STEVENS
INSTITUTE of TECHNOLOGY
THE INNOVATION UNIVERSITY®

Fundamentals of Modeling for Systems Engineering

SYS-611: Simulation and Modeling

Paul T. Grogan, Ph.D.
Assistant Professor
School of Systems and Enterprises

Agenda

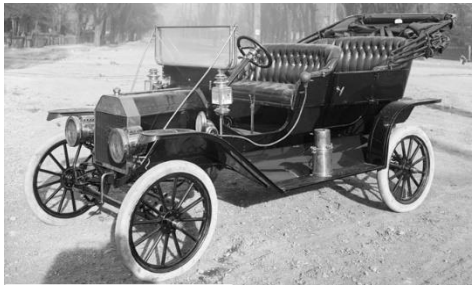
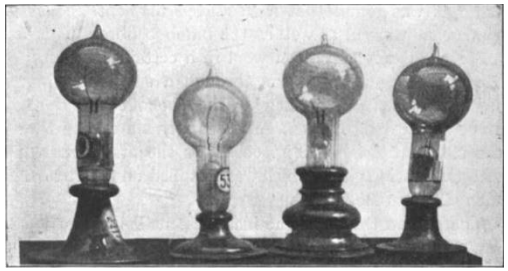
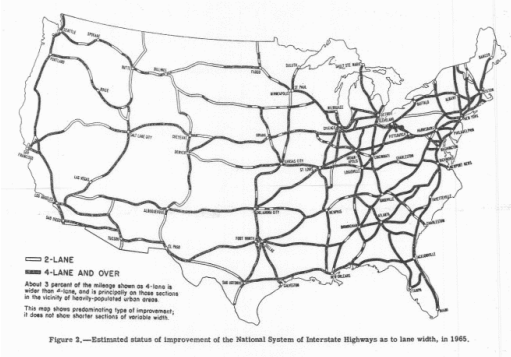
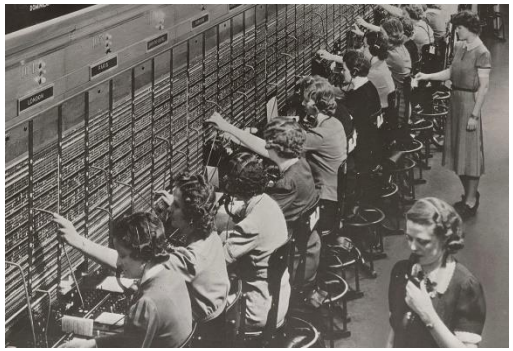
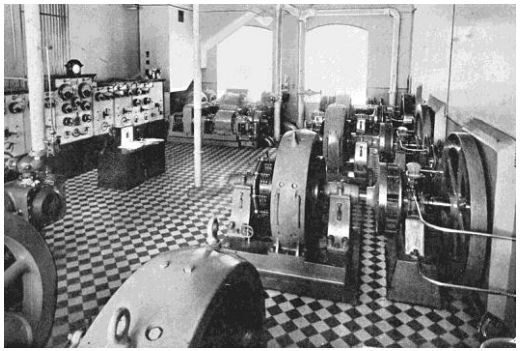
1. Modeling Complex Systems
2. Types of Models and Simulations

Reading: J.V. Farr, “Overview of Modeling and Simulation of Complex Systems,” Ch. 1 in *Simulation of Complex Systems and Enterprises,* Stevens Institute of Technology, 2007.

Modeling Complex Systems

What are Engineering Systems?

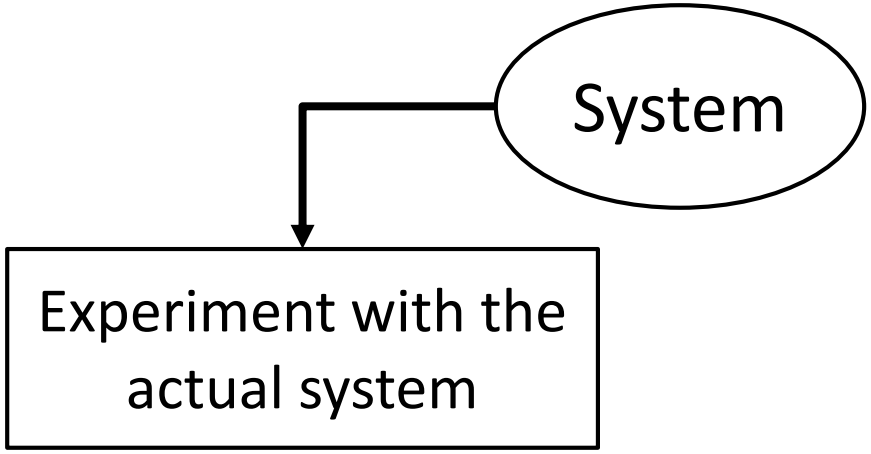
From: de Weck et al. (2011), *Engineering Systems: Meeting Human Needs in a Complex Technological World*

	Transportation	Communications	Electricity
Mid 1800s – Early 1900s			
Early 1900s – Mid 1900s	 Figure 2.—Estimated status of improvement of the National System of Interstate Highways as to lane width, in 1965.		
Regulatory Bodies:	DoT (1967), NHTSA (1970)	FCC (1934), NCTA (1952)	NERC (1968), DoE (1977)
Late 1900s – Early 2000s	Engineering Systems*: Design, Operate, Sustain, Regulate*		

What engineering systems do you study?

What makes them complex?

Studying Complex Systems

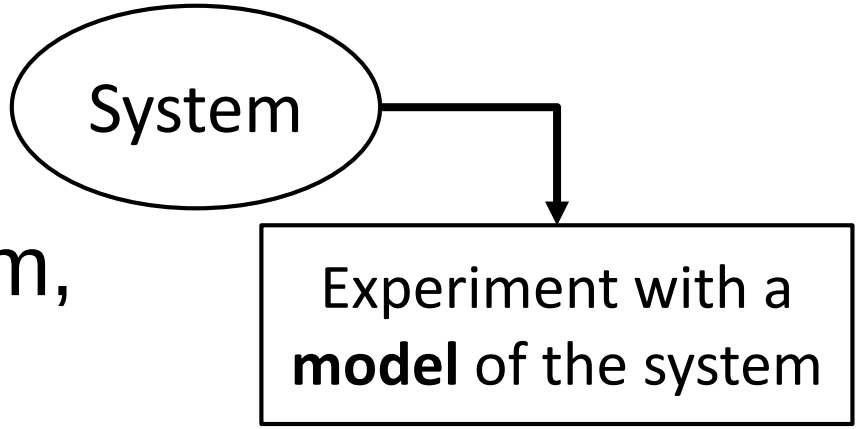


Field test for Trident Ballistic Missile System

Most accurate way to study systems but expensive, time-consuming, and permanent

Studying Complex Systems

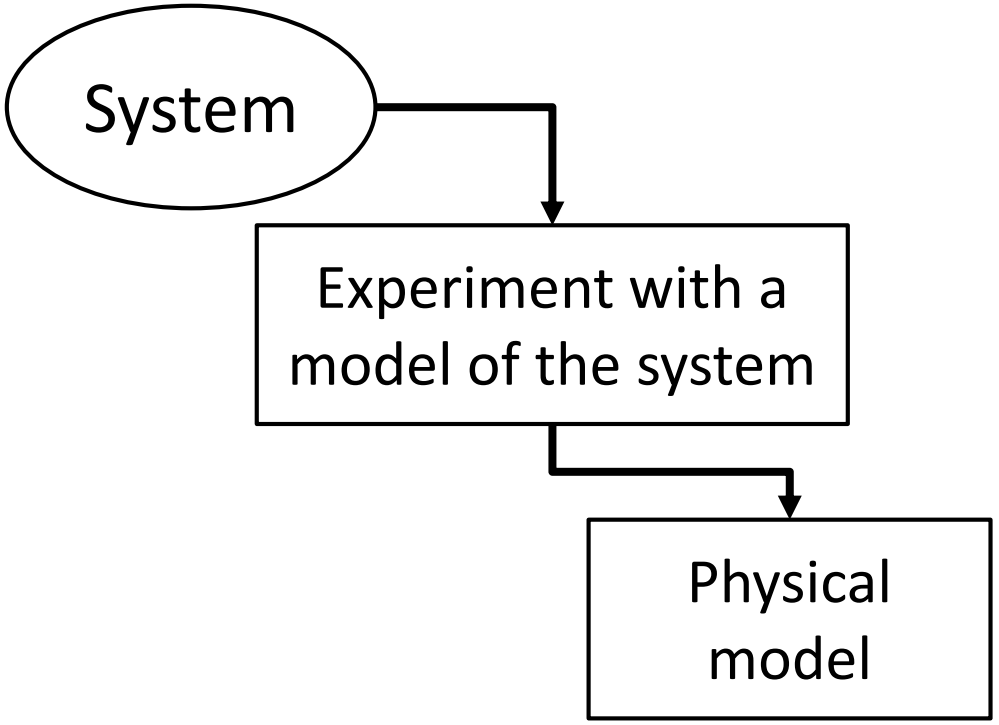
A **model** is a physical, mathematical, or logical representation of a system, entity, phenomenon, or process.



Modeling applies a standard, rigorous, structured methodology to create and validate a model.

Studying Complex Systems

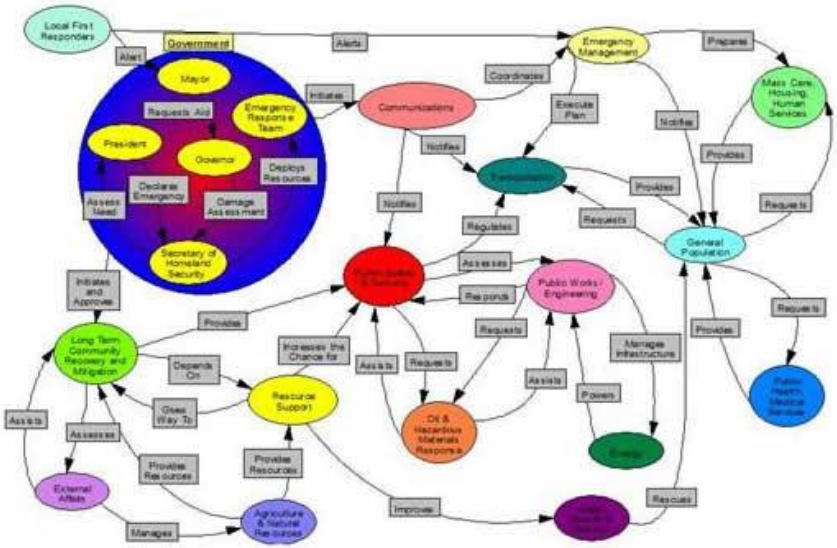
High Speed Tow Tank at Davidson Laboratory



Replicate physical attributes in a simplified but representative environment

Studying Complex Systems

Hurricane Katrina Systemigram (Christine Ballard)



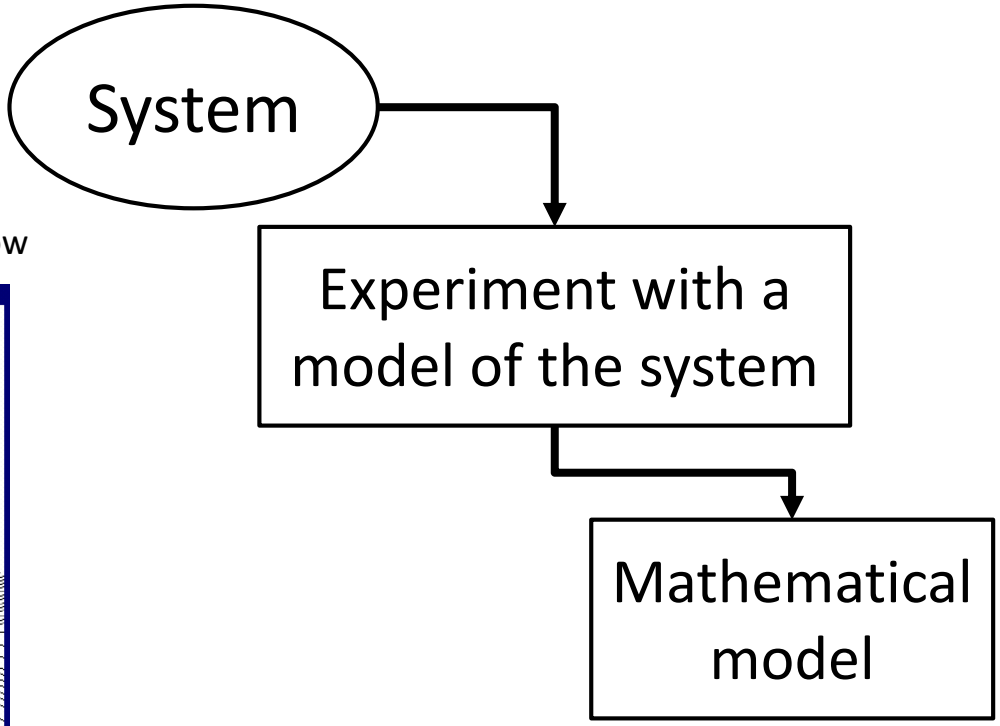
System

Experiment with a model of the system

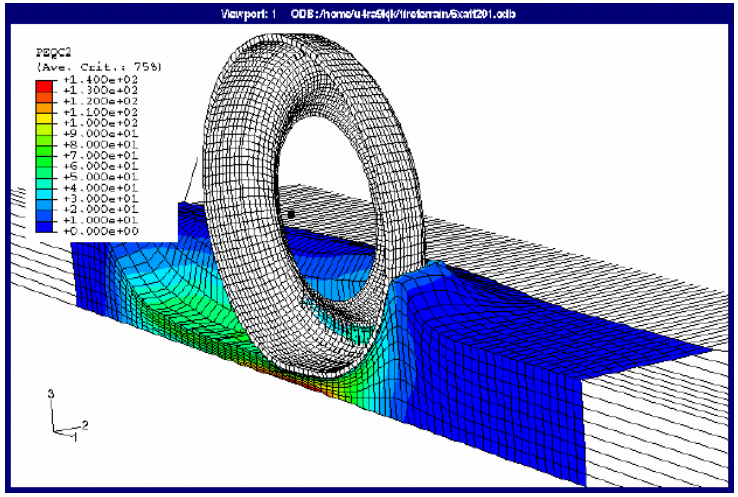
Conceptual model

Represent attributes in an abstract notation (symbols, diagram) to facilitate communication

Studying Complex Systems



Finite element model of tire rolling through snow

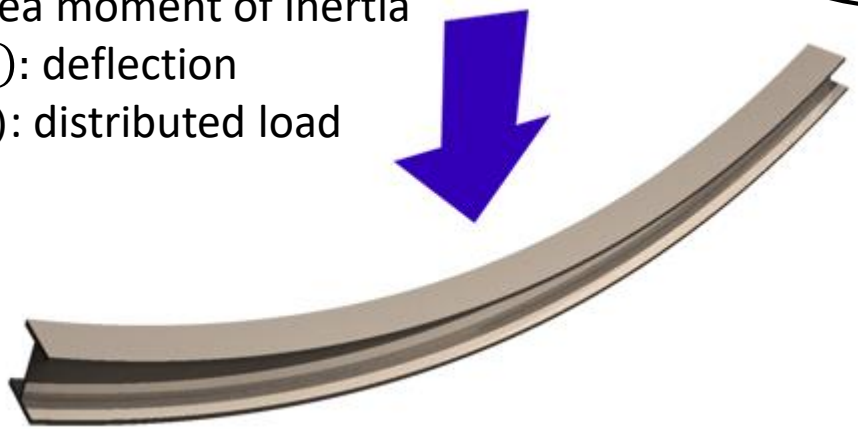


Represent attributes using mathematical symbols and relationships

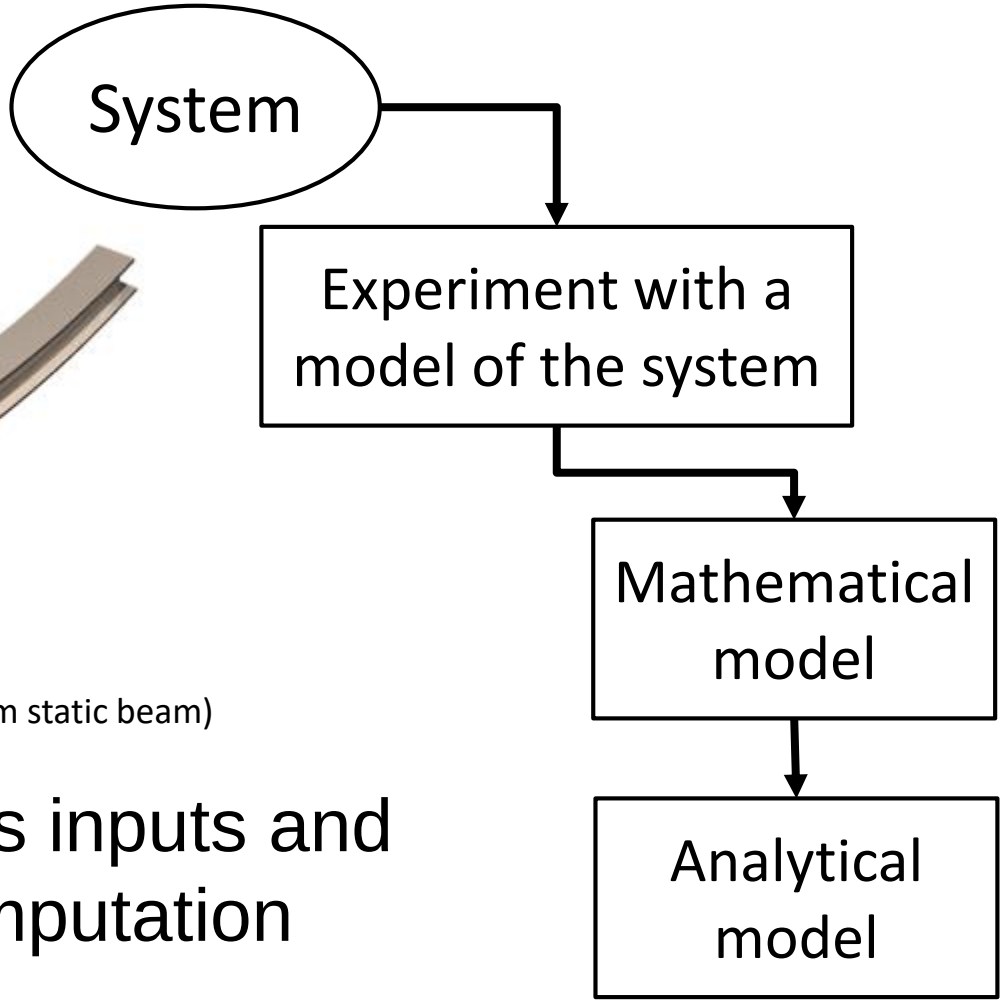
Studying Complex Systems

$$EI\frac{d^4w}{dx^4} = q(x)$$

E: modulus of elasticity
I: area moment of inertia
$w(x)$: deflection
$q(x)$: distributed load

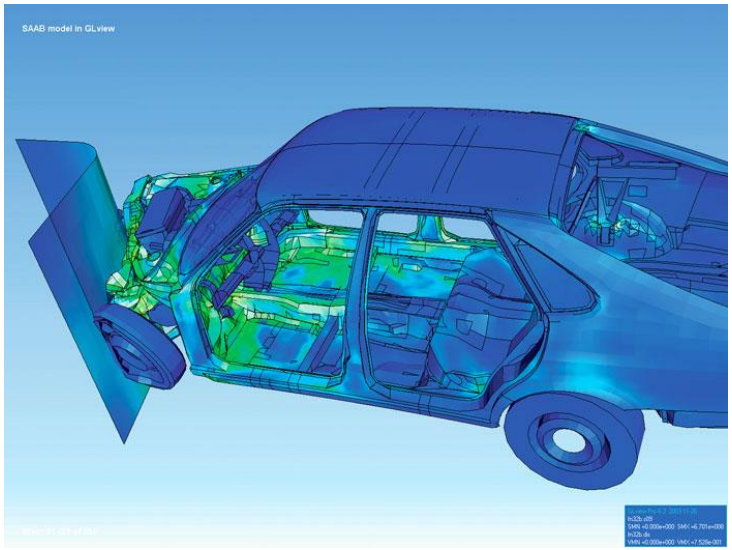


Beam bending under Euler-Bernoulli theory (uniform static beam)

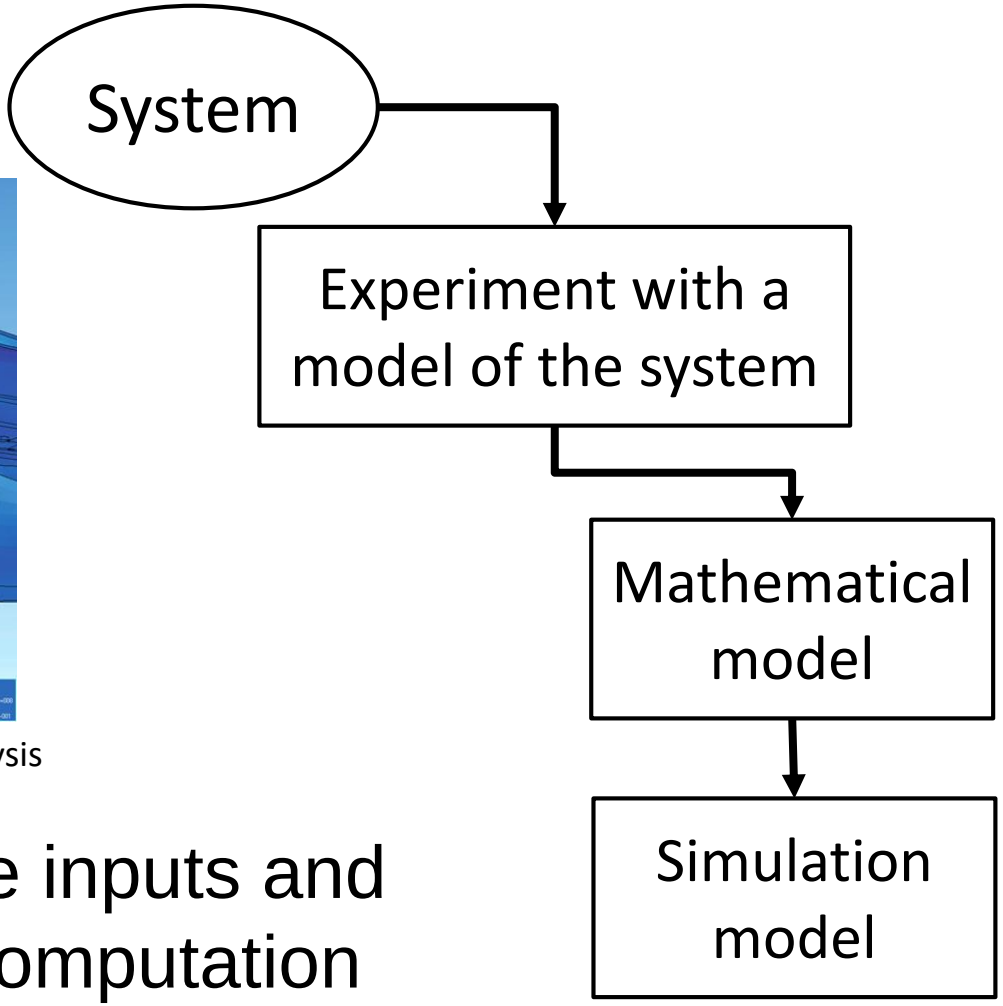


Explicit equation relates inputs and outputs for analytic computation

Studying Complex Systems

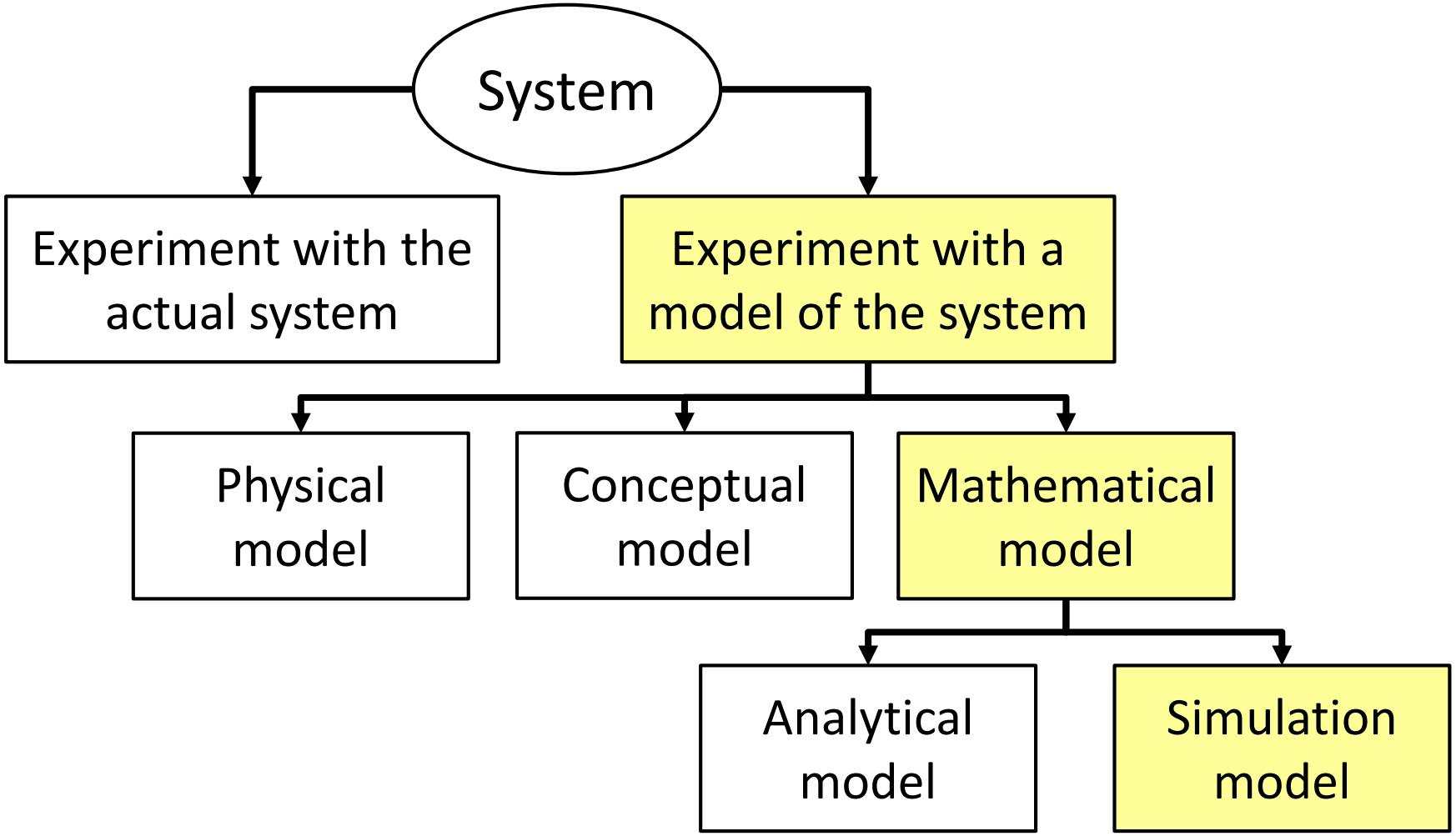


Asymmetrical collision using finite element analysis



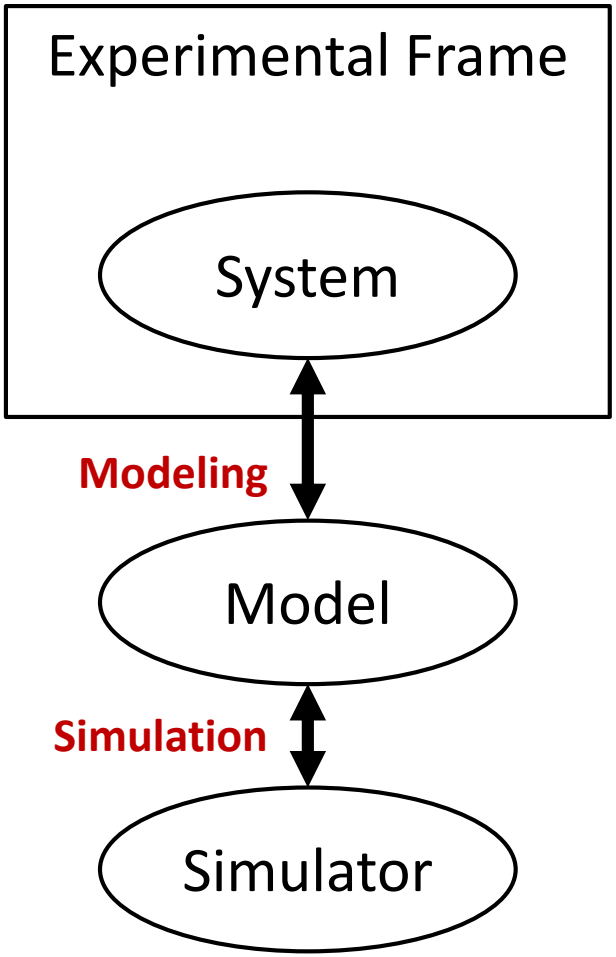
Implicit equations relate inputs and outputs for numerical computation

Studying Complex Systems



Types of Models and Simulations

Modeling & Simulation Entities



Set of limiting conditions under which system is observed or investigated

Real-world system of interest

Do the model and system produce indistinguishable data within the experimental frame?

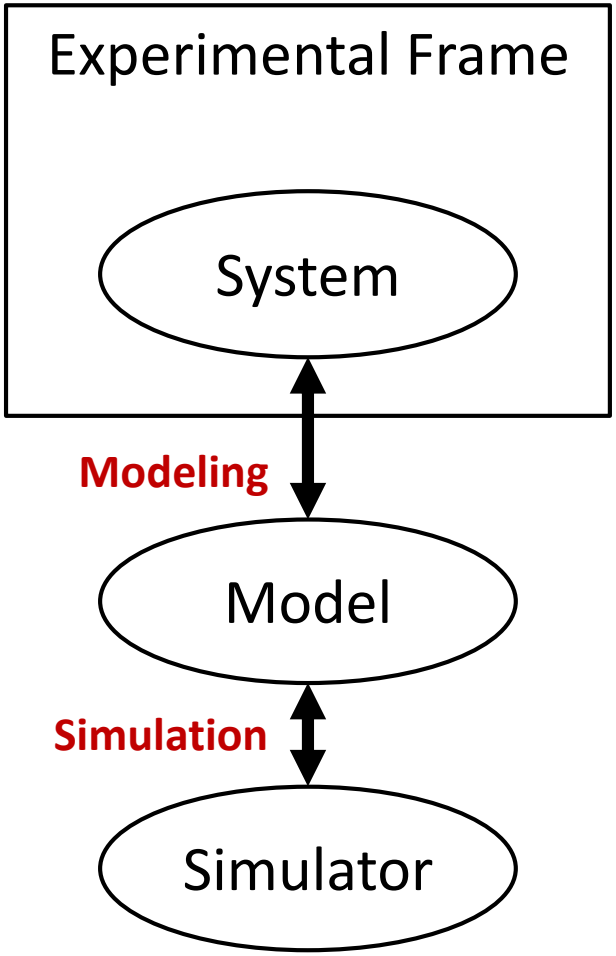
Structure and rules to generate data

Does the simulator correctly follow model rules?

Mechanism to execute a model

Based on Ziegler, Praehofer, and Kim, "Framework for Modeling and Simulation," Ch. 2 in *Theory of Modeling and Simulation: Integrating Discrete Event and Continuous Complex Dynamic Systems*, Second Edition, 2000.

Example: Café Java



Types of Models & Simulations

Model Classification

- Role of Time: *Static* or *Dynamic*
- Time Representation: *Continuous* or *Discrete*
- Role of Uncertainty: *Deterministic* or *Stochastic*

Simulation Classification

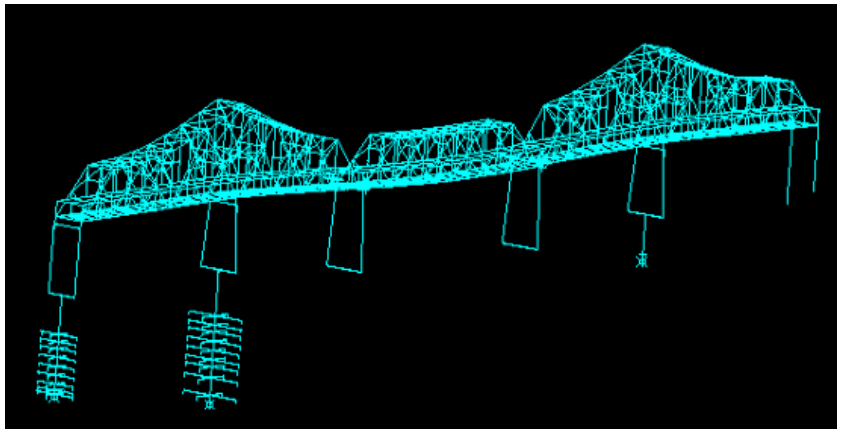
- Mode of Interaction: *Live*, *Virtual*, *Constructive*

Static Models

Static model to evaluate structure or appearance

- No time representation
  - Attributes do not change in time
  - Steady-state analysis

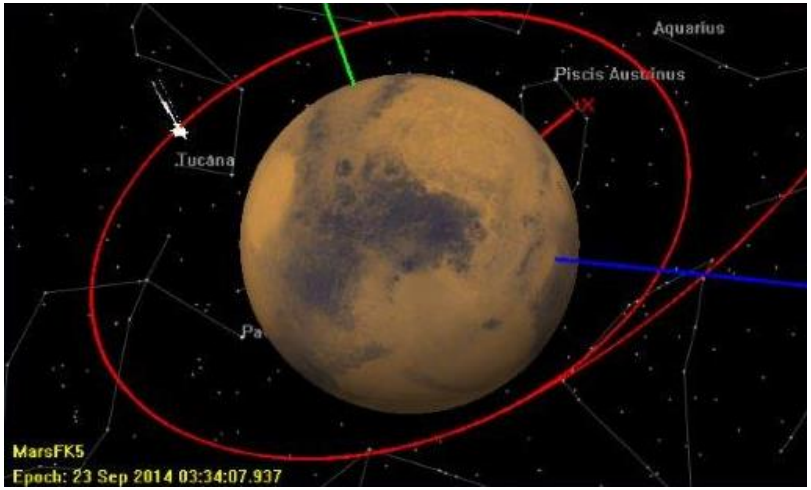
Dynamic Models



Dynamic model to evaluate response to moving loads

- Attributes move or change through space and time
  - Need intermediate data to compute final results
  - Interested in intermediate data

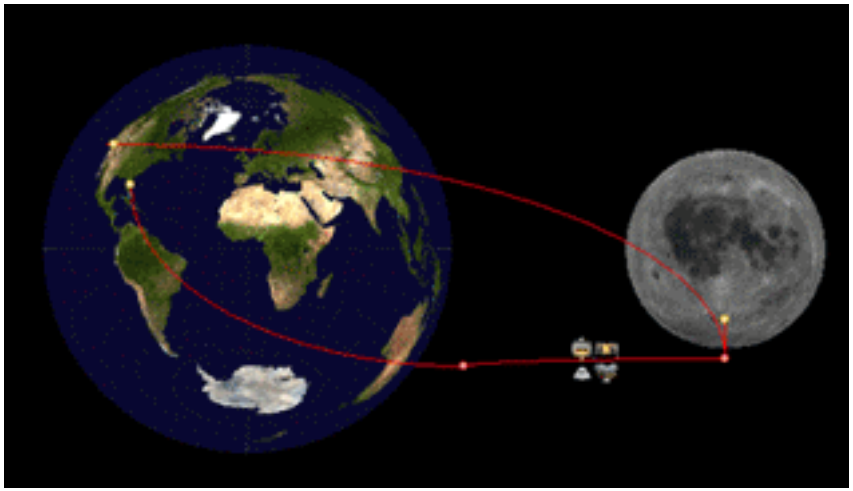
Continuous Time Models



Continuous model to evaluate flight dynamics

- Dynamic model
- Units of time are not inherently quantized
  - Inspect intermediate results at any real-valued time
  - Governed by physical laws and *differential equations*

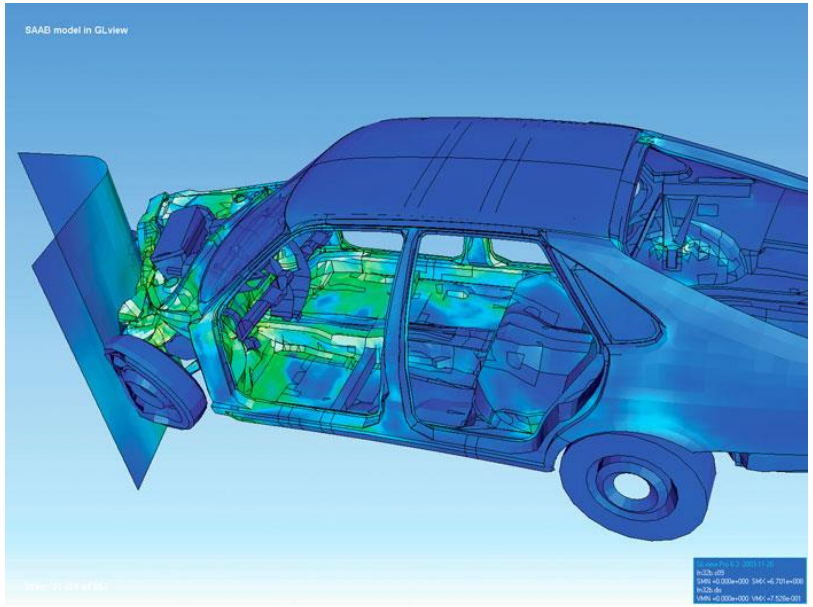
Discrete Time Models



Discrete model to evaluate campaign logistics

- Dynamic model
- Time passes in explicit quanta
  - Can only inspect intermediate data at quanta multiples
  - Governed by abstract laws and *transition functions*

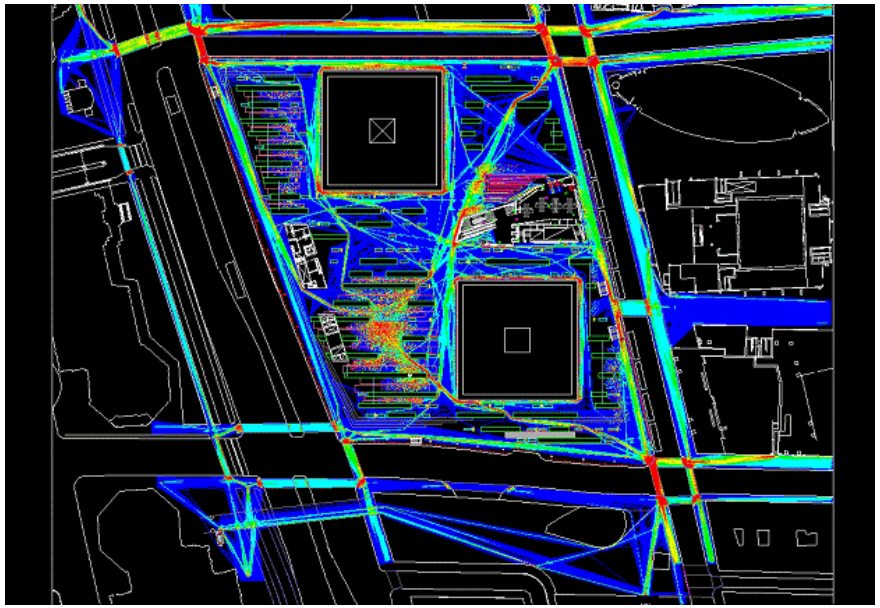
Deterministic Models



Asymmetrical collision using finite element analysis

- No sources of uncertainty within reference frame
  - Identical outputs for given set of inputs
  - Sensitivity analysis may be required if inputs are unknown

Stochastic Models



Pedestrian traffic model at the September 11 Memorial

- At least one input has random values within reference frame
  - Different outputs for same set of inputs
- Epistemic uncertainty (imprecise theory and models)
- Aleatory variability (uncontrollable, natural processes)

Simulation Modes

- **Live**: Real people, real systems
  - Most realistic training and operational readiness exercises
- **Virtual**: Real people, simulated systems
  - Human-in-the-loop decision-making
  - Lower cost training and operational readiness exercises
- **Constructive**: Simulated people, simulated systems
  - Rapid evaluation of large design spaces

What is a Simulation Model?

Stochastic Simulation

- Model uncertainty with repeated random samples
- More common in economic/social sciences

Dynamic Simulation

- Model temporal effects with state change propagation
- More common in natural/engineering sciences

A **simulator** is a device, computer program, or system that performs simulation.

Simulation Models in SYS-611