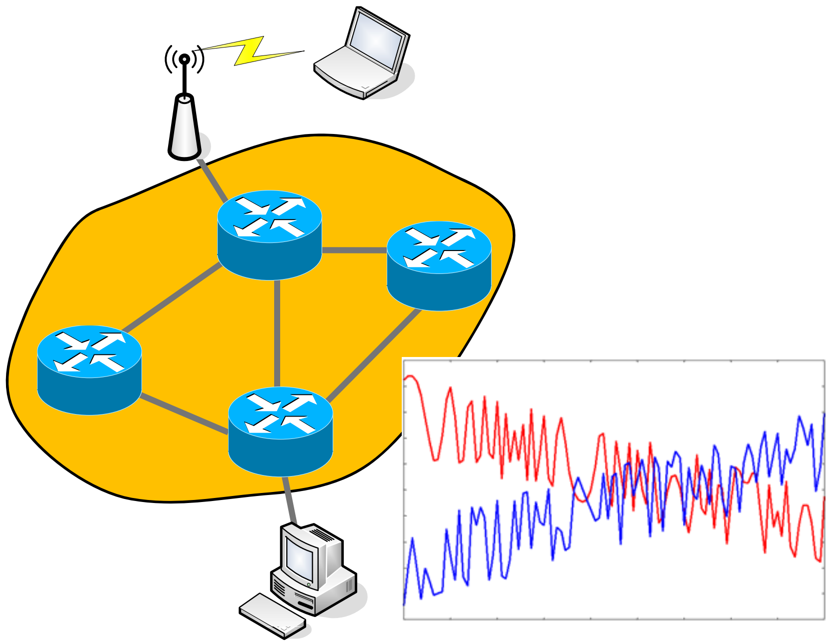
# Chapter 1

## Introduction to Simulation

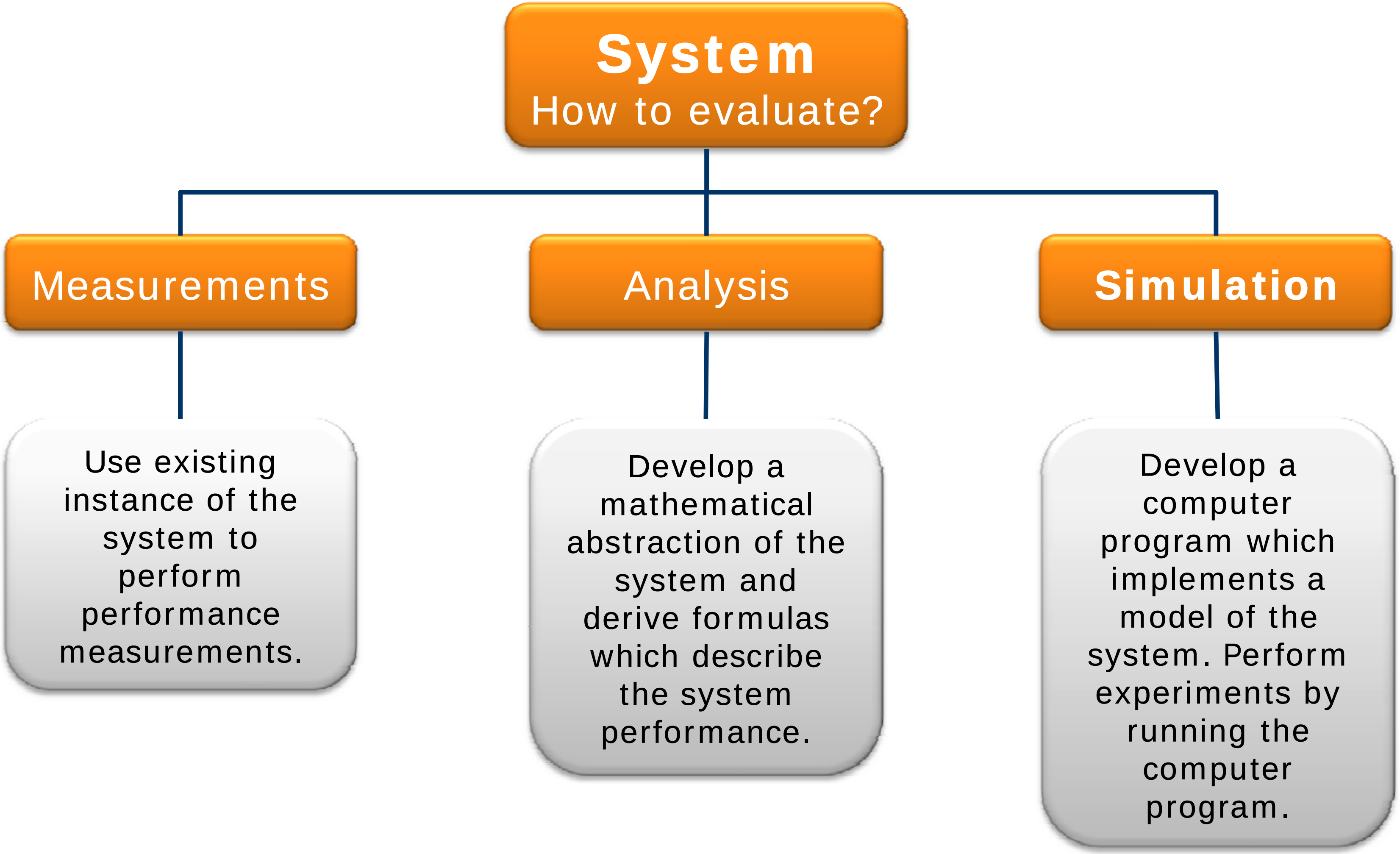


# Contents

# Introduction to Simulation

# Introduction to Simulation

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



# Introduction to Simulation

- How to study a system?
  - Measurements on an existing system
    - What to do, if system does not exist in reality?
    - What to do, if changes are very expensive or time consuming?
    - What to do, if system is not available?
  - Mathematical analysis
    - Good solutions, but only feasible for simple systems.
    - Real world systems are too complex, e.g., factory, computer, network, etc.
  - Simulation
    - Build the behavior of a system within a program

- The content of this course is described better as ...

Modeling and performance analysis of ...
by means of discrete-event simulation

# 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?

# Some examples

# Introduction to Simulation

- 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

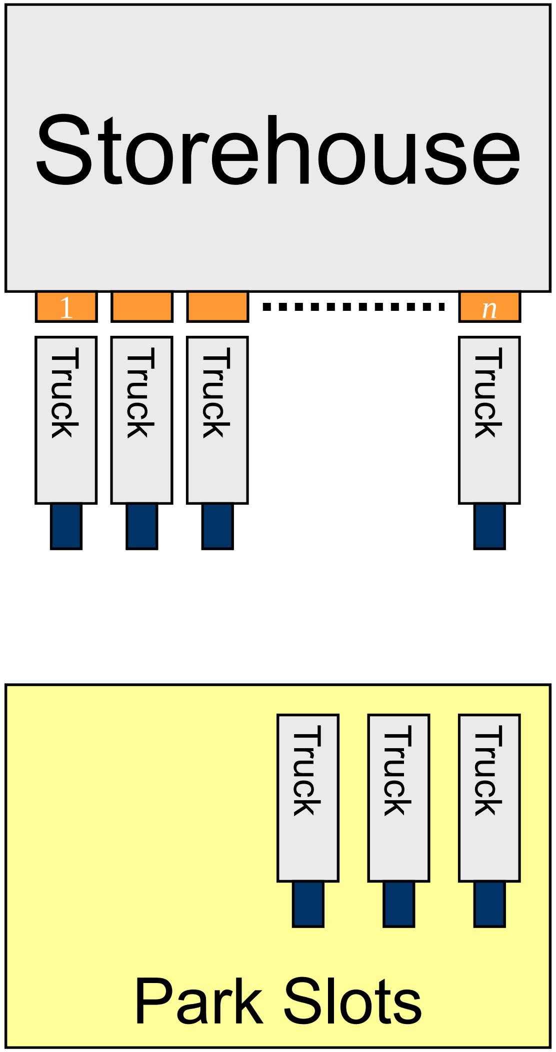
  - Entertainment (this is a new application)
    - Video games
    - Serious games

Wooden mechanical horse simulator during WW1

A soldier in a heavy-wheeled-vehicle driver simulator

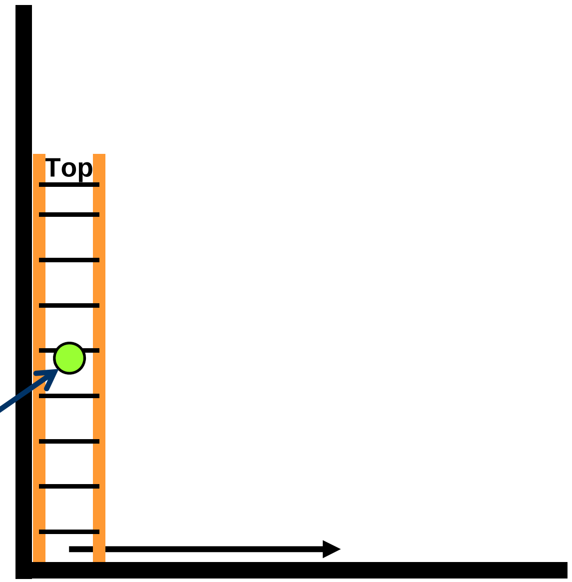
# Introduction to Simulation

- 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

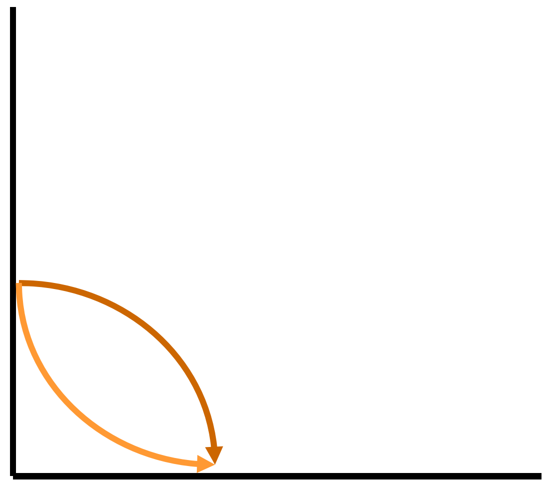



# Introduction to Simulation

- 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.

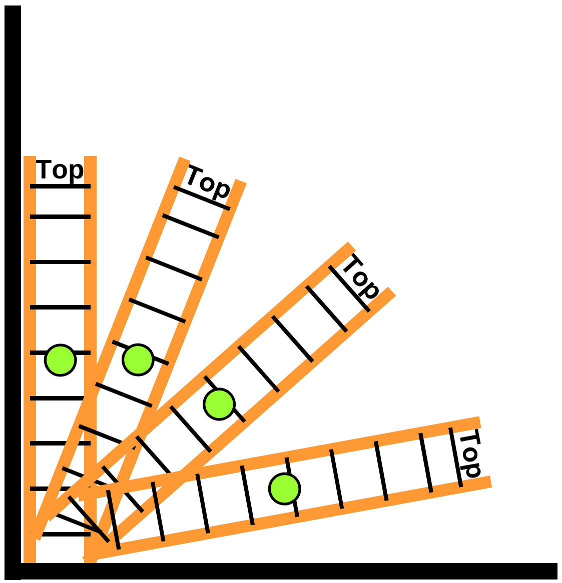



- Question: Which shape draws the center of the ladder?
  - Concave
  - Convex



# Introduction to Simulation

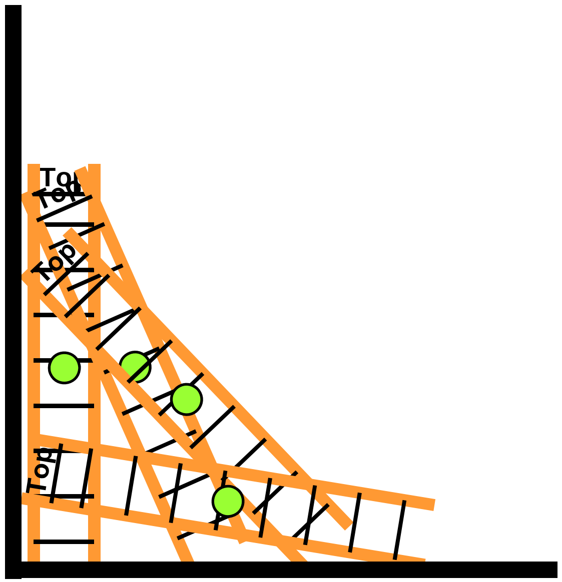
- Variant: The ladder falls down from the wall
- The resulting shape is convex



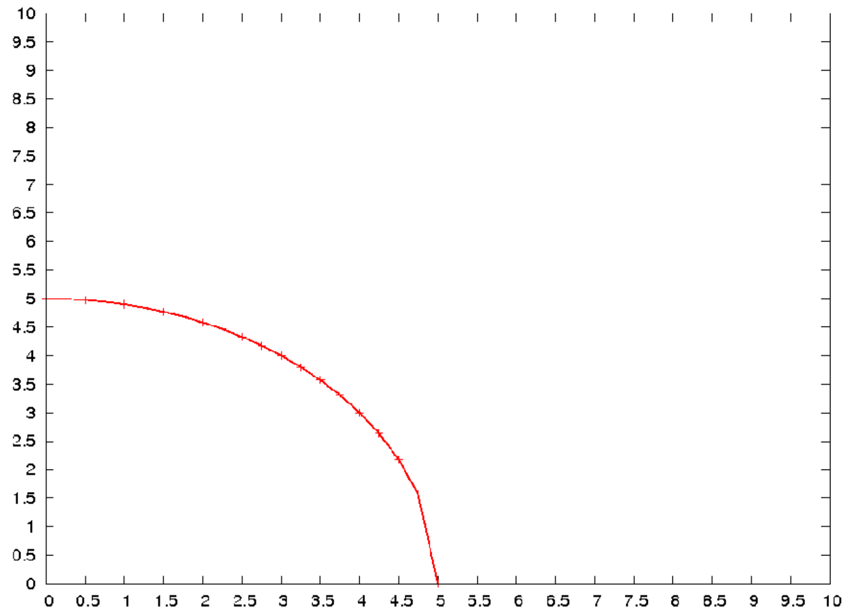

Experiment 1: Ladder falls down from the wall

# Introduction to Simulation

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

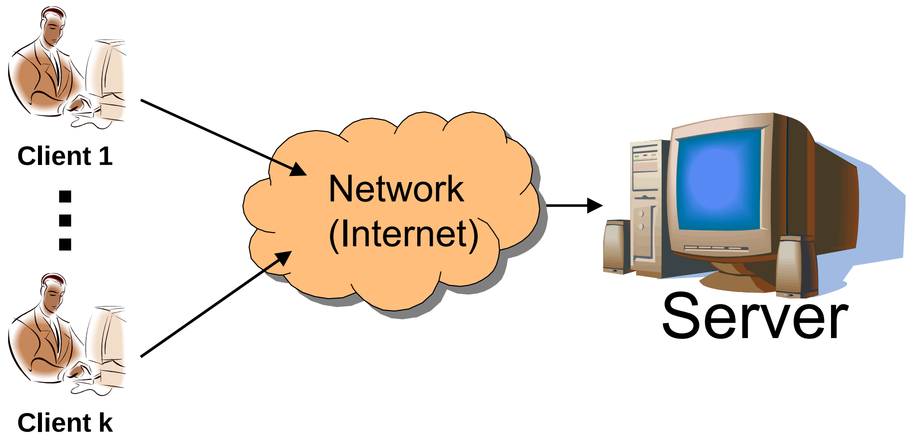


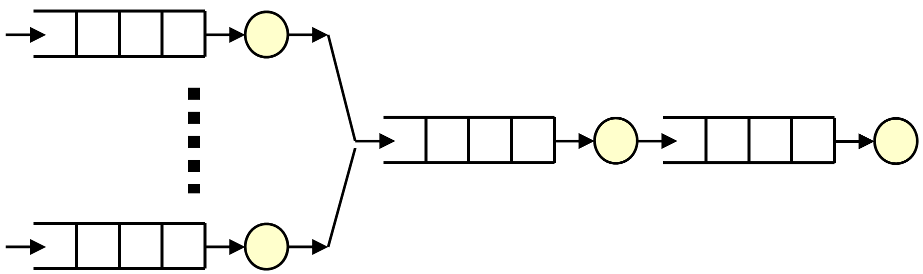

Experiment 2: Ladder slides down on the wall



# Introduction to Simulation

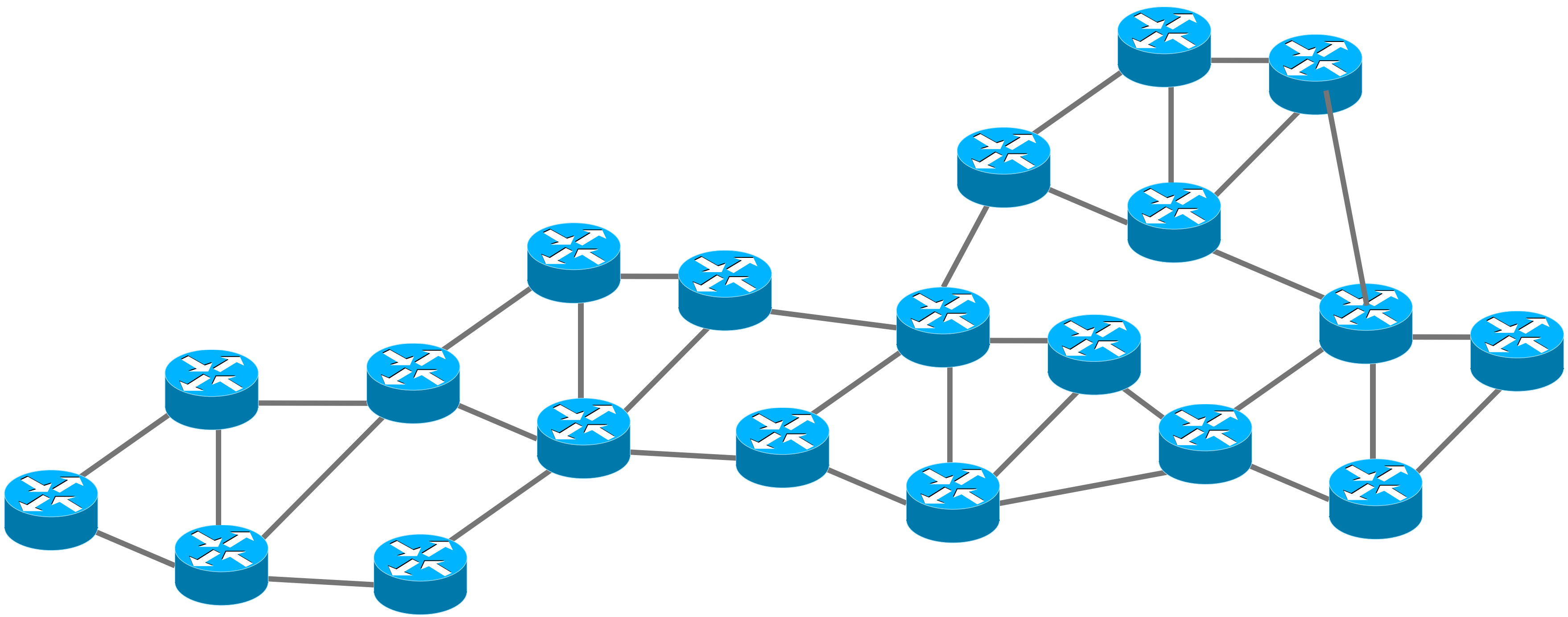
- Clients request some service from a server over a network.
  - Client = user and web browser
  - Service = web page
  - Server = web server
  - Network = local network, Internet, wireless network
- Analysis
  - Performance of the server
  - Performance of the network
- Attention
  - In this example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



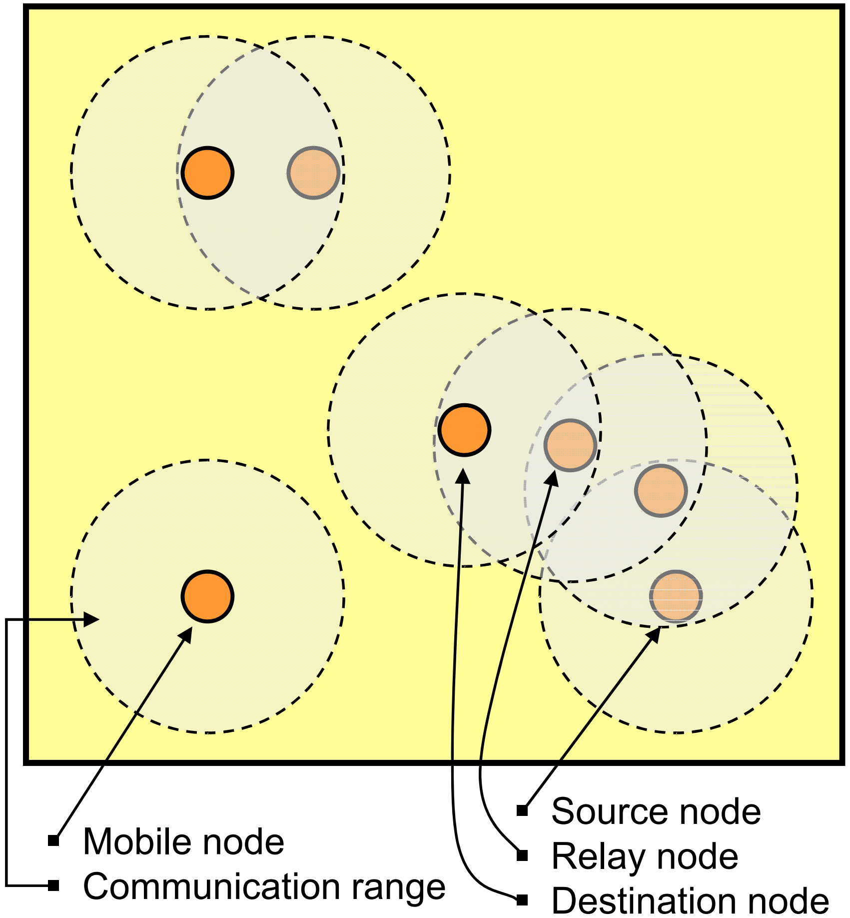
# Introduction to Simulation

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



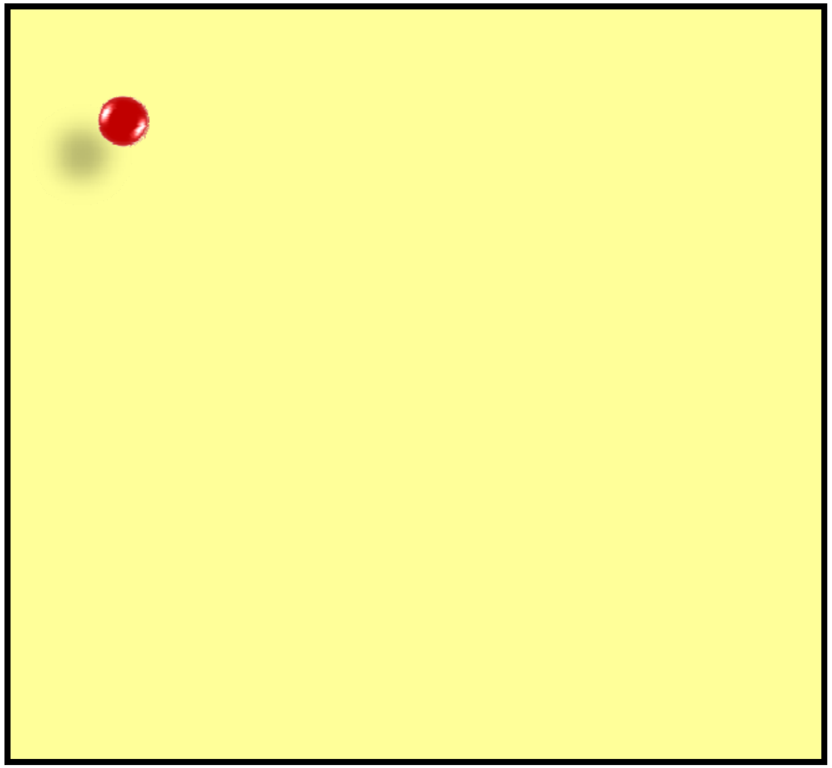
# Introduction to Simulation

- 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



# Introduction to Simulation

- 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 $t_{\text{pause}}$
  - The node moves to the point $p$ with velocity $v$
  - Stays for $t_{\text{pause}}$ time units on $p$ and restarts movement

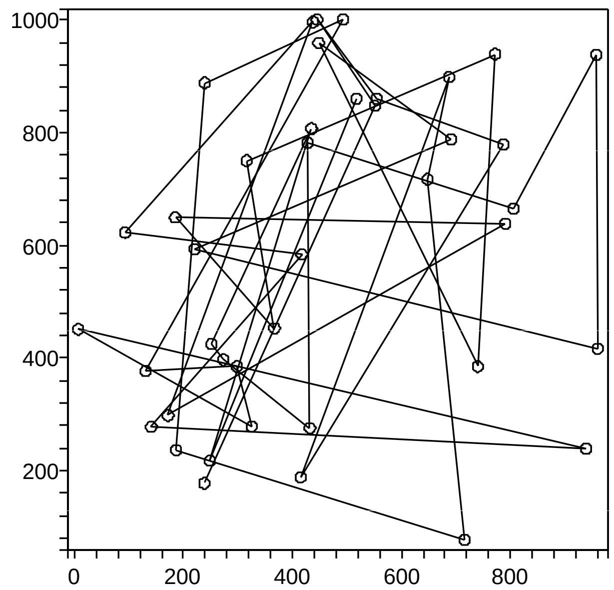


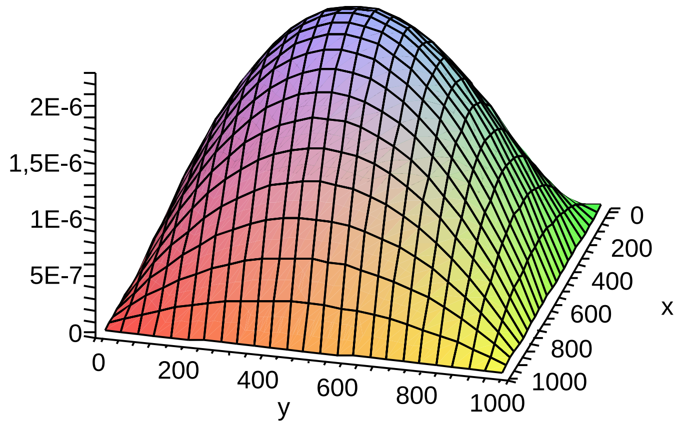
# Introduction to Simulation

- 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.

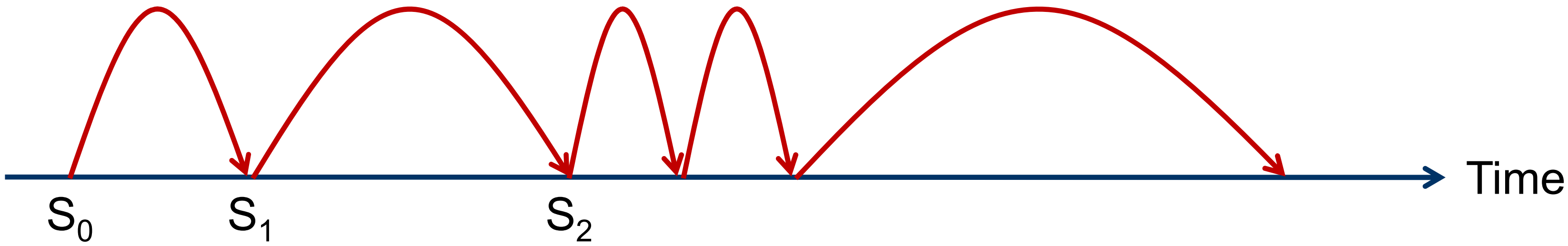


# What is a simulation and how it is done?

# 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 a 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 can be used for the following purposes:
  - 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?

- Simulation should not be used, in the case
  - 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 excessive delays
- 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**

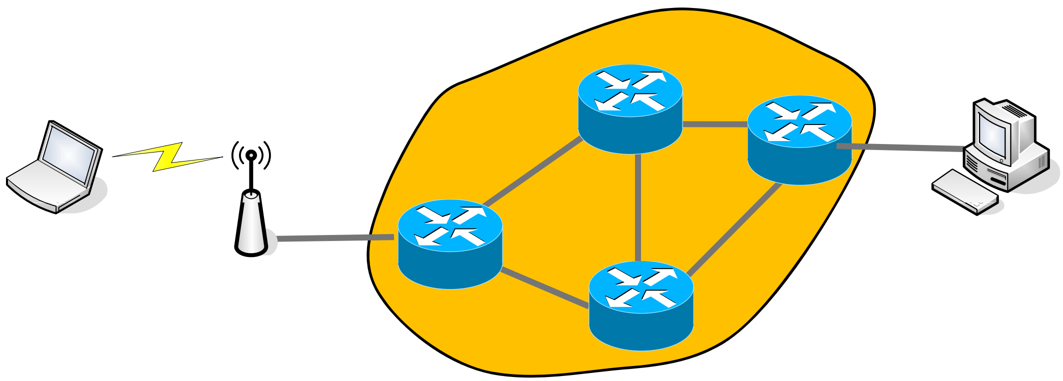
# Application areas of simulation

- 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?

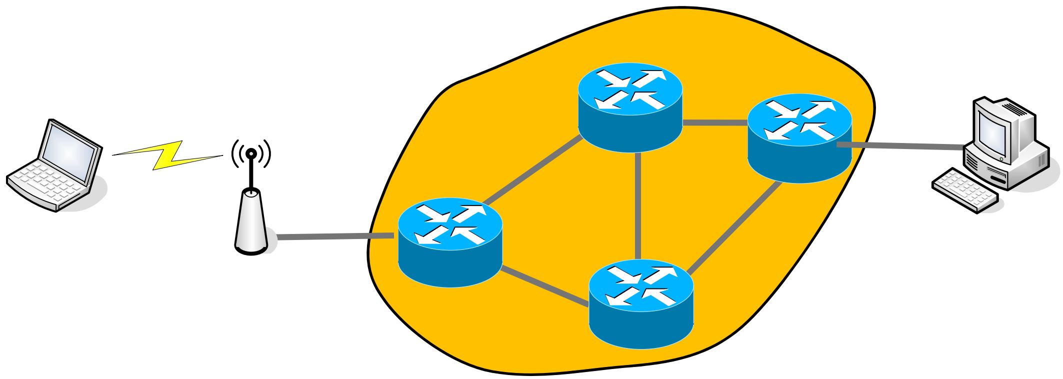
# Systems and System Environment

- 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
  - Example: Computer network
    - User, hosts, routers, lines establish a network



# Systems 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

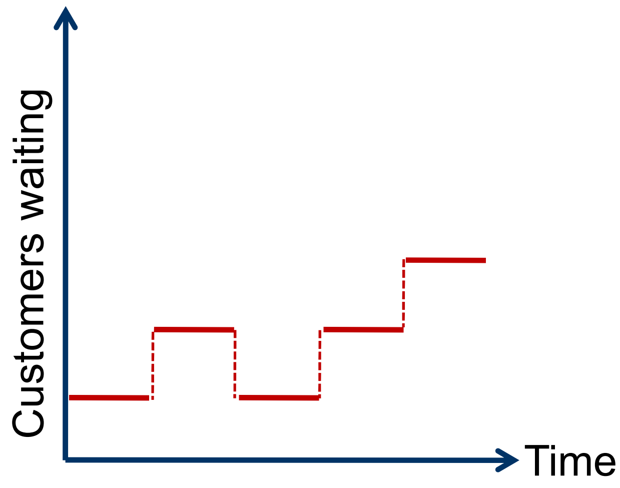
- In order to understand and analyze a system, we need some terms
- General Terminology
  - **Entity** Object of interest in the system
  - **Attribute** Property of an entity
  - **Activity** A time period of specified length
  - **System state** Collection of variables required to describe the system 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

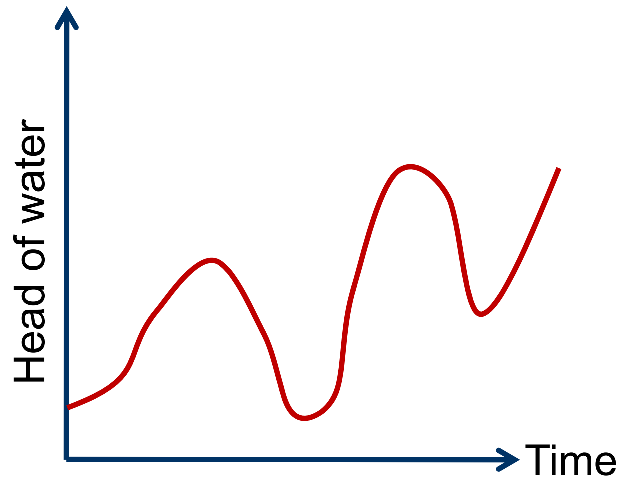
# Components of a System: Examples

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

# Discrete and Continuous Systems

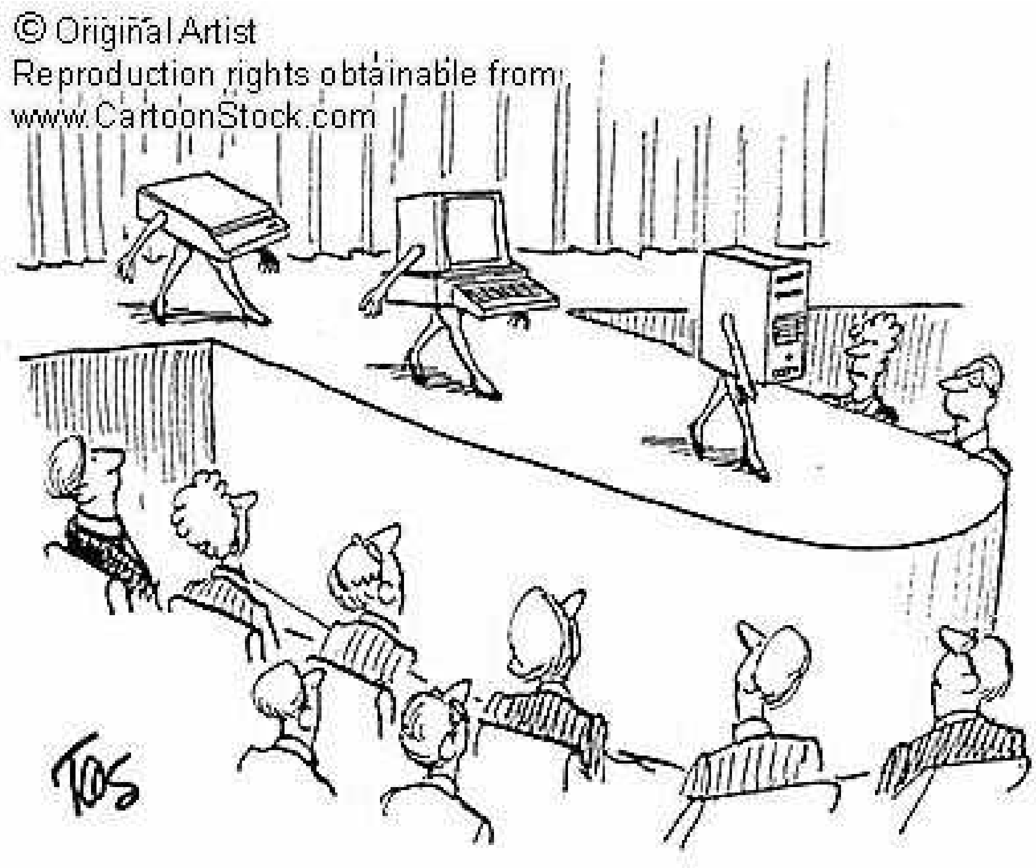
- Discrete Systems
  - State variables change only at discrete set of points
  - Examples
    - Bank, Grocery
    - Router, Host
    - Jobs in queue
- Continuous Systems
  - State variables change continuously over time
  - Examples
    - Head of water behind a dam
    - Temperature



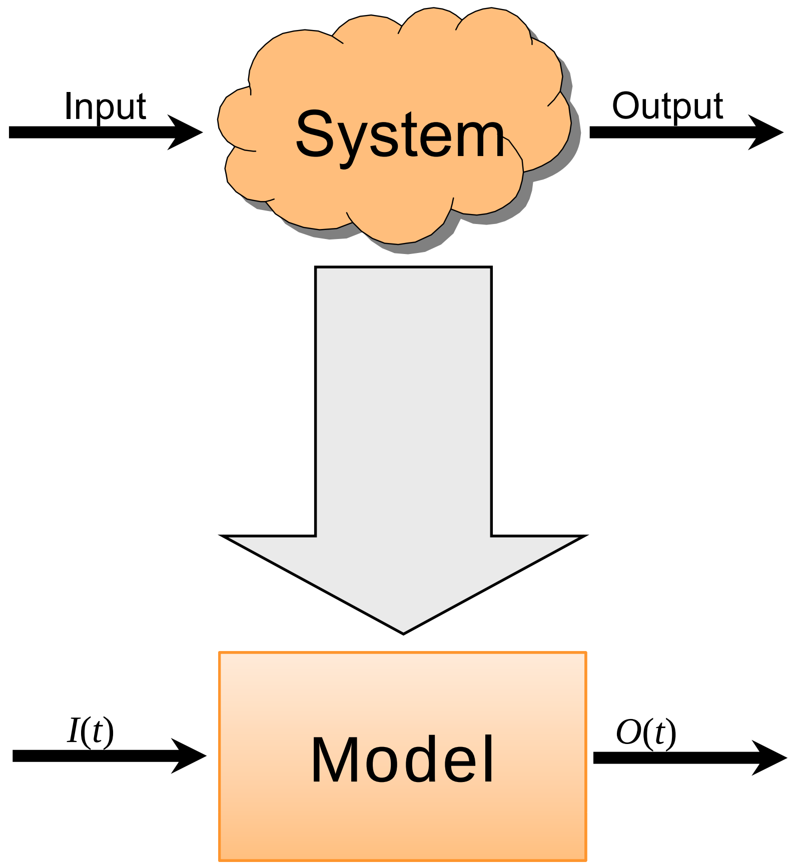
# What is a model?

# Model of a System



# Model of a System

- What is a model?
  - A model is a representation of a system for the purpose of studying the system.
  - It is necessary to consider those aspects of the system that affect the problem under investigation
- Avoid too much detail



# 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.

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

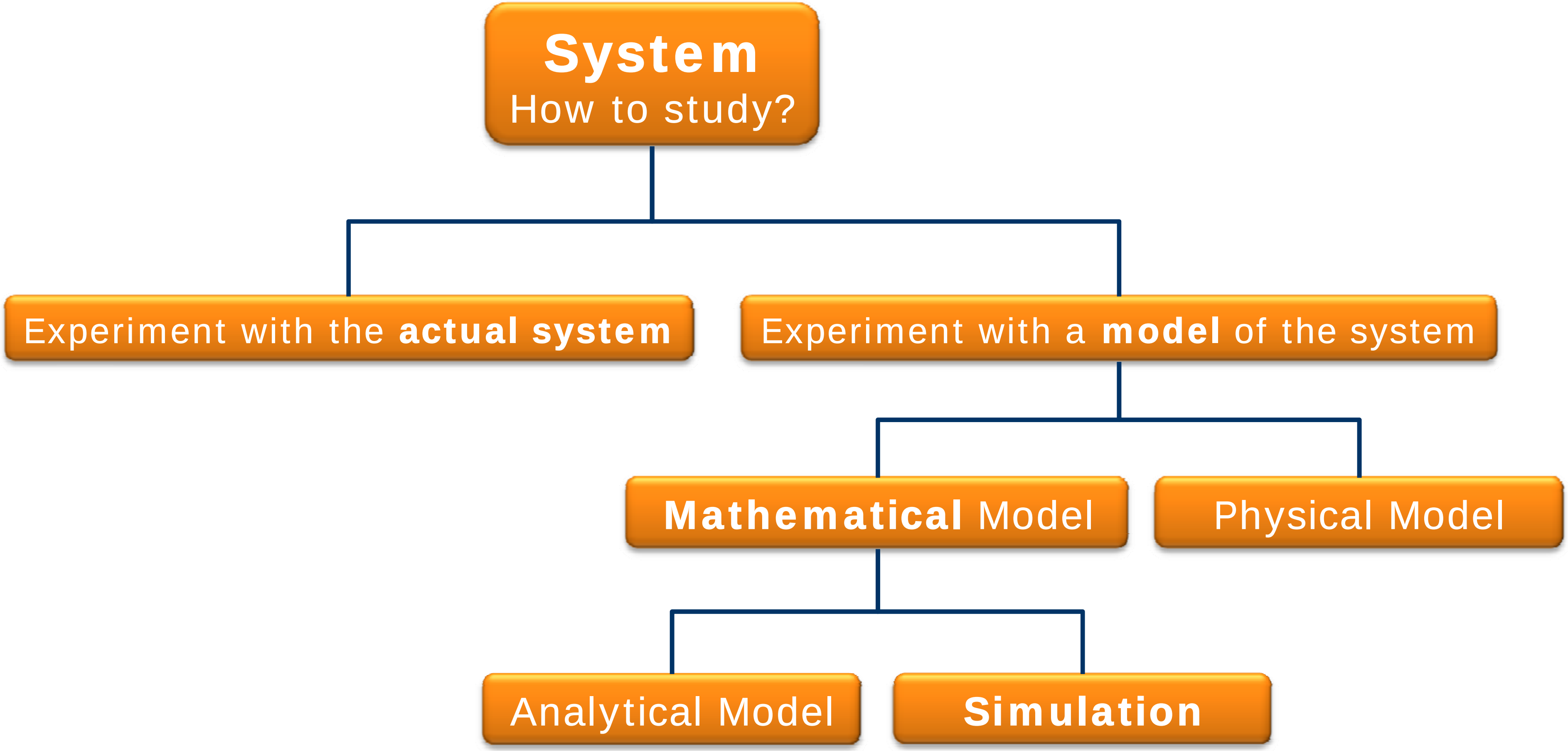
$$
\begin{aligned}
v_q &= -r_s i_q + \frac{\omega_r}{\omega_b}\Psi_d + \frac{p}{\omega_b}\Psi_q, \\
v_d &= -r_s i_d - \frac{\omega_r}{\omega_b}\Psi_q + \frac{p}{\omega_b}\Psi_d, \\
v_o &= -r_s i_o + \frac{p}{\omega_b}\Psi_o, & p\theta_r &= \omega_r, \\
0 &= r_{aq} i_{aq} + \frac{p}{\omega_b}\Psi_{aq},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

# 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.*

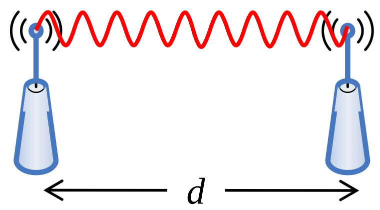
*George E.P. Box*

# Model of a System: Mobility

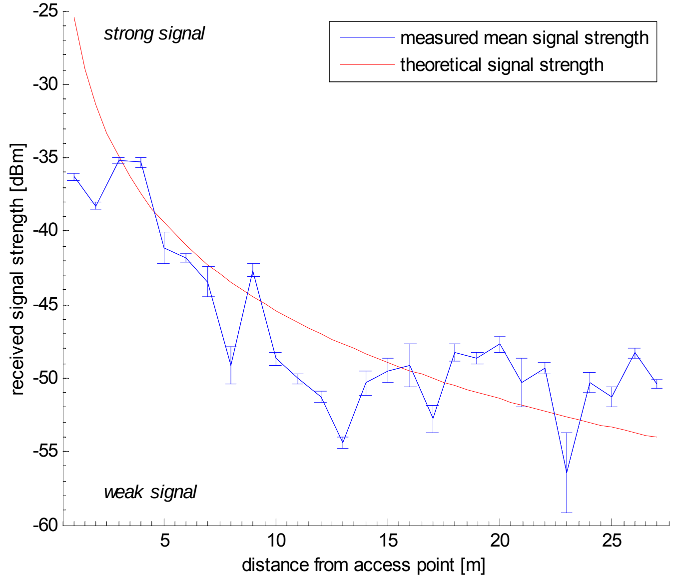
- Movement
  - Model: $d = v \cdot t$
  - Assumptions: Constant velocity $v$ over the whole time $t$
  - Advantage: Simple formulae and intuitive
  - Disadvantage: Seldom valid for a whole travel (human, car, planes)

# Model of a System: Radio Propagation

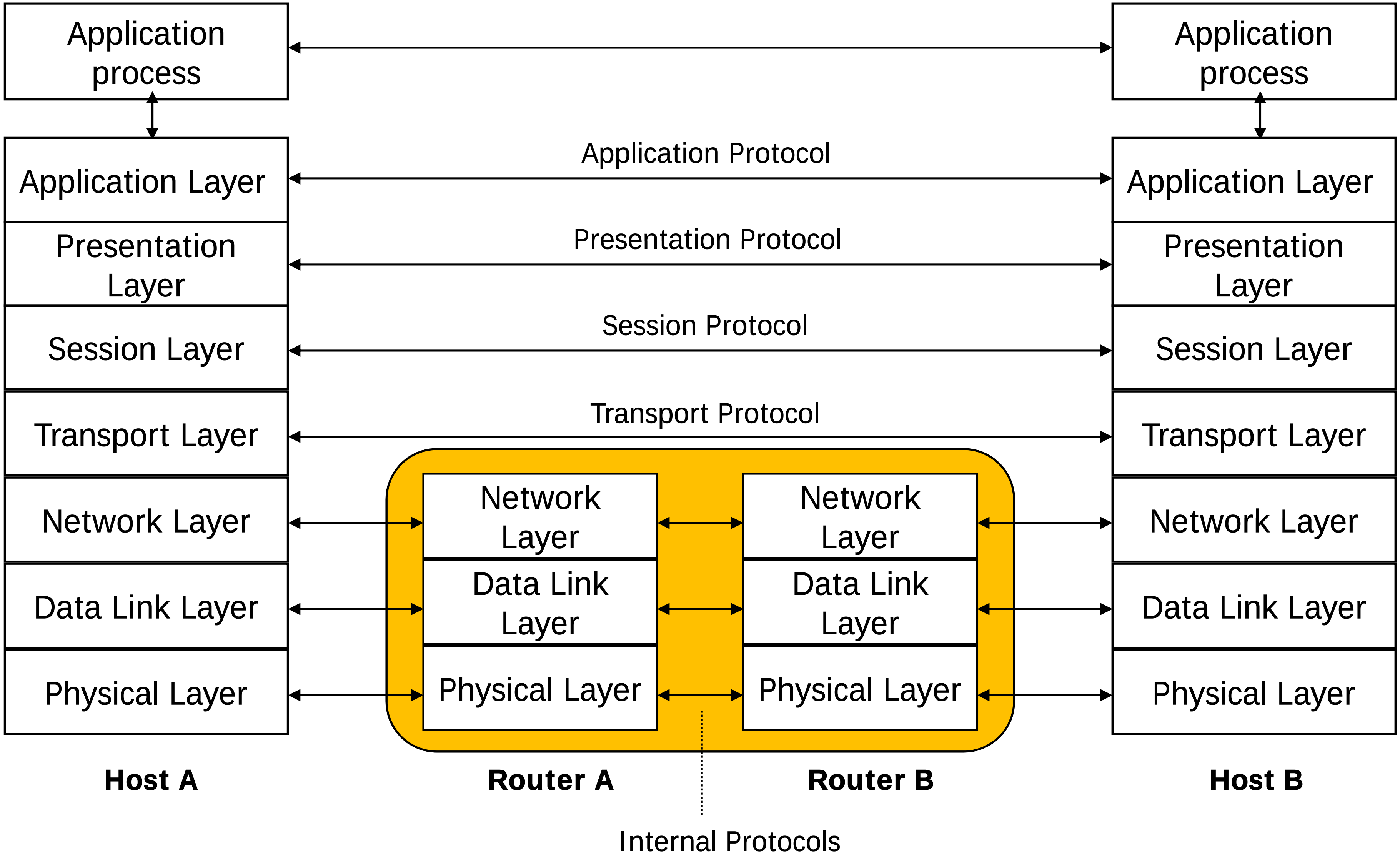
- Radio signal propagation
  - Free-Space-Model




  - 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 |
|---|
| Application Layer |
| Presentation Layer |
| Session Layer |
| Transport Layer |
| Network Layer |
| Data Link Layer |
| Physical Layer |

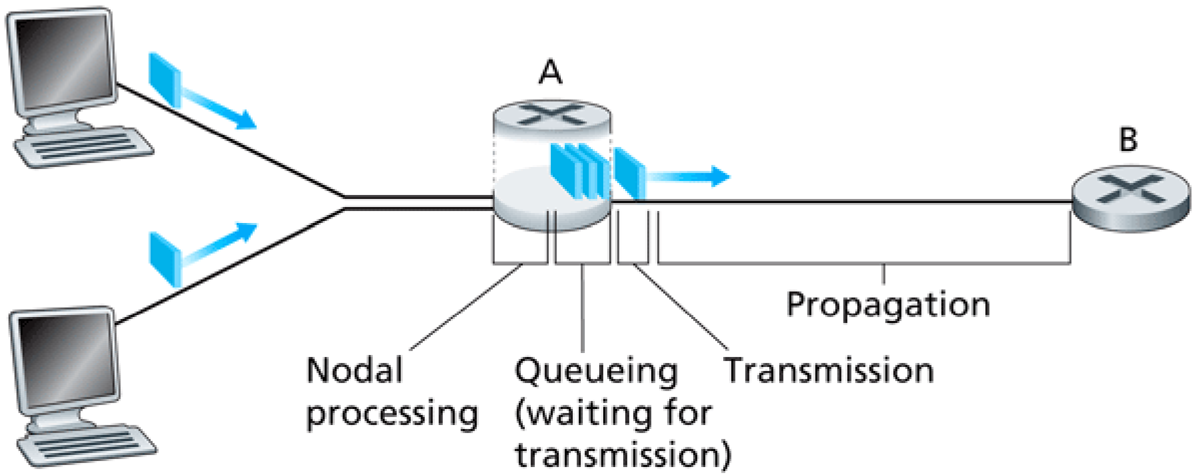
| TCP/IP |
|---|
| Application Layer |
| Don‘t exist |
| Transport Layer |
| Internet Layer |
| Host-to-Network Layer |

# Model of a System: Six-level Computer Model

| Level | |
|---|---|
| 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 |

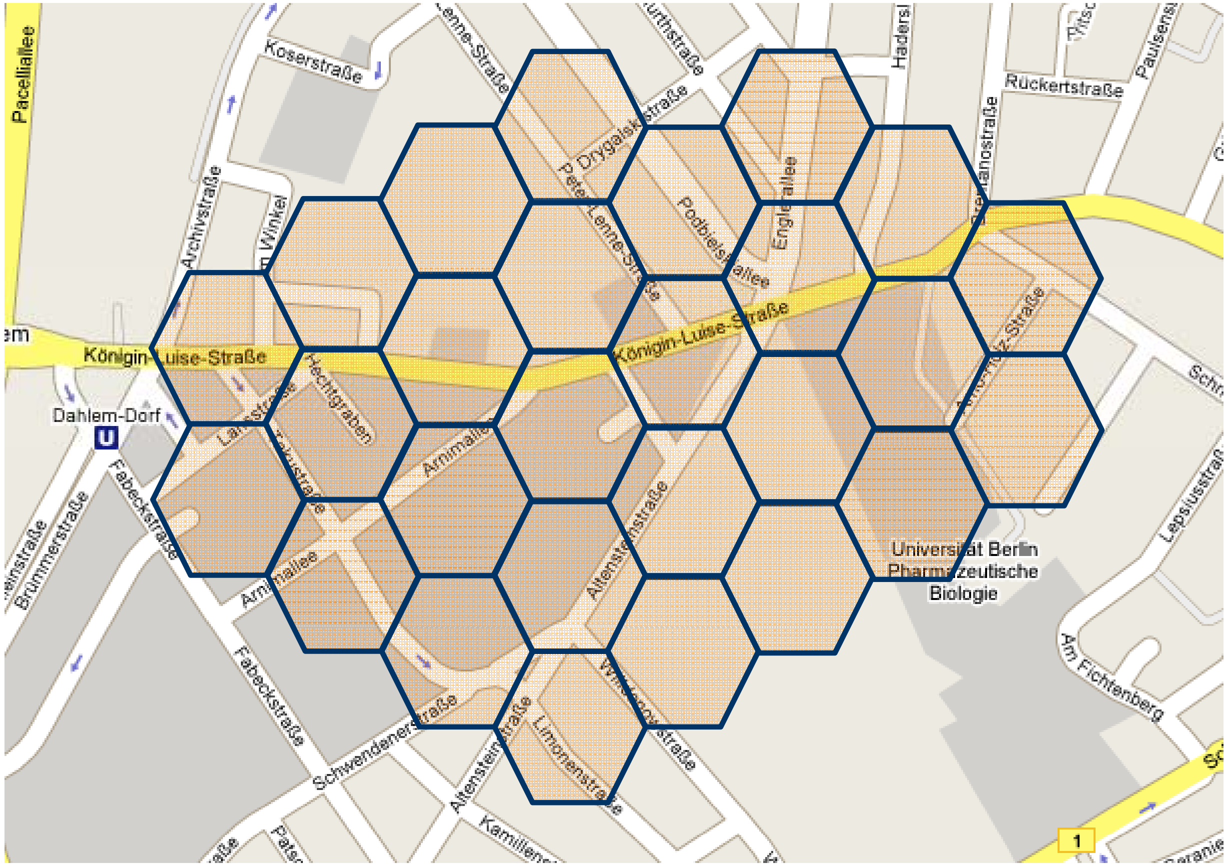
# Model of a System: Communication Link

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



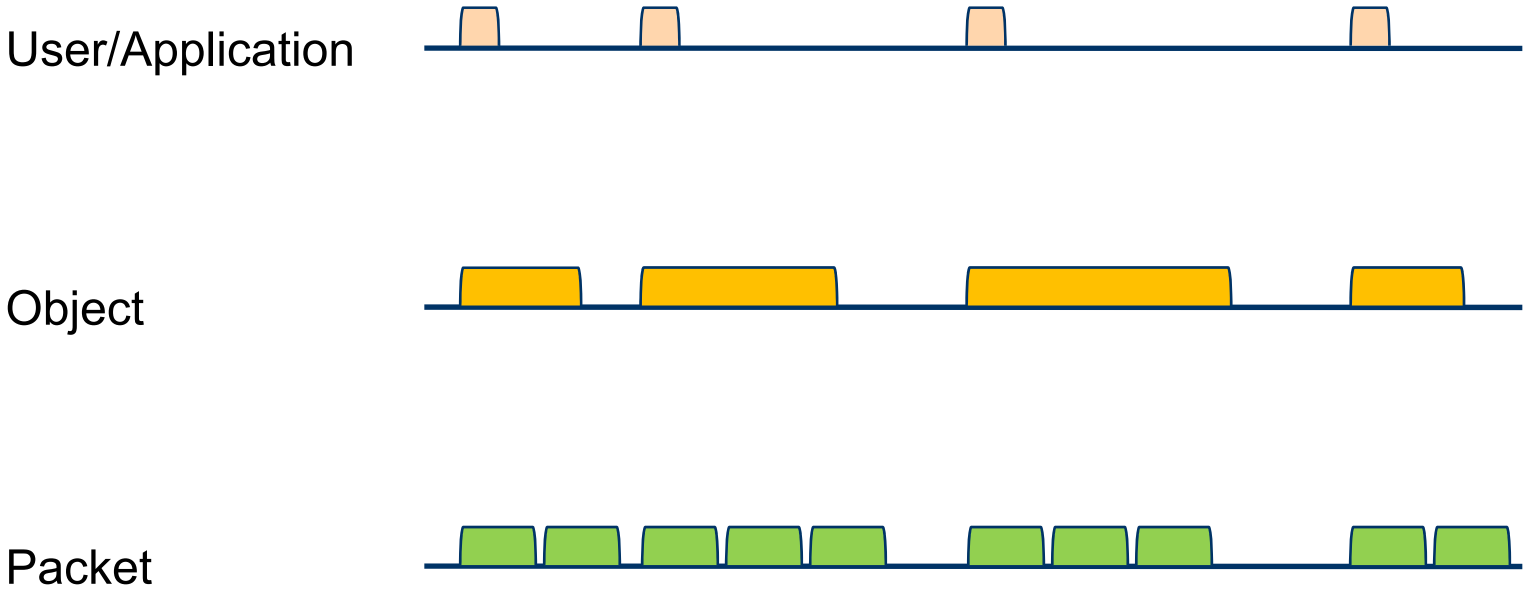
# Model of a System: Cellular System

- 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
- Documentation
- Efficiency
- Verified
- Code quality
- Availability

# 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 change**s occur only at **discrete time** points.
  - Continuous: System **state change**s occur **continuously**.

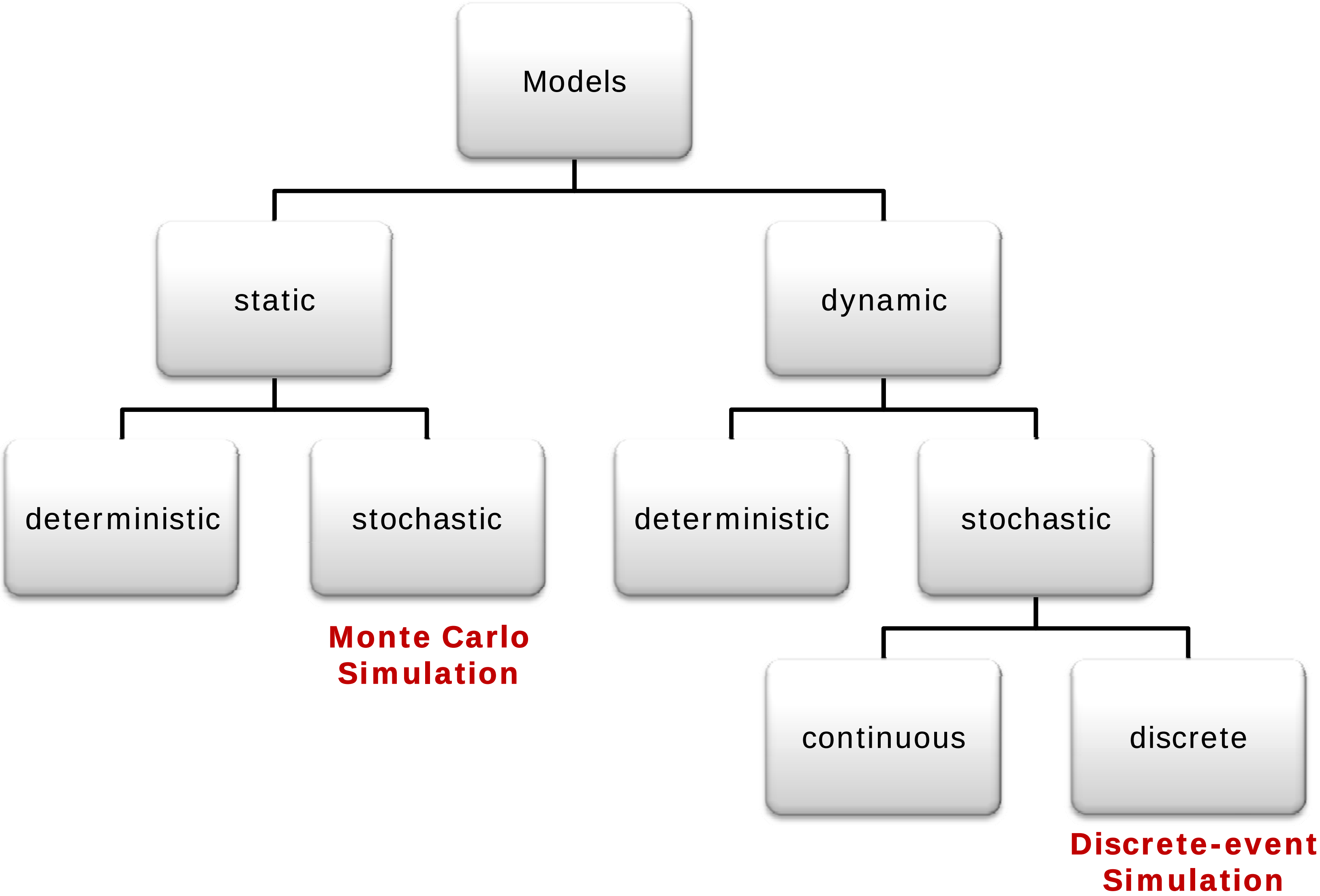
# Simulation Models

*In this class, we will focus on*

***discrete, dynamic, stochastic***

*simulation models*

# Simulation Models

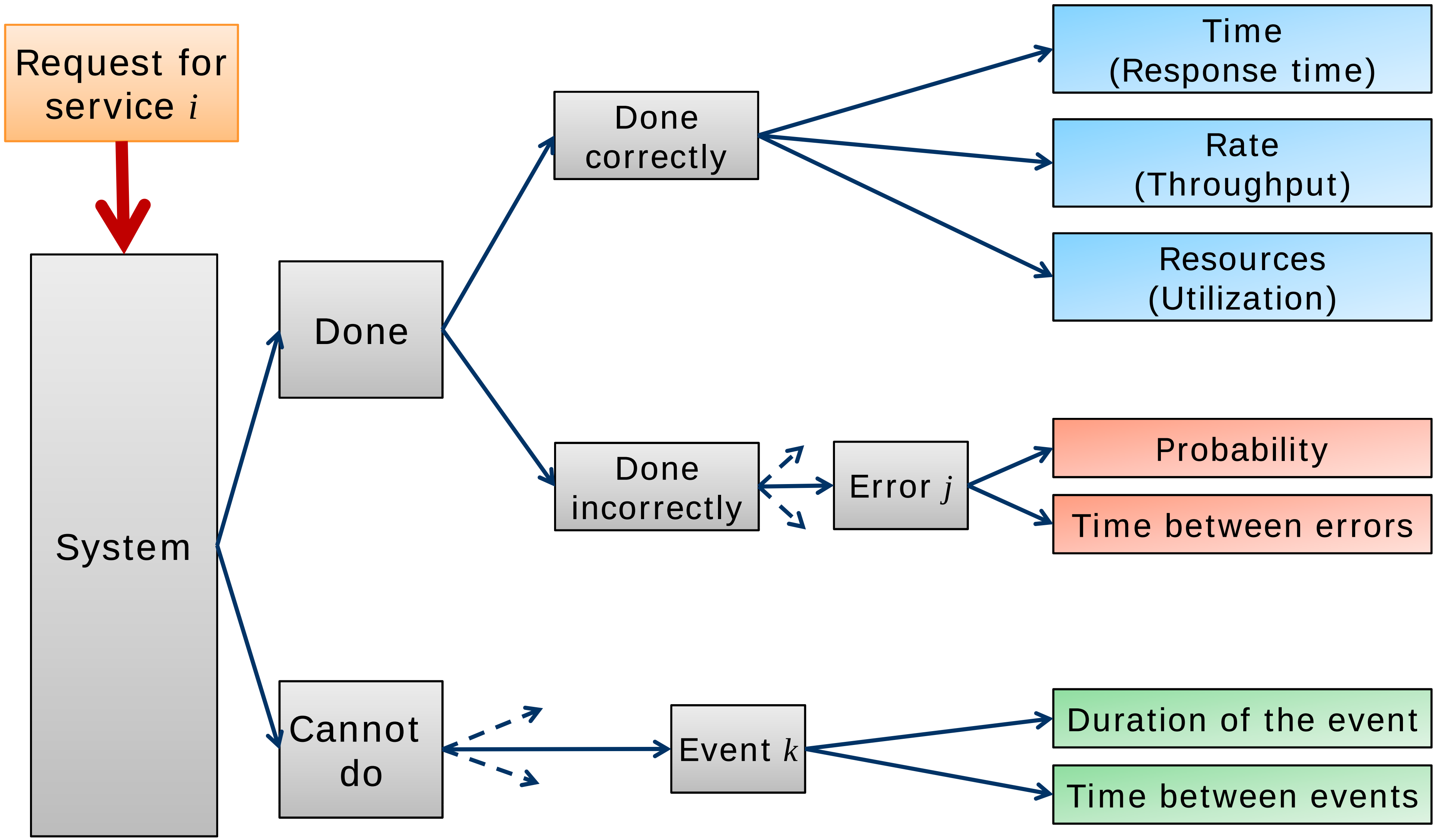


# Discrete-Event System Simulation

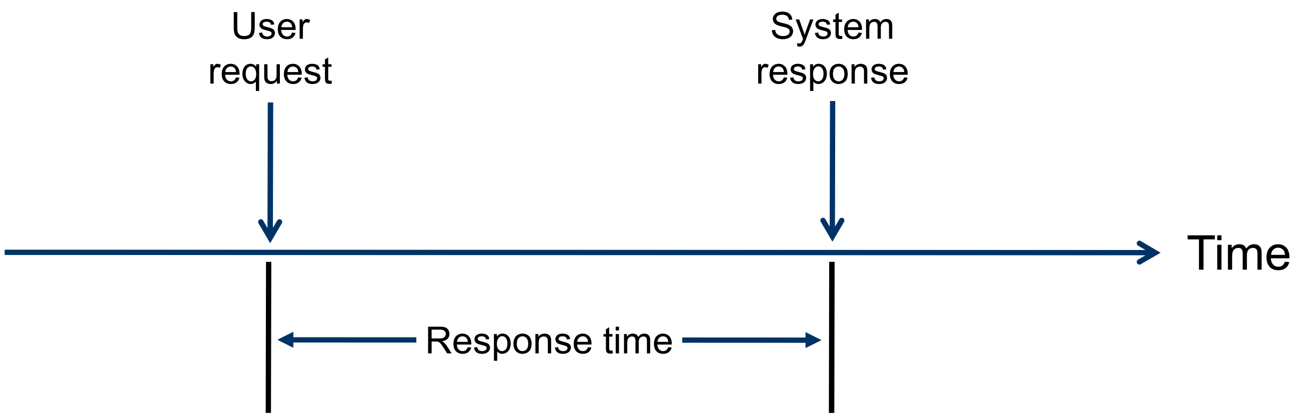
- Discrete-event Simulation
  - System state changes only at discrete set of points in time.
  - Simulation model is analyzed by numerical methods.
  - Numerical methods employ computational procedures to “solve” mathematical models.
  - The model is rather “**run**” than “**solved**”

## What is a performance metric?

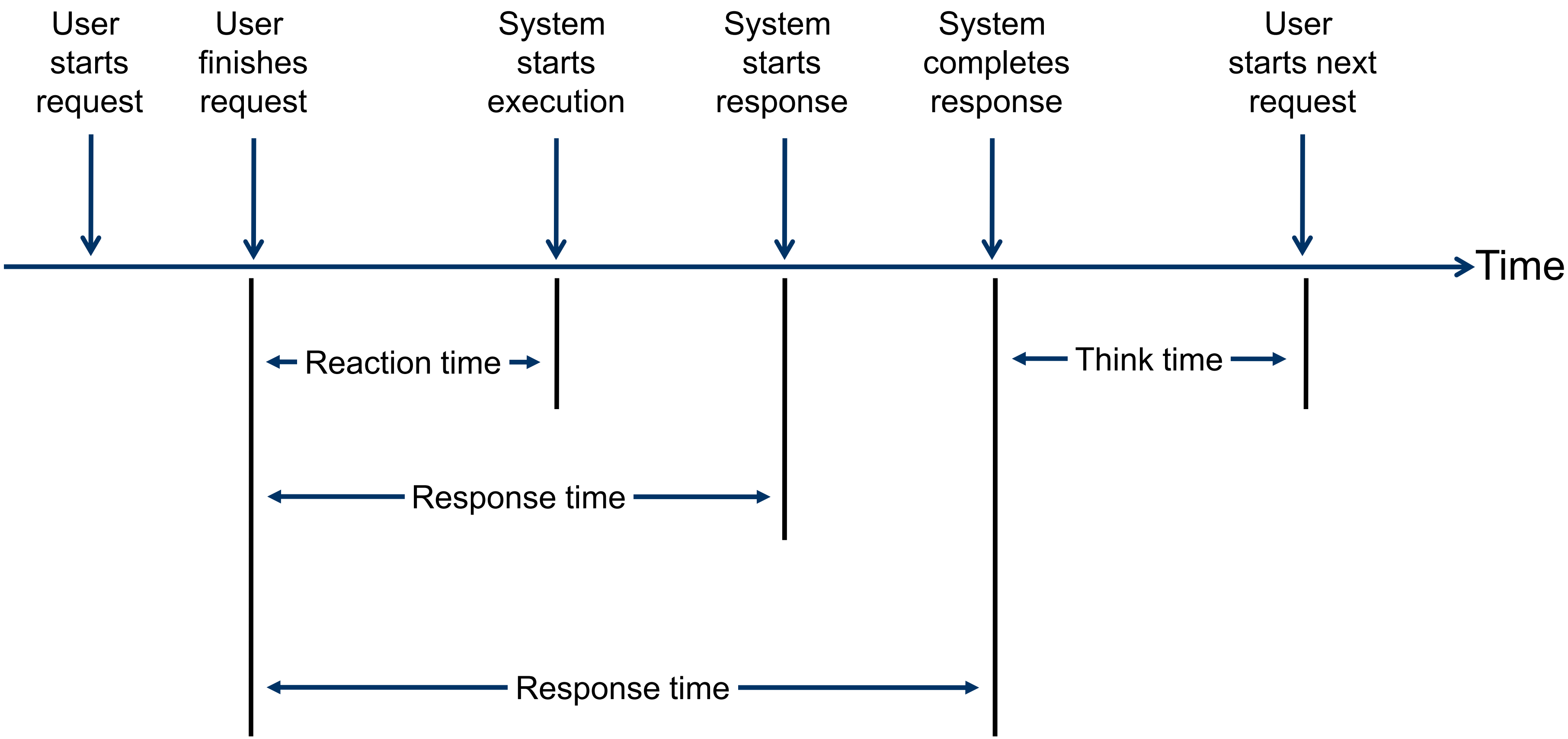
# Selecting performance metrics



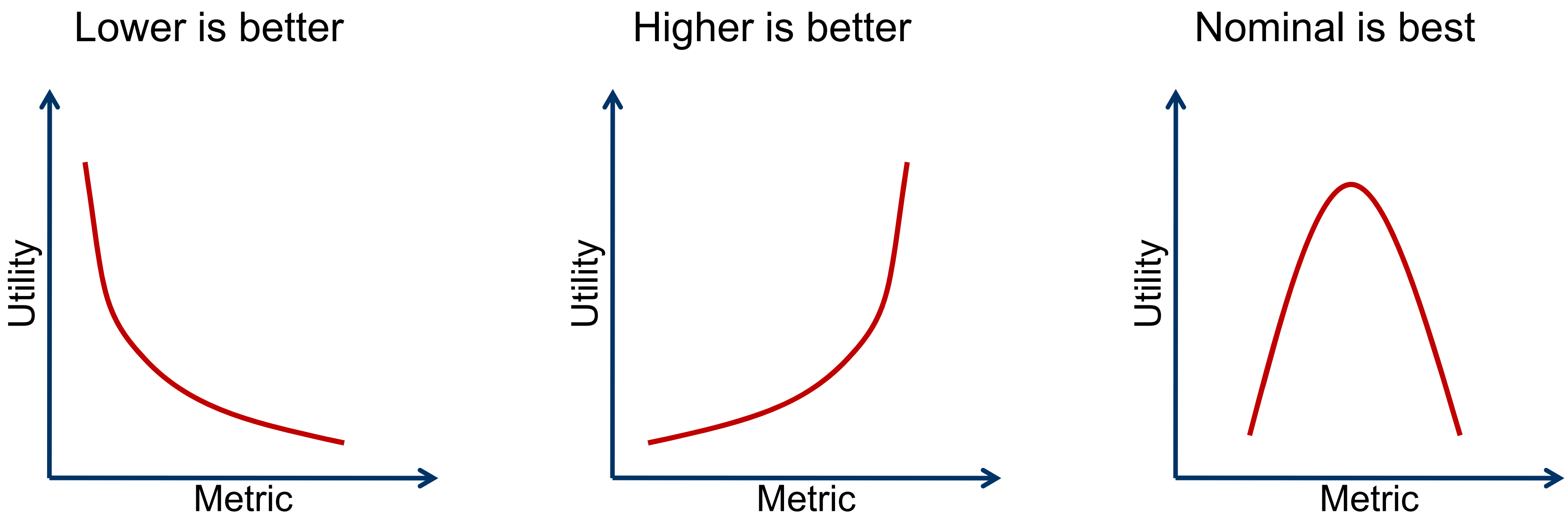
# Common performance metrics



# Common performance metrics



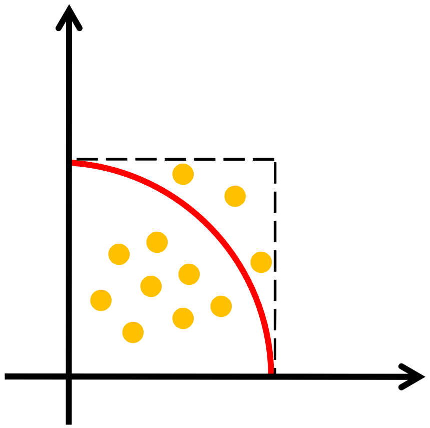
# Utility classification of performance metrics



# 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

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

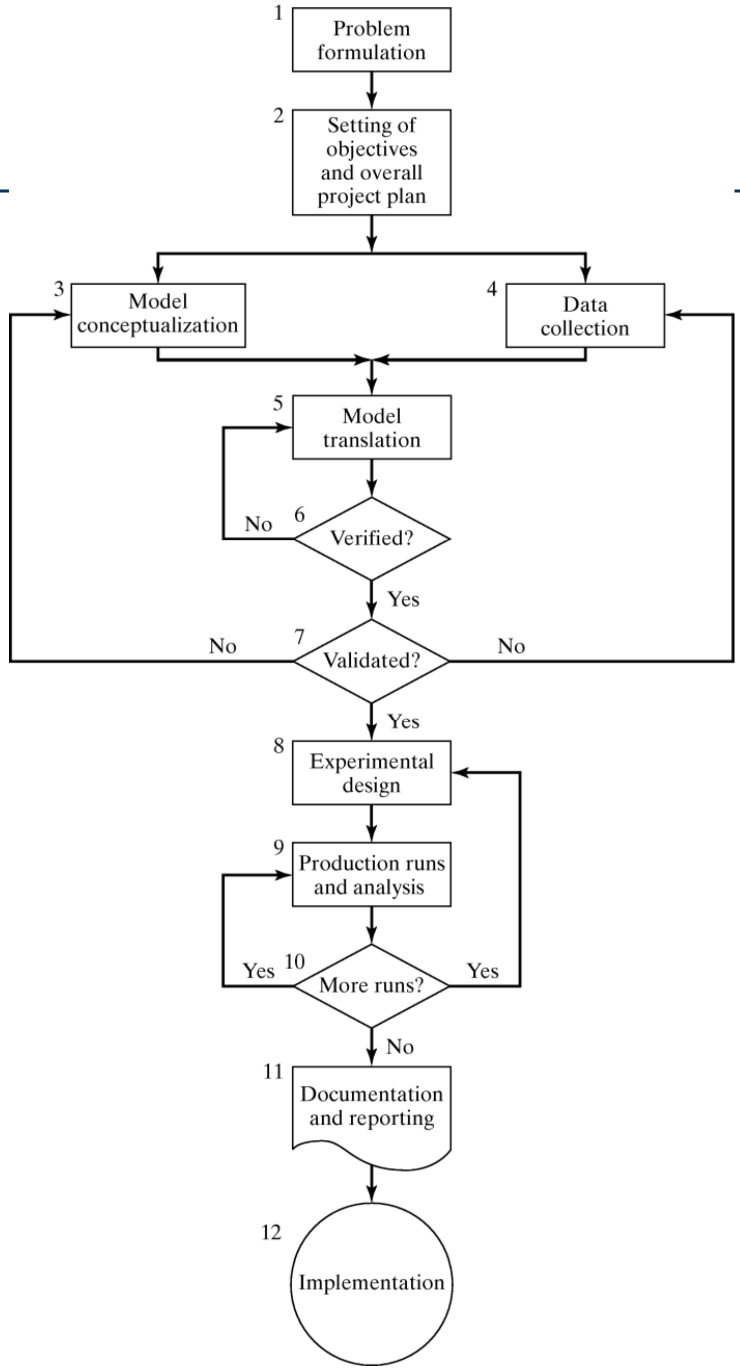
$$\frac{dy}{dt} = -s \cdot y(t) + b \cdot x(t) \cdot y(t)$$

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

# Steps in a simulation study

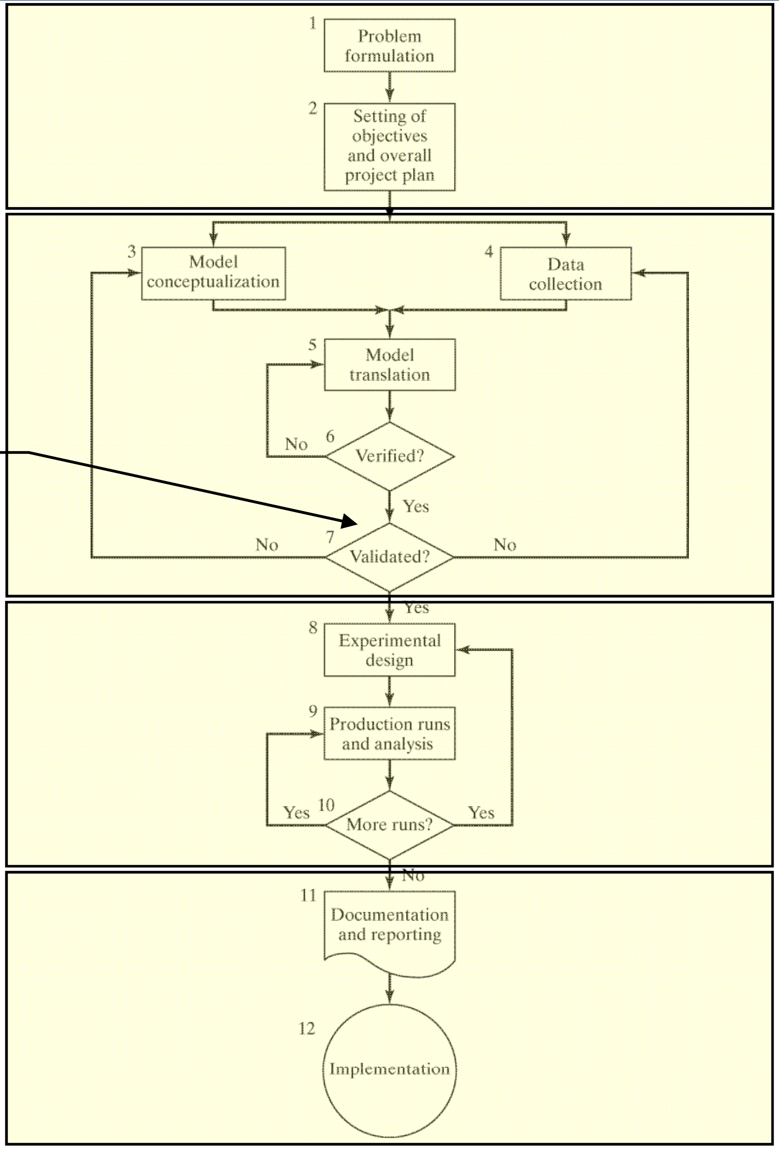
# Steps in a Simulation Study

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