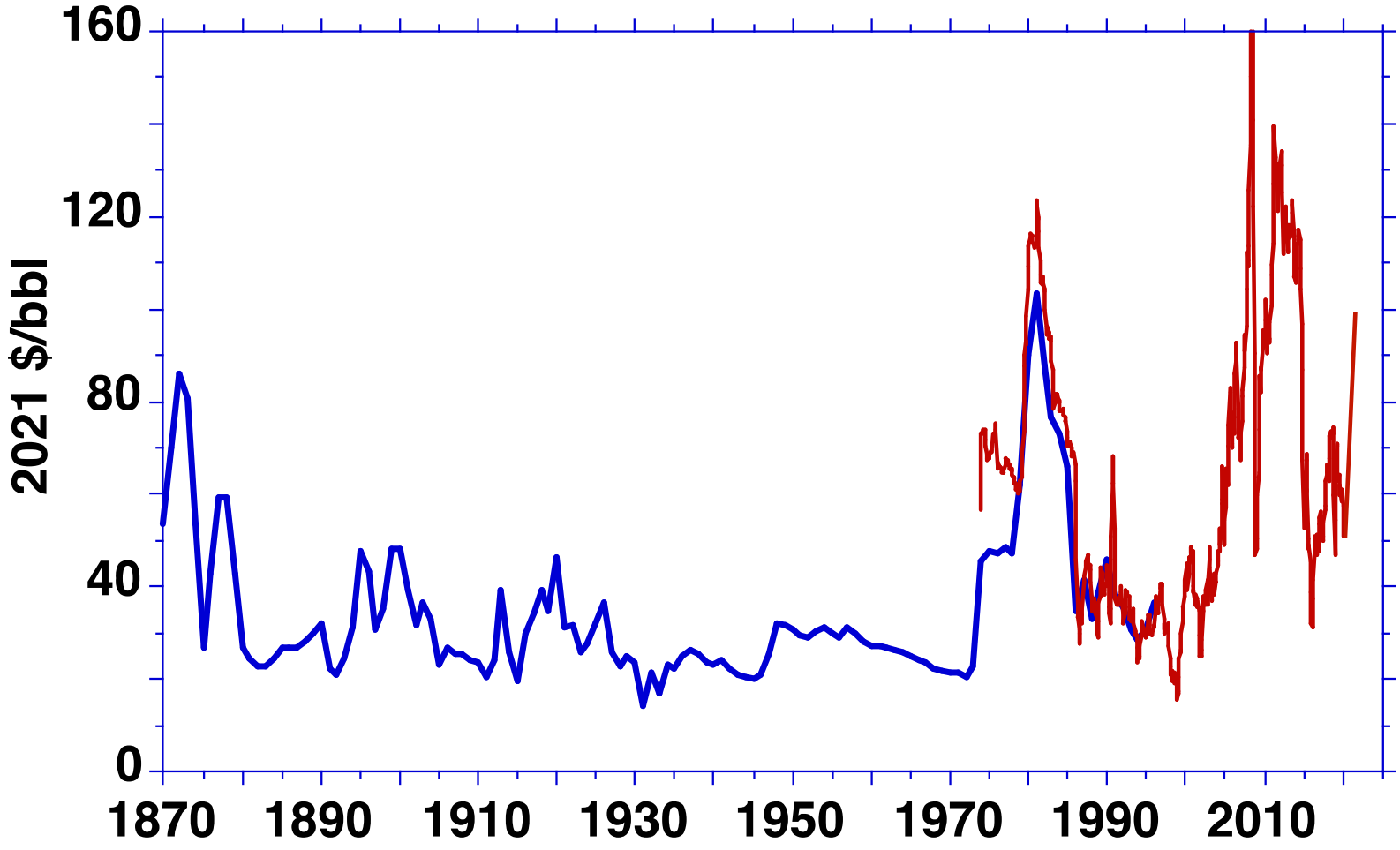
Behavior



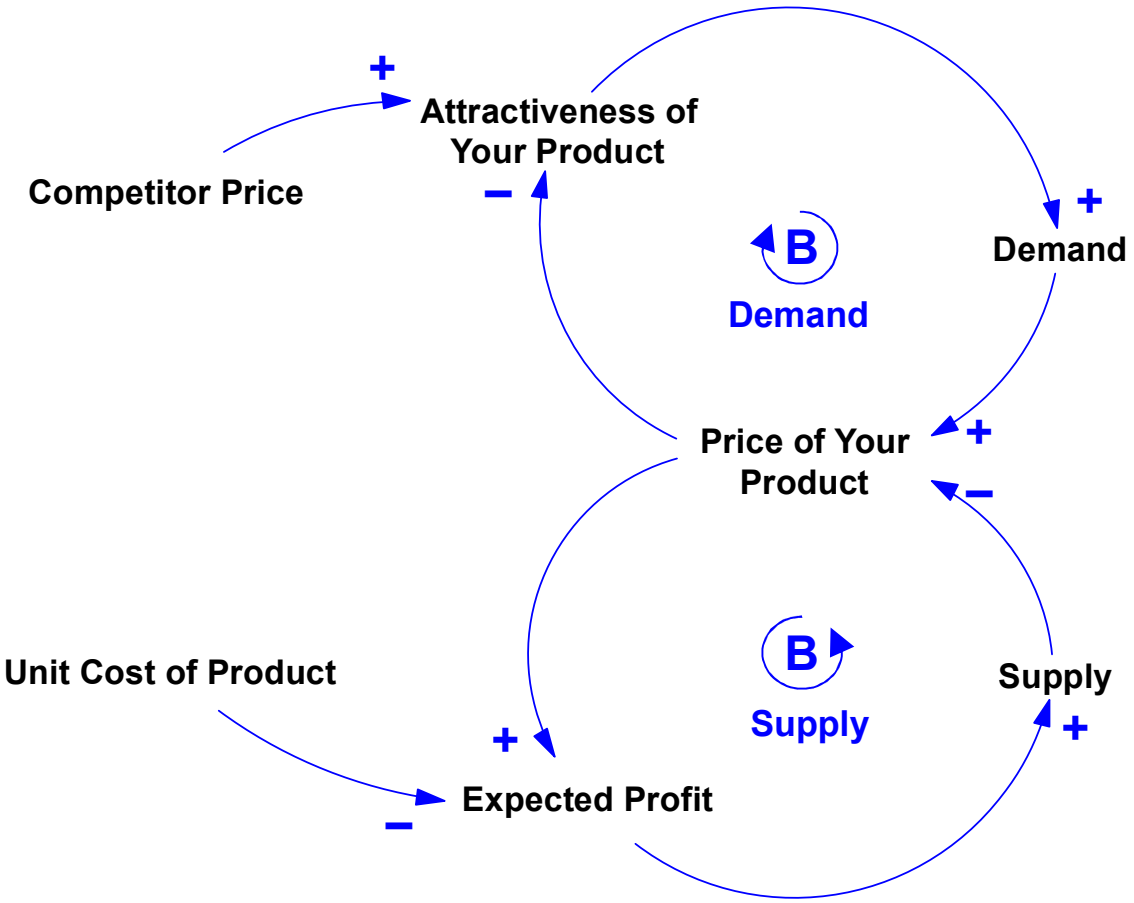
Structure



Real Petroleum Prices



The Invisible Hand



Causal Loop Diagrams: Review

- All links must represent real causal relationships.
- Label link and loop polarities.
- If a polarity is ambiguous, you may be missing causal connections.
- Indicate delays.
- Make intermediate links explicit to clarify relationships.
- Make the goals of negative loops explicit.
- Distinguish between actual and perceived conditions.
- Label and name your loops.
- Keep it simple!

System Dynamics

Causal Mapping and Stocks and Flows

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Administrative

- **Assn 2 due next *Monday 9/26***
- ***No Recitation this Friday 9/23 (MIT hoiday)***
- **Please complete weekly review for week 2 (MITx)**
- **Readings for Wednesday: 6.3-6.4**

Developing Useful Models Requires Data

Use qualitative and quantitative data to surface system structure

Example:

- US Automaker experienced chronic failures to implement and sustain quality improvement programs in their plants.

Method:

- Gather quantitative and qualitative data, including extensive observations of operations at the plants and interviews with employees.
- Use the interviews to identify feedback processes affecting work and improvement activities.
- Use the resulting causal loop diagram to explain the problematic dynamics and identify high-leverage policies for successful implementation of improvement programs.
- Do this iteratively and interactively with stakeholders to build their understanding and commitment to implementation.

Developing CLDs from Qualitative Data

In the minds of the [operations team leaders] they had to hit their pack counts [daily quotas]. This meant if you were having a bad day and your yield had fallen...you had to run like crazy to hit your target. You could say, "You are making 20% garbage, stop the line and fix the problem," and they would say, "I can't hit my pack count without running like crazy." They could never get ahead of the game.

—Manager at Plant A

Supervisors never had time to make improvements or do preventive maintenance on their lines...they had to spend all their time just trying to keep the line going, but this meant it was always in a state of flux. A quality problem might not be discovered until we had produced a pile of defective parts. This meant…we didn't have time to figure out why the problem happened in the first place, since we were now really behind our production schedule. It was a kind of snowball effect that just kept getting worse.

—Supervisor at Plant B

Stocks and Flows

Stock and Flow Diagram:

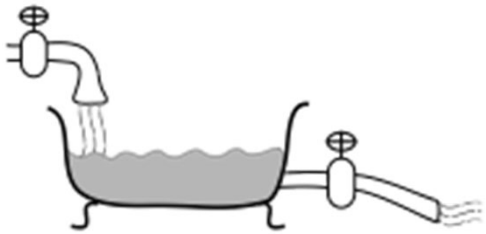
Integral Equation:

$$Stock(t) = \int_{t_0}^{t} \left[Inflow(s) - Outflow(s) \right] ds + Stock(t_0)$$

Differential Equation:

$$d\left(Stock\right) / dt = Net\,Change\,in\,Stock = Inflow(t) - Outflow(t)$$

Hydraulic Metaphor:



Two critical skills

- **Identification:**
  - **Identifying and mapping the stock and flow networks in systems**
  - **Challenging the clouds (expanding the model boundary)**
- **Inference:**
  - **Inferring the behavior of stocks given the flows (and vice-versa)**

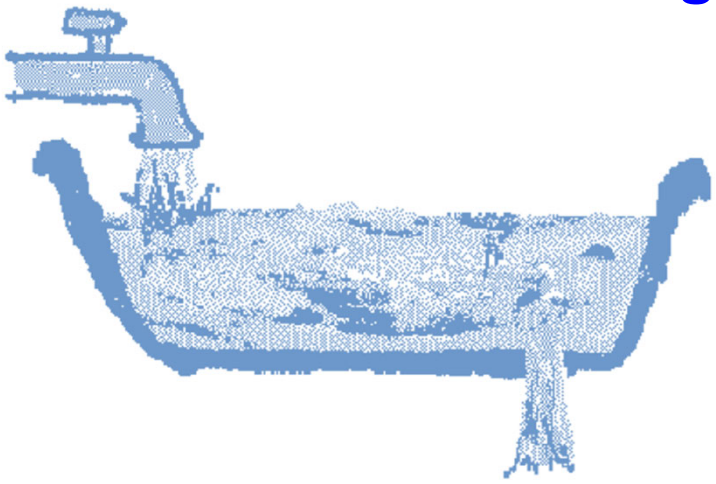
How to Tell Stocks from Flows

- **Stocks are accumulations**
- **Flows are actions**
- **Units for stocks are usually ‘things’**
- **Flows are measured in ‘units per time’**
- **Snapshot test: If you freeze the system only stocks are observable. Flows will all be zero**
  - **Once you have identified stocks, seek flows that change those stocks**

Inertia **Memory** **Delays** **Basis for action**

Stocks and Flows

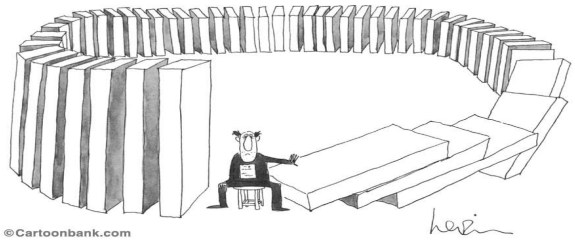
Balance Sheet	Cash Flow Statement
Wealth	Income, Expenditures
CO_2 in atmosphere	CO_2 emissions
Prevalence	Incidence, Mortality
Integrals	Derivatives
Water in Bathtub	Flows through faucet and drain

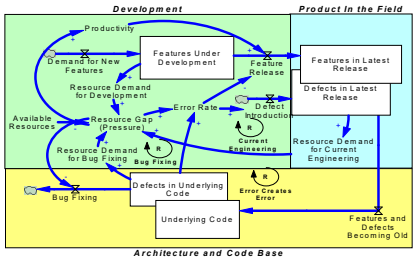


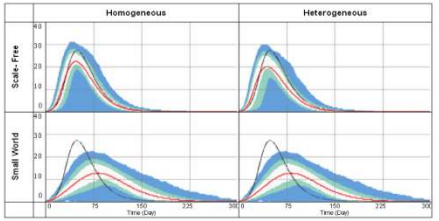
Understanding and Mapping Stock and Flow Structures

15.871/3 System Dynamics

Hazhir Rahmandad







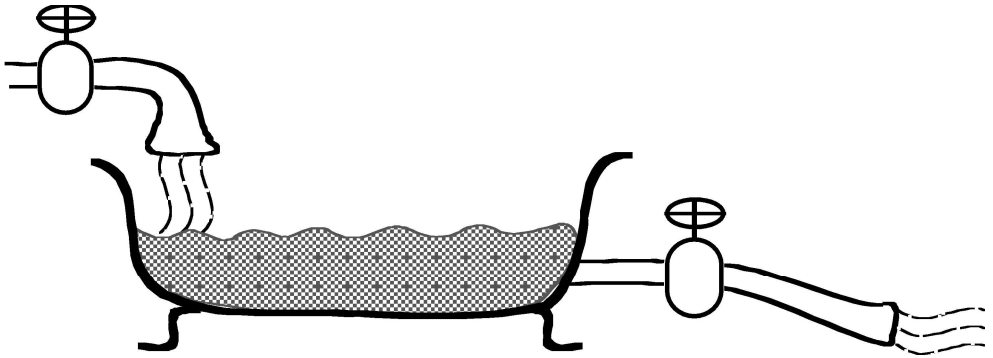
Administrative

- **Assignment 2 due Monday noon**
- **Readings for Monday BD Ch 7.2, skim 8.1-8.4**
- **Weekly reviews for Week 3 are out**

Next

Graphical Integration

Consider the bathtub shown below. Water flows in at a certain rate, and exits through the drain at another rate:

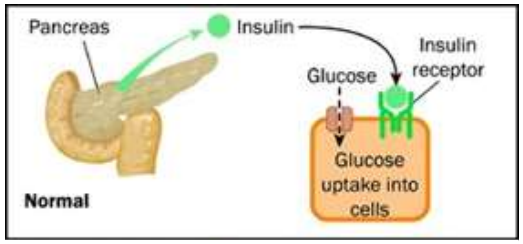


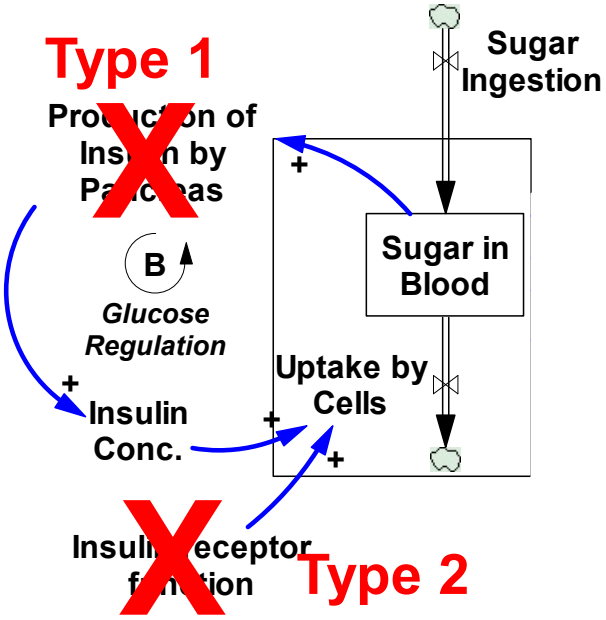
The graph below shows the hypothetical behavior of the inflow and outflow rates for the bathtub. From that information, draw the behavior of the quantity of water in the tub on the second graph below.

Assume the initial quantity in the tub (at time zero) is 100 liters.

Mapping Intel’s Stocks and Flows

Diabetes: The basics



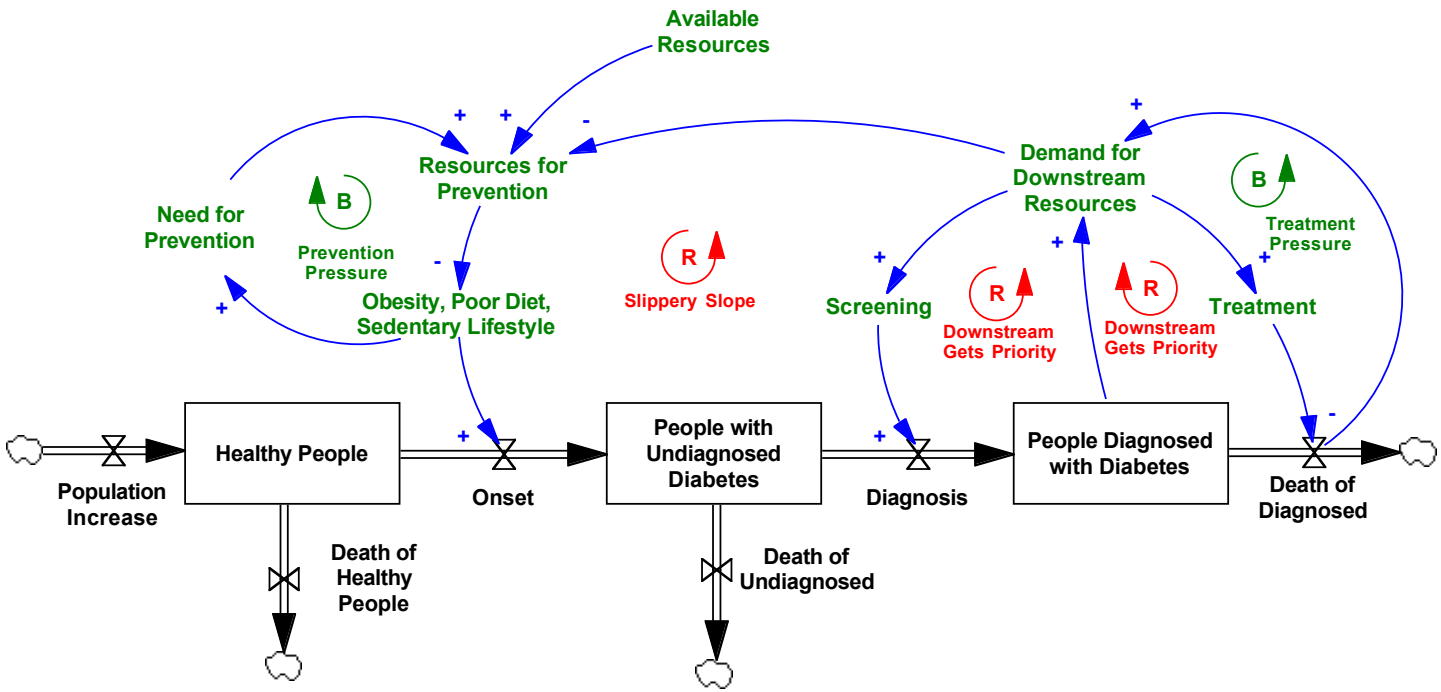


https://www.endocrineweb.com/endocrinology/overview-pancreas

https://medlineplus.gov/diabetes.html

Mapping the Stock and Flow Structure of Diabetes

Prevalence Starves Prevention



ReThink Health
A RIPPEL INITIATIVE

About | Stewards' Pathway | Stewards' Resources | Our Work | The Stew

Dynamics Model

ReThink Health SD Model
https://www.rethinkhealth.org

Easy to use to collaborate

Best used in a group, the Model is meant to make it easier for people with differing viewpoints to find common ground and strategize together.

Evidence-based

Designed by an award-winning team of MIT-trained system modelers, the Model brings together decades of evidence and is updated periodically to reflect new research and input from users.

Also...

100+ Strategy Labs

5,000+ Leaders

20+ Universities

Finalist, Social Impact Exchange Business Competition

UVA Frank Batten School of Leadership and Public Policy

Dartmouth

MIT

The Health Generation GEN-H Greater Cincinnati / N. Kentucky

ACH Accountable Communities for Health

THRIVE

The University of Alabama

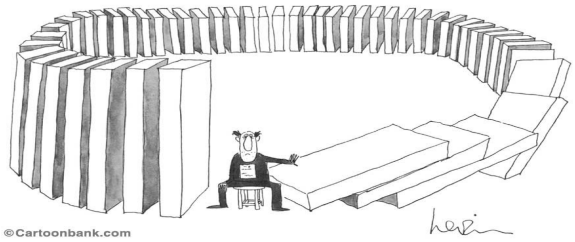
ASU Arizona State University

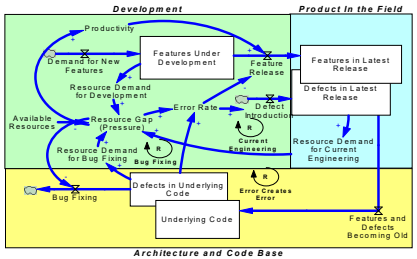
MIT MANAGEMENT SLOAN SCHOOL

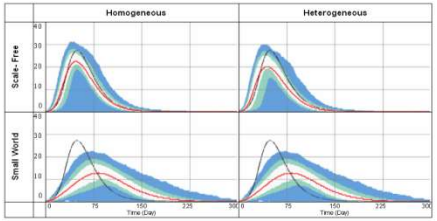
Integrating Stocks and Flows with Feedback

15.871/3 System Dynamics

Hazhir Rahmandad



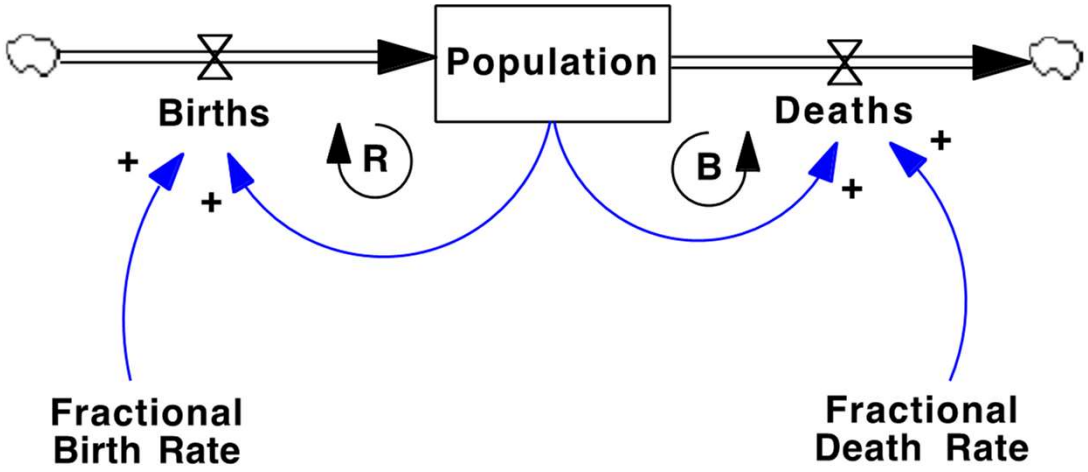




Administrative

- **Assignment 3 out; due next Monday at Noon**
  - **Work as a team, but only submit through one MITx account (of any member of the team)**
- **Readings for Wednesday:**
  - **BD Chapters 9.3 and 9.4**
- **Work on Weekly Review material for week 4**

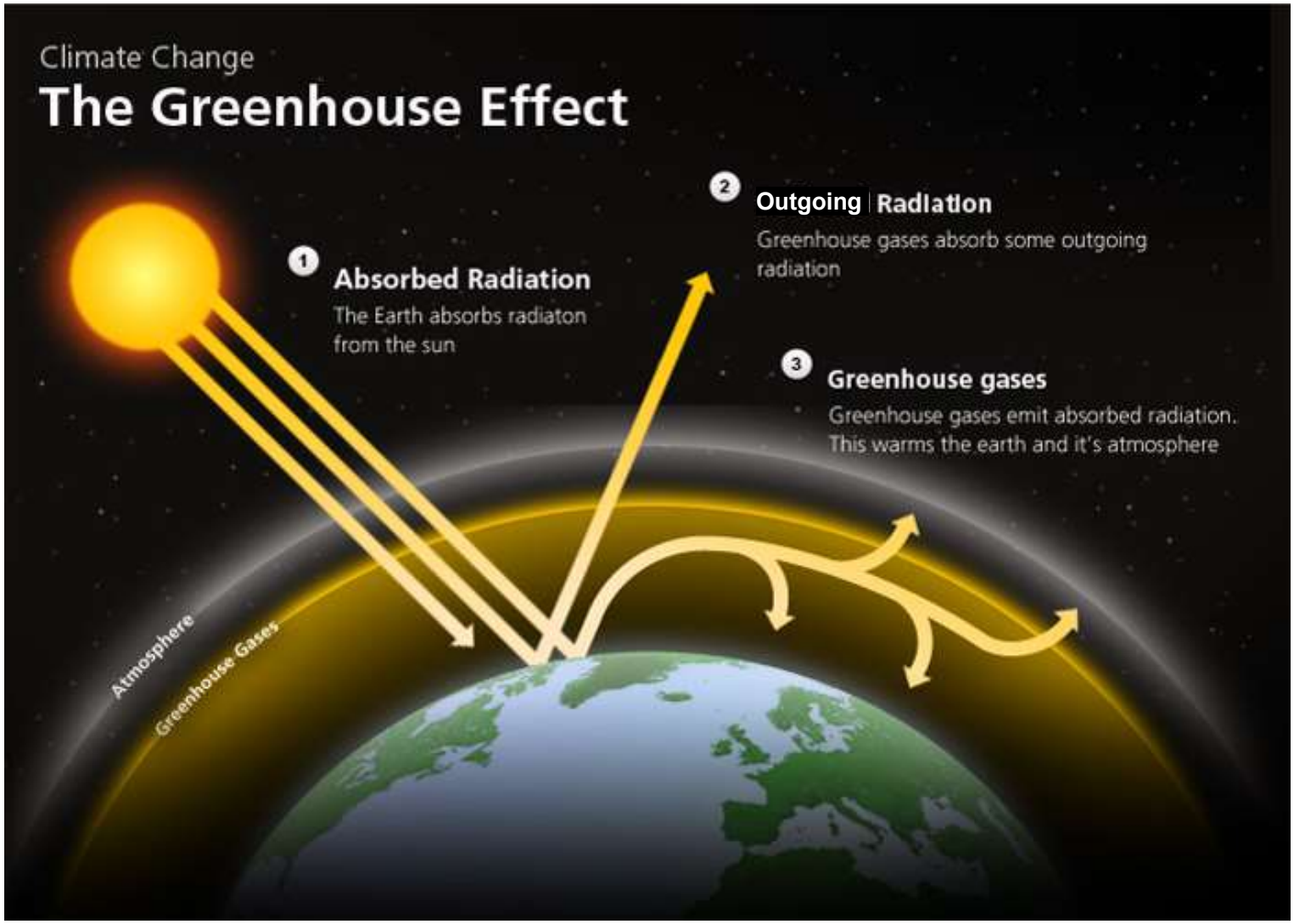
Multiple Loops



Births = bP

Deaths = dP

Net Births = bP – dP = (b – d)P


Climate Change
The Greenhouse Effect
1
Absorbed Radiation
The Earth absorbs radiaton from the sun
2
Outgoing Radiation
Greenhouse gases absorb some outgoing radiation
3
Greenhouse gases
Greenhouse gases emit absorbed radiation. This warms the earth and it's atmosphere
Atmosphere
Greenhouse Gases

How is C-ROADS and En-ROADS are used?

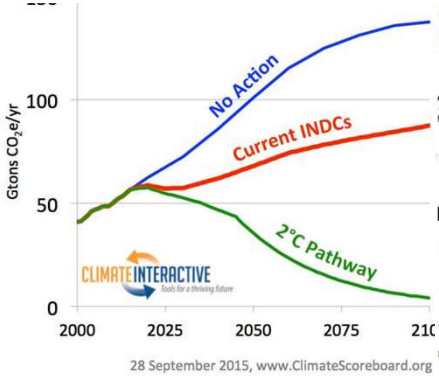
- **Policymakers & negotiators:**
  - US, China, Brazil, others
  - UN SG's office
  - UN "Emissions Gap" studies

En-ROADS Climate Ambassadors

537 AMBASSADORS **71 COUNTRIES** **138,276 PARTICIPANTS**

is important, and it is already getting broad dissemination... I used it!"

John Kerry



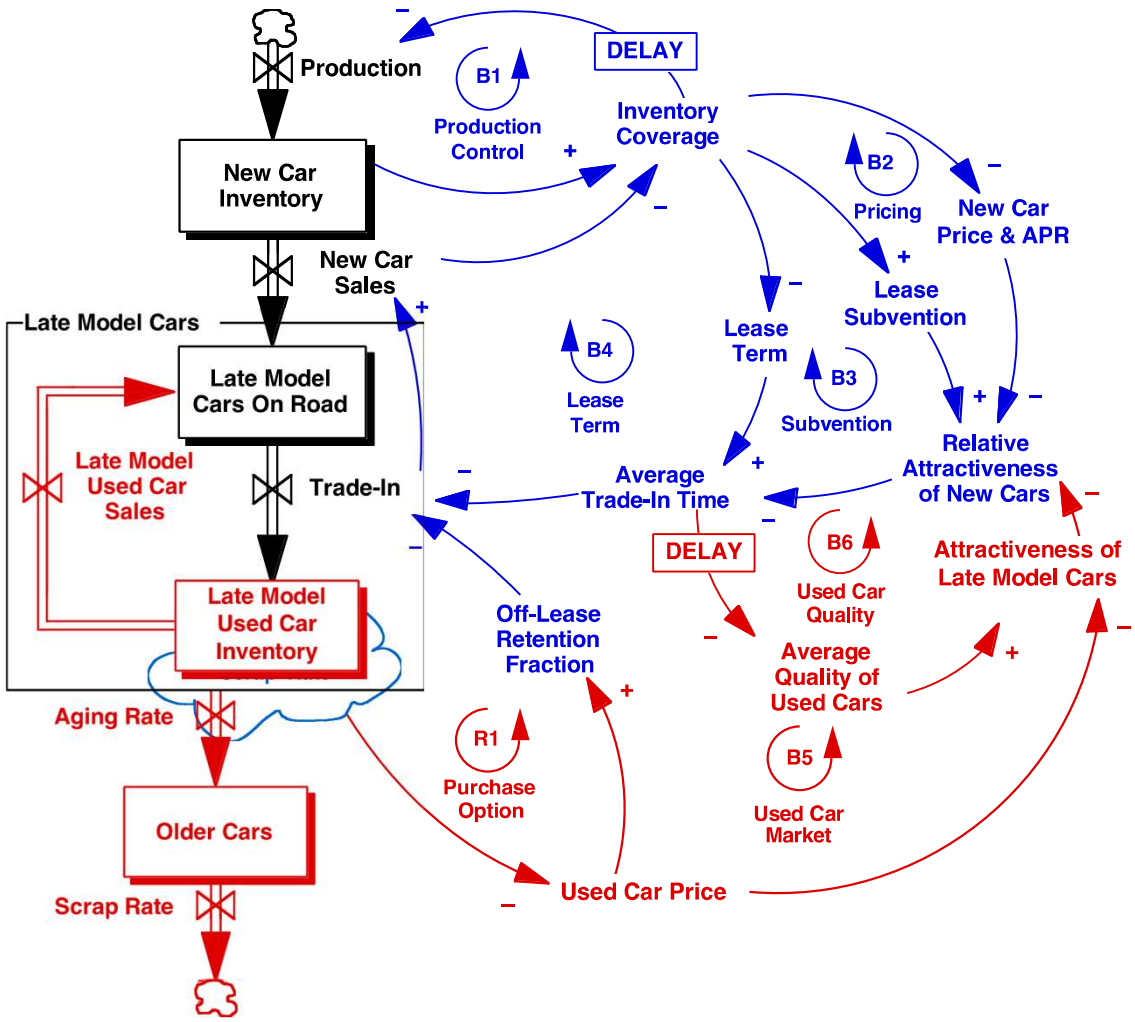
System Dynamics in Action

"Gone Today, Here Tomorrow"
Automobile Marketing
at General Motors

Excerpted from Sterman, J. (2000) *Business Dynamics: Systems Thinking and Modeling for a Complex World* (Irwin/McGraw-Hill) Chapter 2

Defining the Problem

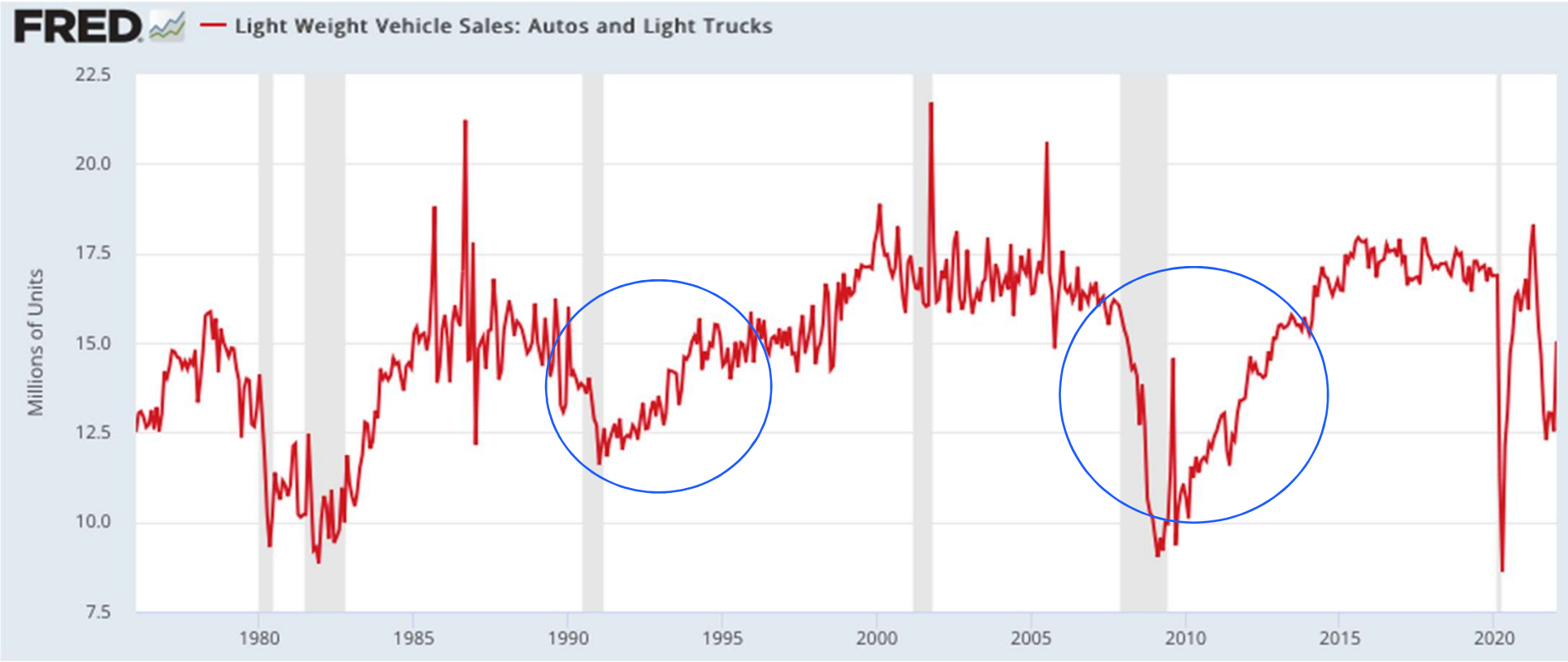
- **Mid 1990s: Used car superstores growing rapidly, offer high quality, low mileage cars.**
  - **1992: Superstores don't exist**
  - **1998: Superstore sales $13 billion**
- **Internet sales channels coming**


Production
New Car Inventory
New Car Sales
Late Model Cars
Late Model Cars On Road
Late Model Used Car Sales
Trade-In
Late Model Used Car Inventory
Aging Rate
Older Cars
Scrap Rate
B1
Production Control
DELAY
Inventory Coverage
B2
Pricing
New Car Price & APR
Lease Subvention
Lease Term
B4
Lease Term
B3
Subvention
Relative Attractiveness of New Cars
Average Trade-In Time
DELAY
B6
Used Car Quality
Attractiveness of Late Model Cars
Off-Lease Retention Fraction
Average Quality of Used Cars
R1
Purchase Option
B5
Used Car Market
Used Car Price

New Light-Duty Vehicle Sales

(Seasonally adjusted, annual rates)

Learning from Experience?

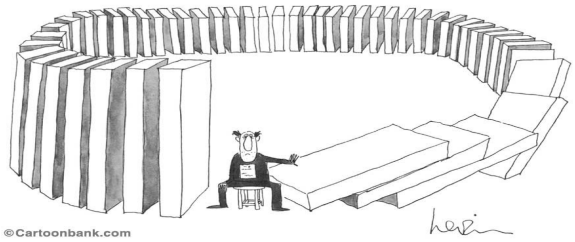


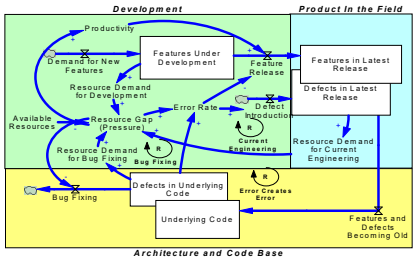
MIT MANAGEMENT SLOAN SCHOOL

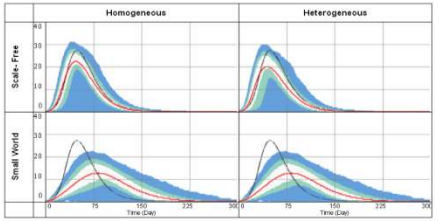
Modeling Innovation Adoption and the Product Lifecycle

15.871/3 System Dynamics

Hazhir Rahmandad







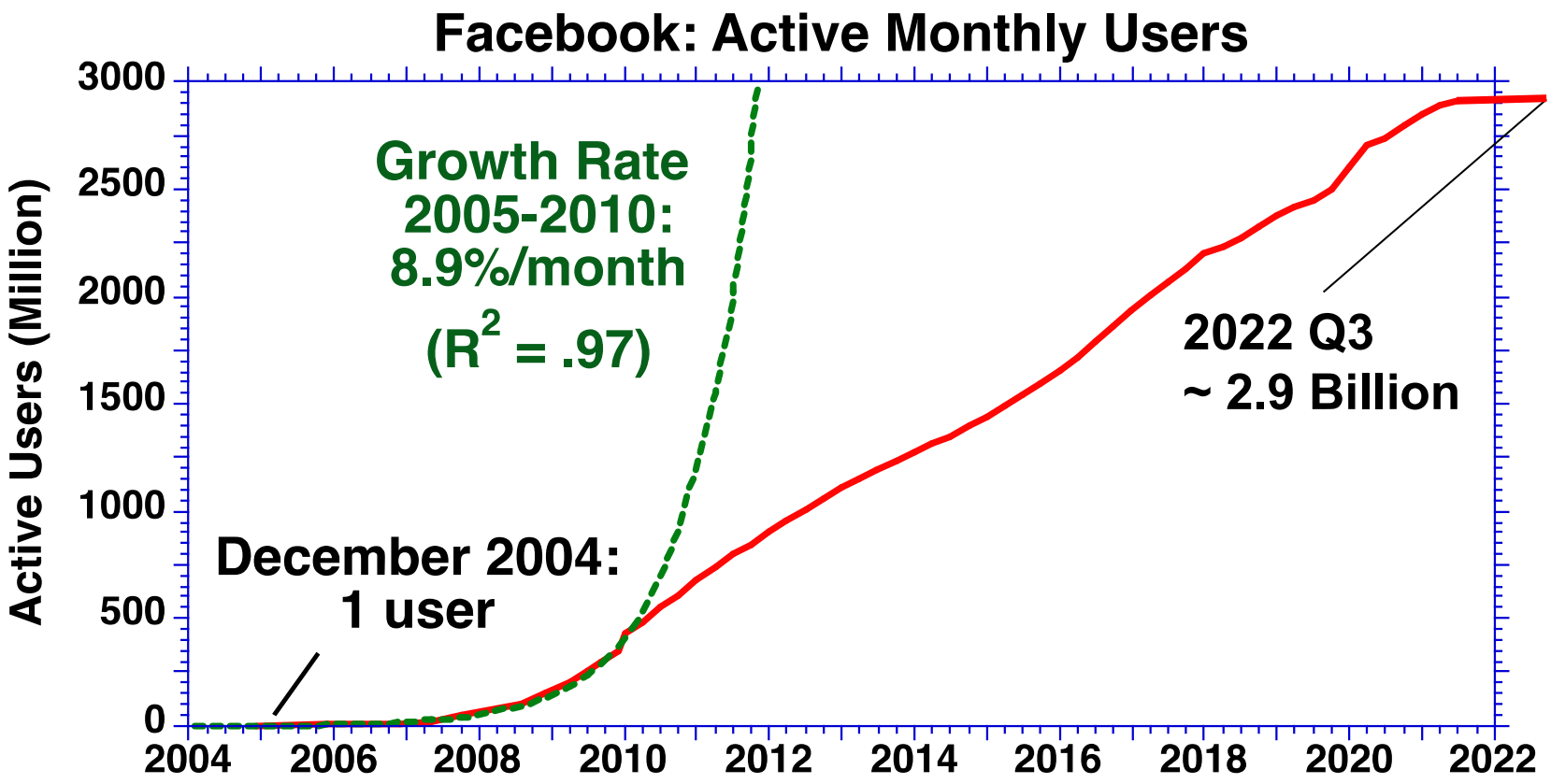
Administrative

- Assignment 3 due on Monday
- Friday recitations different location this week:
  - 10-11:30: E62-250
  - 2:30-4: E51-145
- Readings for Monday BD Ch10

Purpose

- **Substance**
  - What are the dynamics of product and corporate growth?
  - Introduce the model for assignment 4
- **Process**
  - Loop through steps of modeling again with a real, important issue in corporate strategy and entrepreneurship
  - Further develop your skills in model formulation, simulation, testing, policy design

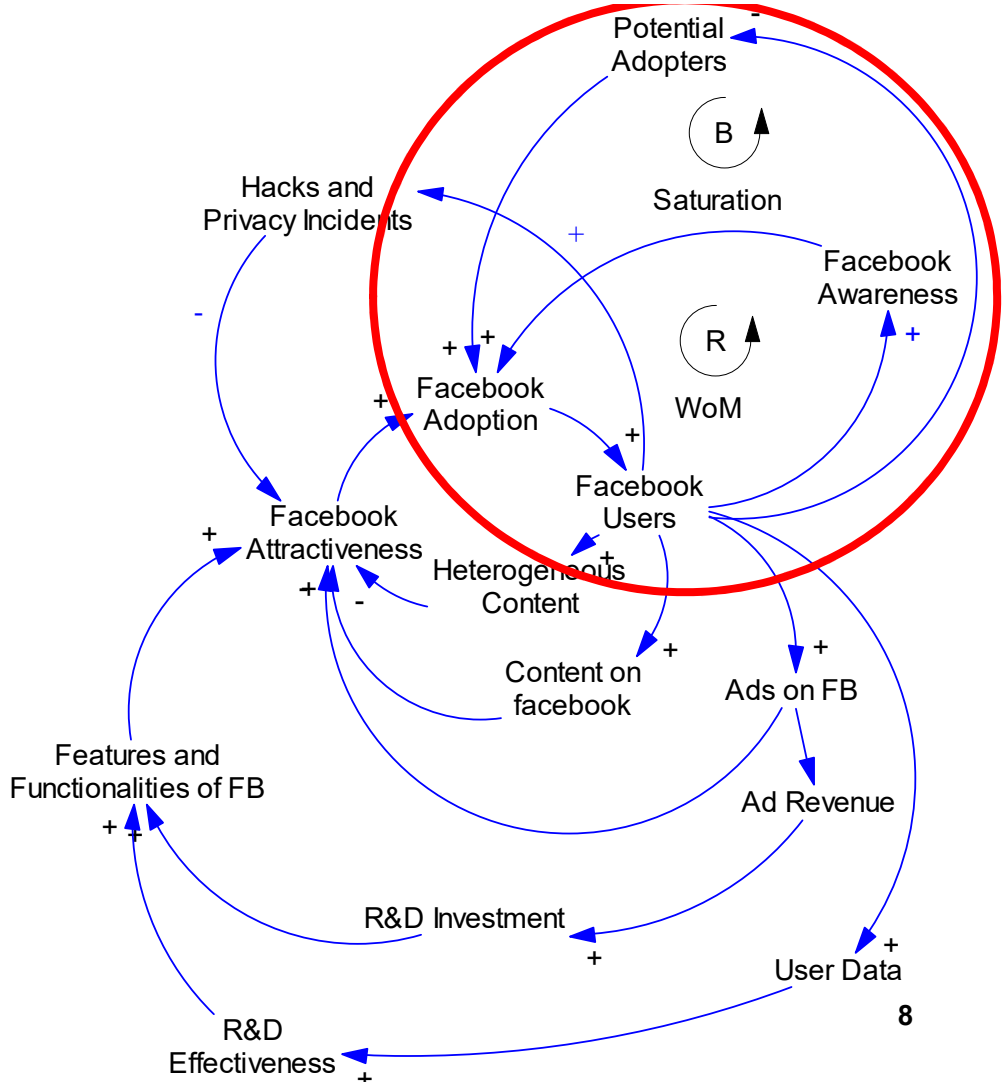
Limits to Growth



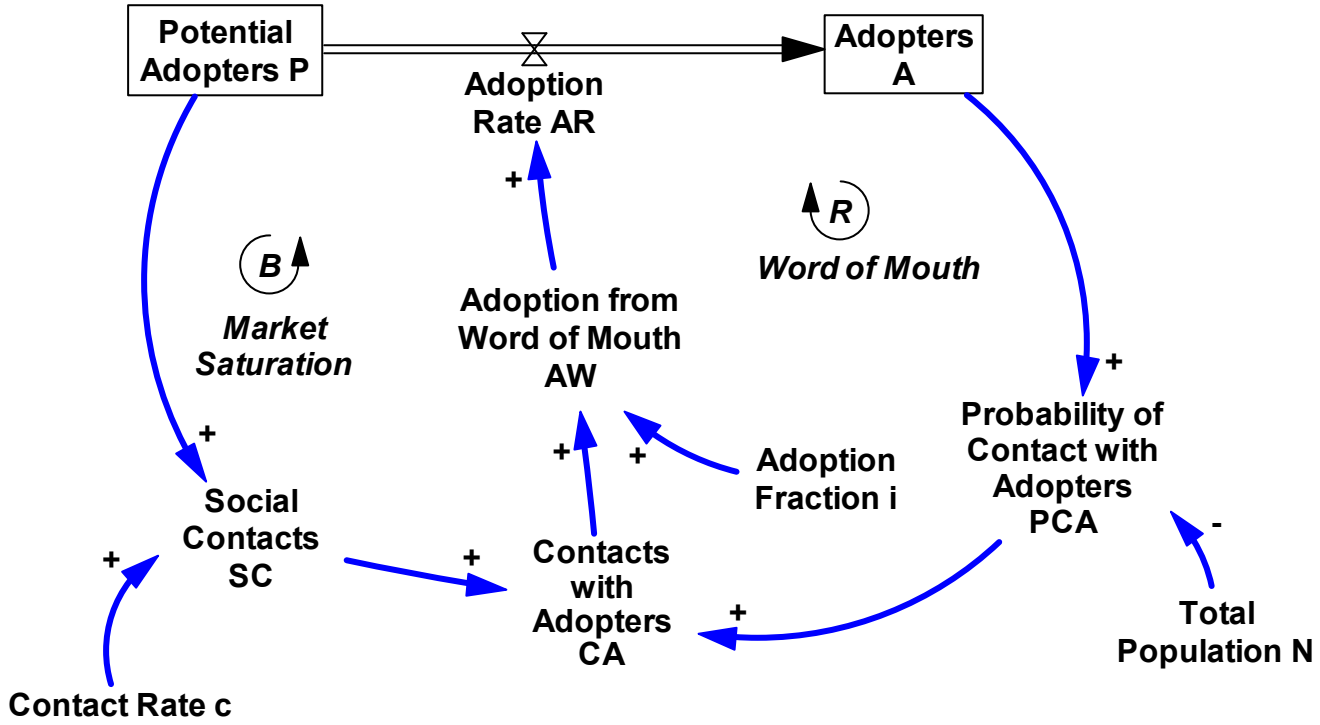
http://www.statista.com/statistics/264810/number-of-monthly-active-facebook-users-worldwide/

Facebook Loops (from session 3)

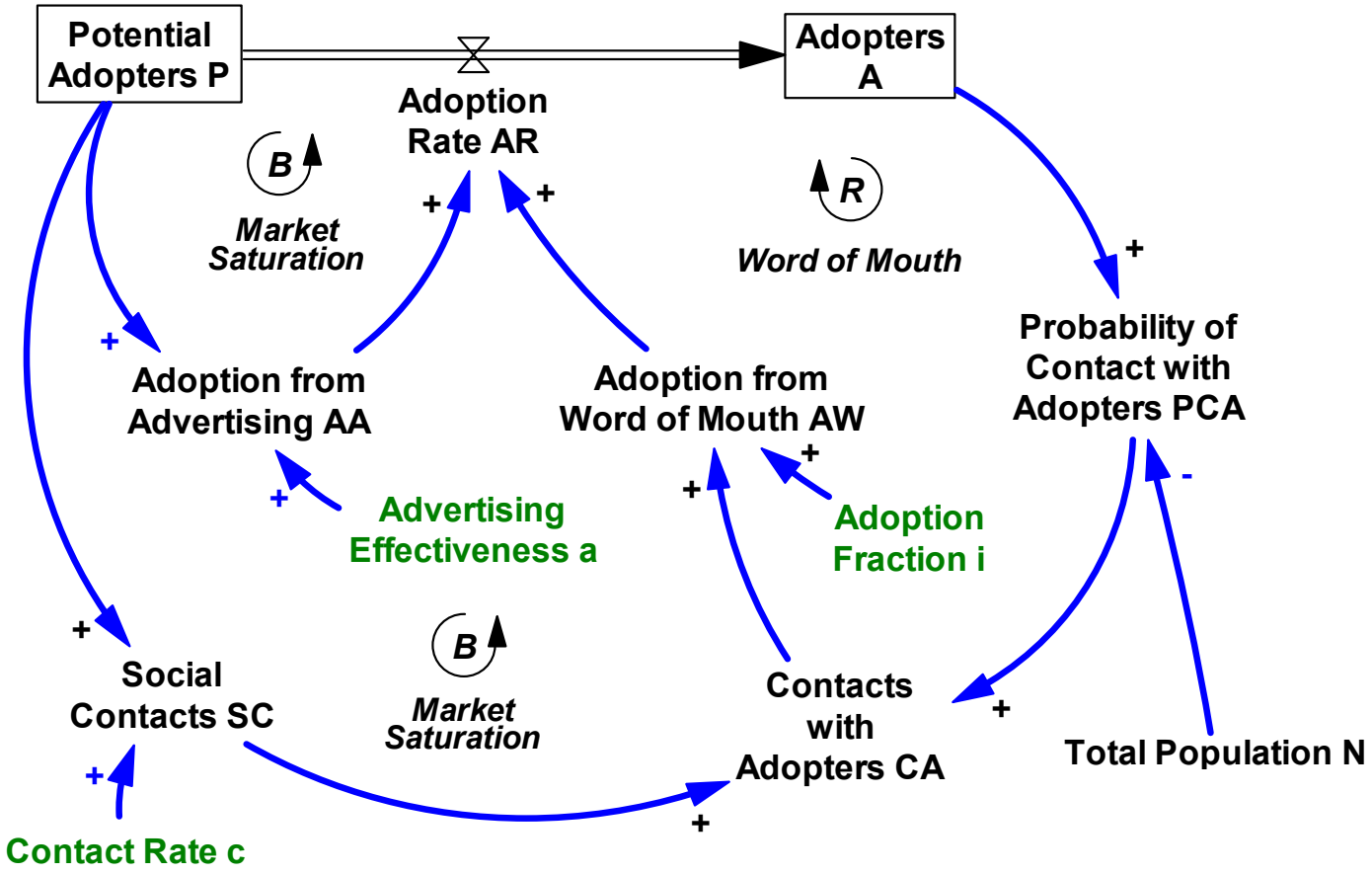
What Stocks?
What Flows?



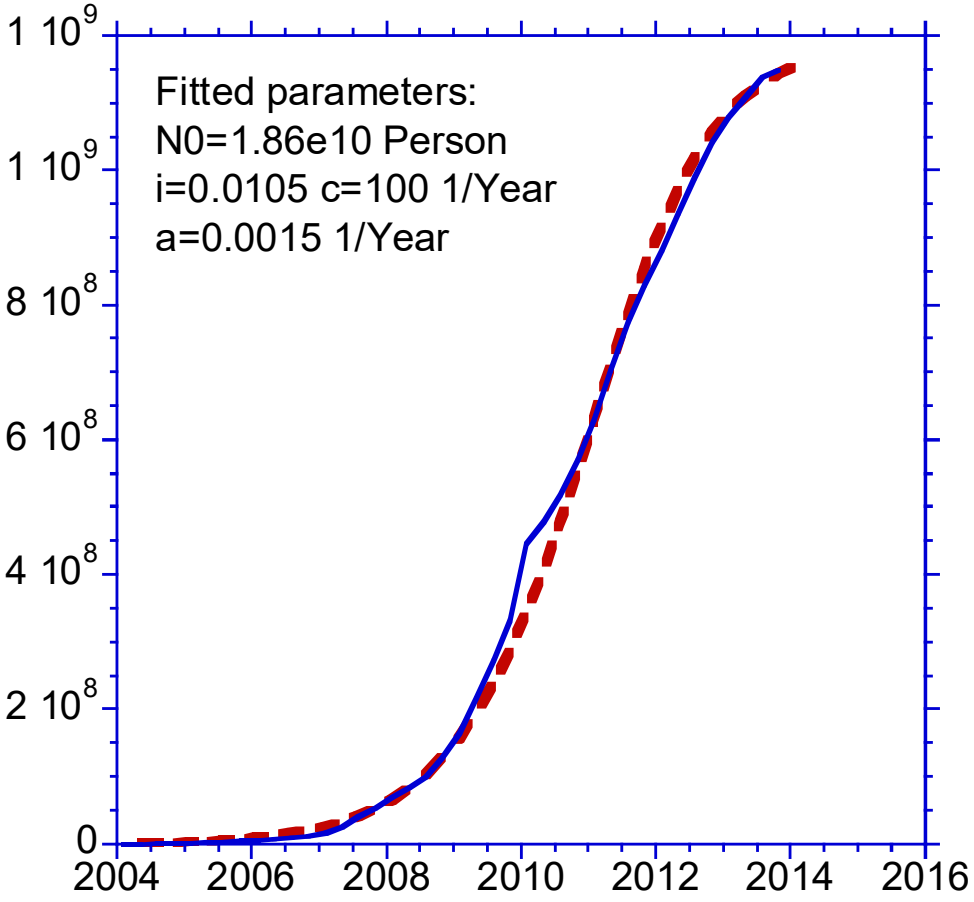
Innovation Diffusion as Contagion



Bass Diffusion Model

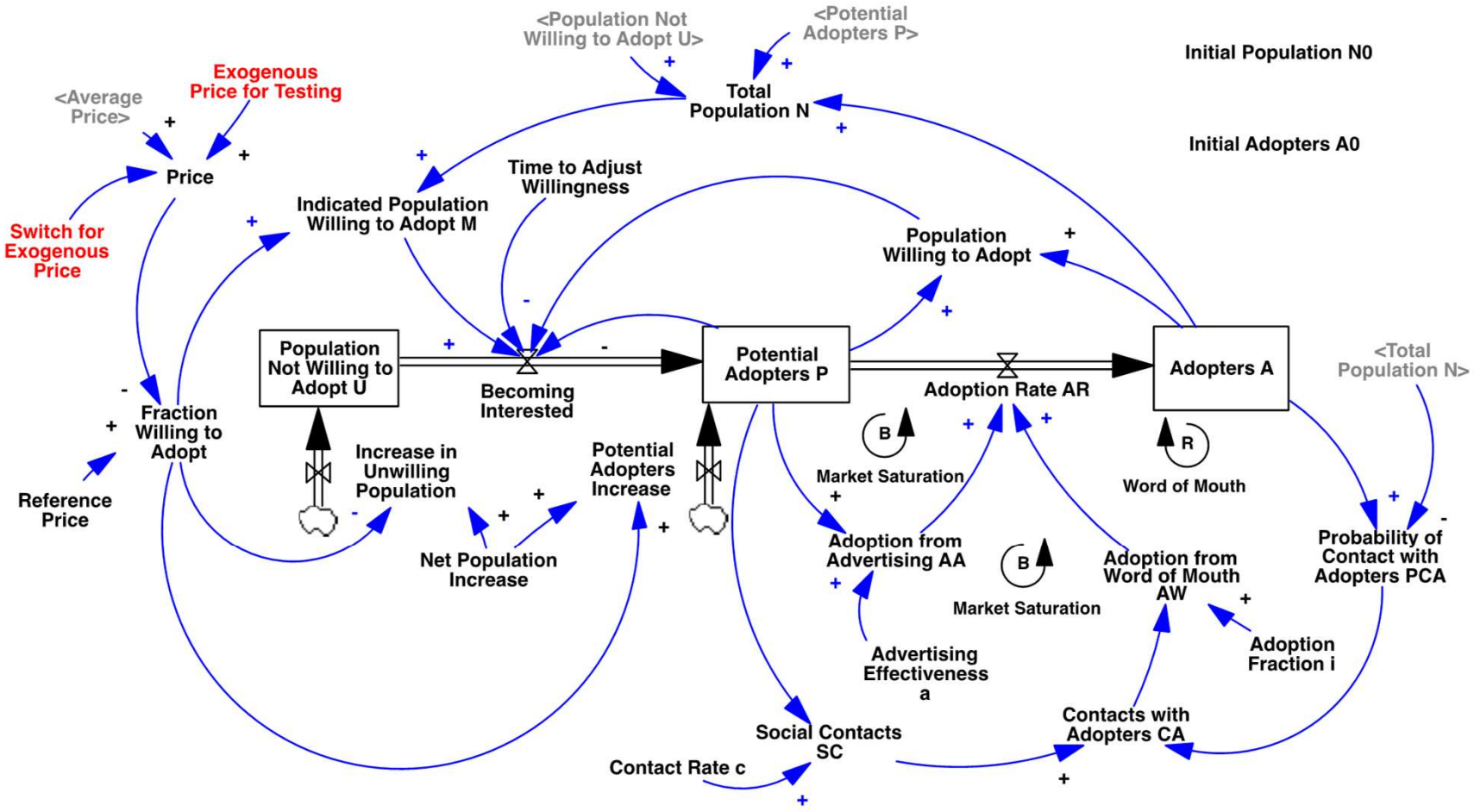


Facebook Users and Bass Model Fit



What important mechanisms are missing from Bass diffusion model?

Modified Bass Diffusion Model



Basic Learning Curve Formulation

$$c_t = f(Q_t)$$

$$c_t = c_0\left(\frac{Q_t}{Q_0}\right)^{-\lambda}$$

$$\lambda = -\log_2(PR)$$

or

$$\lambda = -\log_2(1-LR)$$

- **c_0, Q_0 = initial unit costs and cumulative production, $Q_t = \int_0^t q_s ds$**
- **λ = learning rate**
- ***PR* = Progress Ratio (costs relative to initial level after a doubling of cumulative output).**
- **Some authors use the Learning Rate, LR, the fractional reduction in costs per doubling of cumulative production.**
- **Example: *PR* = 80% implies a 20% cost reduction for every doubling of cumulative production ($\lambda \approx 0.323$)**