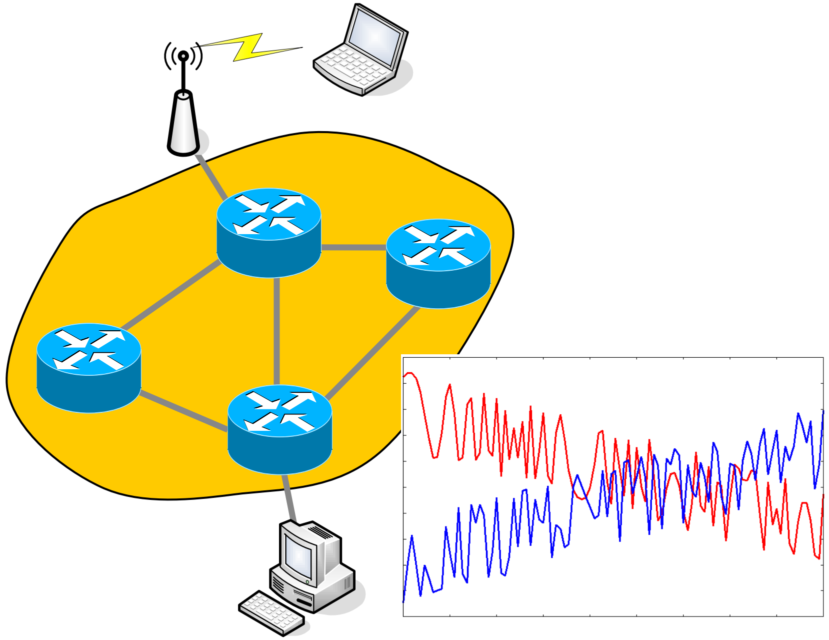
Chapter 1

Introduction to Simulation



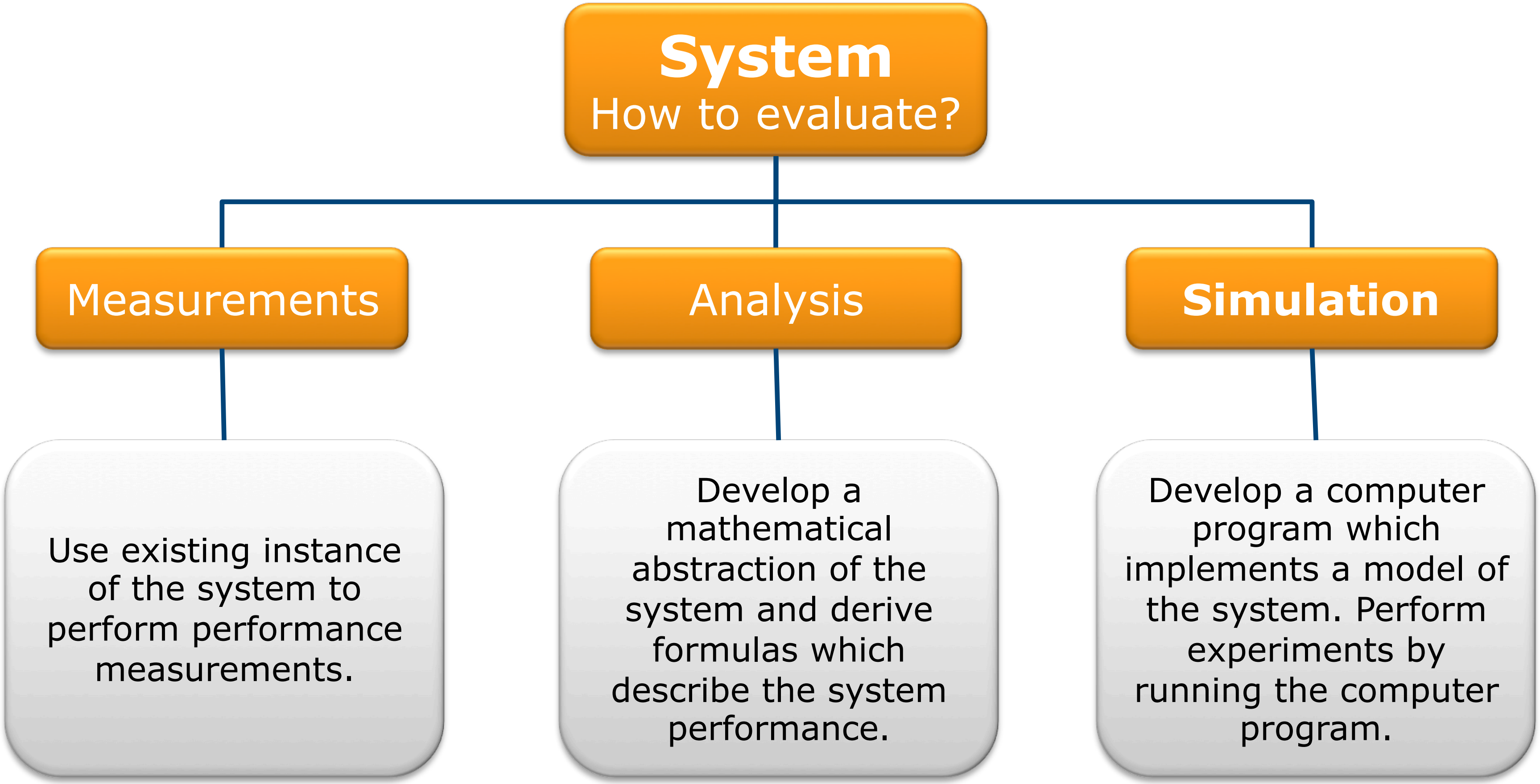
Contents

- Introduction
- Simulation examples
- What is a simulation and how it is done?
- What is a system?
- What is a model?
- What is a performance metric?
- Other simulation paradigms
- Steps in a simulation study

Introduction to Simulation

Introduction to Simulation

- Given a system, how do you evaluate its performance?



Introduction to Simulation

- Given a system, how do you evaluate its performance?

System
How to evaluate?

- Measurements
  - What to do
    - if system does not exist in reality?
    - if changes are very expensive or time consuming?
    - if system is not available?
- Analysis
  - Good solutions, but only feasible for simple systems.
  - Real world systems are too complex, e.g., factory, computer, network, etc.
- **Simulation**
  - How to assure that model-implementation-analysis do not show randomness
  - Garbage-In Garbage-Out (GIGO)

Introduction to Simulation

- There are many open questions
  - What is a system?
  - What is a model?
  - What is performance and how to measure it?
  - On what does performance depend?
  - How to build a model?
  - How to numerically evaluate it?
  - How to interpret such results?

Simulation examples

Simulation examples

Wooden mechanical horse simulator during WW1

A soldier in a heavy-wheeled-vehicle driver simulator

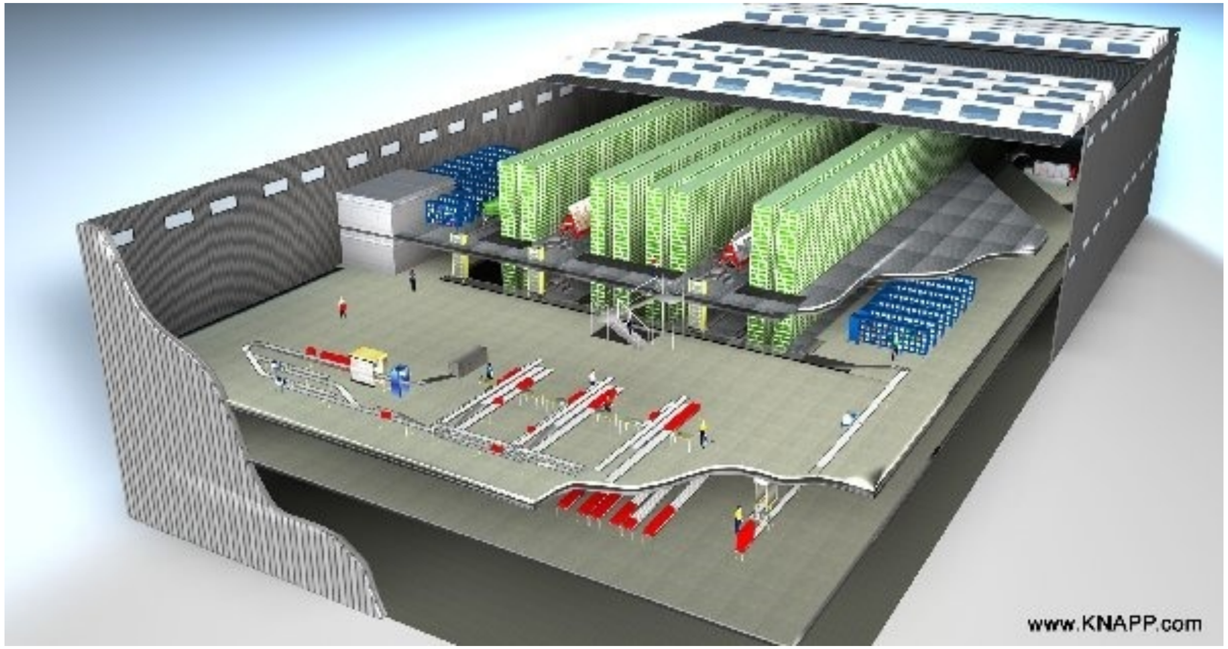
Simulation examples

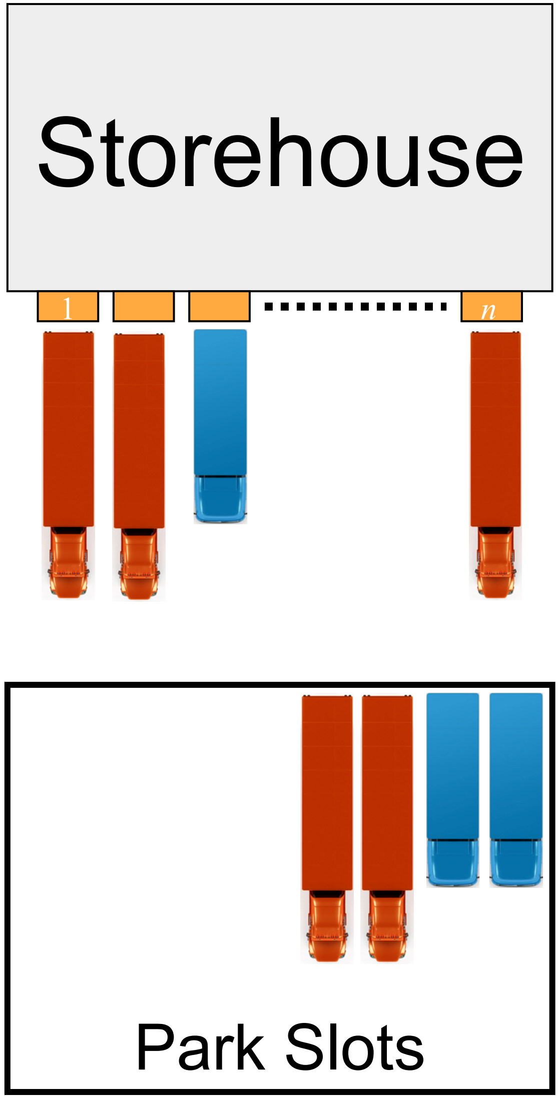
Entertainment Games

Serious Games

Simulation examples

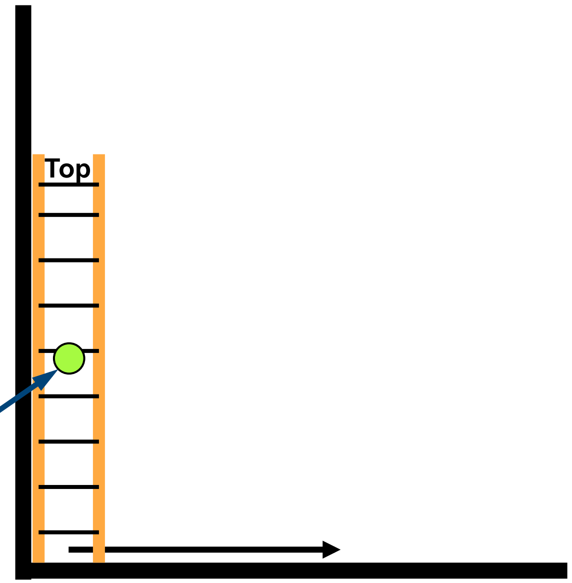
- A storehouse with n loading berths
- Several 100 trucks daily to serve
- Loading time of a truck is 50 minutes
- Goal: Cost-effective loading **and** short waiting time



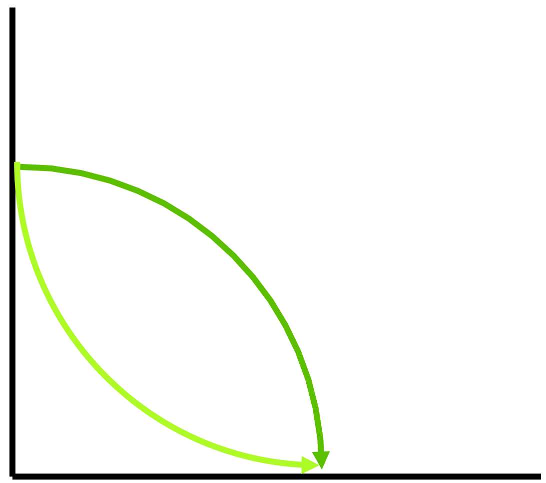


Simulation examples

- Experiment
  - Sliding of a ladder on the wall
  - A ladder is at the wall
  - We draw the bottom of the ladder and the top of the ladder is leant on the wall and slides down.

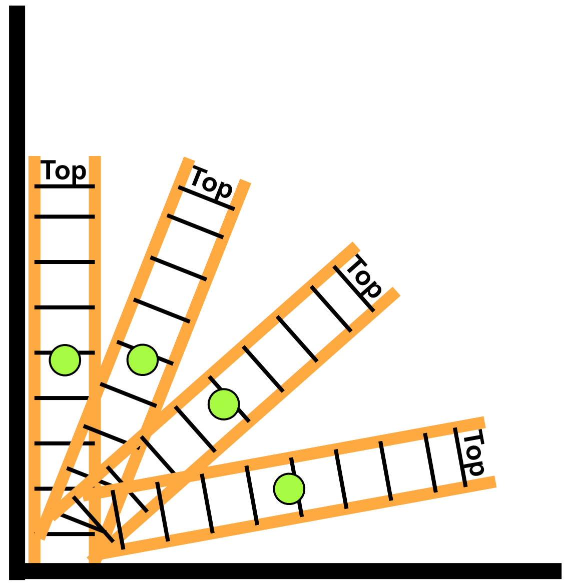


- Question: Which shape draws the center of the ladder?
  - Concave
  - Convex



Simulation examples

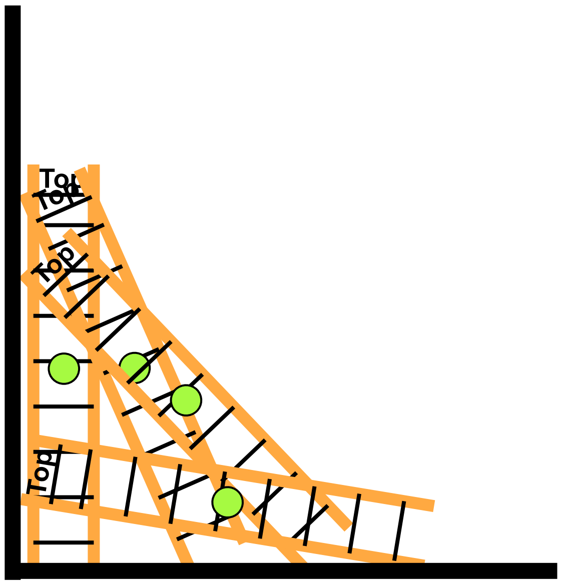
- Variant: The ladder falls down from the wall
- The resulting shape is convex



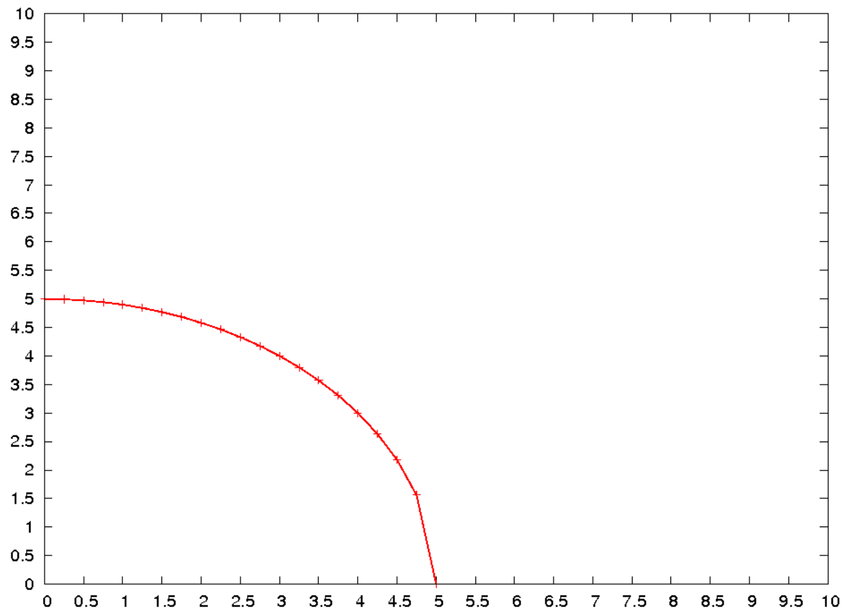
Experiment 1: Ladder falls down from the wall

Simulation examples

- One intuitively thinks the driven shape will be concave.
- However, the resulting shape is also convex.
- Astonished?

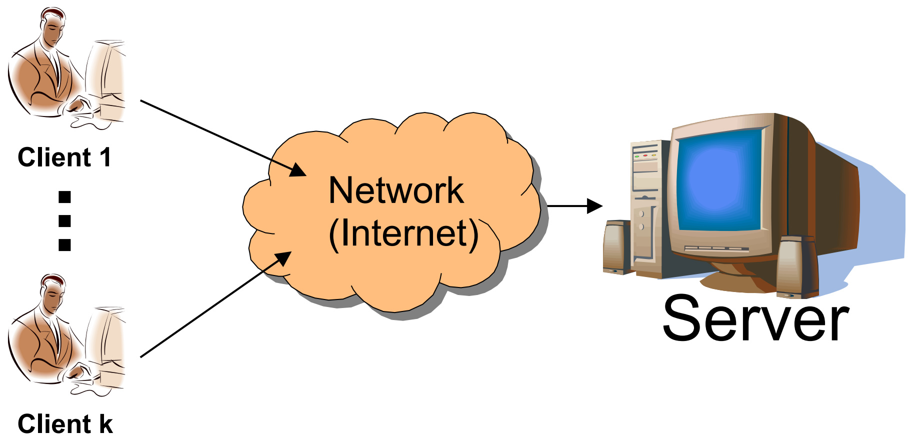


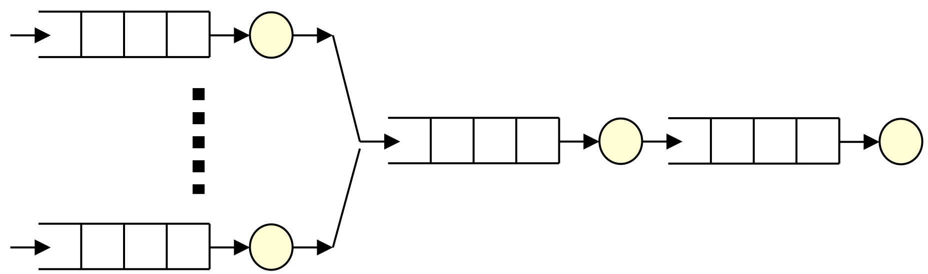
Experiment 2: Ladder slides down on the wall



Simulation examples

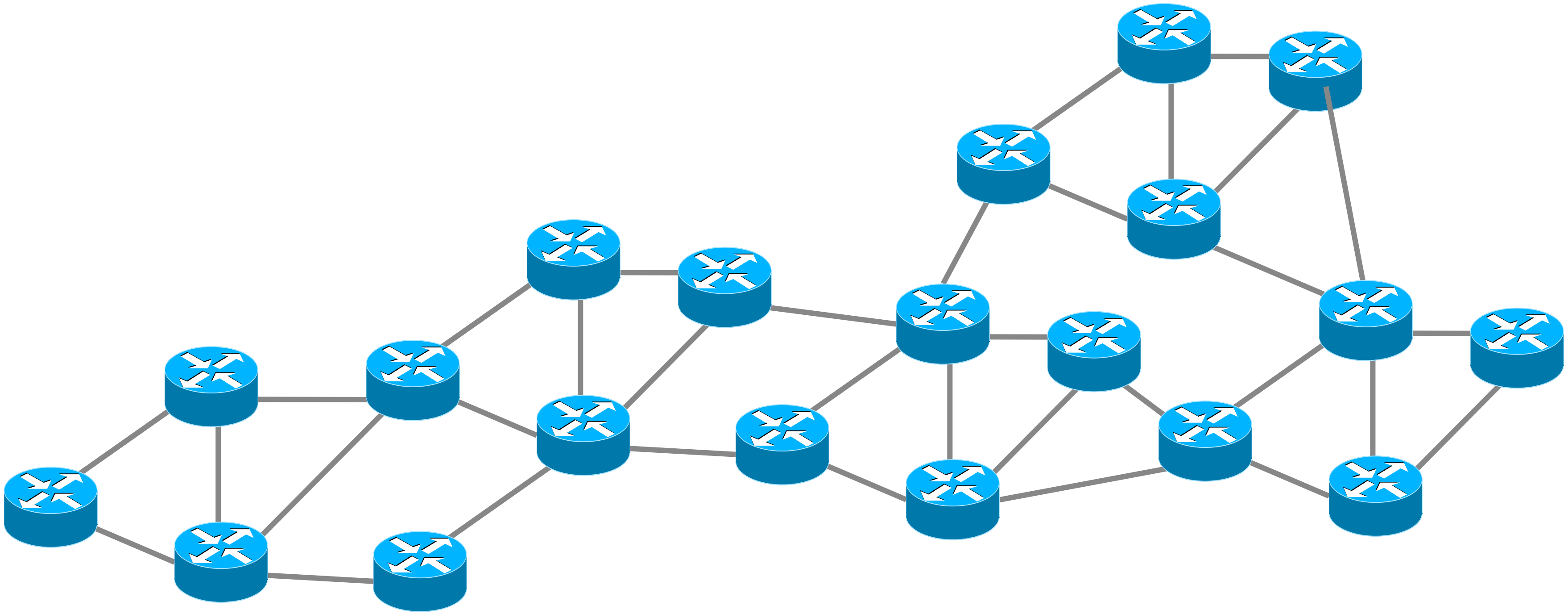
- Computer network
- Clients request some service from a server over a network.
  - Client = user and web browser
  - Service = web page
  - Server = web server
  - Network = {local network, Internet, wireless network}
- Analysis
  - Performance of the server
  - Performance of the network
- Attention
  - In this example the server as well as the network is depicted very simple!





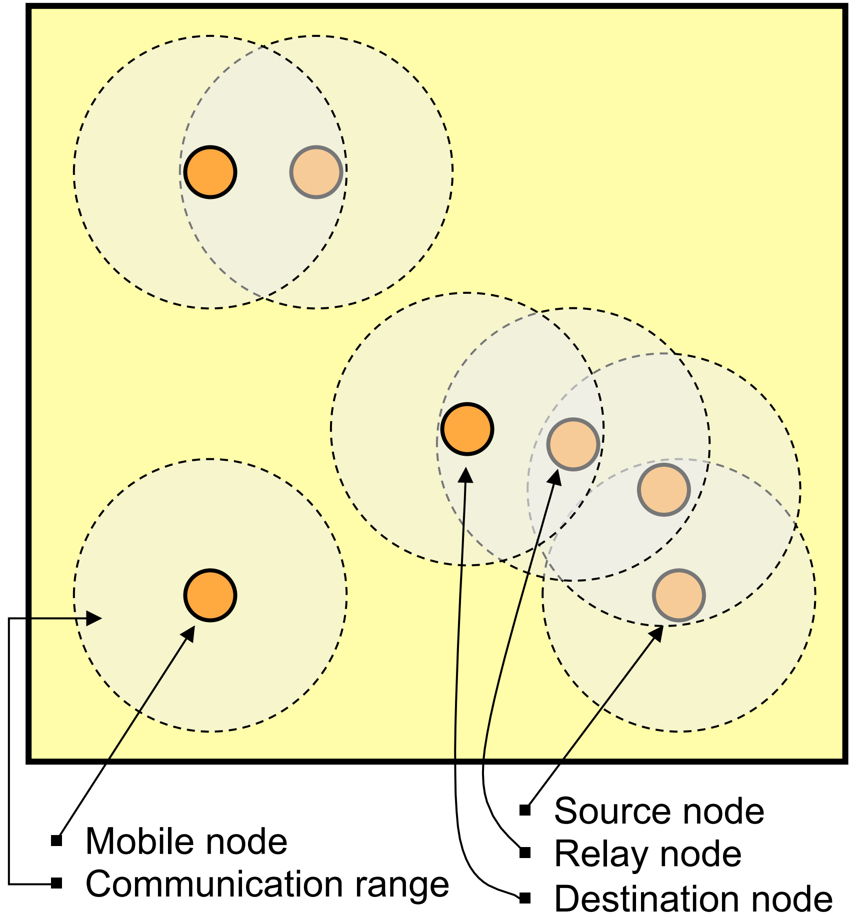
Simulation examples

- Large computer networks like the Internet
  - Topology
  - Routing
  - Traffic
  - Background traffic



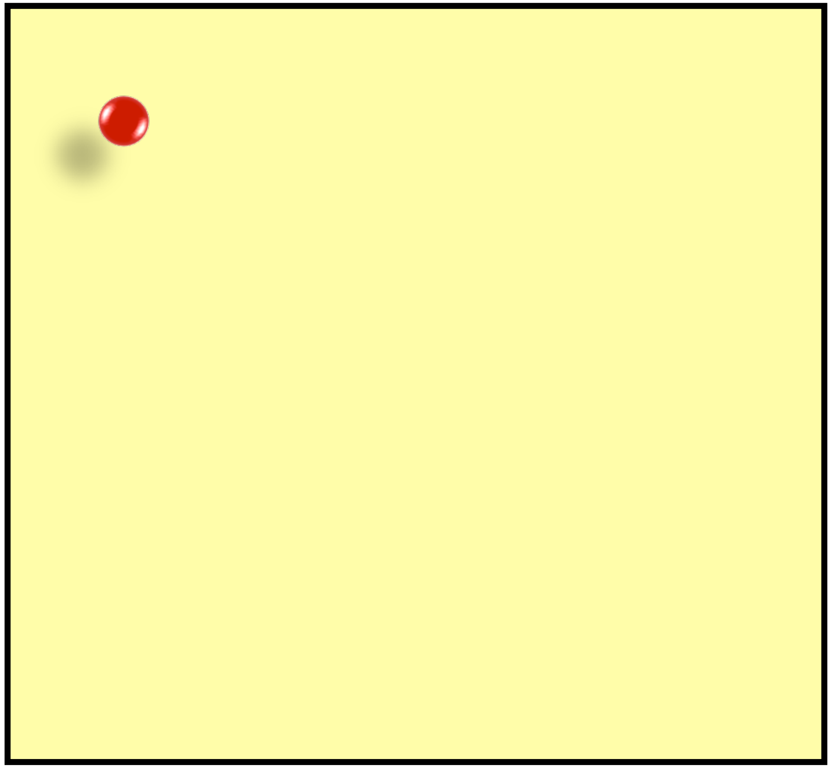
Simulation examples

- Mobile multi-hop ad-hoc network (MANET)
  - Wireless network consisting of mobile nodes
  - No infrastructure, i.e., no Access Points or Base Stations
  - Two nodes can communicate if they are in their mutual communication range
  - Typically, the source and destination nodes of a connection are several hops away
  - Thus, all nodes have to forward data for others



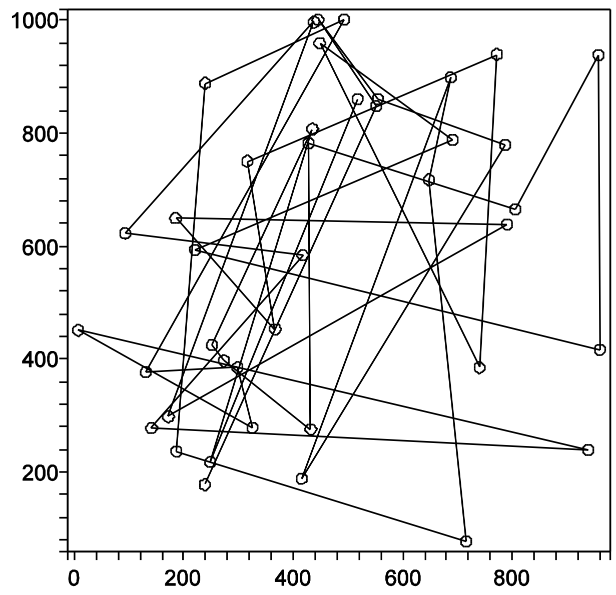
Simulation examples

- For the analysis of a MANET a mobility model is needed
- Assumption
  - Movement area: Rectangle without obstacles
- Simple model: Random-Waypoint mobility model
  - A node selects uniformly a point on the simulation area $p = (x, y)$
  - Velocity $v \in [v_{min}, v_{max}]$
  - Pause time t_{pause}
  - The node moves to the point p with velocity v
  - Stays for t_{pause} time units on p and restarts movement



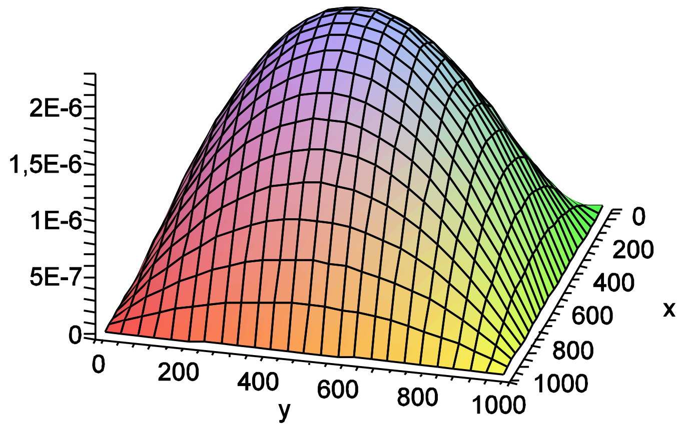
Simulation examples

- What about the probability that a node is on point $p = (x,y)$ on the movement area?
  - Uniformly distributed?
    - Since x and y are uniformly selected.
  - Are some areas preferred?



- What's about the influence of the parameters?
  - Velocity
  - Pause time

- Although simple to describe, it is hard to get a closed form formulae $f(x,y)$.



Simulation examples: Summary

- Simulation is used to imitate the real world
  - It is not as new as we think ;-)

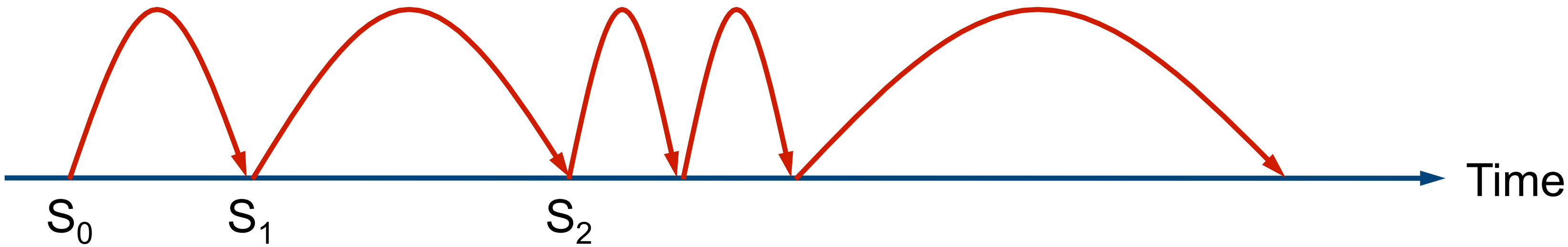
- According to Elmaghraby [1968]
  - Aid to thought
  - Communication
  - Training/Education
  - Experimentation
  - Predicting

  - Entertainment (this is a new application)
    - Video games
    - Serious games

What is a simulation and how it is done?

Introduction to Simulation

- What is a simulation?
  - A simulation is the **imitation** of the operation of a real-world system **over time**.



- What is the method?
  - Generate an **artificial history** of the system
  - Draw **inferences** from the artificial history concerning the characteristics of the system
- How it is done?
  - Develop a **model**
  - Model consists of entities (objects)

When is simulation appropriate?

- Simulation enables the **study of experiments** with internal interactions
- Informational, organizational, and environmental changes can be simulated to see the model's **behavior**
- Knowledge from simulations can be used to **improve** the system
- Observing results from simulation can give **insight to** which variables are the most important ones
- Simulation can be used as **pedagogical device** to reinforce the learning material
- Simulations can be used to **verify** analytical results, e.g., queueing systems
- Animation of a simulation can show the system in action, so that the plan can be **visualized**

When is simulation not appropriate?

- When problem is **solvable** by **common sense**
- When the problem can be **solved mathematically**
- When direct **experiments** are **easier**
- When the simulation **costs** exceed the **savings**
- When the simulation requires **time**, which is **not available**
- When **no** (**input**) **data** is **available**, but simulations need data
- When the simulation can **not** be **verified** or **validated**
- When the system **behavior** is too **complex** or **unknown**

- Example: human behavior is extremely complex to model

Advantages of simulation

- Policies, procedures, decision rules, information flows can be explored **without disrupting** the real system
- New hardware designs, physical layouts, transportation systems, protocols, computer systems, and network architectures can be **tested** without committing resources
- Hypotheses about how or why a phenomenon occurs can be **tested** for feasibility
- **Time** can be **compressed** or **expanded**
  - Slow-down or Speed-up
- Insight can be obtained about the **interaction** of variables
- Insight can be obtained about the **importance** of variables to the performance of the system
- **Bottleneck analysis** can be performed to detect problems
- Simulation can help to **understand** how the **system operates** rather than how people think the system operates
- **“What if …”** questions can be answered

Disadvantages of simulation

- Model building requires training, it is **like an art**.
  - Compare model building with programming.
- Simulation results can be **difficult to interpret**
  - Most outputs are essentially **random variables**
  - Thus, not simple to decide whether output is randomness or system behavior
- Simulation can be **time consuming** and expensive
  - Skimping in time and resources could lead to useless/wrong results
- The disadvantages are offset as follows
  - Simulation packages contain models that only **need input data**
  - Simulation packages contain **output-analysis capabilities**
  - Sophistication in computer technology improves **simulation times**
  - For most of the **real-world problems** there are **no closed form solutions**

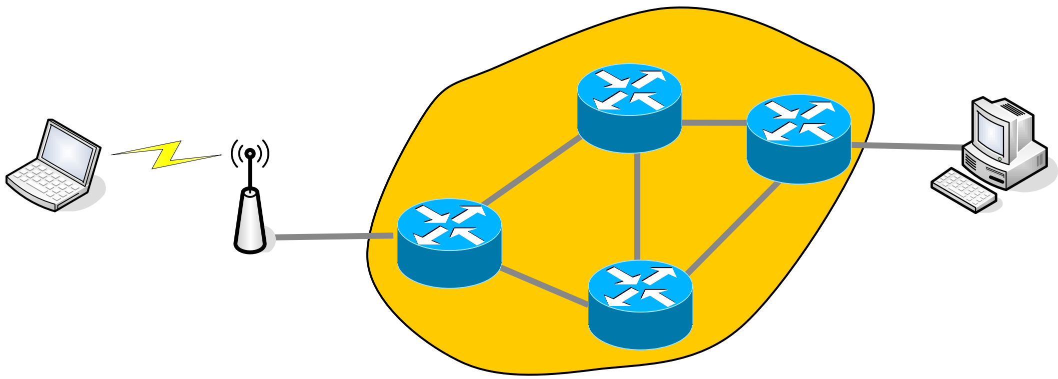
Application areas of simulation

- Manufacturing applications
- Semiconductor manufacturing
- Construction engineering and project management
- Military applications
- Logistics, supply chain and distribution applications
- Transportation models and traffic
- Business process simulation
- Health care
- Call-center
- Computers and Networks
- Games, Entertainment
- ...

What is a system?

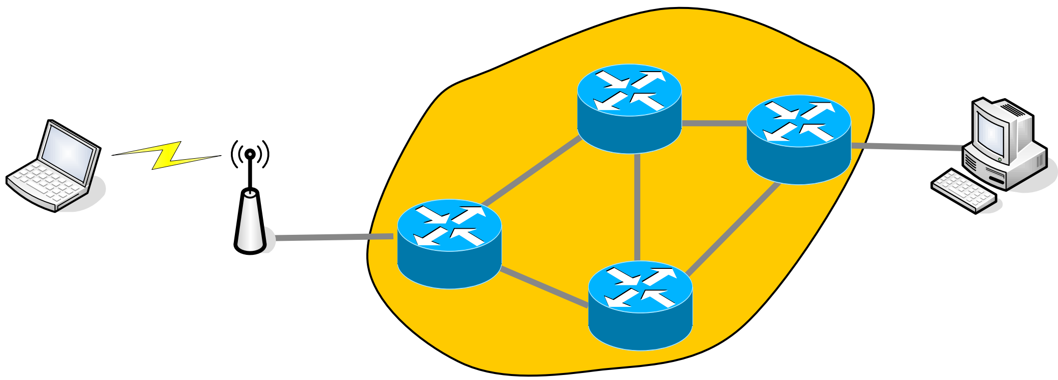
System and System Environment

- System
  - A system is a **group of objects** that are joined together in some regular interaction or interdependence toward the **accomplishment** of some **purpose**.
- Example:
  - Automobile factory
    - Machines, parts, and workers operate jointly to produce a vehicle
  - Computer network
    - User, hosts, routers, lines establish a network



System and System Environment

- System environment
  - Everything **outside** the system, but **affects** the system



- Attention
  - It is important to **decide** on the boundary between the **system** and the **system environment**
  - This decision depends on the **purpose of the study**

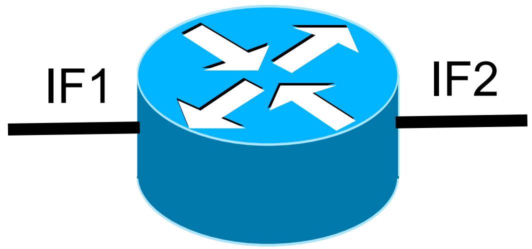
Components of a System

- In order to understand and analyze a system, we need some terms
- General Terminology
  - **Entity** Object of interest in the system
  - **Attribute** Property of an entity
  - **Activity** A time period of specified length
  - **System state** Collection of variables required to describe the system at any time
  - **Event** An instantaneous occurrence that might change the state of the system
  - **Endogenous** Activities and Events occurring within the system
  - **Exogenous** Activities and Events in the environment (outside the system) that affect the system

Components of a System: Example

Example of a simple system

- **Entity** Router with two interfaces
- **Attributes**
  - {IF1, IF2}
- **Activity**
  - Transmit IF1 -> IF2, 20µs
  - Transmit IF2 -> IF2, 15µs
  - Drop on IF1, 10µs
  - Drop on IF2, 10µs
- **System state**
  - S = {R1, T1, D1, Q1, R2, T2, D2, Q2}
  - Ri = Received packets on interface i
  - Ti = Transmitted packets on interface i
  - Di = Dropped packets at interface i
  - Qi = Queue length of interface i
- **Events**
  - Arrival of packet {IF, Time, Packet length}

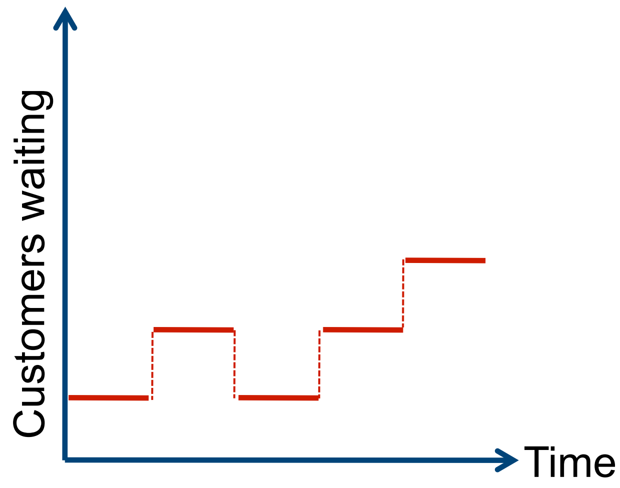


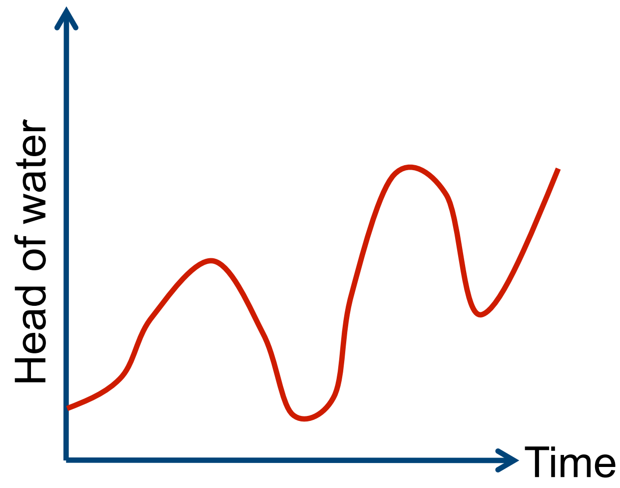
Components of a System: Examples

System	Entities	Attributes	Activities	Events	State Variables
Banking	Customers	Checking-account balance	Making deposits Draw money	Arrival; departure	Number of busy tellers Number of waiting customer
Rapid rail	Riders	Source Destination	Traveling	Arrival at station Arrival at destination	Number of riders at each station Number of rider in transit
Production	Machines	Speed Capacity Breakdown rate	Welding Stamping	Breakdown	Status of machines
Communications	Messages	Length Destination	Transmitting	Arrival at destination	Number of waiting messages to be transmitted
Inventory	Warehouse	Capacity	Withdrawing	Demand	Levels of inventory
Mobility model	Node	Position Velocity	Travel	End of movement	Position Velocity

Discrete and Continuous Systems

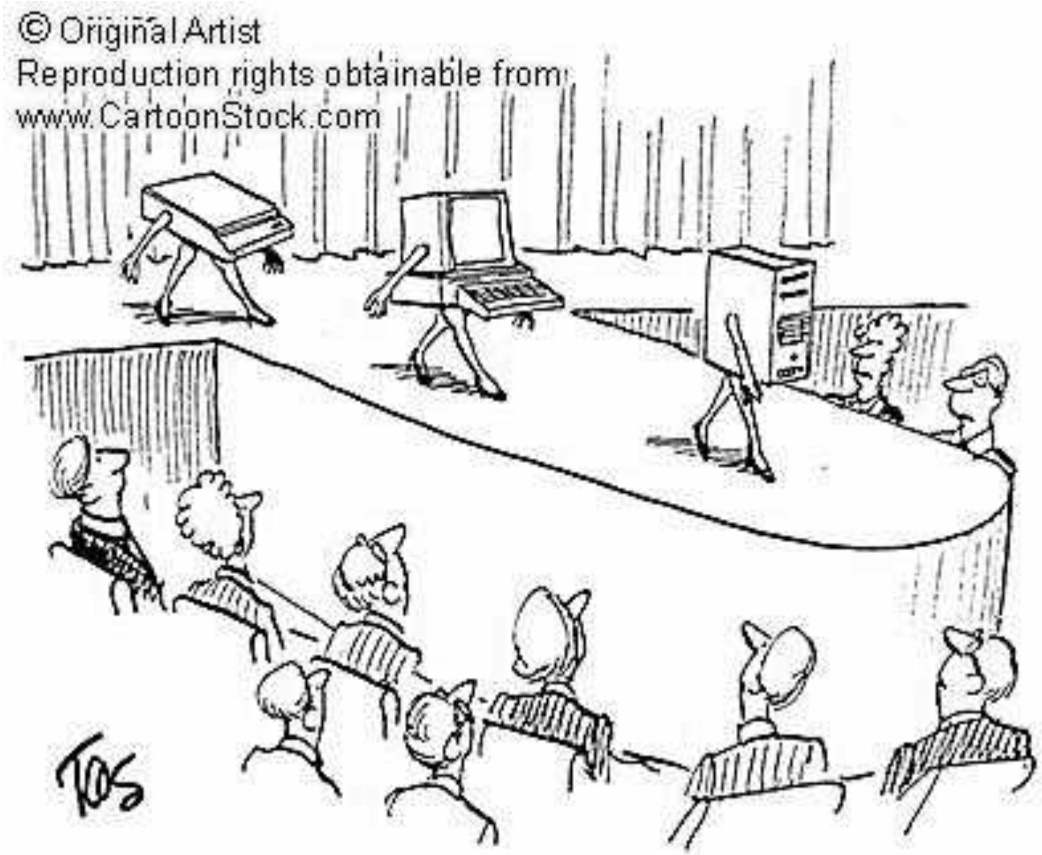
- Discrete Systems
  - State variables change only at discrete set of points
  - Examples
    - Bank, Grocery
    - Router, Host
    - Jobs in queue
- Continuous Systems
  - State variables change continuously over time
  - Examples
    - Head of water behind a dam
    - Temperature





What is a model?

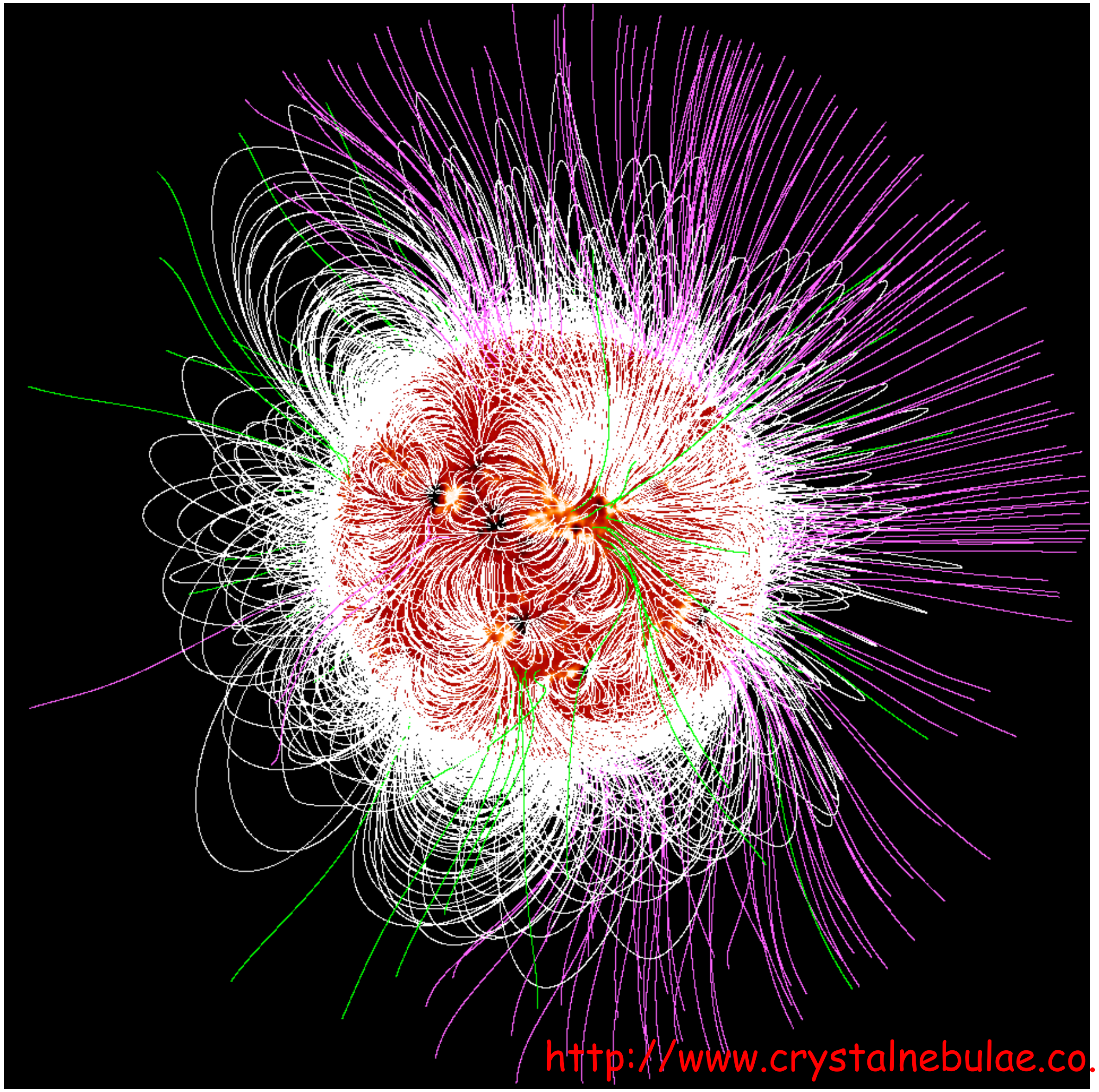
Model of a System



Model of a System

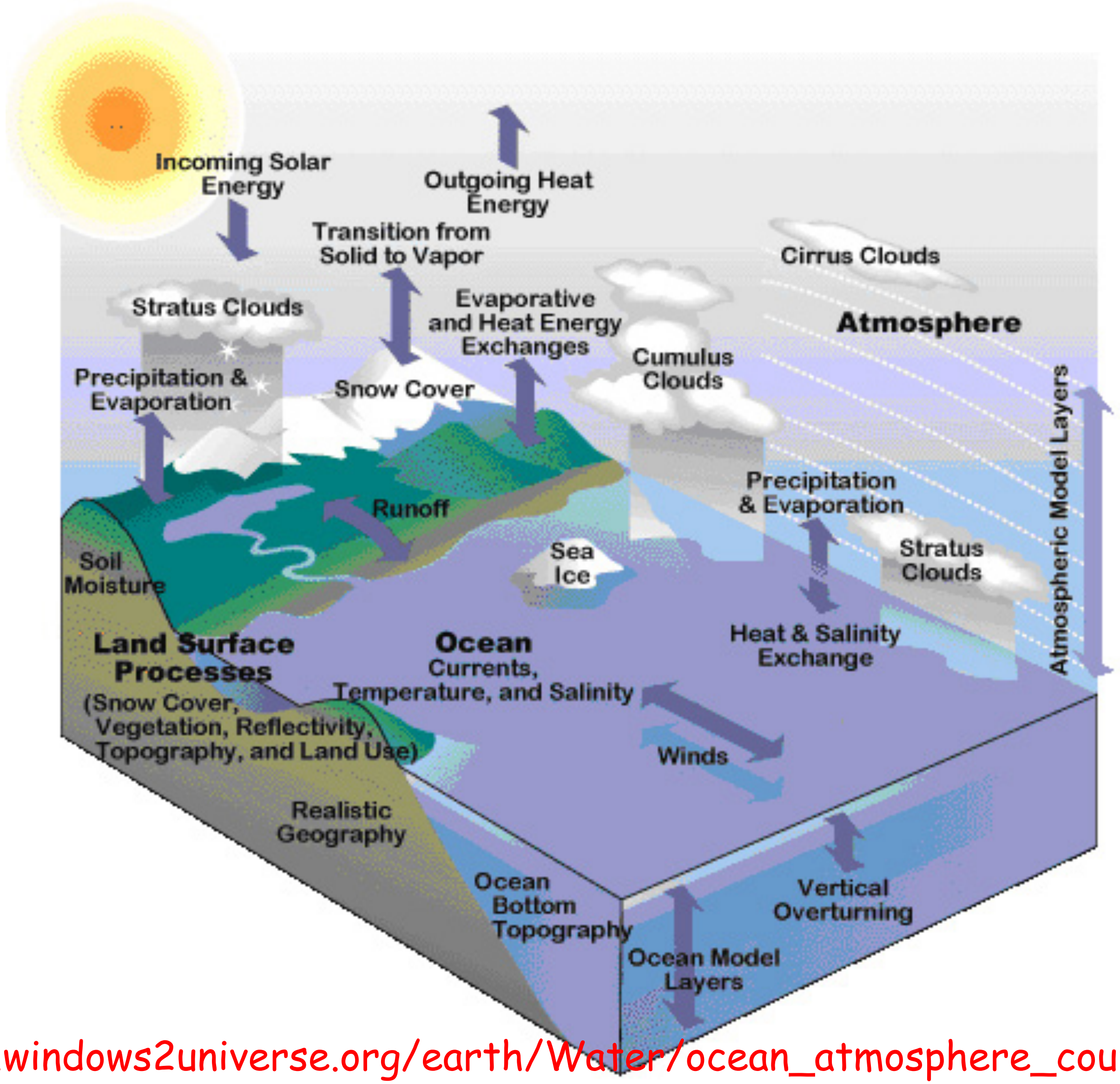
http://www.princeton.edu/~asce/const_95/ayasofya.html

Model of a System



http://www.crystalnebulae.co.uk/sunmodel.html

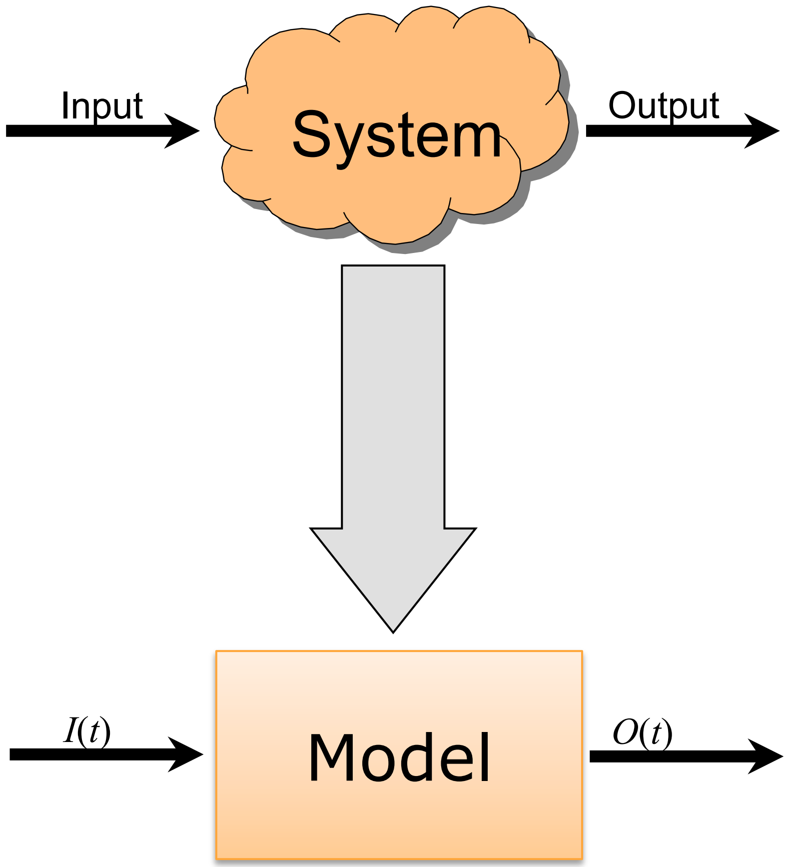
Model of a System



http://www.windows2universe.org/earth/Water/ocean_atmosphere_coupled_models.html

Model of a System

- What is a model?
  - A model is a representation of a system for the purpose of studying the system.



- Approach
  - Consider only those aspects of the system that affect the problem under investigation

- Problem
  - Granularity of details
  - Models are not unique

Model of a System

> The tendency is nearly always to simulate too much detail rather than too little. Thus, one should always design the model around the question to be answered rather than imitate the real system exactly.
>
> *Shannon, 1975*

Model of a System

- Physical model
  - Prototype of a system for the purpose of study.

Model of a System

- Mathematical model
  - A mathematical model uses symbolic notation and mathematical equations to represent a system.

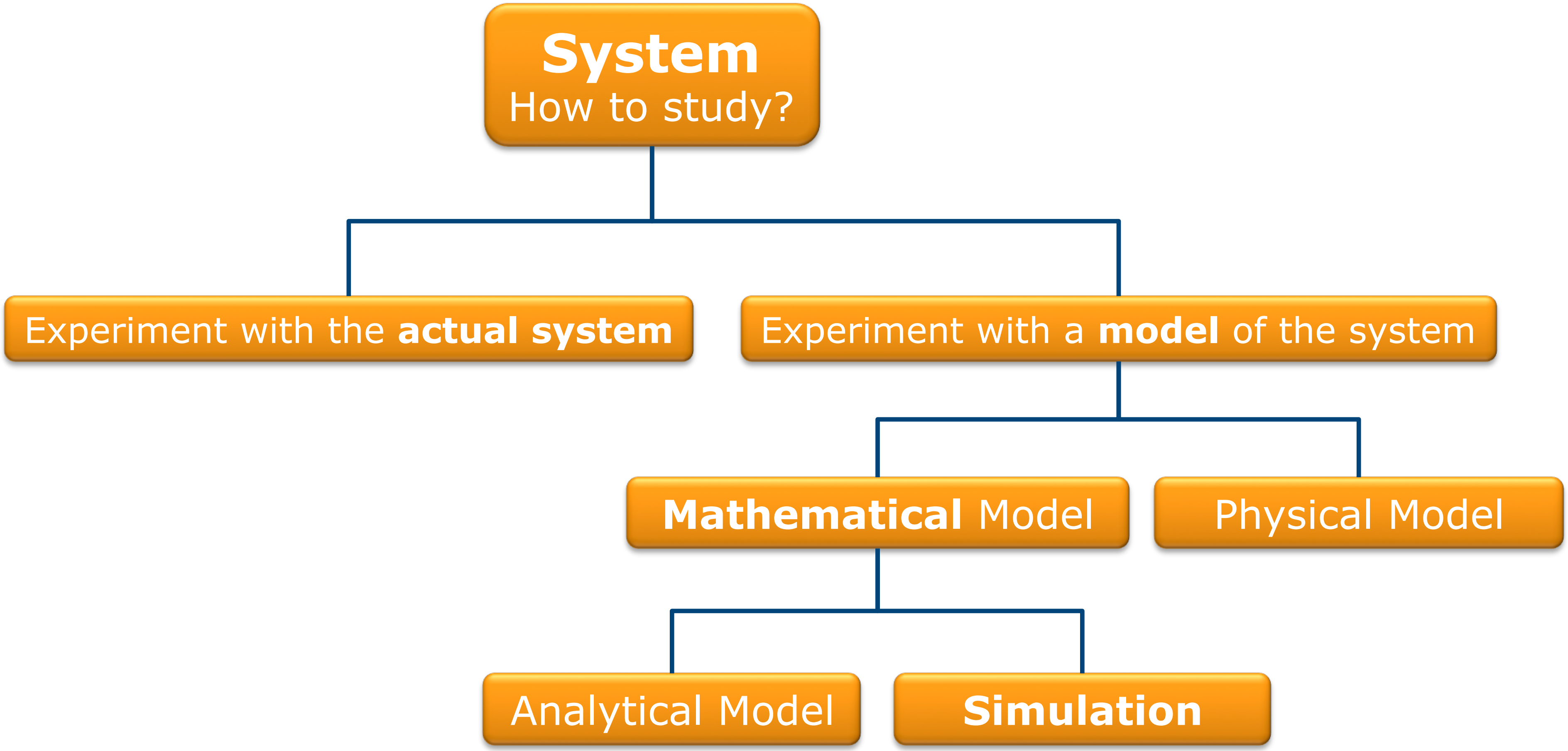
$$
\begin{aligned}
v_q &= -r_s i_q + \frac{\omega_r}{\omega_b}\Psi_d + \frac{p}{\omega_b}\Psi_q, \\
v_d &= -r_s i_d - \frac{\omega_r}{\omega_b}\Psi_q + \frac{p}{\omega_b}\Psi_d, \\
v_o &= -r_s i_o + \frac{p}{\omega_b}\Psi_o, & p\theta_r &= \omega_r, \\
0 &= r_{aq} i_{aq} + \frac{p}{\omega_b}\Psi_{aq}, & p\theta_e &= \omega_e, \\
v_f &= r_f i_f + \frac{p}{\omega_b}\Psi_f, & \delta &= \theta_r - \theta_e, \qquad (1) \\
0 &= r_{ad} i_{ad} + \frac{p}{\omega_b}\Psi_{ad}, & \omega_m &= \frac{2}{p}\,\omega_r, \\
T_e &= \frac{3}{2}\,\frac{P}{2}\,\frac{1}{\omega_b}(\Psi_d i_q - \Psi_q i_d), \\
p\omega_r &= \frac{P}{2J}\,(T_a - T_e),
\end{aligned}
$$

Model of a System

Today's scientists have substituted mathematics for experiments, and they wander off through equation after equation, and eventually build a structure which has no relation to reality.

Nikola Tesla (1857 - 1943), Modern Mechanics and Inventions, 1934

Model of a System



Model of a System

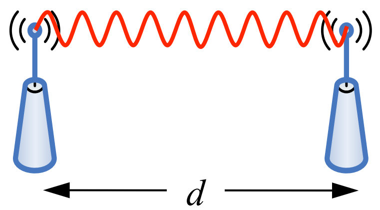
> Essentially, all models are wrong,
> but some are useful.
>
> *George E.P. Box, Empirical Model-Building and Response Surfaces, 1987*

Model of a System: Mobility

- Movement
  - Model: $d = v \cdot t$
  - Assumptions: Constant velocity v over the whole time t
  - Advantage: Simple formulae and intuitive
  - Disadvantage: Seldom valid for a whole travel (human, car, planes)

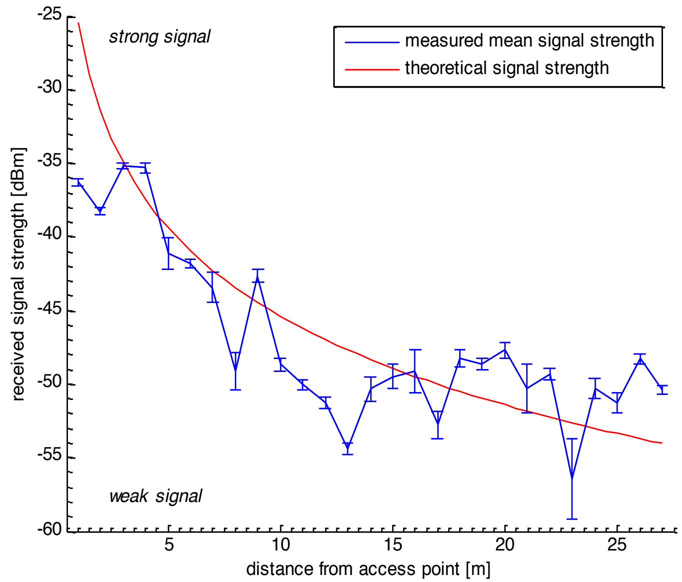
Model of a System: Radio Propagation

- Radio signal propagation
  - Free-Space-Model

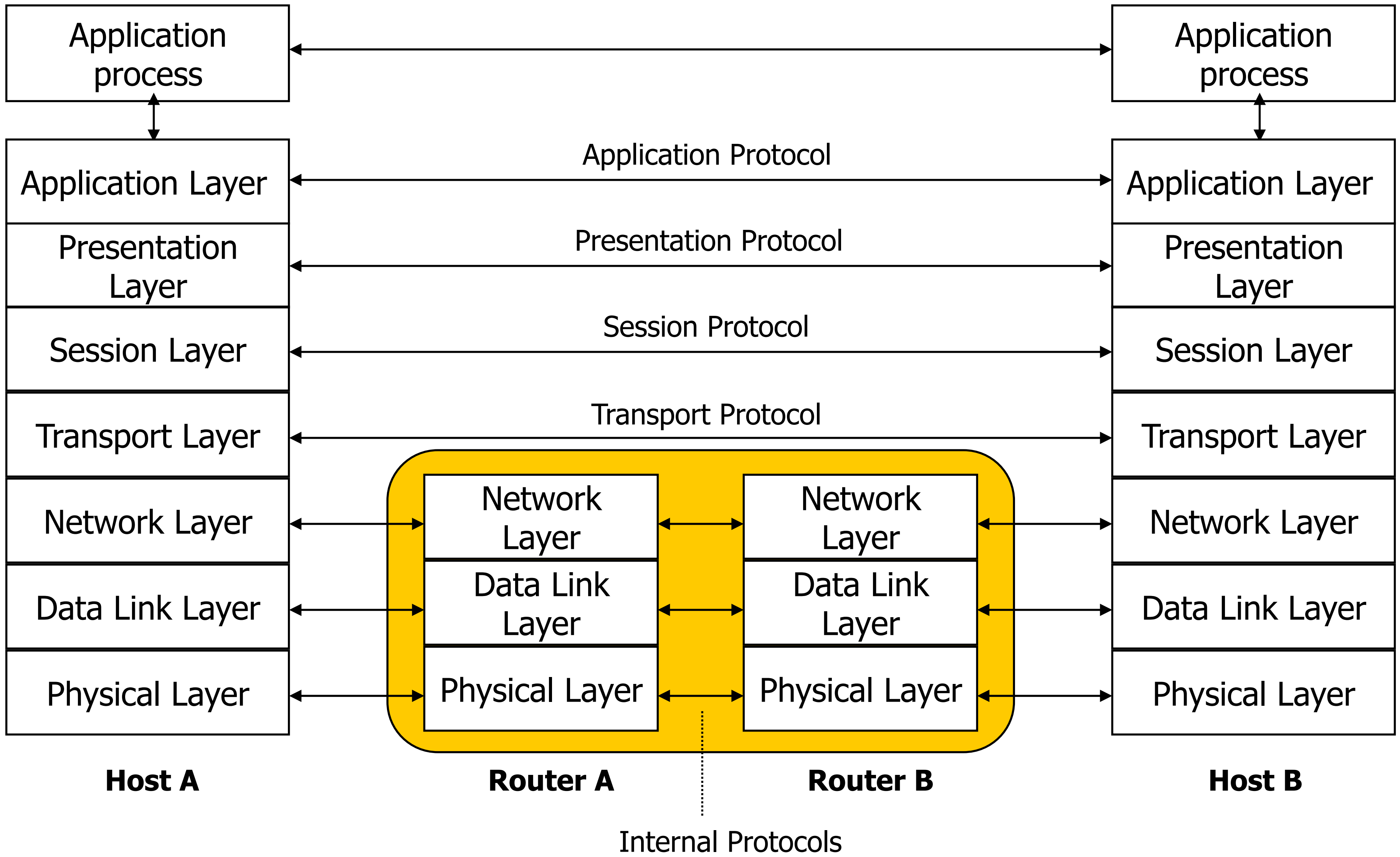


  - Model: $$PL_{dB}(d) = -10\log\left(\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2}\right)$$

- Assumptions:
  - Direct line of sight (LOS) between communication peers
  - No obstacles
- Advantages:
  - Simple asymptotic formulae for open space
- Disadvantages:
  - Not really useful for indoor and city environments



Model of a System: ISO/OSI Network Model



Model of a System: TCP/IP Reference Model

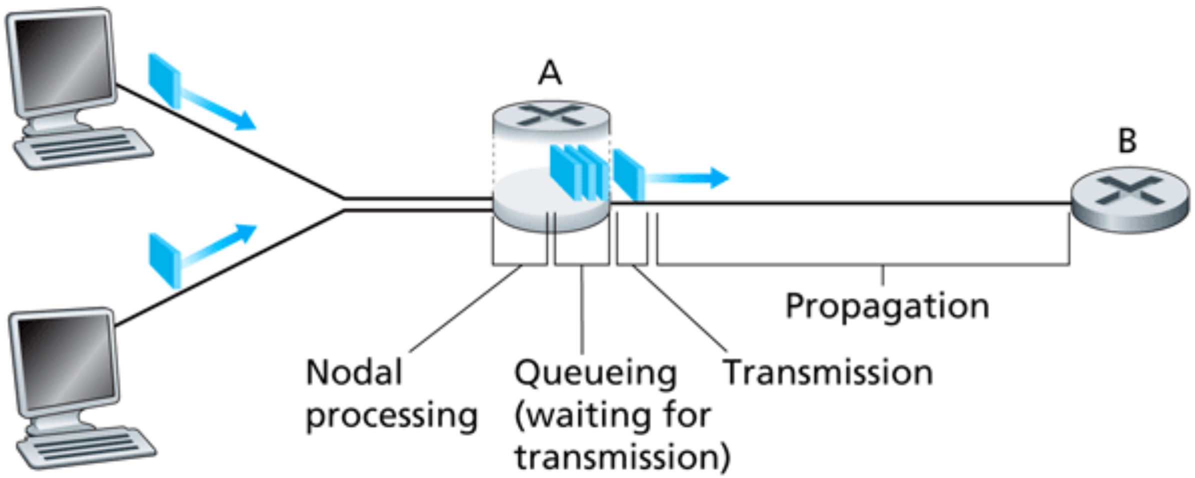
ISO/OSI	TCP/IP
Application Layer	Application Layer
Presentation Layer	Don't exist
Session Layer	
Transport Layer	Transport Layer
Network Layer	Internet Layer
Data Link Layer	Host-to-Network Layer
Physical Layer	

Model of a System: Six-level Computer Model

Level 5	Problem-oriented language level	
		Translation (Compiler)
Level 4	Assembly language level	
		Translation (Assembler)
Level 3	Operating system machine level	
		Partial interpretation (operating system)
Level 2	ISA (Instruction Set Architecture) level	
		Interpretation (microprogram) or direct execution
Level 1	Microarchitecture level	
		Hardware
Level 0	Digital logic level	

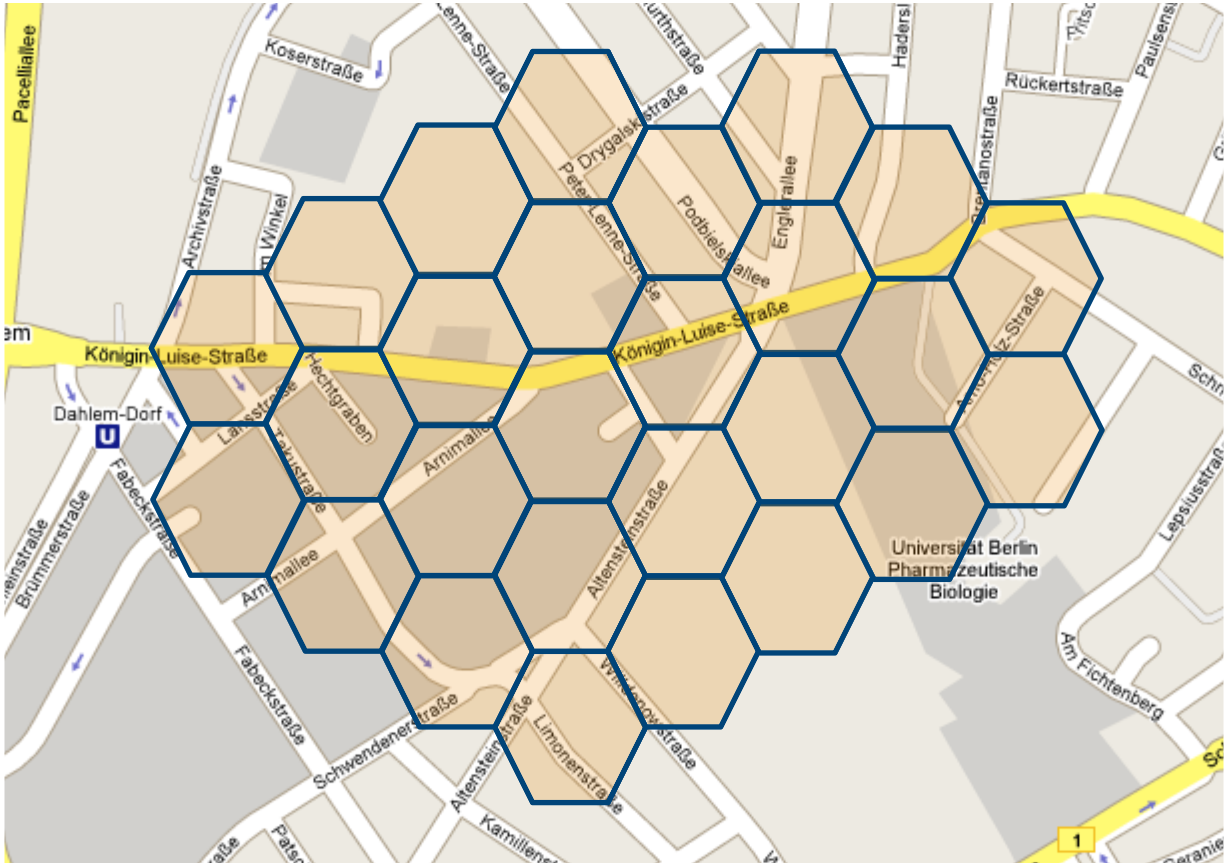
Model of a System: Communication Link

- A packet in a network suffers various delays
  - Processing in the node: examine packet header
  - Queueing: packet waits for transmission
  - Transmission: time to put all bits of a packet on the medium
  - Propagation: time to propagate on the medium from A to B



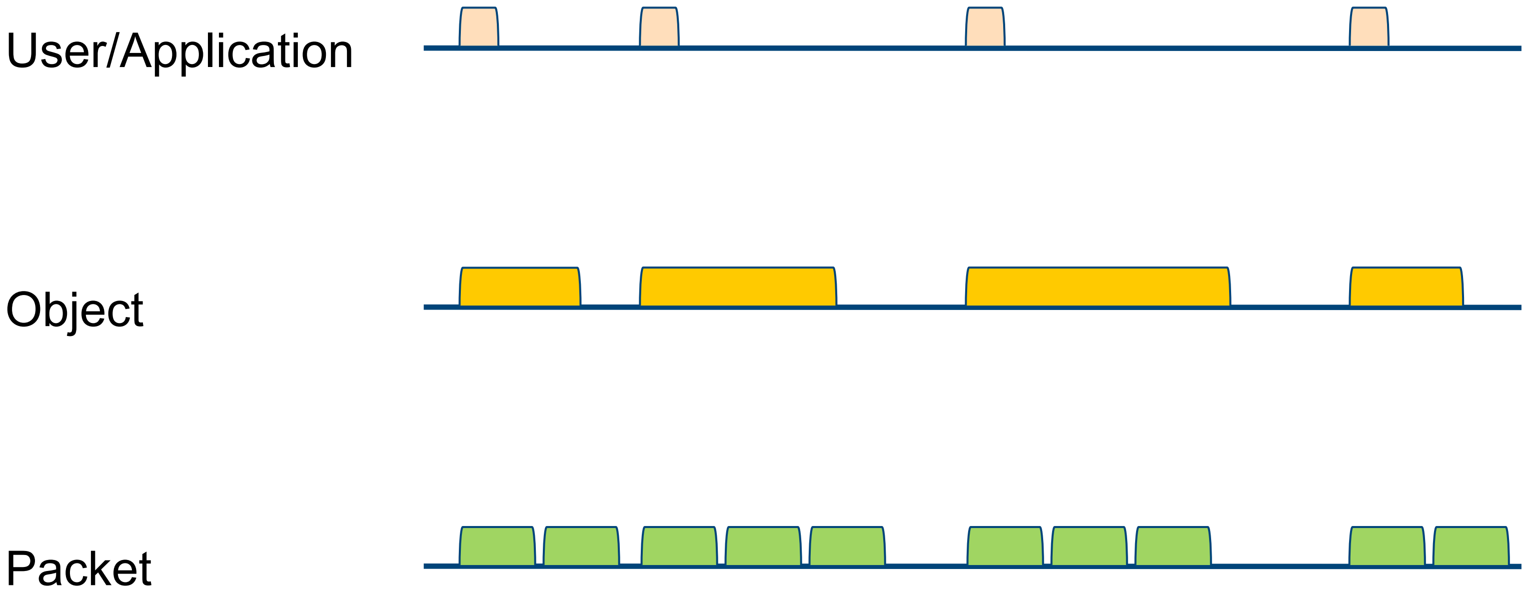
Model of a System: Cellular System

- Multi cellular network system model
  - Can be used for cellular networks, WLAN, WIMAX, Wireless Mesh networks



Model of a System: User Behavior

- User behavior, application behavior
  - User level, object level, packet level



Principles of Modeling

- Conceptualizing a model requires **system knowledge**, engineering judgment, and model-building tools.
- The secret to being a good modeler is recognizing the need and having the ability to **remodel**.
- The modeling process is **evolutionary** because the act of modeling reveals important information piecemeal.
- The problem or **problem statement** is the primary controlling element in model-based problem solving.
- In modeling **combined systems**, the **continuous** aspects of the problem should be considered **first**. The **discrete** aspects of the model should then be developed.
- A **model** should be **evaluated** according to its **usefulness**. From an absolute perspective, a model is neither good or bad, nor is it neutral.
- The **purpose** of modeling is **knowledge** and **understanding**, not models.
- Know when to model "**top-down**" and when to model "**bottom-up**".
- It is important to learn **modeling techniques**, but more important to learn to consider the **tradeoffs** among **alternative techniques**.

A. Alan B. Pritsker, James O. Henriksen, Paul A. Fishwick, Gordon M. Clark, "Principles of Modeling", Winter Simulation Conference, 1991.

What is a Good Model?

- Simplicity
- Credibility
- Efficiency
- Availability
- Verified
- Code quality
- Documentation

What is a Good Model?

> Everything should be made as simple as possible, but not simpler.
>
> *Albert Einstein*

Simulation Models

- Simulation Model
  - A simulation model is a particular type of mathematical model of a system.

- Types of simulation models
  - Static: Represent a system at a particular **point in time**.
  - Dynamic: Represent a system **over a time interval**.

  - Deterministic: Simulation models **without random** variables.
  - Stochastic: Simulation models **with random** variables.

  - Discrete: System **state changes** occur only at **discrete time** points.
  - Continuous: System **state changes** occur **continuously**.

Simulation Models

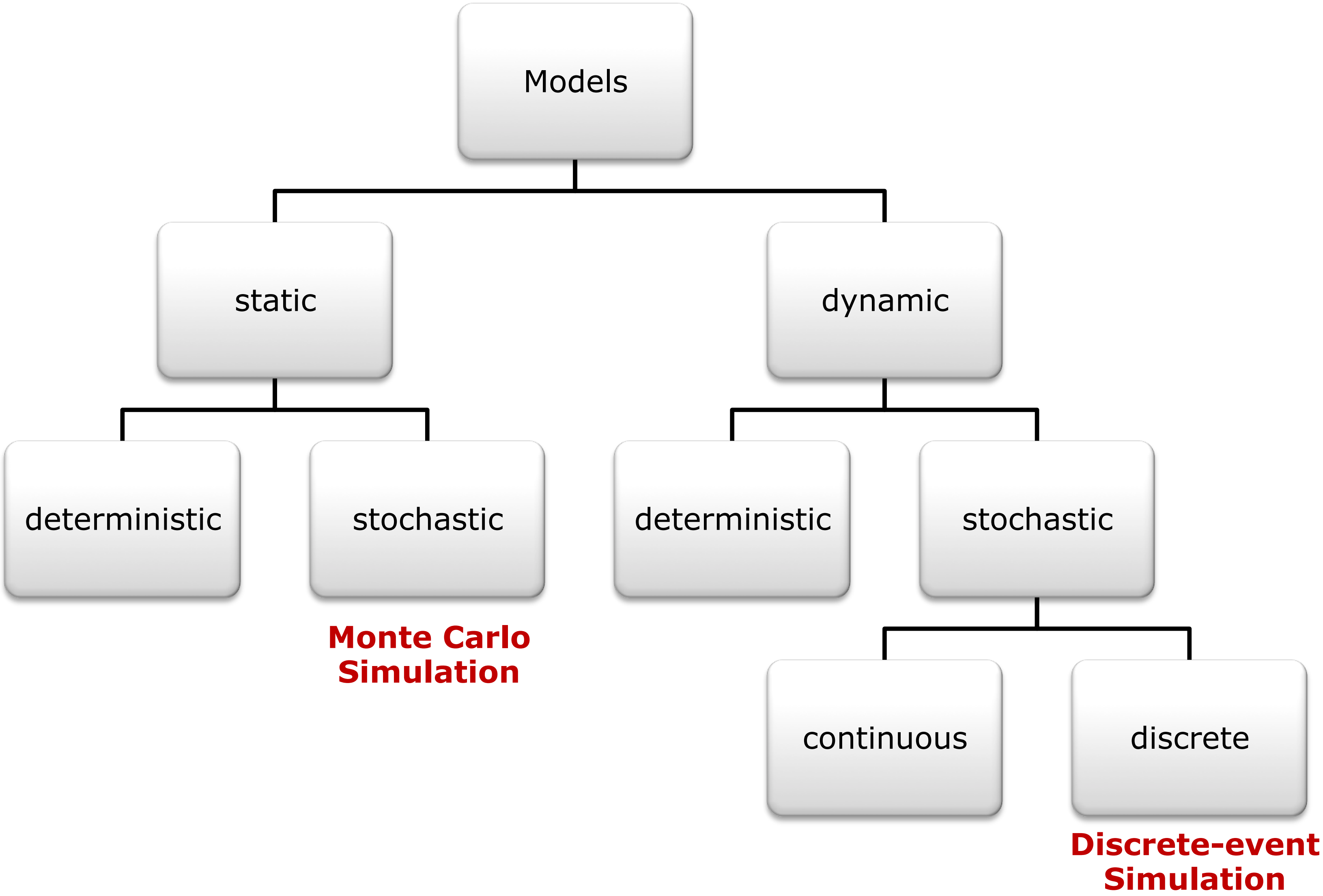
In this class, we will focus on

discrete, dynamic, stochastic

simulation models.

Mesut Güneş

Simulation Models

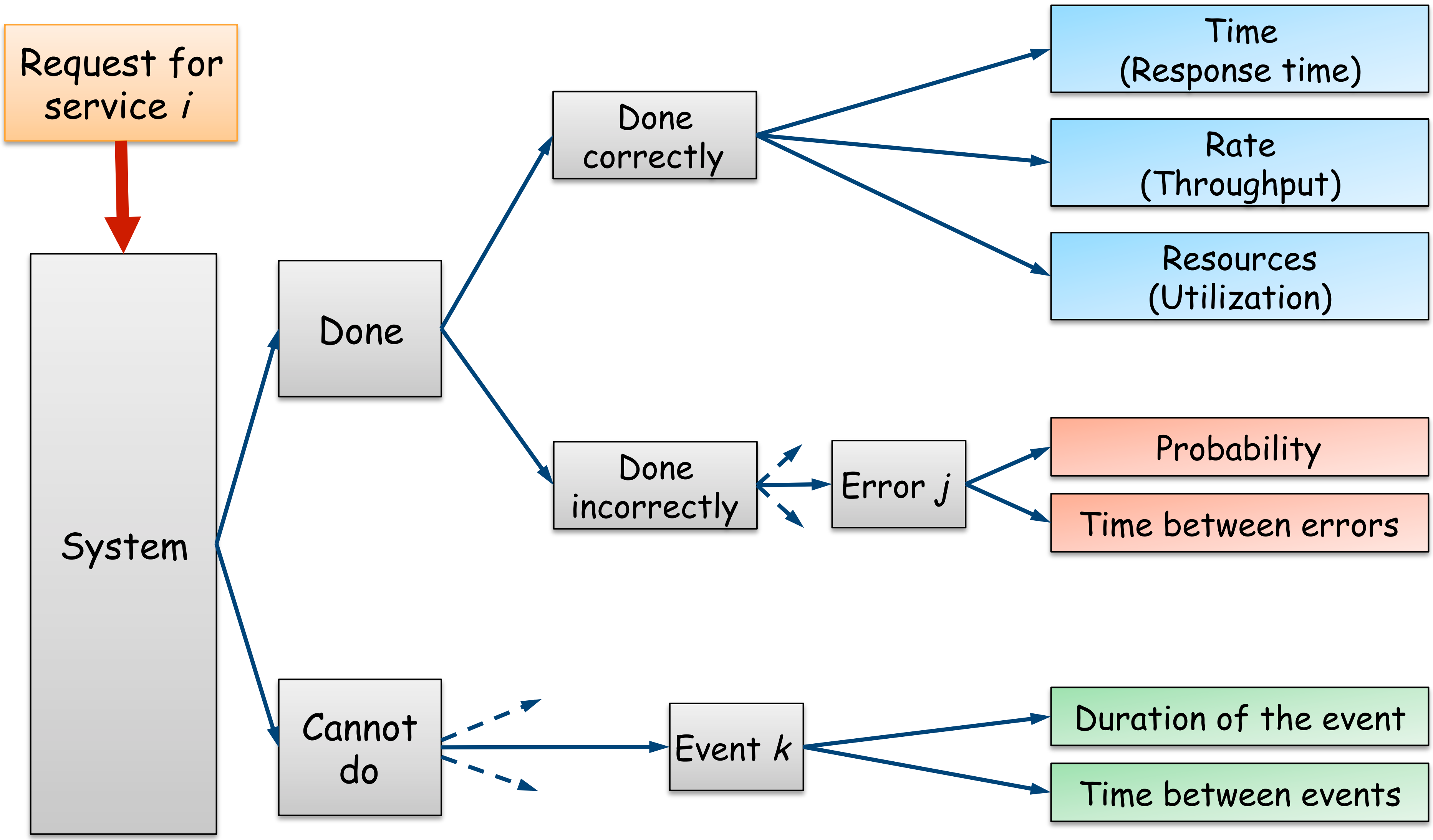


Discrete-Event System Simulation

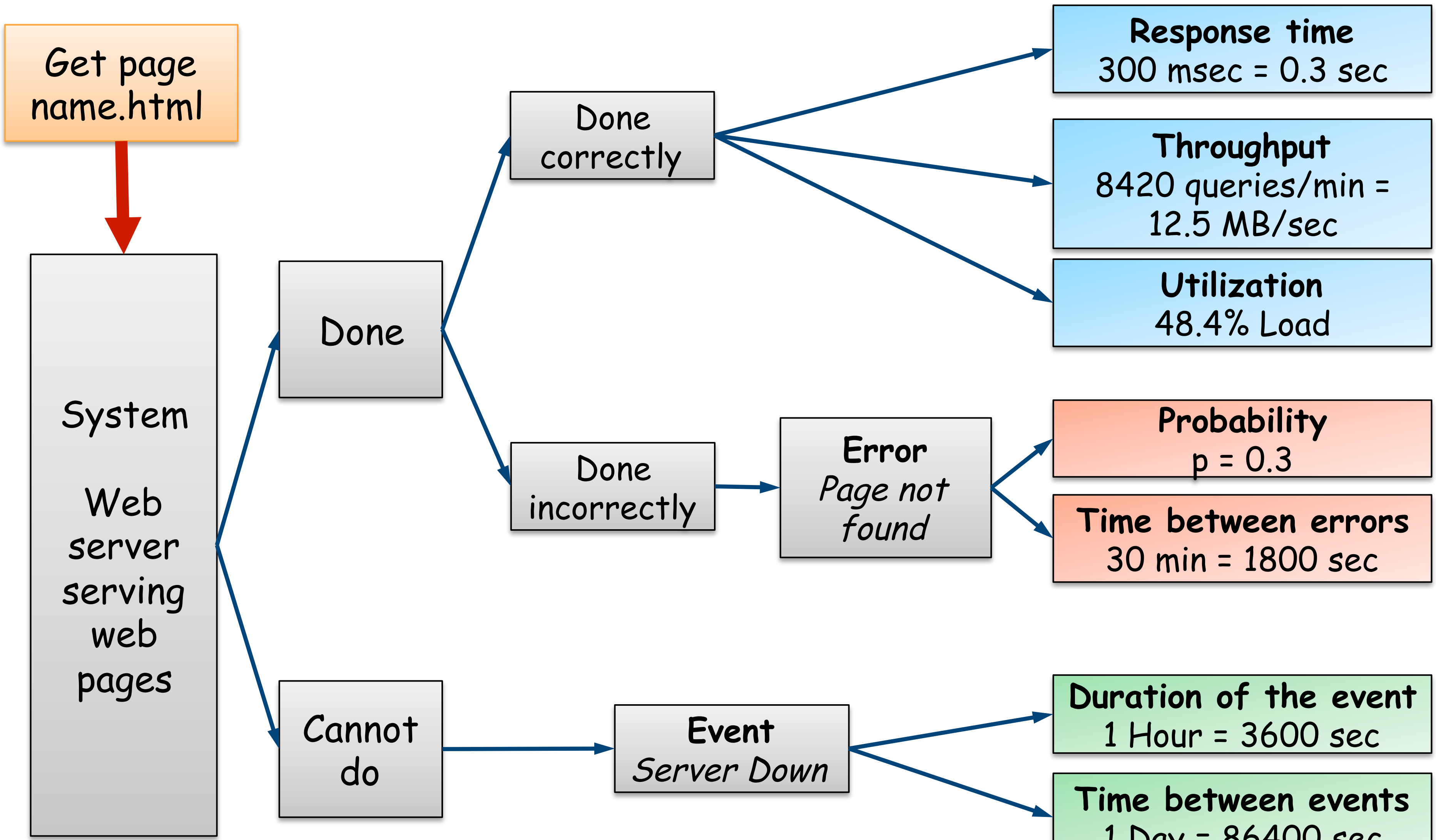
- Discrete-event Simulation
  - System state changes only at discrete set of points in time.
  - Simulation model is analyzed by numerical methods.
  - Numerical methods employ computational procedures to “solve” mathematical models.
  - The model is rather “**run**” than “**solved**”

What is a performance metric?

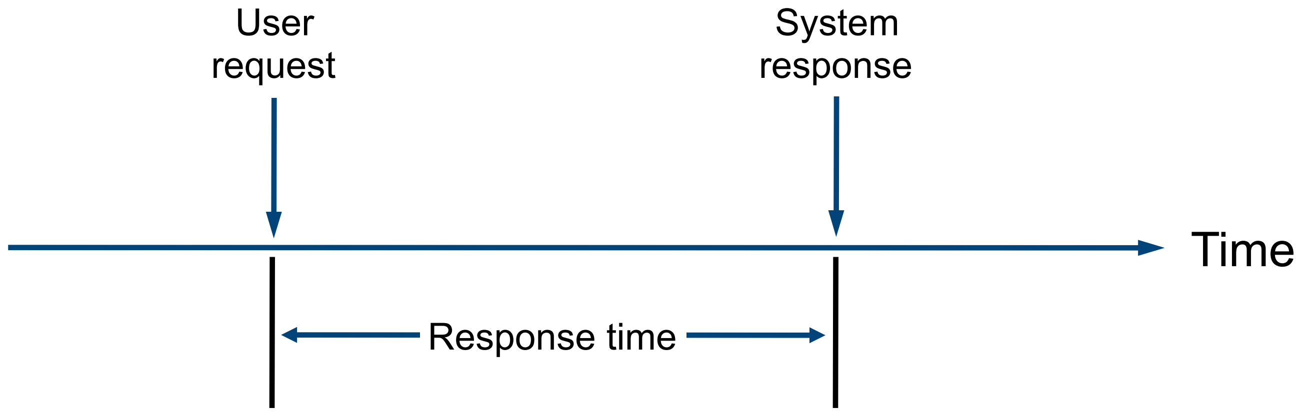
Selecting performance metrics



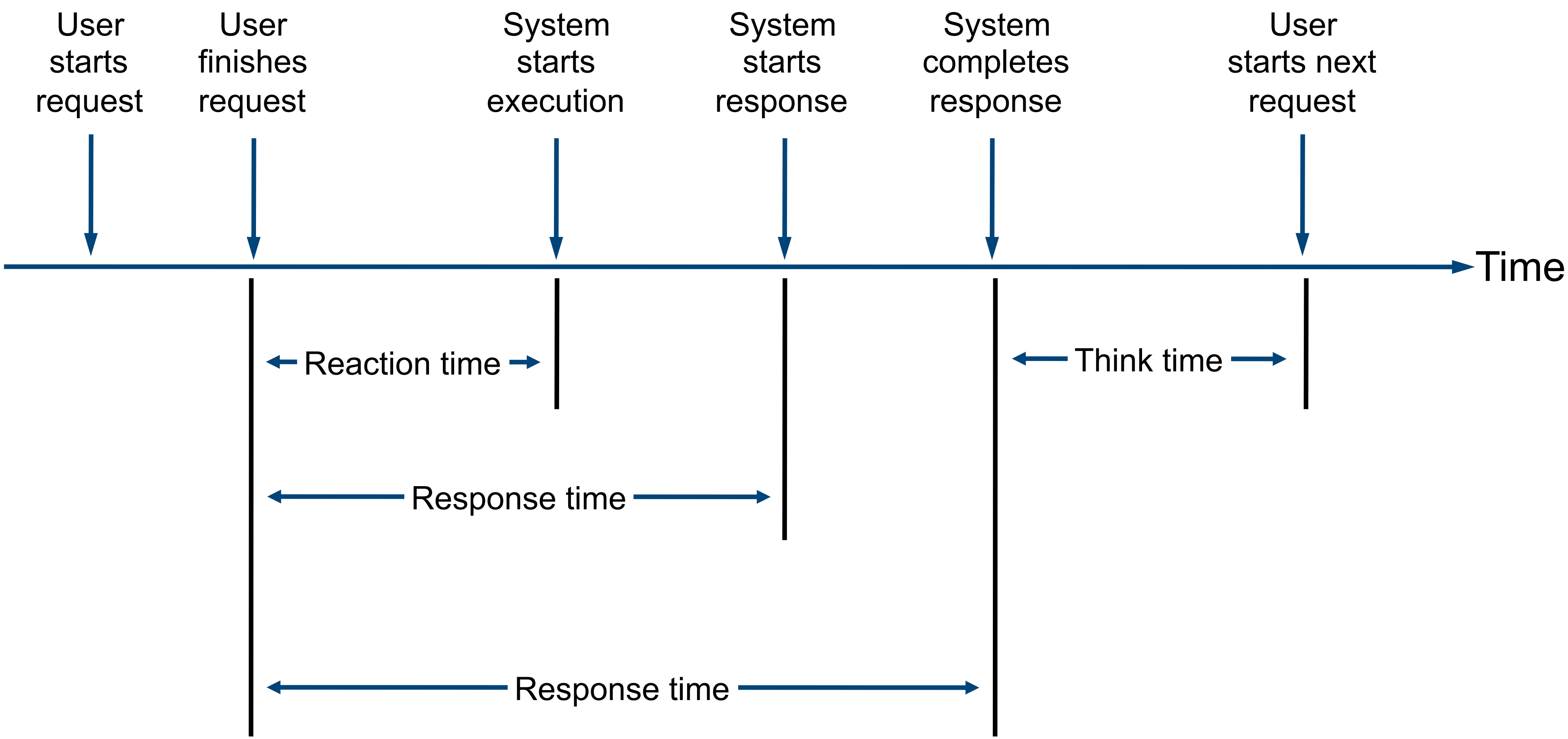
Selecting performance metrics: Example



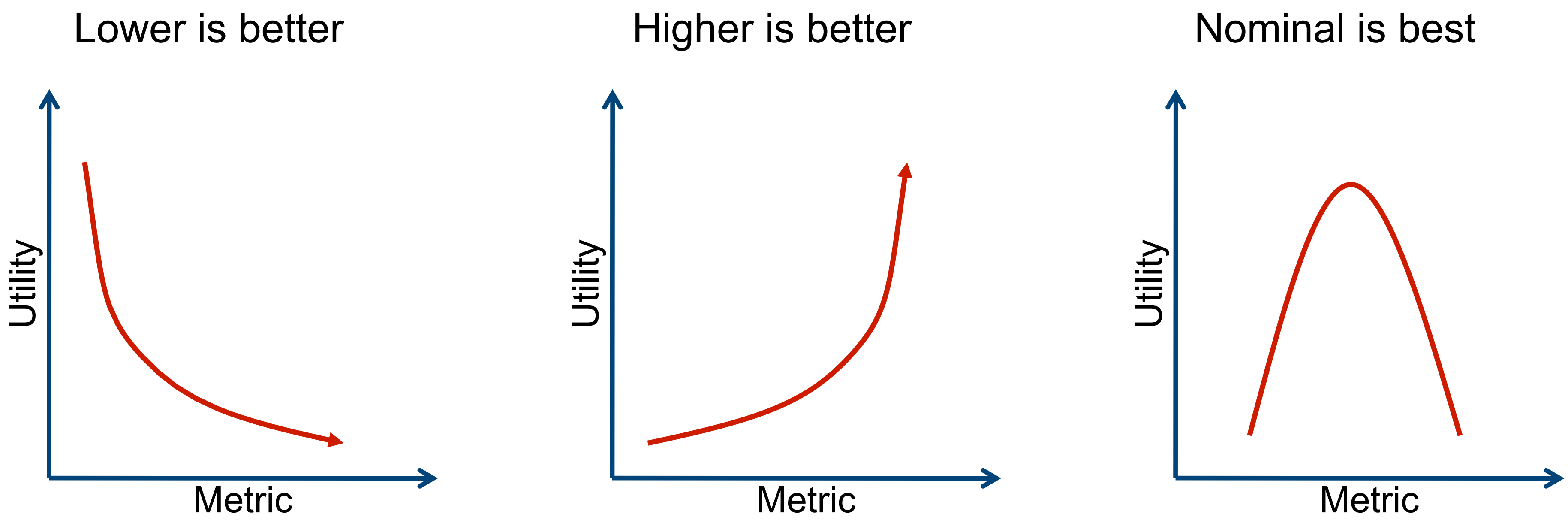
Common performance metrics



Common performance metrics



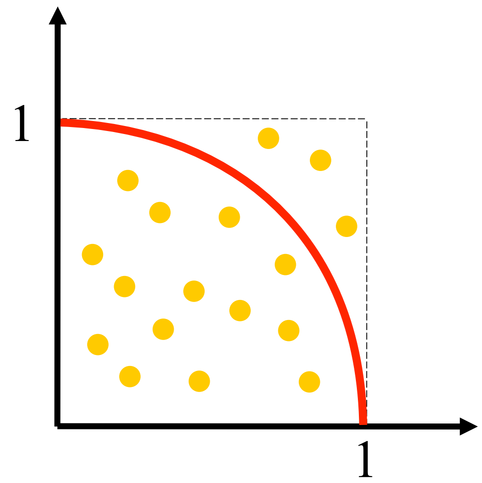
Utility classification of performance metrics



Other simulation paradigms

Simulation for static models

- Monte Carlo simulation
- Mainly used for mathematical problems which are not analytically tractable
- Example: Approximate π
  - Area of a circle: $A = \pi \cdot r^2 \quad \text{if} \quad r = 1 \;\Rightarrow A = \pi$
  - Count the number of points inside and outside a unit quarter circle.



The Monte Carlo simulation was first extensively used in 1944 in the research to develop the first nuclear bomb, the Manhattan project!

Simulation of dynamic, continuous models

- System described by differential equation
- Typically involves numerical solution of these equations
- No real difference to a numerically based mathematical solution
- Typical example: predator/prey systems
  - Let $x(t)$ be the size of the prey population
  - Let $y(t)$ be the size of the predator population
- Growth rate of the prey population without predators
  - $r \cdot x(t)$
- Predator change rate
  - $-s \cdot y(t)$
- Interactions

$$\frac{dx}{dt} = r \cdot x(t) - a \cdot x(t) \cdot y(t)$$

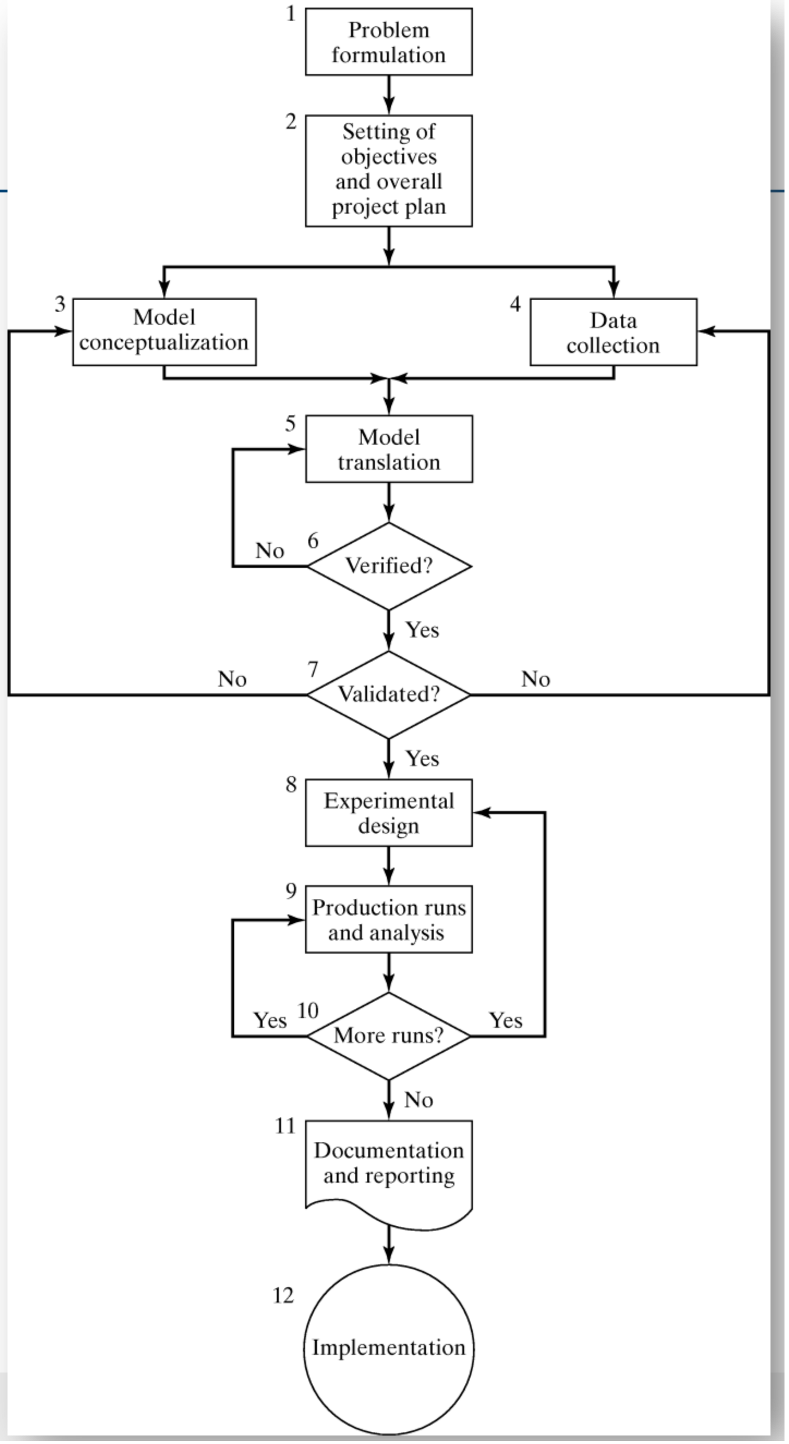
$$\frac{dy}{dt} = -s \cdot y(t) + b \cdot x(t) \cdot y(t)$$

- Parameters
  - $x(0)$, $y(0)$, a, b, r, s
- Metrics
  - $x(t), y(t)$
- Solve system of differential equations

Steps in a simulation study

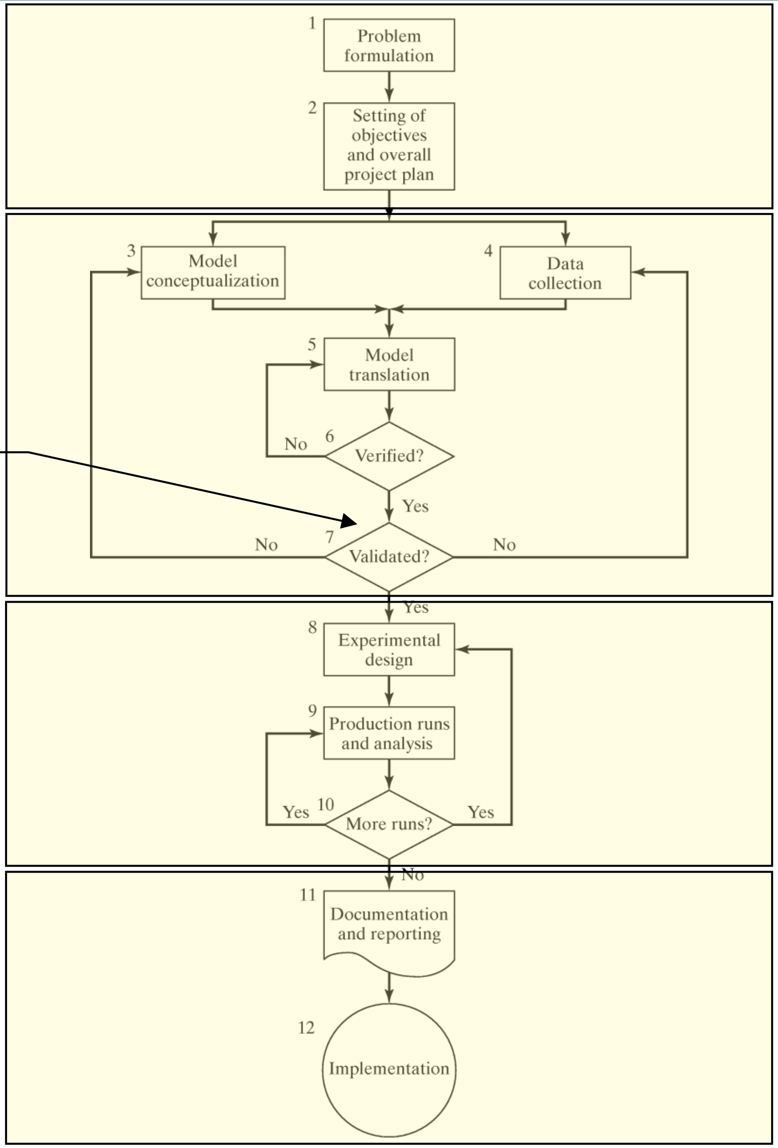
Steps in a Simulation Study

1. Problem formulation
   - Clearly understand problem
   - Reformulation of the problem
2. Setting of objectives and overall project plan
   - Which questions should be answered?
   - Is simulation appropriate?
   - Costs?
3. Model conceptualization
   - No general guide
   - Modeling tools in research, e.g., UML
4. Data collection
   - How to get data?
   - Are random distributions appropriate?
5. Model translation
   - Program, which runs on a Computer.
6. Verified?
   - Does the program that, what the model describes?
7. Validated?
   - Do the results match the reality? Calibration?
   - In cases with no real-world system, hard to validate
8. Experimental design
   - Which alternatives should be run?
   - Which parameters should be varied?
9. Production runs and analysis
10. More runs?
11. Documentation and reporting
    - Program documentation – how does the program work
    - Progress documentation – chronology of the work
12. Implementation



Steps in a Simulation Study

Most crucial step is validation.
If model is invalid results can lead to dangerous and expensive decisions!



Phase 1:
Discovery and Orientation

Phase 2:
Model building and data collection

Phase 3:
Run the model

Phase 4:
Implementation

Summary

- Motivated the course by examples
- Introduced simulation as a notion
- Discussed for what purposes simulation is useful
- Introduction of a general terminology
- Introduction of discrete-event simulation
- Discussed the steps of a simulation study
- Performance metrics