Advanced Systems Lab
Tutorial III
Planning Experiments

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Why Experiments?

Quantitative questions about systems

- Absolute or comparative performance analysis
  - How many operations can a system run per second? How long does an operation take?
  - How many concurrent clients does a system support?
  - Do SSDs make an application faster than hard disks?
  - Should I use quick sort instead of merge sort for an online catalogue?
  - Where is the bottleneck in the system?

How to answer such questions?

- Experiments
  - You implement / install „system(s) under test“ (SUT)
  - You run benchmarks and measure observable results
- Modeling
  - You build a model of the „system(s) under test“
  - You calculate results with model
- Simulation
  - You implement a system that behaves like SUT
  - You run benchmarks and measure computed results

Experiments vs. Modeling

- Experiments
  - Often expensive to implement
  - Specific to environment (e.g., hardware used)
  - Accurate (quantitative) results
  - Sometimes misleading
- Modeling
  - Typically cheap
  - General
  - Qualitative results
  - You always learn something
- Use modeling whenever you can
  - Unfortunately, modern systems are too complex

Methodology

1. Ask the right question
   – Define the „system(s) under test“
   – Define what to measure and understand why
   – Define relevant workloads, understand parameters
2. Make a hypothesis
   – „A good scientist predicts the results and explains later why something totally different happened.“
3. Carry out experiment (real system, model)
   – Run workloads, measure metrics
4. Report results, analyze results, gotoStep 1
   – Give answer to question, possibly refine question

Making a Hypothesis

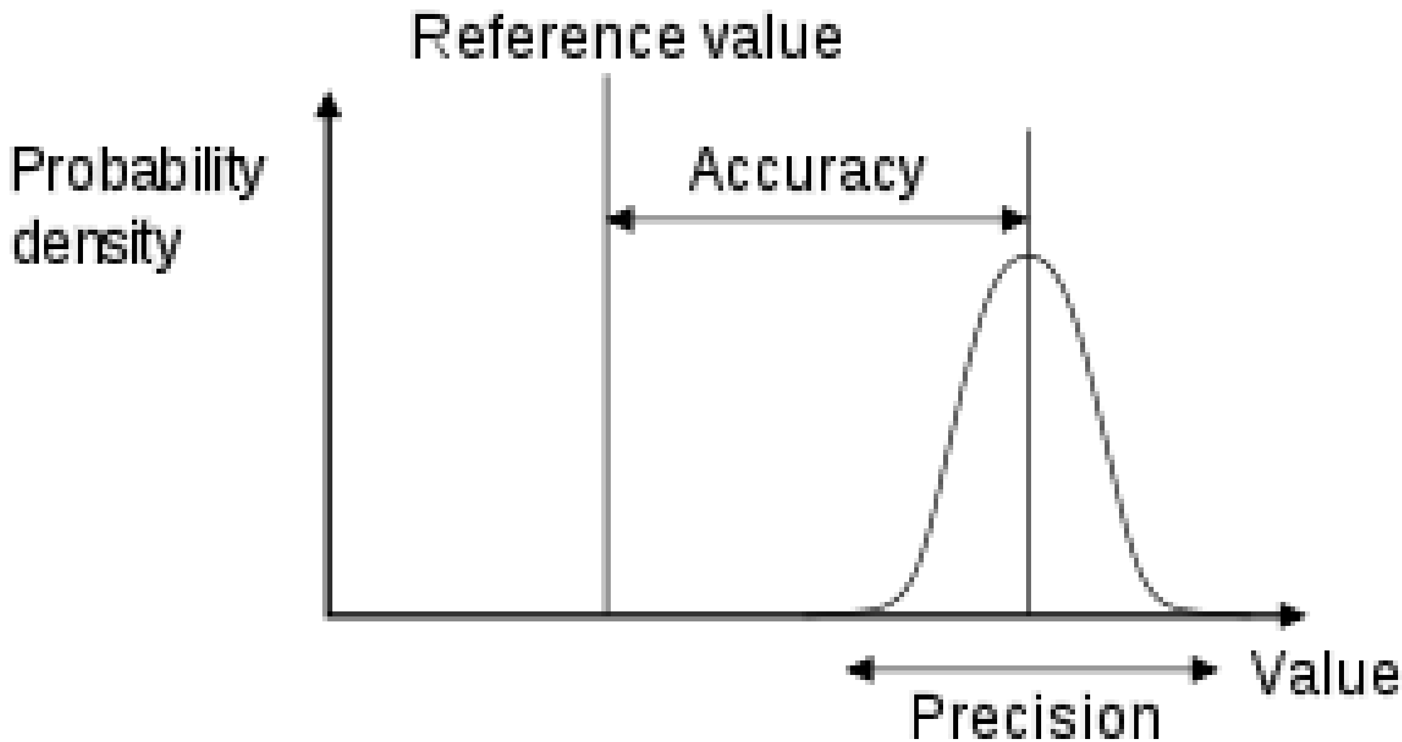
- Use the same format as the final results
  - Draw graphs with expected results
  - Even try to predict variance and statistical properties
  - Make bullet points with explanations
  - Use „modeling“ to make hypothesis
- Share hypothesis with your customer
  - Validates whether you are asking the right question
  - i.e., can you make decisions if results turn out like that
- Comparison of expected vs. real results
  - Essential to find bugs in your experiments
  - Essential to understand real results

Data distributions

Accuracy vs. Precision

Accuracy = how close to the real value (often unknown)

Precision = similarity of the results of repeated experiments



http://en.wikipedia.org/wiki/Accuracy_and_precision

Dealing with Accuracy

- Understand the System under Test
- Understand the environment in which the tests are being done:
  - Identify potential interference and sources of noise
  - Characterize those sources and try to estimate their value
- Correct (if possible and meaningful) the measured values to improve accuracy

Dealing with Precision

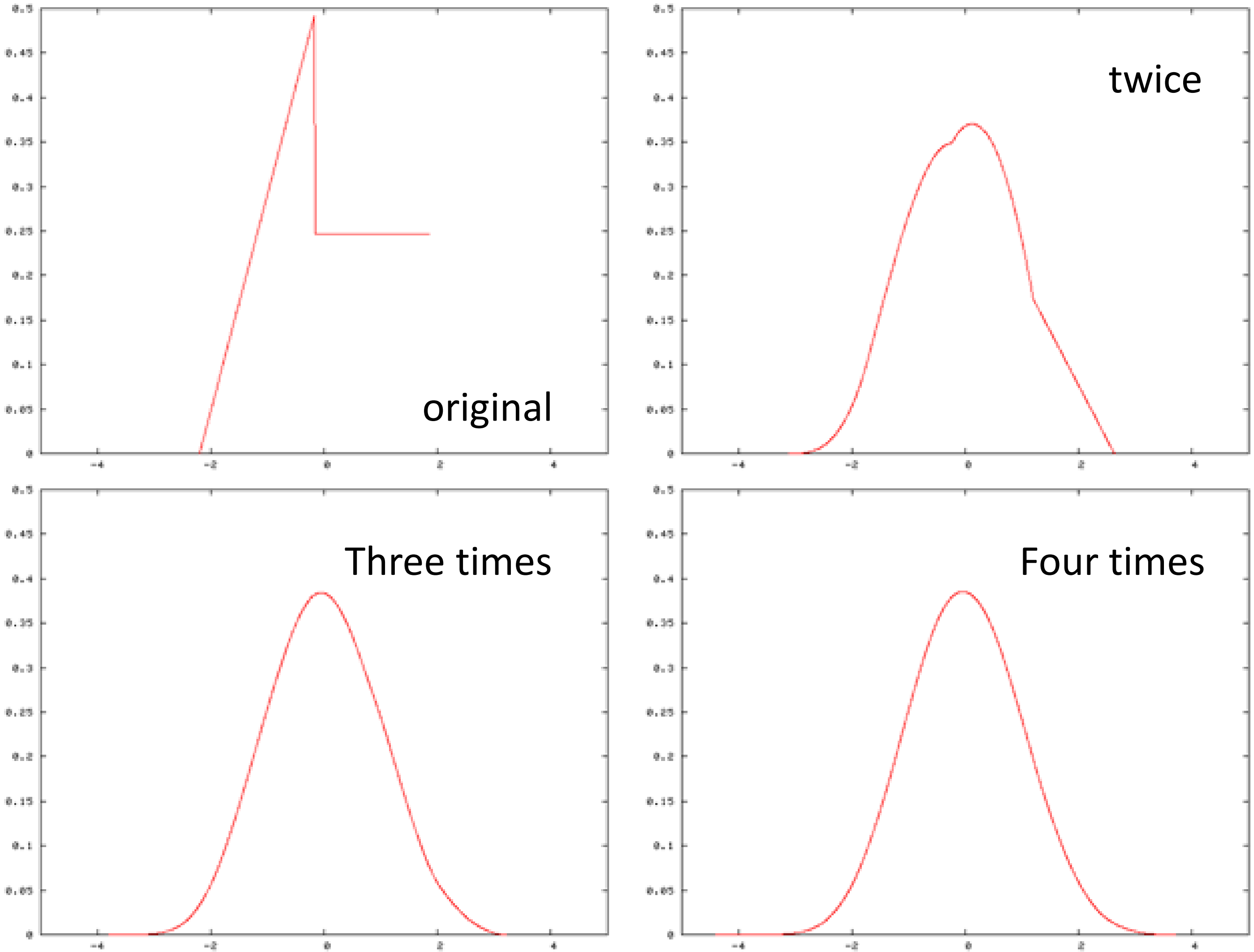
- When measuring, we are trying to estimate the value of a given parameter
- The value of the parameter is often determined by a complex combination of many effects and is typically not a constant
- Thus, the parameter we are trying to measure can be seen as a RANDOM VARIABLE
- The assumption is that this random variable has a NORMAL (GAUSSIAN) DISTRIBUTION

Central limit theorem

- Let X_1, X_2, X_3, … X_n be a sequence of independently and identically distributed random variables with finite values of
  - Expectation (μ)
  - Variance (σ^2)

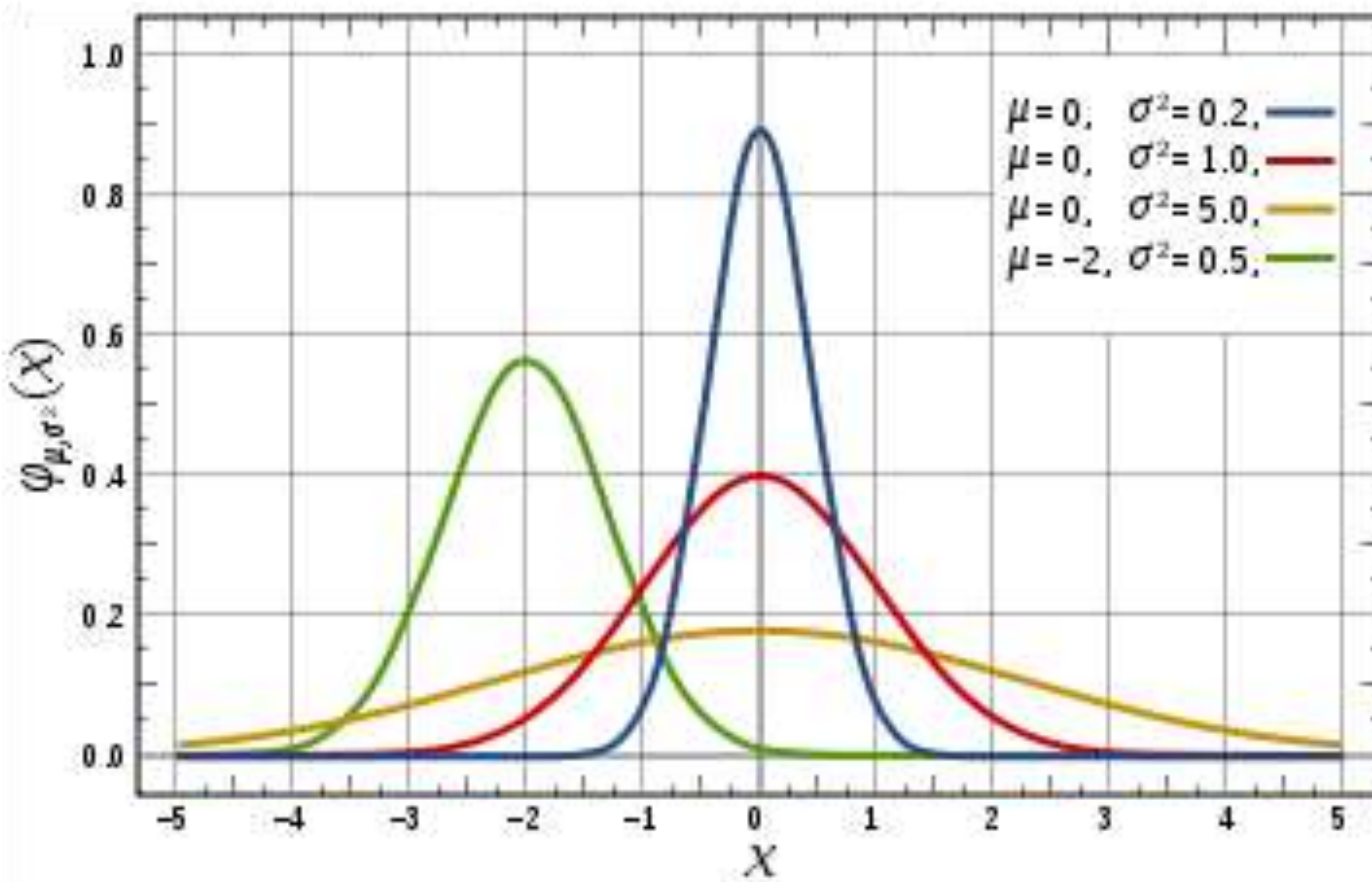
as the sample size n increases, the distribution of the sample average of the n random variables approaches the normal distribution with a mean μ and variance σ^2/n regardless of the shape of the original distribution.

How does it work?



http://en.wikipedia.org/wiki/File:Central_limit_thm.png

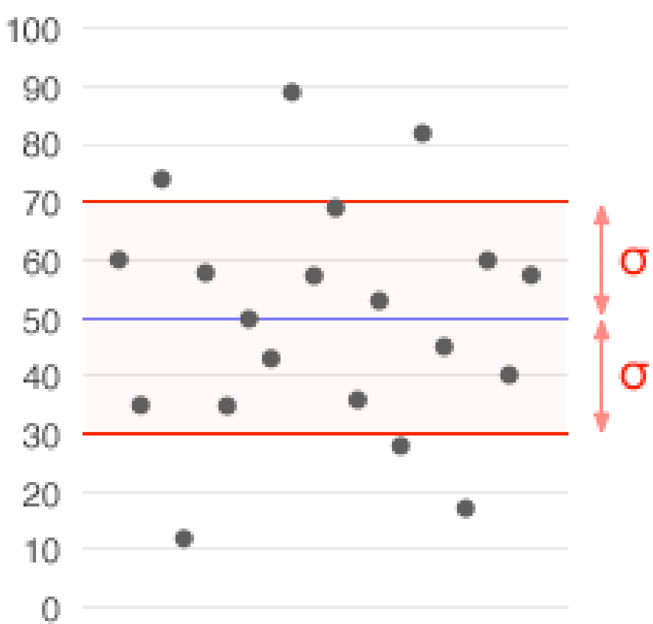
Normal or Gaussian distribution



http://en.wikipedia.org/wiki/Normal_distribution

Meaning of standard deviation

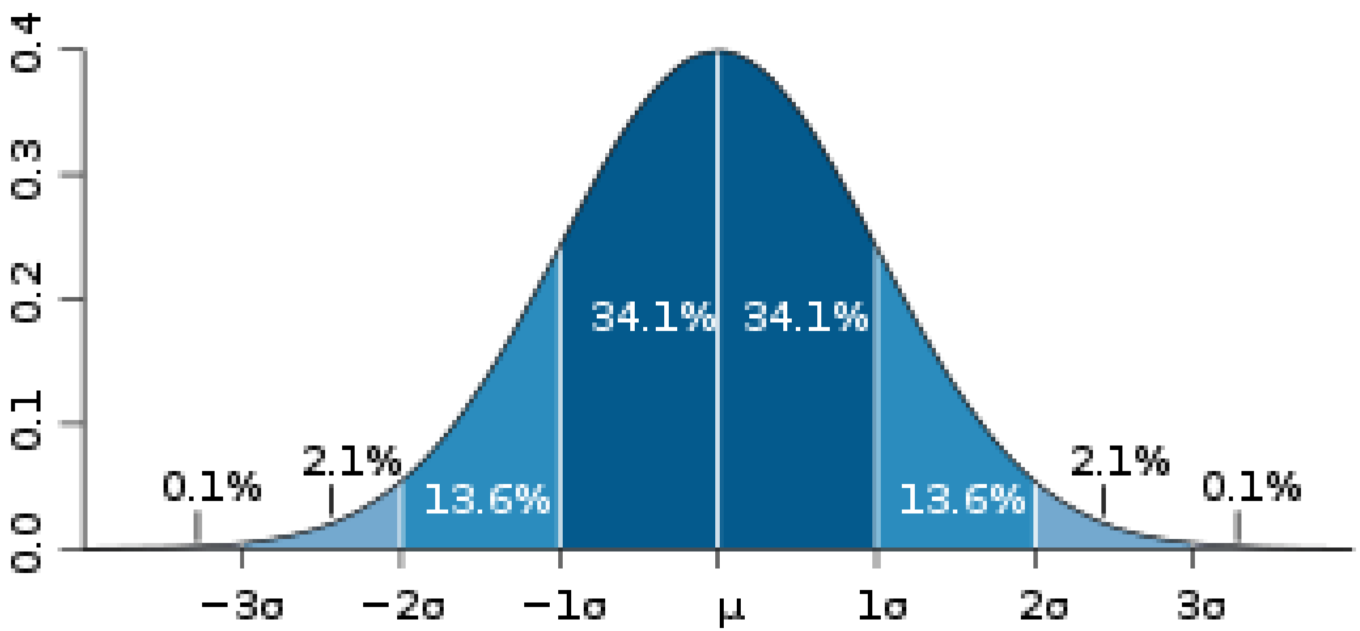
- The standard deviation gives an idea of how close are the measurements to the mean
  - important in defining service guarantees
  - important to understand real behavior



Mean is 50 but standard deviation is 20, indicating that there is a large variation in the value of the parameter

Mean of a sample

- To interpret a given measurement, we need to provide complete information
  - The mean
  - The standard deviation around the mean



http://en.wikipedia.org/wiki/Standard_deviation

Mean and standard deviation

- The standard deviation defines margins around the mean:
  - 64% of the values are within $\mu \pm \sigma$
  - 95% of the values are within $\mu \pm 2\sigma$
  - 99.7% of the values are within $\mu \pm 3\sigma$
- For a real system is very important to understand what happens when the values go beyond those margins (delays, overload, thrashing, system crash, etc.)

Calculating the standard deviation

- Mean and standard deviation:

$$\mu = \frac{\sum_{i=1}^{N} x_i}{N} \qquad \sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}$$

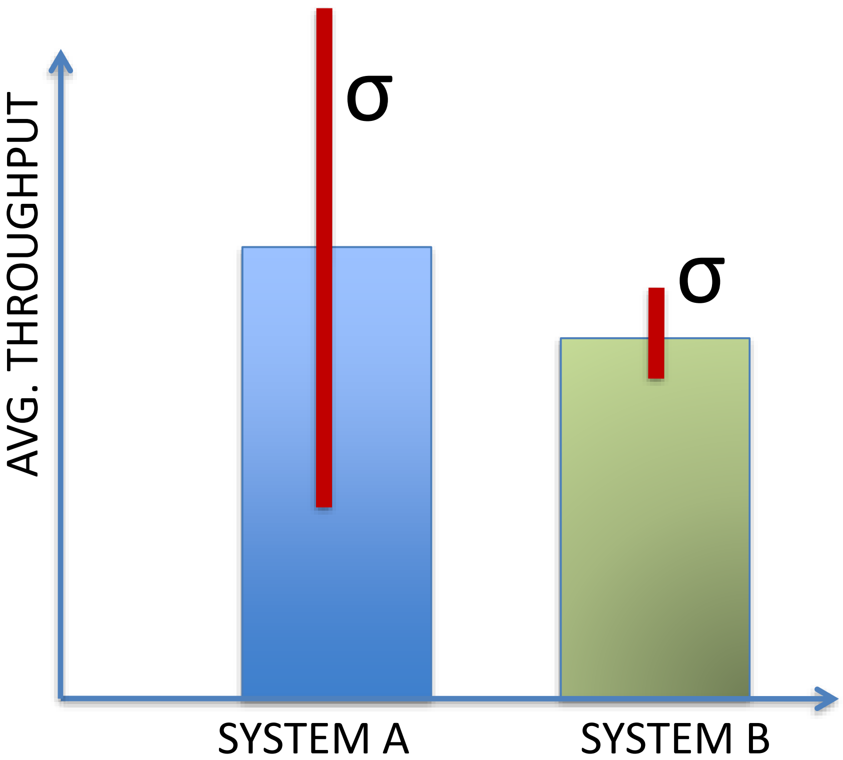
- In practice, use:

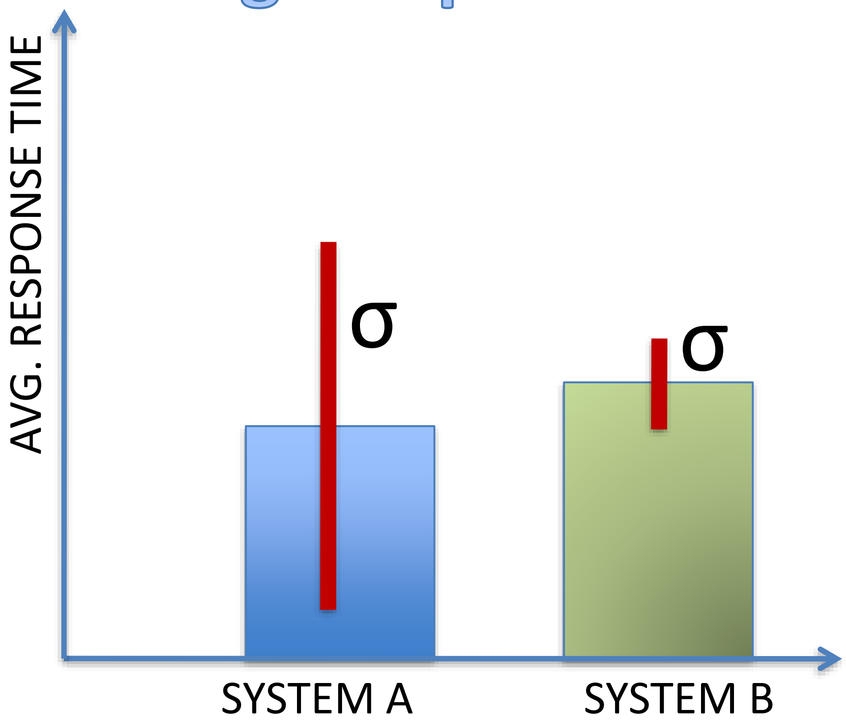
$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2}$$

Comparisons

- What is better?

Deterministic behavior is often more important than good performance

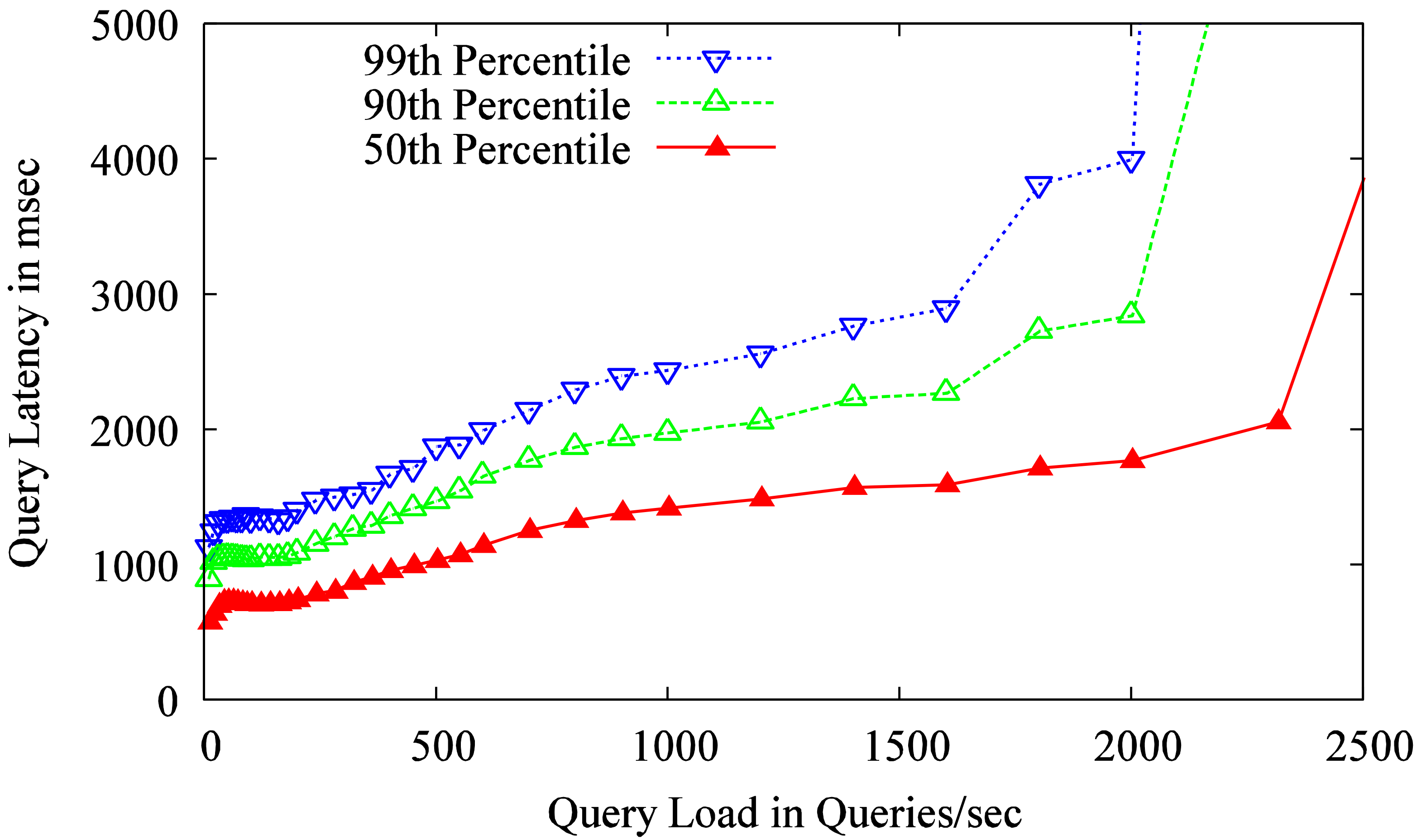




In practice

- In many systems, the standard deviation is almost more important than the mean:
  - 90% of the queries need to be answered in less than X seconds
  - No web request can take longer than 5 seconds
  - Changes have to be propagated in less than 10 seconds
  - Guaranteed bandwidth higher than X 90% of the time
- Achieving determinism is often done at the cost of performance

Percentile Example



Amazon Example (~2004)

- Amazon lost about 1% of shopping baskets
  - Acceptable because incremental cost of IT infrastructure to secure all shopping baskets much higher than 1% of the revenue
- Some day, somebody discovered that they lost the *largest* 1% of the shopping baskets
  - Not okay because those are the premium customers and they never come back
  - Result in much more than 1% of the revenue
- Be careful with correlations within results!!!

Putting it all together

Look at all the data

- Make sure you are looking at the complete picture of the experiment and your measurements do not include side effects (warm up, cool down, repetition effects)
- Once you are sure you have identified the valid data and that it looks reasonable, then apply statistics to it

Standard deviation

- All measurements and graphs have to be accompanied by the standard deviation, otherwise they are meaningless
  - Provides an idea of the precision
  - Provides an idea of what will happen in practice
  - Provides an idea of how predictable performance is
- Repeat the experiments until you get a reasonable standard deviation (enough values are close enough to the mean)

Advice

- It is a good idea to run a long experiment to make sure you have seen all possible behavior of the system:
  - Glitches only every 3 hours
  - Memory leaks after 1 M transactions
- In reality, tests have to resemble how the system will be used in practice

Designing an experiment

Experiments, but which ones?

- What does it mean to design an experiment?
- Performance is affected by a large number of factors
  - Workloads
  - Systems
  - Knobs
- We are interested in:
  - Which ones are the most important?
  - Which ones are related?
- Goal: get the most information with least effort (minimum number of experiments)

Definitions

- A *response variable* is the outcome of an experiment - typically the measured performance of the system (e.g., throughput, response time)
- A *factor* is any variable that affects the response, and which has several alternatives (amount of memory, number of cores, data sizes)
- *Levels* are the values that a given factor can assume – the alternatives for a factor.
- *Primary factors* are those whose effects need to be quantified
- *Secondary factors* are those that impact performance but whose effect we are not interested in quantifying
- *Replications* are the number of times each experiment is to be repeated with particular levels for each factor.

An experiment

- An experimental design consists of:
  - the number of different experiments
  - the factor level combinations for each experiment
  - the number of replications of each experiment
- An experimental unit is any entity used for the experiment

Interaction

- Two factors interact if the effect of one depends on the level of the other.
- Interaction considerably complicates the business of interpreting experimental results

Non-Interacting

	A_1	A_2
B_1	3	5
B_2	6	8

Interacting

	A_1	A_2
B_1	3	5
B_2	6	9

Avoid mistakes

- Try to avoid the following:
  - Ignoring the variation due to experimental errors
  - Not controlling important parameters (secondary factors)
  - Not isolating the effects of different factors
  - Overly simple (and very inefficient designs)
  - Ignoring interactions between factors
  - Conducting too many experiments
    - Take it slowly!
    - Break up the project into steps

Exploring the space

- Given a number of factors, what to do?
- Bad idea:
  - Vary one factor at a time
  - Find best value, fix it
  - Repeat for each factor
- Why is this a bad idea?: too many experiments, will get stuck in local minimum

2^k Factorial Designs

- Experimental technique to find the relative weight of different factors
  - Pick K factors
  - Pick two levels for each factor
  - Behavior of factors must be unidirectional or monotonic in the range explored (!)

Example 2^2 Factorial Design

Observation: can update book examples by multiplying by 1000!

Cache size (MB)	Memory size 4GB	Memory size 16GB
1	15	45
2	25	75

Define variables x_A and x_b to represent levels for each factor:

$$x_A = \begin{cases} -1 & \text{if 4 GB main memory;} \\ 1 & \text{if 16 GB main memory.} \end{cases}$$

$$x_B = \begin{cases} -1 & \text{if 1 MB cache,} \\ 1 & \text{if 2 MB cache.} \end{cases}$$

Solving the model

A useful fiction: non-linear regression model for performance:

$$y = q_0 + q_A x_A + q_B x_B + q_{AB} x_A x_B$$

This means we can write:

$$15 = q_0 - q_A - q_B + q_{AB}$$
$$45 = q_0 + q_A - q_B - q_{AB}$$
$$25 = q_0 - q_A + q_B - q_{AB}$$
$$75 = q_0 + q_A + q_B + q_{AB}$$

Relative weights on response variable

Solving:

$$y = 40 + 20x_A + 10x_B + 5x_Ax_B$$

What does this mean?

- Mean performance is 40
- Effect of memory is 20
- Effect of cache is 10
- Interaction between the two accounts for 5

In the form of a table

The same calculation can be done using a sign table:

I	A	B	AB	y
1	-1	-1	1	15
1	1	-1	-1	45
1	-1	1	-1	25
1	1	1	1	75
160	80	40	20	Total
40	20	10	5	Total/4

Repetitions and errors

- Look in the book
  - How to allocate variation
  - How to consider repetitions of the experiments to look for errors

- For the report, please use repetitions to get meaningful results.