TUM – Courses
IN2045
Discrete Event Simulation

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Course organization

- Lecturer
  - Dr. Alexander Klein, klein@net.in.tum.de
    Office hours: Monday 10-11 / after arrangement, Room 03.05.61
  - Stephan Günther, guenther@net.in.tum.de
  - Prof. Dr. Georg Carle, carle@net.in.tum.de
- Course
  - Lectures: 14 x 90/120 minutes, Tuesday 10–12 (c.t.), Room: 03.07.023
  - Exercises: 10 x 60 minutes, Wednesday 12:30–14 (s.t.), Room: 03.07.023
- ECTS:
  - 4 credits => 5 credits (currently under discussion)
- Exam:
  - Oral exam (approx. 20 minutes) at the end of the semester
- Course Material
  - http://www.net.in.tum.de/de/lehre/ws1112/vorlesungen/
- Login:
  - Username: simtech-ws20112012 Password: iwantaccess

Course organization

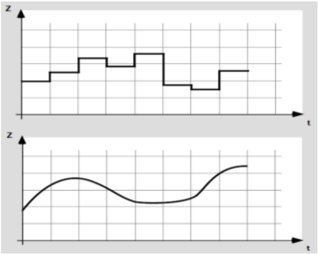
- Exercises:
  - Exercises are rated (+/0/-)
  - Students have to pass 7 out of 10 exercises (+/0) to receive a 0.3 bonus
  - Mainly programming and result evaluation
  - Up to three students can and should submit their exercise together
  - Registration for exercises will be available tomorrow on our web page
  - A PDF is available on our web page which outlines information about the submission of exercises and the usage of the subversion system
  - Figures and descriptions should be submitted as PDF
  - !!! Exercises are part of the exam !!!
- Goal:
  - Get familiar with statistical issues (statistical significance)
  - Learn how to evaluate different systems (simulation/measurements)
  - Learn how to visualize simulation results and measurements

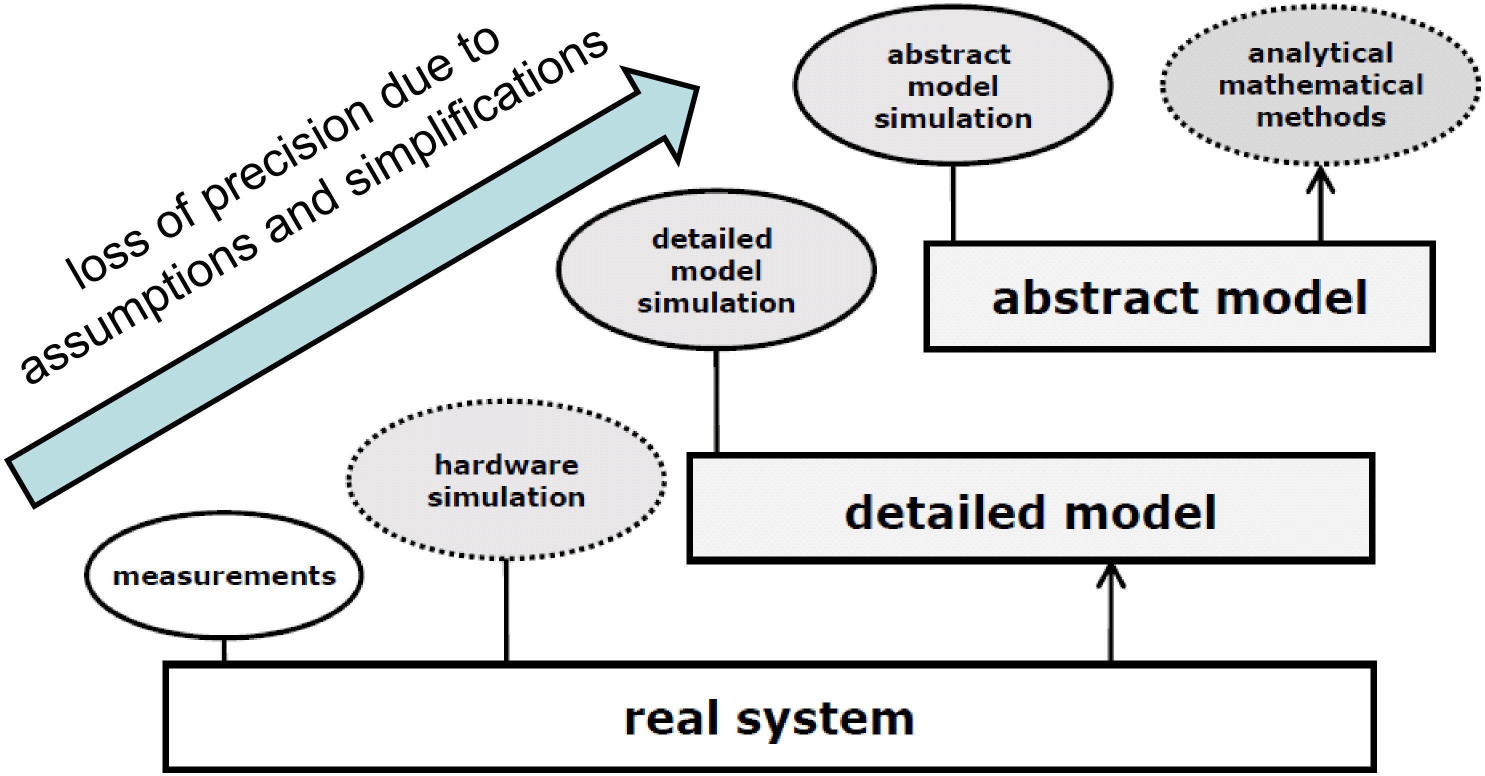
⇨ **Prepare students for their BA/MA thesis**

Course outline

1. Simulation
   - Simulation: What it is and when to use it
   - Types of simulators
   - Internals of discrete event simulators
   - Continuations and co-routines

Duration: 150 minutes

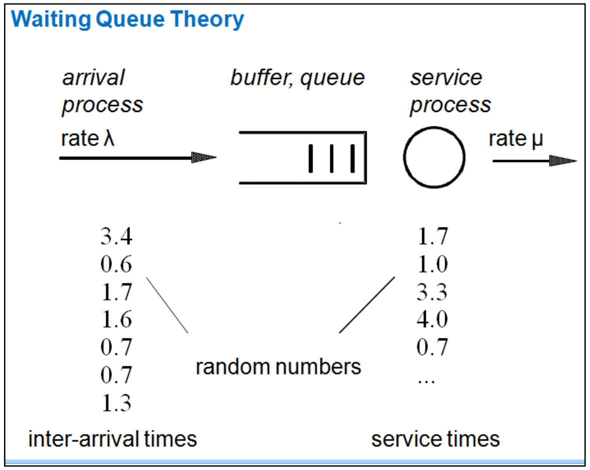


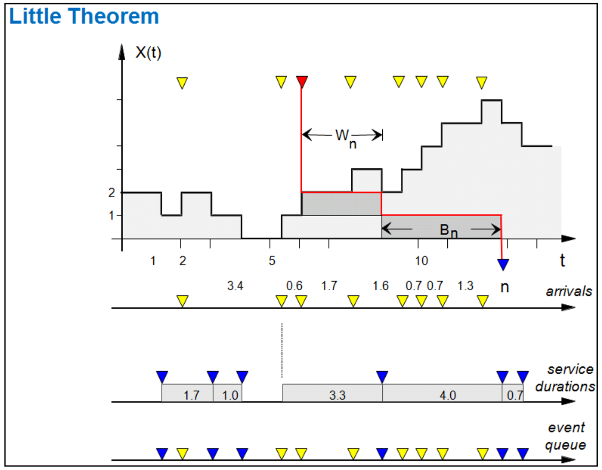


Course outline

2. Statistics fundamentals — Duration: 180 minutes

- ❑ Introduction to Waiting Queues
- ❑ Random Variable (RV), Discrete and Continuous RV
- ❑ Probability Space, Frequency Probability
- ❑ Distribution(discrete), Distribution Function(continuous)
- ❑ Probability Density Function, Cumulative Density Function
- ❑ Definitions: Expectation/Mean, Mode, Standard Deviation, Variance, Coefficient of Variation, p-percentile(quantile), Skewness, Scalability Issues, Covariance, Correlation, Autocorrelation Visualization of Correlation

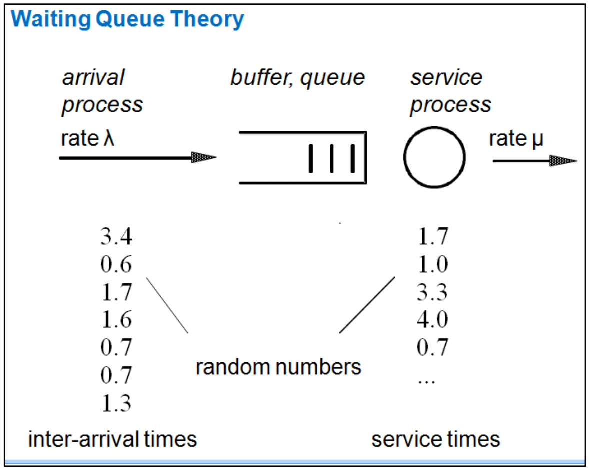


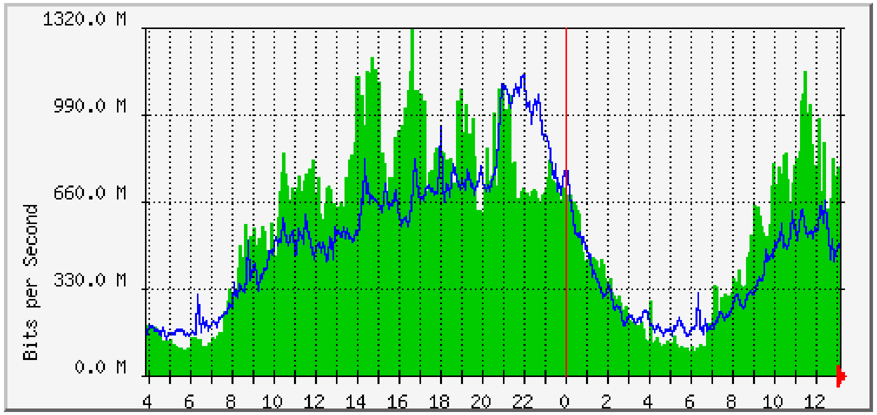


Course outline

2. Statistics fundamentals

Duration: 180 minutes





Throughput MWN – Router - Garching

- ❑ Single high performance service process vs. multiple low performance service processes
- ❑ Impact for limited buffer size / storage capacity
- ❑ State / time dependent arrival process
- ❑ Performance parameters

Course outline

3. Random Numbers

Duration: 140/240 minutes

- Random Variables:
  - Generation of Random Variables (RV)

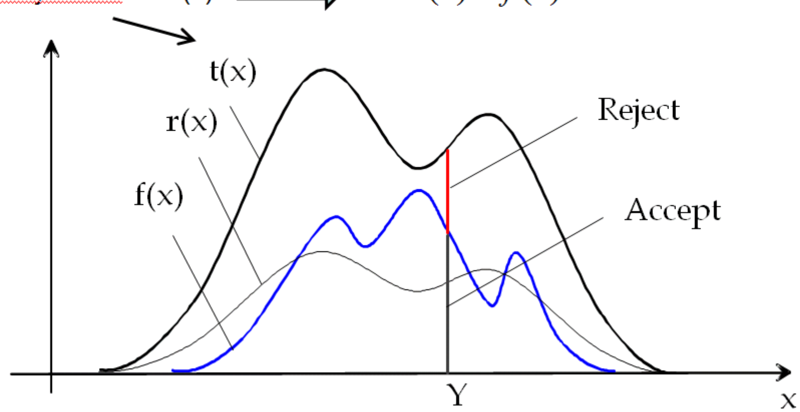
    Inversion, Composition, Convolution, Accept-Reject
  - Distributions and their Characteristics

    Uniform(continuous), Normal, Triangle, Lognormal, Exponential, Erlang-k, Gamma, Uniform(discrete), Bernoulli, Geom, Poisson, General Discrete

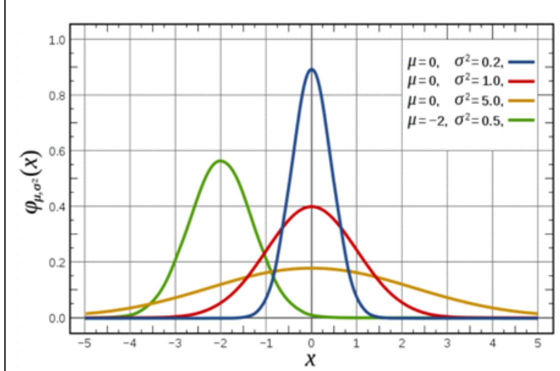
Accept-Reject

- Geometrical interpretation

  Y will be accepted if the point $(Y, U \cdot t(Y))$ falls under the curve *f* .
- The acceptance probability is high if *t(Y)-f(Y)* is small.
- Majorante von f(x) ⟹ $\forall x : t(x) \geq f(x)$



- **Normal distribution(3/3):**



Probability Density Function

Course outline

3. Random Numbers

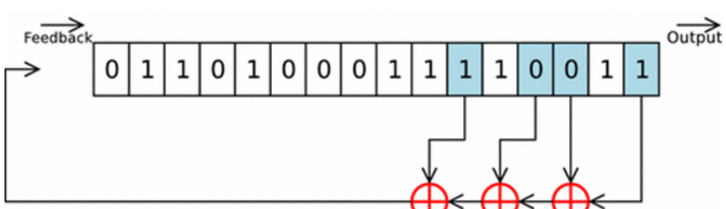
Duration: 100/240 minutes

- Random Number Generators:
  - Linear Congruential Generator(LCG), Shift Register, Generalized Feedback Shift Register, Mersenne Twister
  - Tests χ^2 Test, Spectral Test, Serial Test

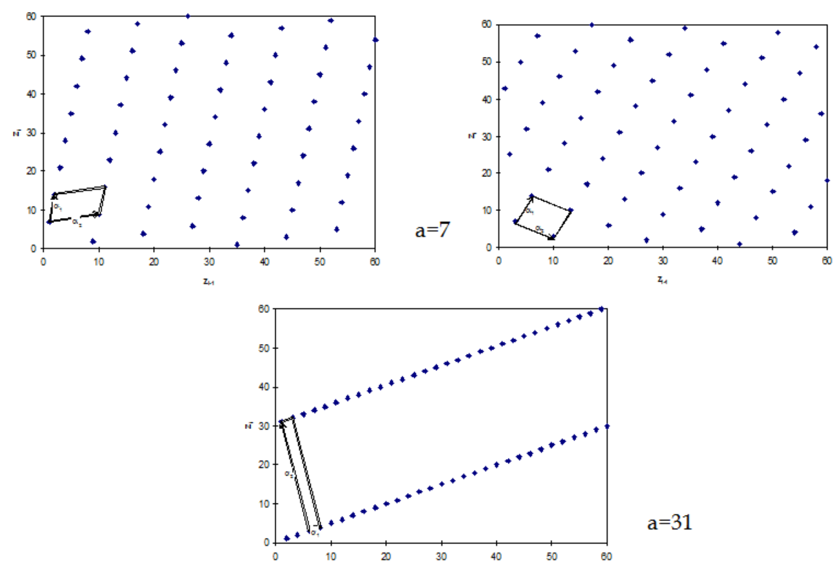
- Linear feedback shift register generator (LFSR) introduced by Tausworthe (1965)
- Operate on binary numbers (bits), not on integers
- Mathematically, a multiple recursive generator:

  $$b_i = (c_1 b_{i-1} + c_2 b_{i-2} + c_3 b_{i-3} + \ldots + c_q b_q) \bmod 2$$

  - c_i: constants that are either 0 or 1
  - $c_q = 1$ (why?)
  - Observe that + mod 2 is the same as XOR (makes things faster)
- In hardware:



$$Z_i = a \cdot Z_{i-1} \pmod{61}$$



Course outline

3. Random Numbers

Duration: 100/240 minutes

00101110101001101100010011101010100011

00101110101001101100010011101010100011

Random 

Autocorrelation Lag 4

Course outline

4. Evaluation of simulation results: Duration: 150 minutes

- Consistent Estimator, Unbiased Estimator, Variance of an Estimator, Bessel's Correction, Efficient Calculation
- Confidence Interval
  - Chebyshev
  - Central Limit Theorem
  - t-Distribution
- Evaluation and comparison of Simulation Results Replicate-Delete Method, Batch Means Method, Stationarity

Confidence interval according to the central limit theorem

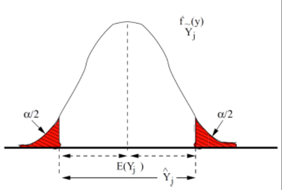
- Idea: The central limit theorem is still valid if σ^2 is replaced by $\tilde{S}^2$. Thus, it is possible to calculate the critical values out of the normal distribution.
- Recapitulate the “flipping of a coin example” with $\tilde{Y}$ representing the distribution of the estimator and Y being the distribution of the estimand. Then we can calculate the confidence interval as follows:

$$P[|Z| \geq \varepsilon] = P\left[\left|\frac{\tilde{Y} - E(Y)}{\tilde{S}/\sqrt{n}}\right| \geq \varepsilon\right] = \alpha$$

$$P[|\tilde{Y} - E(Y)| \geq \varepsilon \cdot \tilde{S}/\sqrt{n}] = \alpha$$

$$\boxed{\tilde{Y} \pm z_\alpha \cdot \tilde{S}/\sqrt{n}}$$

z_α is the $\alpha/2$ percentile of $N(0,1)$



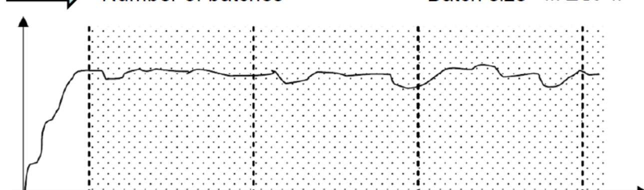
Picture taken from Buchholz

Batch-Means Method (LK 9.5.3)

- Estimate the duration of the transient phase
- Perform a long simulation run
- Remove the transient phase
- Divide the gathered results in n intervals of equal length (Batches) which hold m samples

Assure that the mean of subsequent batches is uncorrelated (calculate the empirical autocorrelation)

Number of batches $n \geq 10$ Batch size $m \geq 10 \cdot x$

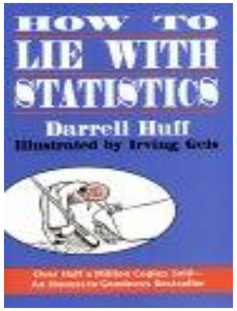


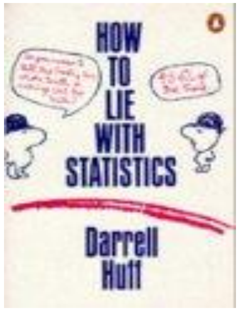
Course outline

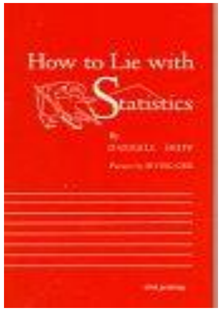
4. Evaluation of simulation results:

Duration: 90 minutes

- How to Lie with Statistics:
  - Lessons for Authors and Readers
  - Examples and Discussion



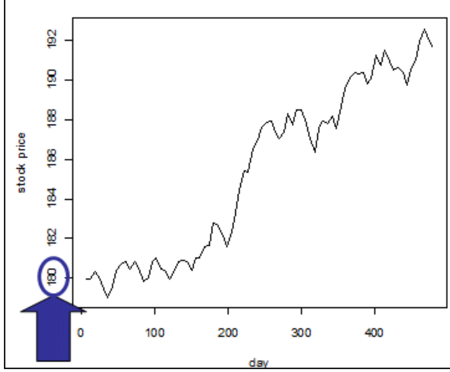


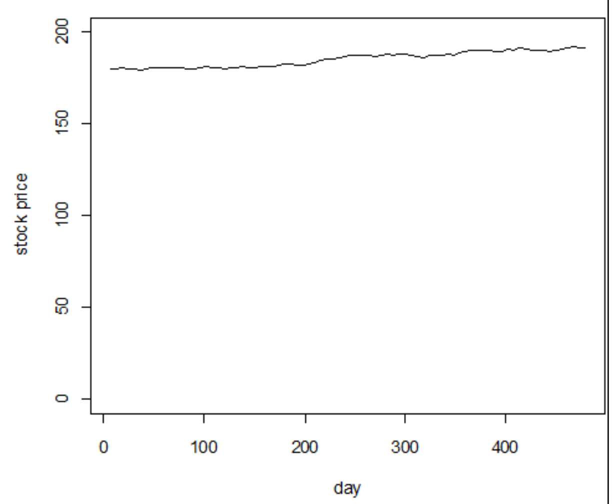


Scales can be misleading

- What really happened is shown here:

  We intuitively interpret a trend plot on a ratio





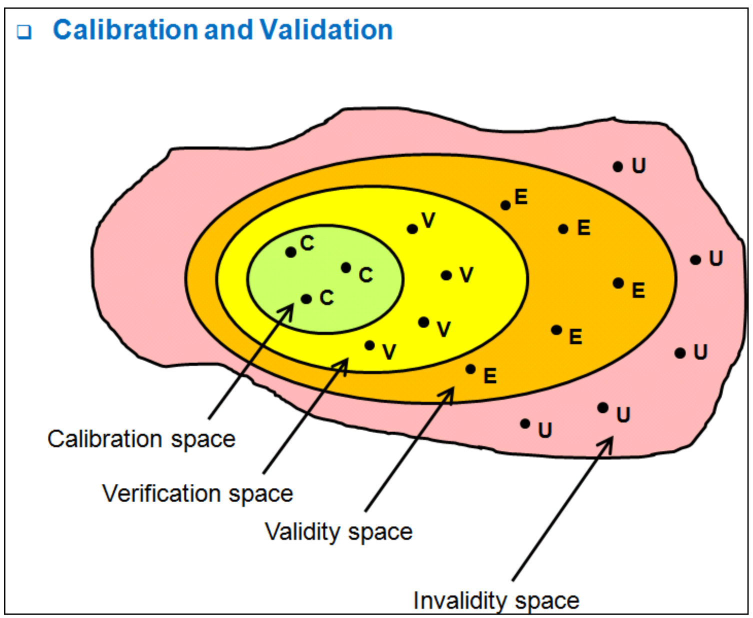
Course outline

4. Evaluation of simulation results:

Duration: 90 minutes

- Model Validation:
  - Calibration, Overfitting
  - Structural Change, Parameter Change
  - Comparison of Confidence Intervals:

    Welsh, Law & Kelton



Comparison of confidence intervals

Welch

- Estimators

$$\tilde{\mu}_R = \frac{1}{n}\cdot\sum_{i=1}^{n} V_{R_i} \qquad \tilde{S}_R^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(V_{R_i} - \tilde{\mu}_R\right)^2$$

$$\tilde{\mu}_S = \frac{1}{m}\cdot\sum_{i=1}^{m} V_{S_i} \qquad \tilde{S}_S^2 = \frac{1}{m-1}\sum_{i=1}^{m}\left(V_{S_i} - \tilde{\mu}_S\right)^2$$

- Difference of both samples are defined as follows:
  - $v_{RS\,i} = v_{Ri} - v_{S\,i}$
  - $v_{RS} = \left\{v_{RS_1}, v_{RS_2}, \ldots, v_{RS_n}\right\}$
  - $\tilde{\mu}_{RS} = \frac{1}{n}\cdot\sum_{i=1}^{n} V_{RS_i}$
  - $\tilde{S}_R^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(V_{R_i} - \tilde{\mu}_R\right)^2$

$$\boxed{\hat{\mu}_{RS} \pm t_{n-1,1-\alpha/2}\cdot \tilde{S}_{RS} / \sqrt{n}}$$

Both samples have to be statistically independent.

The samples must be of the same size. $m = n$

The variance of both samples must be equal. $Var(V_R) = Var(V_S)$

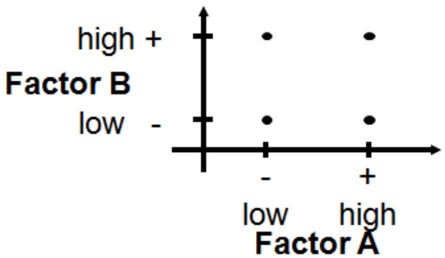
Course outline

5. Experiment planning:
   - Hypothesis Testing
   - Linear Regression
   - Factorial Design

Duration: 90 minutes

2^k factorial designs

- Example: 2 factors, i.e., a 2^2 design
- 4 design points:



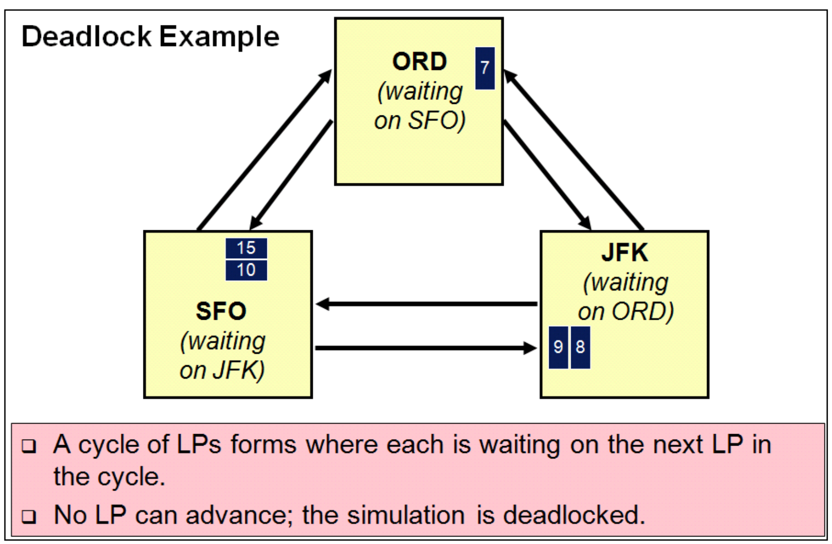
- Design matrix:

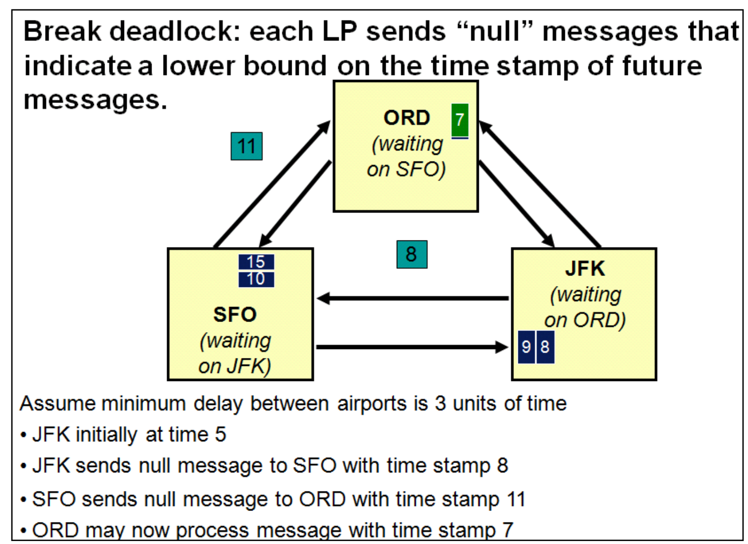
Run	Factor A	Factor B	Response
1	-	-	r_1
2	+	-	r_2
3	-	+	r_3
4	+	+	r_4

Course outline

6. Parallel Simulation: Duration: 180 minutes

- Conservative approach:
  - Deadlock avoidance
  - Deadlock detection
  - Deadlock recovery
- Optimistic approach:
  - Time Warp
- Alternatives to parallel simulation

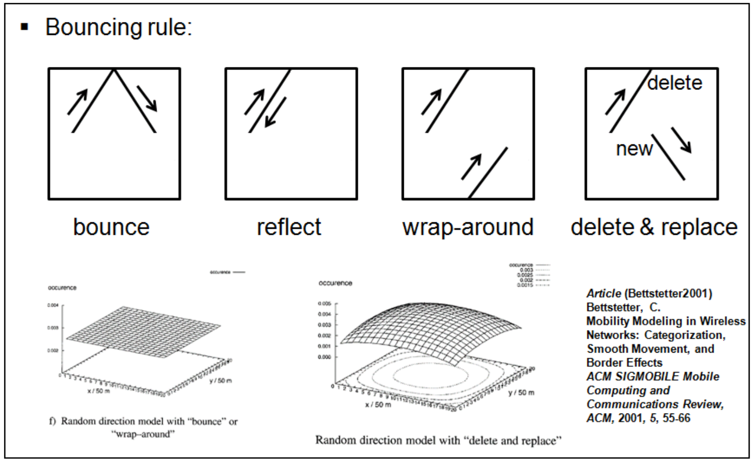


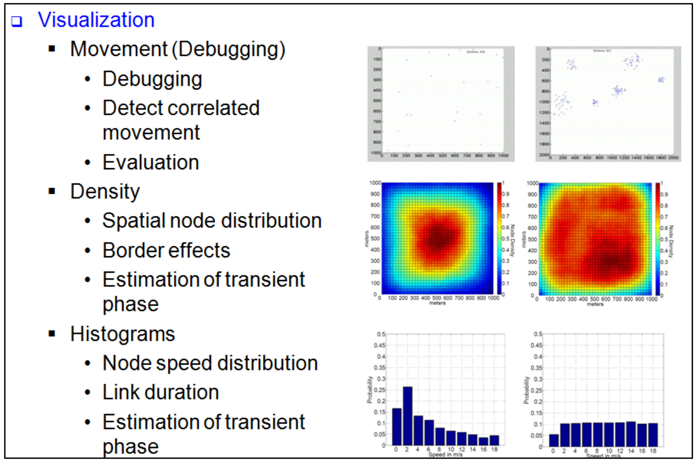


Course outline

7. Mobility: **Duration: 90 minutes**

- Mobility in General
  - Human Mobility Pattern
  - Visualization:
    - Density, Speed Histograms, Bouncing Rule, Obstacles
- Characteristics of Mobility Pattern:
  - Link Duration, Transient Phase, Node Distribution, Speed Distribution, Correlated Movement
- Synthetic Mobility Models:
  - Random Waypoint, Random Direction, Random Walk, Levi-Flight, Brownian Motion, Group Mobility



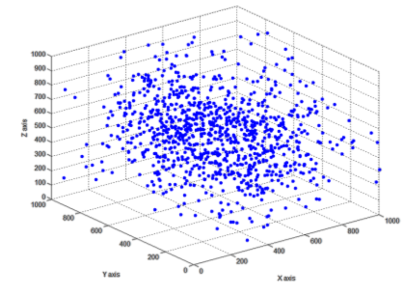


Course outline

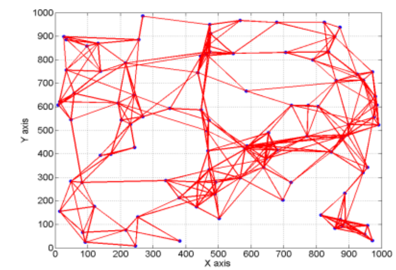
8. Advanced Topics:

Duration: 90 minutes

- Point Fields:
  - Generation of Point Fields
  - Homogeneous and Inhomogeneous Point Fields
  - Poisson Field, Cluster fields, Matern Cluster Field



- Random Graphs:
  - Graph Definition
  - Generation of Random Graphs
  - Probabilistic Model, Waxman Model
  - Random Graphs with Predefined Characteristics
  - Scale-free Graphs, Social-networks



- Scale-free networks – real-world examples:
  - Social networks - Facebook:

Facebook Friendships

Picture taken from http://www.opte.org

- Scale-free graph:

A graph is called scale-free if its node degree k follows the power law.

$$P(k) = ck^{-\gamma}$$

c and γ are constants. Typical range 0 < c < 1, 2 < γ < 3.

- Examples:
  - Social networks
  - Collaboration networks
  - Computer networks
  - Disease transmission

Random Graph   Scale-free Graph

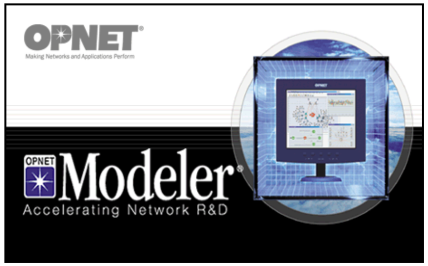
Course outline

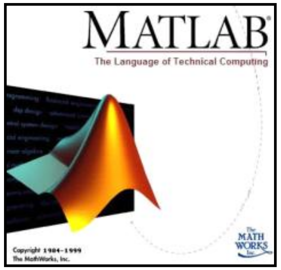
- **Exercises:** Processing Time: 120/180 minutes Duration: 60 minutes(each)
  - Exercise 1:
    - Implementation of a GI / GI / 1 - 1 queuing system
  - Exercise 2:
    - Evaluation of waiting queues / Evaluation of medium access procedures
  - Exercise 3:
    - Evaluation of waiting queues / Implementation of random variables
  - Exercise 4:
    - Implementation of histogram / Evaluation of system performance
  - Exercise 5:
    - Generation of random variates / Evaluation of samples
  - Exercise 6:
    - Implementation of random number generators / Evaluation of random numbers
  - Exercise 7:
    - State dependent service unit / Intelligent system initialization
  - Exercise 8:
    - Implementation of a 2D point field generator / Random Graphs
  - Exercise 9:
    - Random Graphs / Comparison of confidence intervals

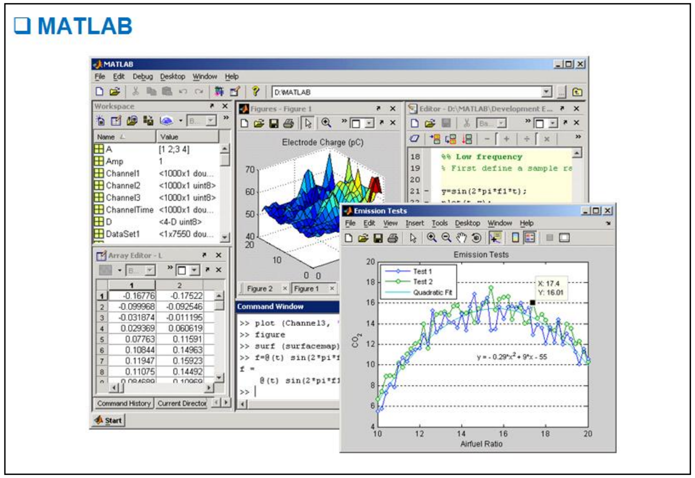
Course outline

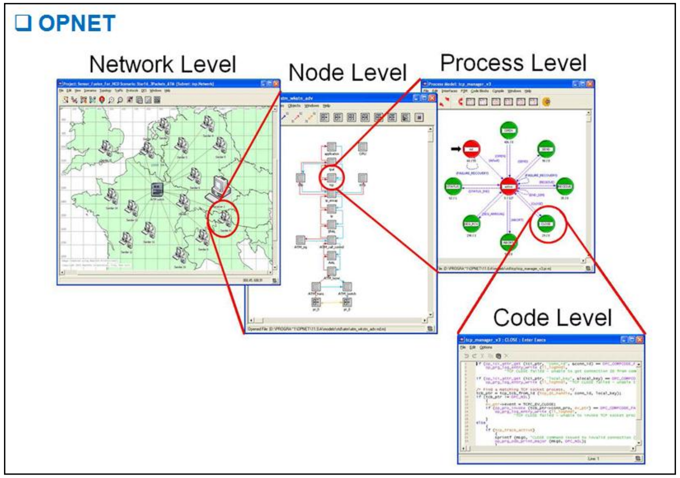
- Tutorial:
  - Matlab / Octave / Gnuplot
    - Practical exercises
    - Evaluation of sample data
    - Visualization
  - OPNET Modeler
    - Discrete Event Simulator
    - Development of waiting queue model
    - Evaluation of results

Duration: 180 minutes





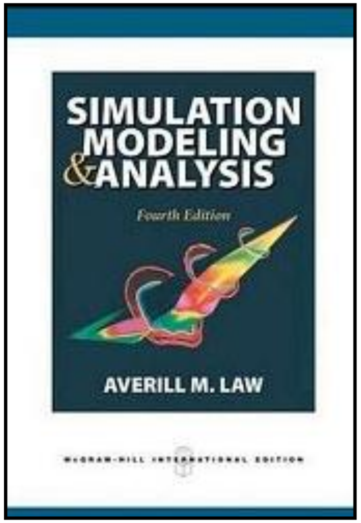




Material

- *Book:*

  Simulation Modeling and Analysis
  4th edition.
  Averill M. Law
  McGraw-Hill, 2007.



- Lecture:
  - Parallel and Distributed Simulation Systems CS4230 / CS 6236)

    Prof. Fujimoto

    College of Computing Georgia

    Institute of Technology

    Atlanta, GA 30332-0280
  - Modellgestützte Analyse und Optimierung

    Prof. Peter Buchholz

    Informatik IV

    Technische Universität Dortmund