Analytical Methods for System Dynamicists

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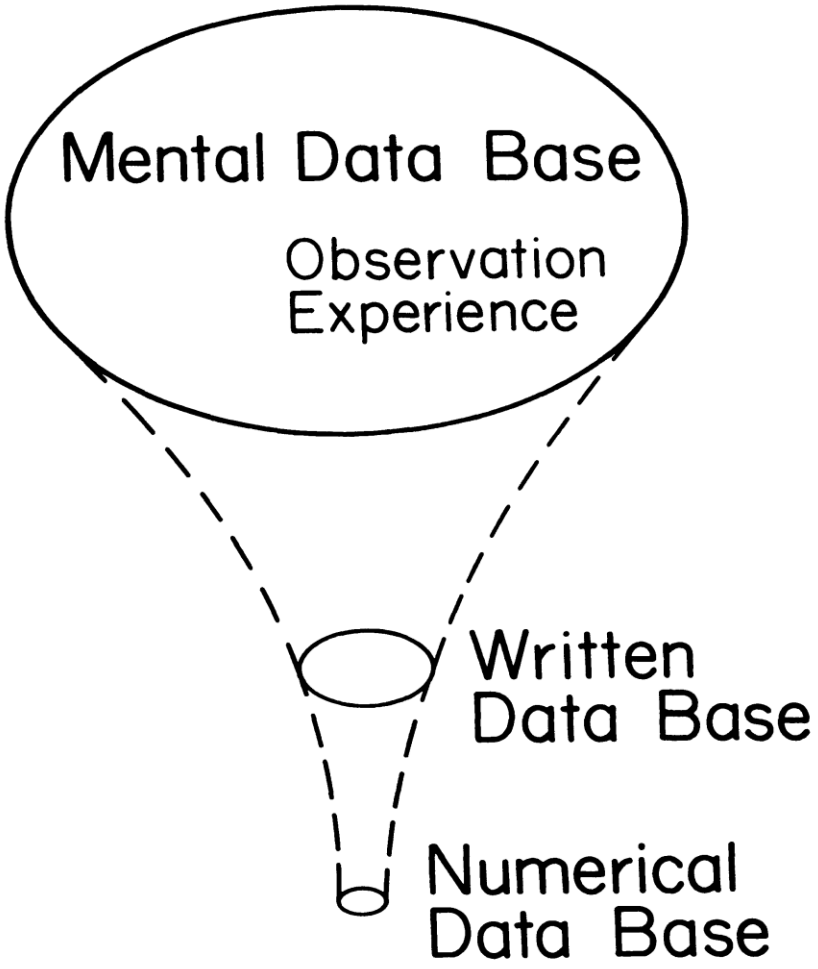
اولین کنفرانس ملی

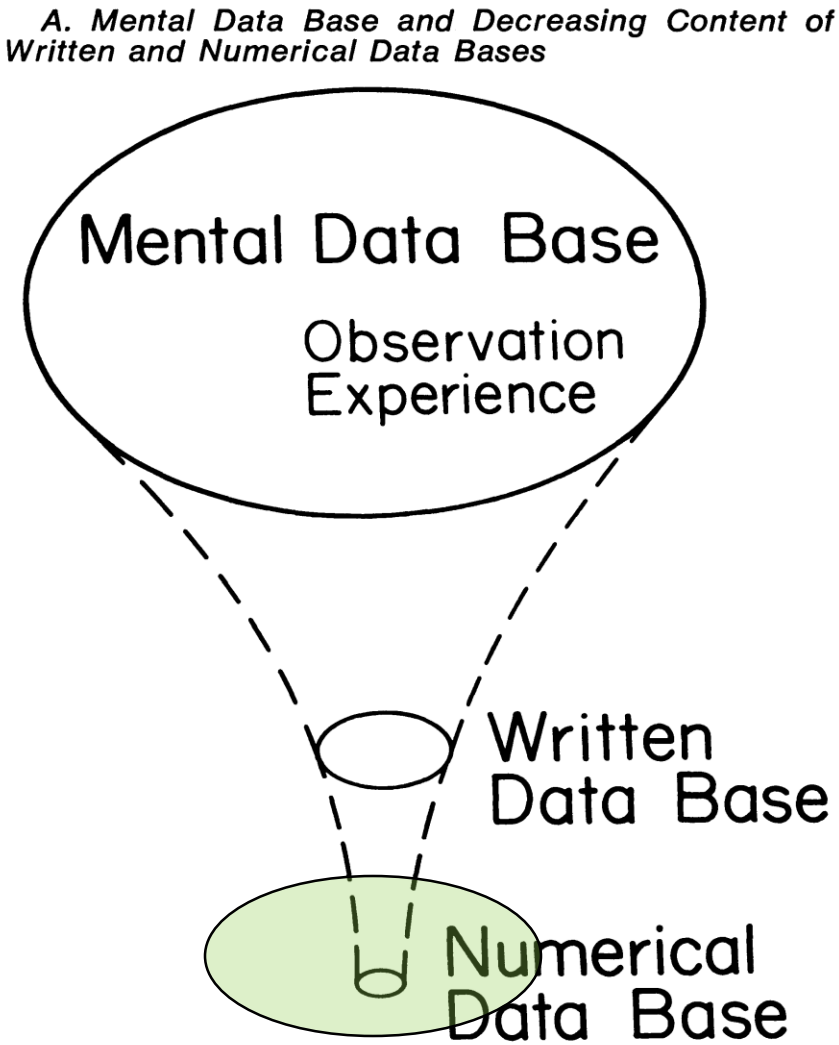
انجمن ایرانی پویاشناسی سامانه ها

Forrester's Representation of Three Data Bases

A. Mental Data Base and Decreasing Content of Written and Numerical Data Bases



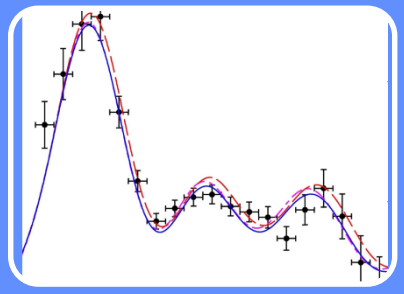
… but numerical data is increasingly ubiquitous



The Modeling Process

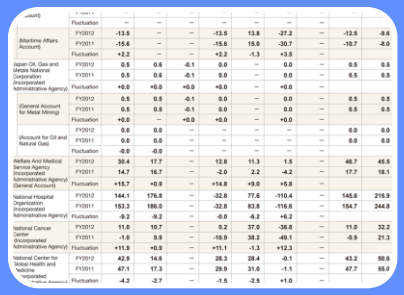
Model building

- Qualitative & archival data, expert opinion, prior theory
- Boundary & structure, dimensions, extreme conditions



Calibration & Parameter Estimation

- Quantitative data from diverse sources
- Various methods depending on the data and model structure



Model and Policy Analysis

- Structure and behavior analysis
- Sensitivity & robustness analysis
- Various optimization methods

Use of Data in Simulation Models

- Use multiple types of data for multiple purposes and different stages of modeling
  - Qualitative data is more appropriate for identification of the structure of problem and important dynamic hypotheses
  - Numerical and archival data is needed for parameter estimation and validation
  - Time series can feed into model the factors outside of model boundary

From Qualitative to Quantitative Data

- Following the SD modeling process, you can get high structural reliability through extensive use of qualitative data
- The qualitative insights allow you to tell convincing stories
  - This is good: lots of insights; convincing.
  - This is bad: you can fool the client; and yourself.
- Hard data can keep you straight and allow for testing of hypotheses
- It also makes your work much stronger, both in persuasion and impact

Two potential misconceptions

- Misconception 1: We can't build models without numerical data
  - If model structure is to follow real-world structures in charge of problem, qualitative data is needed for building it
  - Insights can be generated before starting to use numerical data
- Misconception 2: Numerical data adds little value to the modeling
  - Uncertainties in parameter values can only be set with empirical data
  - Many theoretical and practical implications depend on these parameters

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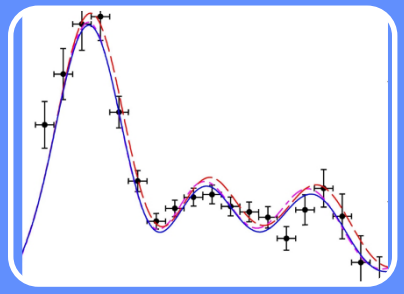

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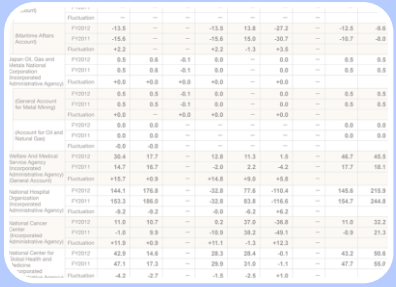

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Calibration

- Calibration is the fitting of a model to data
  - We do this using an optimization
- The purpose of calibration
  - Rejection
    - Reject a model when it fails to fit data
    - We need to know the criteria for rejection
  - Parameter and structure estimation
    - Confidence intervals

Calibration Process

- Assume the model is right
- Set up the model and run calibration
  - Specify the data items to match, the corresponding model variables, and the payoff (measure of closeness of data items to model outcomes)
  - Specify the parameter space for search
  - Specify the optimization algorithm
  - Run the calibration/optimization
- After finding the results
  - Measure the closeness, should model be rejected?
  - Find the confidence intervals for the estimated parameters

Menu of Estimation Choices

- **Estimation scope**:
  - **Partial model/regression**: Estimate relationships separately
  - **System level**: Estimate the full model (or larger chunks with multiple items to match)
- **Calibration payoff function**:
  - Ad hoc, e.g. weighted least squares
  - Maximum likelihood
  - MSM/Indirect inference
- **Use of state resetting and filtering**:
  - Simple simulation
  - Simple regressions
  - Filtering (e.g. Extended Kalman Filter (EKF) or Particle filter)
- **Confidence intervals**:
  - Likelihood based
  - MSM based
  - Bootstrapping and subsampling

Model Calibration Tips

- Include in calibration problem ALL knowledge available about system parameters
  - known parameters
  - physical constraints on parameters
  - likely uncertainty range
- Use the smallest calibration problems possible
    - Breakdown the model into separate pieces and estimate the parameters for each piece
    - Estimate the next pieces based on external data and input from already estimated pieces
  - More manual, but more robust results due to immediacy of parameters to independent and dependent variables
- Test the hypotheses “The estimated parameter matches the observable structure of the system”
  - Does the model match the historical behavior
  - Does the model match the structure

Tips for Calibration and Optimization

- Creating the payoff function
  - Audience matters: engineering and applied communities prefer simple metrics such as MSE, MAPE. Statistically oriented communities want confidence intervals and that requires MLE or Method of Simulated Moments.
- Optimization: No single algorithm dominates; order of magnitude differences in efficiency; thus explore:
  - Quadratic methods feasible or payoff landscape noisy?
  - Starting from different points, how varied are the local peaks found by gradient-based methods?
  - How effective are gradient-free methods (e.g. Powell set method)?
- Stop calibration only when the majority of new searches converge to a peak already identified.

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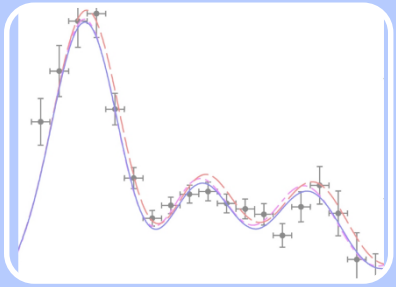

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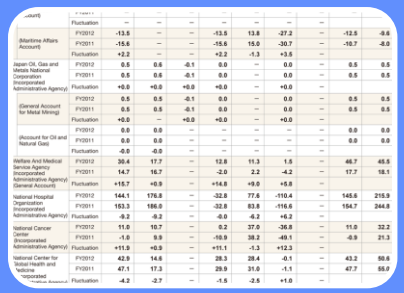

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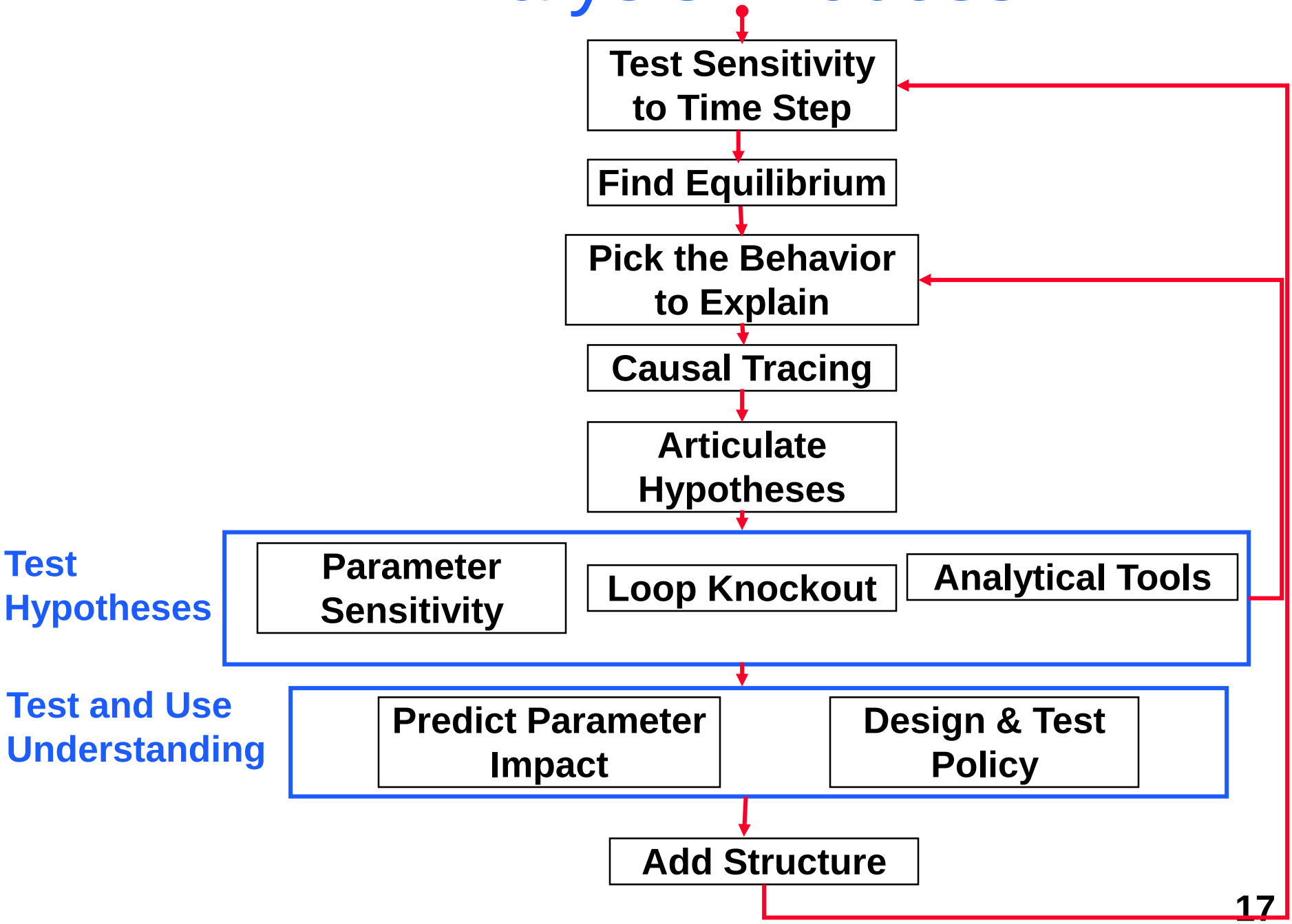
Analysis Process

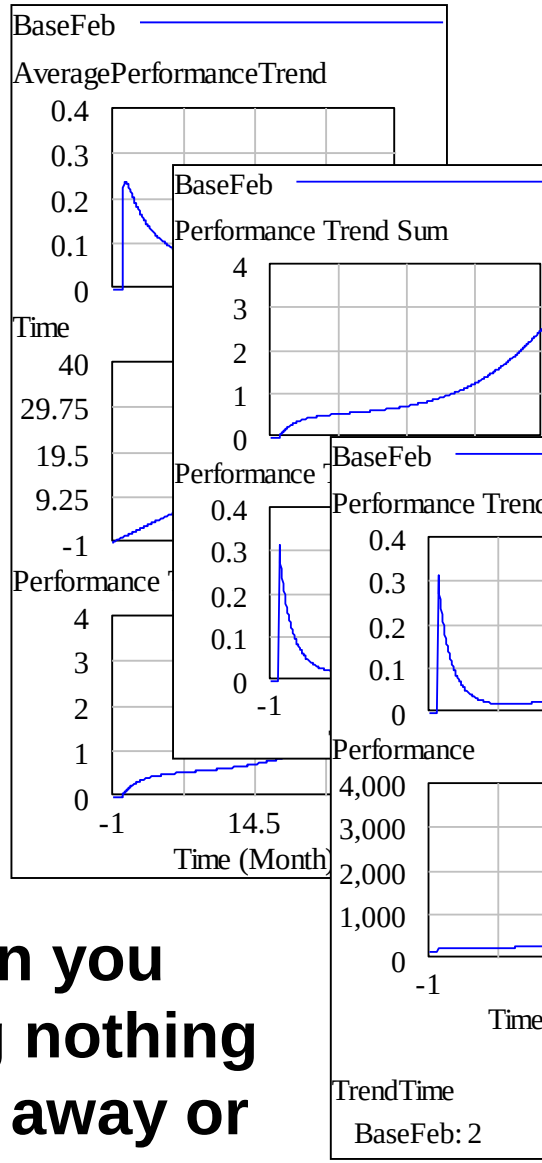


Pick the Behavior to Explain

- Different variables may have different modes of behavior, and the sources of dynamics are not always the same
- Pick one variable's behavior and understand that
- Usually by doing this for 2-3 variables, you will know the model's behavior completely

Causal Tracing and Hypotheses

- Look at the causes for each variable and trace back until:
  - Single source is found (e.g. a draining, isolated stock)
  - A loop hypothesis is found (you loop back to the original variable)
  - You form other hypothesis why the behavior happens
- Design an experiment to test your hypothesis: **if hypothesis is X➔ Y, then you remove X (while changing nothing else) to see if Y also goes away or not (e.g. loop knock-out analysis)**



Structural Dominance Analysis

- Objectives of SDA
  - Articulate structural explanations for behavior
  - Support policy design

- Three flavors of SDA
  - Exploratory analysis of dominant structure
    - Simulation-based and/or manual approaches; e.g. loop-knockout, sensitivity analysis and statistical screening
  - Formal assessment of dominant structure
    - Eigenvalue/eigenvector analysis of linearized model
    - Pathway Participation Method

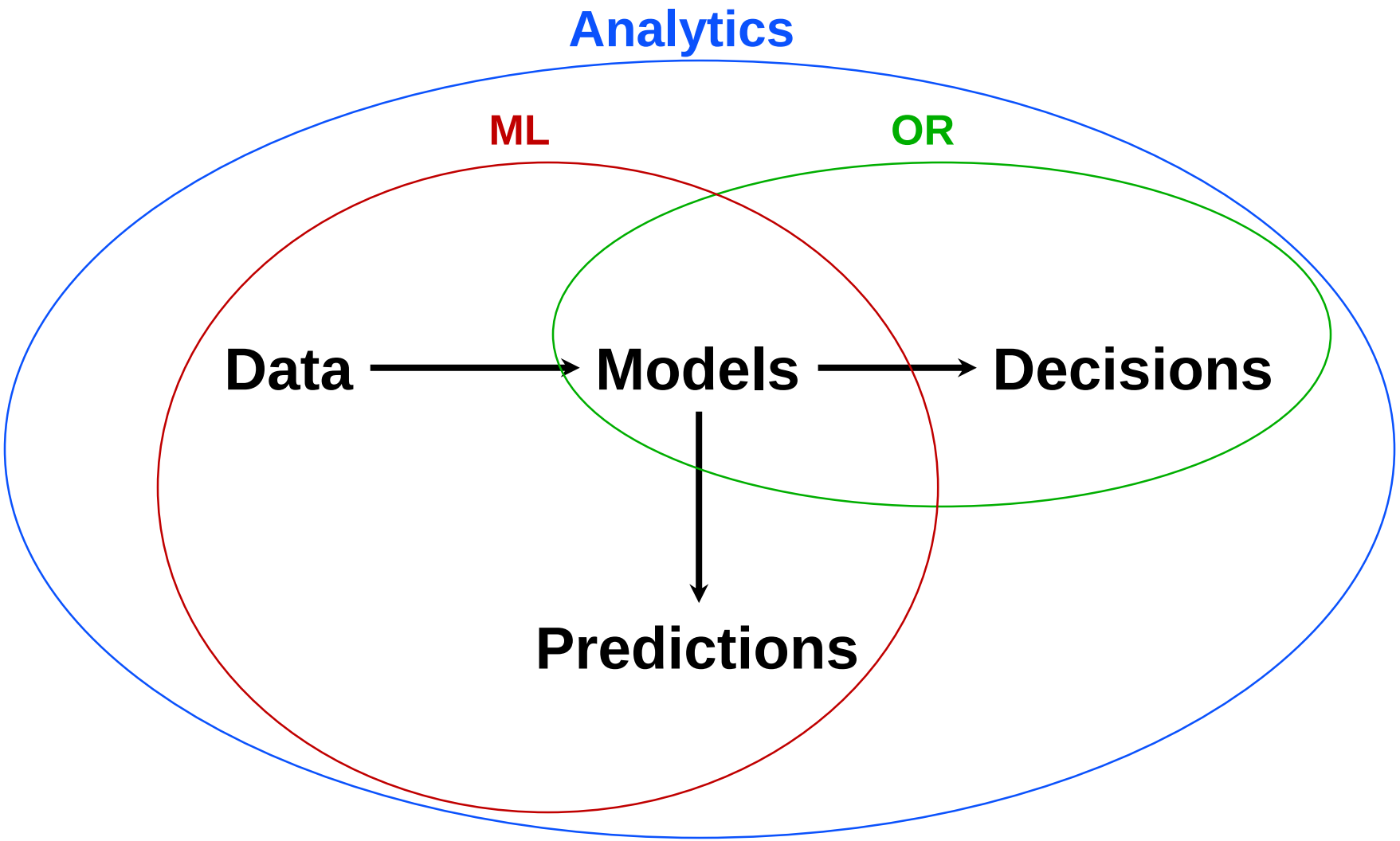
Test and Use Your Understanding

- Predict parameter impact
  - List the model parameters in a table
  - Predict what will happen if you change each (e.g. the mode increases/decreases)
  - Test and see if your prediction was correct
  - When wrong, find out what you missed
- Help build client's mental models
  - Design simple simulations to communicate the basic insights to your client
  - Be ready to explain in simple terms why the model behaves the way it does
  - Go through likely scenarios and their mechanisms
  - Engage client in explaining dynamics

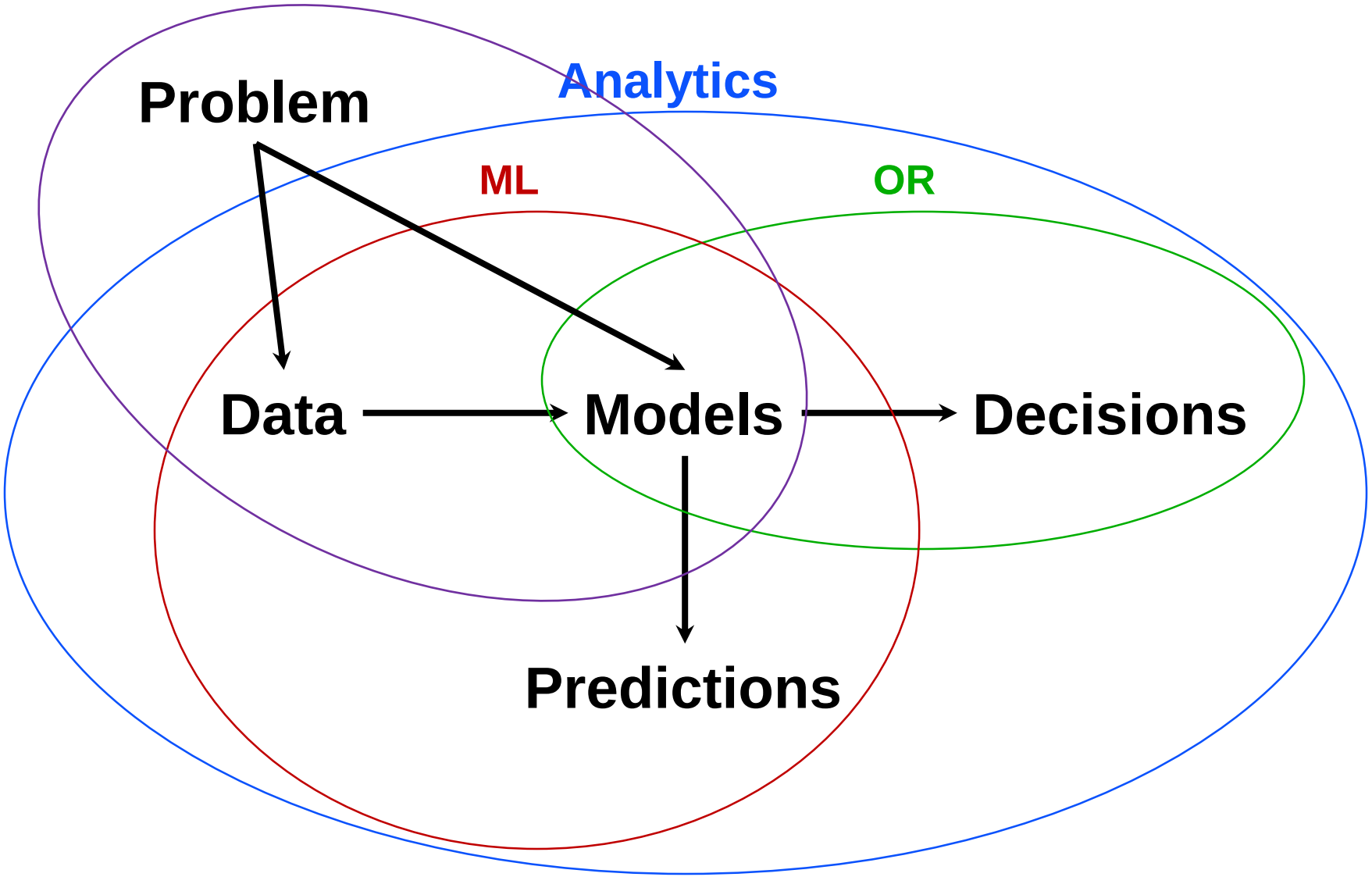
Controlling Dynamic Systems

- **Overview**: you have (a model of) a dynamic system, how can you use this model to best manage (control) the system?
  - You are the main actor➔ e.g. Managing your inventory, vehicle control, epidemic planning
    - optimal control, (approximate) dynamic programming and policy optimization
    - Decision analysis, decision trees, stochastic optimization
  - There are other (rational) actors with different or opposing goals ➔e.g. Pricing in competition, missile defense, Market entry decisions
    - Dynamical games

Analytics



SD and Analytics



SD models, Big Data, and Analytics

- The model is build from data beyond the numerical base
- Emphasis on operational explanations means the focus of SD is in describing the system that generates the data
  - Question the source of the data
  - Question the quality of the data
    - Violations of conservation of matter
    - Biases on data collection of classification
- Use OR, ML, Econometric methods for estimation, optimization, and decision analysis