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Performance evaluation, capacity planning and reliability

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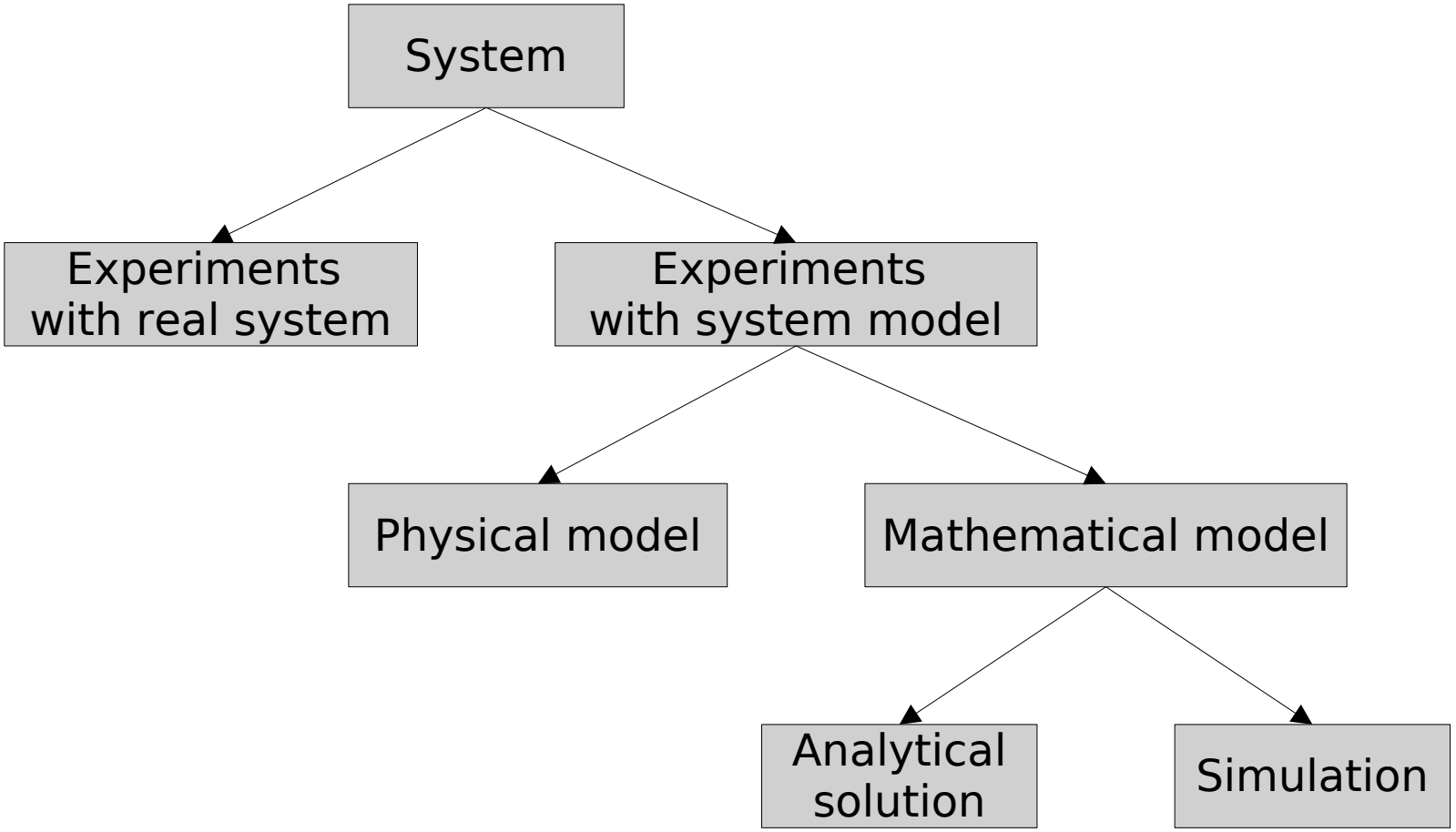
Performance evaluation

Possible approaches



Possible approaches

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- Real system
  - Full-scale system
  - Testing and Benchmarking
- Physical model
  - Small scale prototype
  - Testing and benchmarking
  - Scaling up results
  - May be tricky in case of non-linear scalability

Possible approaches

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- Mathematical model
  - Equations that describe system behavior
  - Easy to handle
  - What-if scenarios, comparison fo alternatives
  - Part of management algorithms
  - Simplified system description
- Simulator
  - Software that implement system behavior
  - More complex and realistic than mathematical model

Comparison of approaches

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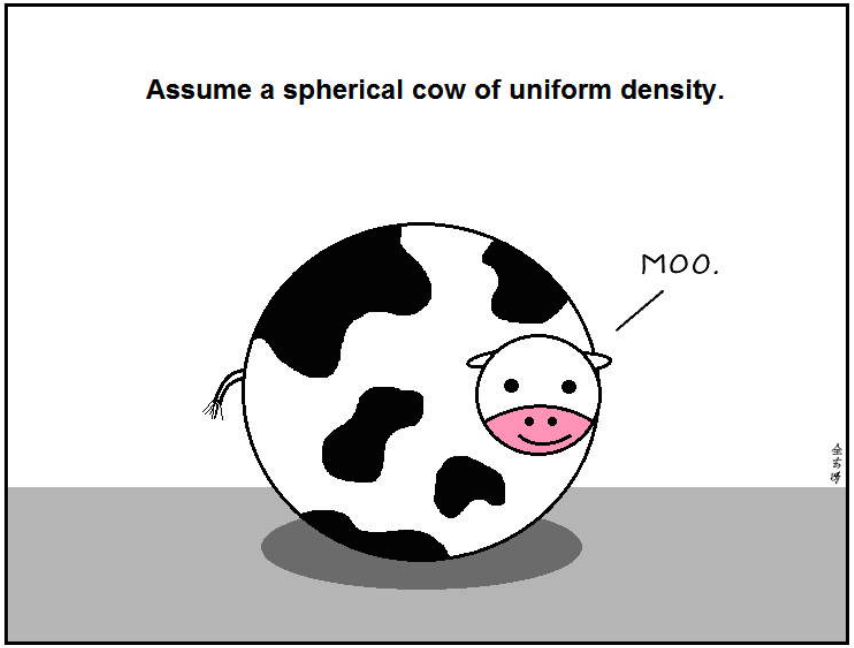
- Actual system *vs*. System model
  - Easier to do/Less dangerous (if system exists)
  - Less expensive than building a real system
- Physical *vs*. Mathematical model
  - Easier and less expensive to implement
  - Easier to modify
  - Mathematical model must be accurate enough
  - Remember the Spherical Cow
- Analytical solution *vs.* Simulation
  - Analytical is more precise
  - Simulation is more flexible



Motivational examples

Performance parameters

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- Response time:
  - Elapsed time between
    - Beginning of request
    - End of Response
- Throughput:
  - Number of requests satisfied within a time unit
- Error rate:
  - Fraction fo requests not server correctly
- Parameters depend on current load

Performance parameters

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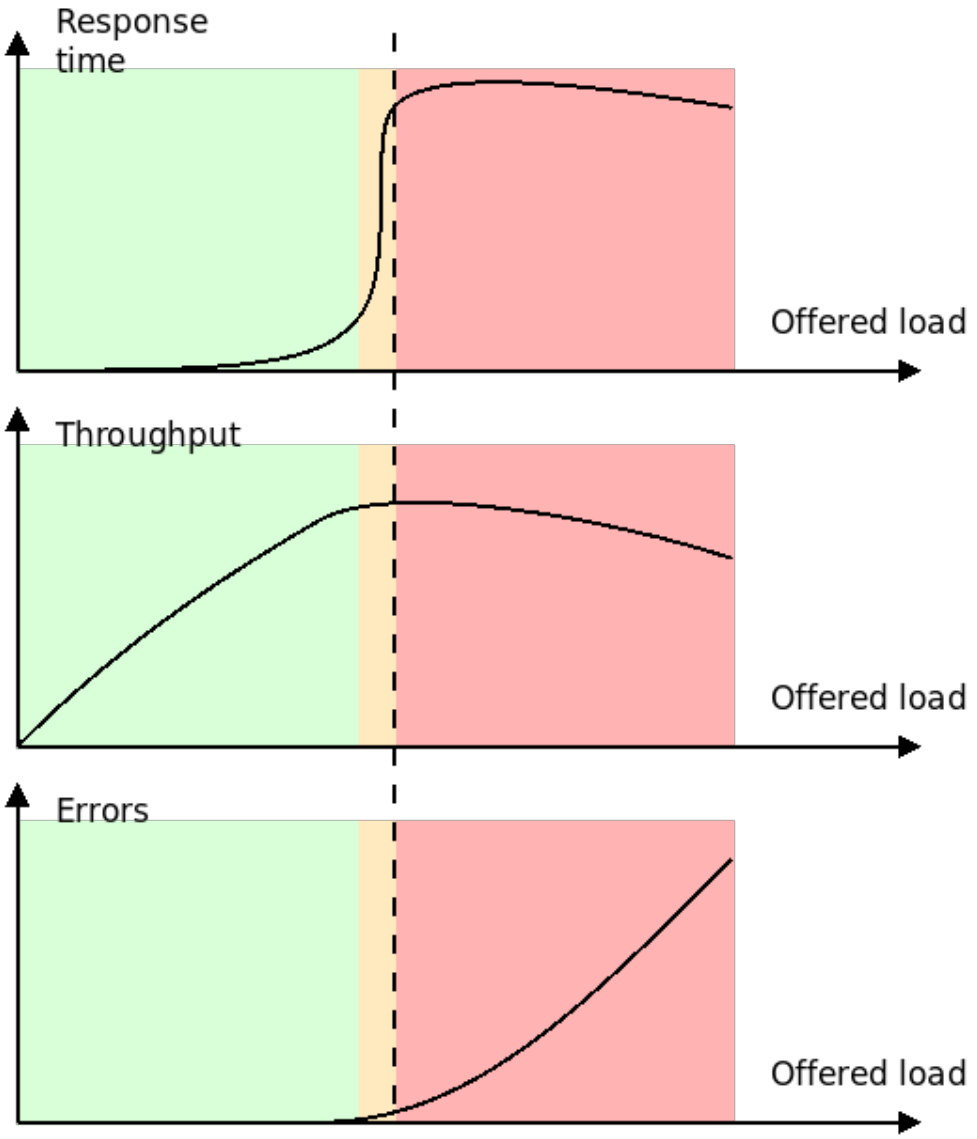

Operating conditions

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- OK/Underutilized (Green)
  - Response time is low
  - Response time scarcely correlated with load
  - Throughput increases linearly with offered load
  - Error rate remains low
- Knee region (Yellow)
  - Response time increases dramatically with load
  - Throughput saturates
  - Error rate starts to grow

Operating conditions

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- Overload/Thrashing (Red)
  - Response time explodes
  - Response time limited by timeout
  - Throughput is constant (overload)
  - Throughput drops (trashing)
  - High error rate
- Our goal:

  → remaining at the end of the green zone

The cost of errors

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- Configuration errors have a cost
- A mis-configured system can be:
- Poor performing
  - 60% slowdown observed in cloud deployments
  - A single bottleneck can slow down a huge chain of services
- Expensive
  - Performance are OK, but cost is huge
  - 10× cost increase observed in cloud deployments

Capacity planning

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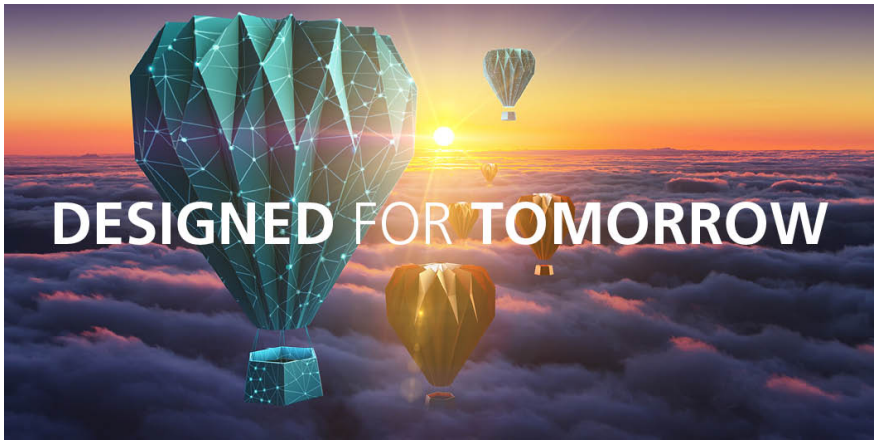
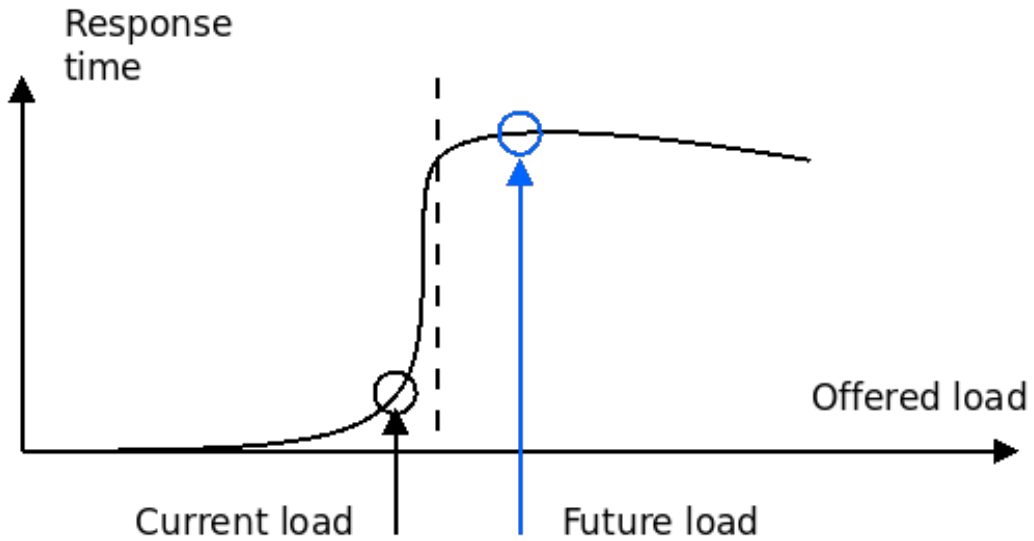
- A system may be running fine
  - Today
  - Tomorrow?
- What about workload evolution?
- What if the load increases by *X*%?
  - Are we still providing acceptable performance
  - If not, how do we cope with this?

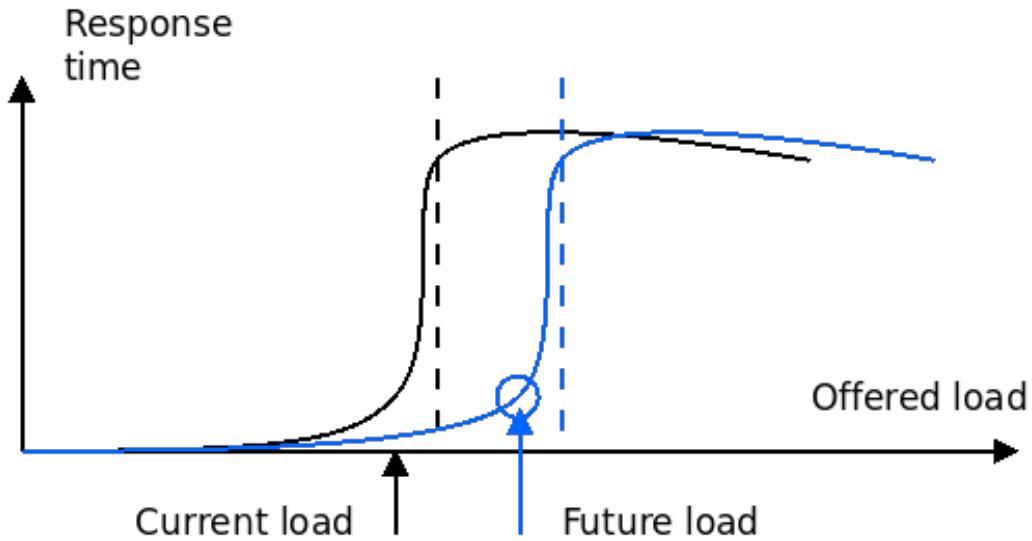


Load evolves



- Current situation:
  - Ideal operating condition
- Future situation
  - High risk of overload

Capacity planning



- Scaling is required
- New provisioning
  - How much more processing power do we need?
  - How to design the new infrastructure

Elasticity done well

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- Cloud computing is elastic
  - Can purchase new computing power as needed
- We still need to understand performance:
  - How many VMs?
  - Which size of VMs?
  - For how much time?
  - What resource is the performance bottleneck?
- Cloud without understanding performance ~~*can be*~~ *is*
  - Tricky
  - Expensive
- Would risk your credit card?

Another (unfortunate) case

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- Scaling based on a model
  - Distributed infrastructure
  - Compute number of replicas to meet SLA
- Use of a (over-)simplified model
  - M/M/1 queuing model

$$N = \sum_{j \in \mathcal{F}} E_j \geq \left\lceil \frac{\Lambda}{\overline{\mu}} \cdot \frac{K-1}{K} \right\rceil$$

  - Neglecting variance of service time variable
- What happens if the service time is highly variant
  - Common scenario: high variance
  - Should use log-normal distribution to describe service

Another (unfortunate) case

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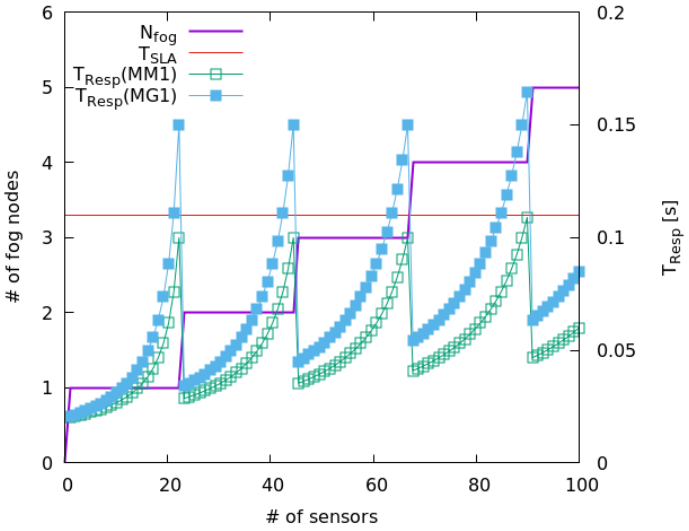
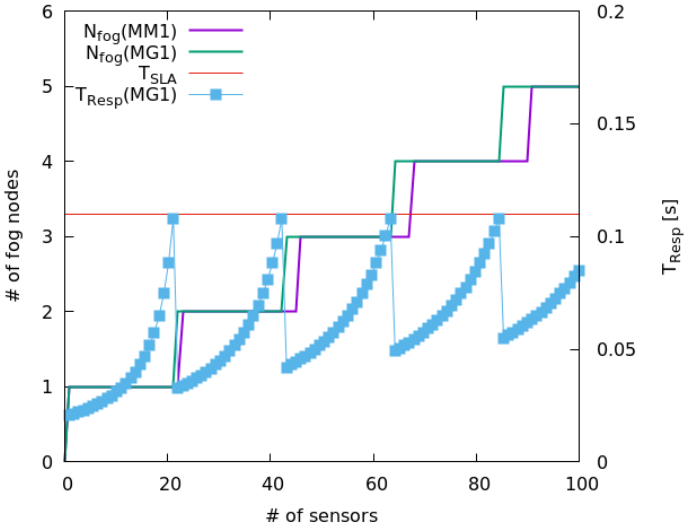
- Wrong model leads to wrong results
  - Expected (green) → OK
  - Real (blue) → SLA violations
- Should use correct model
  - Based on Pollaczek-Khinchin formula

$$N \geq \left\lceil \frac{\Lambda}{\overline{\mu}} \cdot \frac{\mathrm{CoV}^2 - 2K - 1}{2K - 2} \right\rceil$$

  - Correct scaling





Real system testing

Possible approaches

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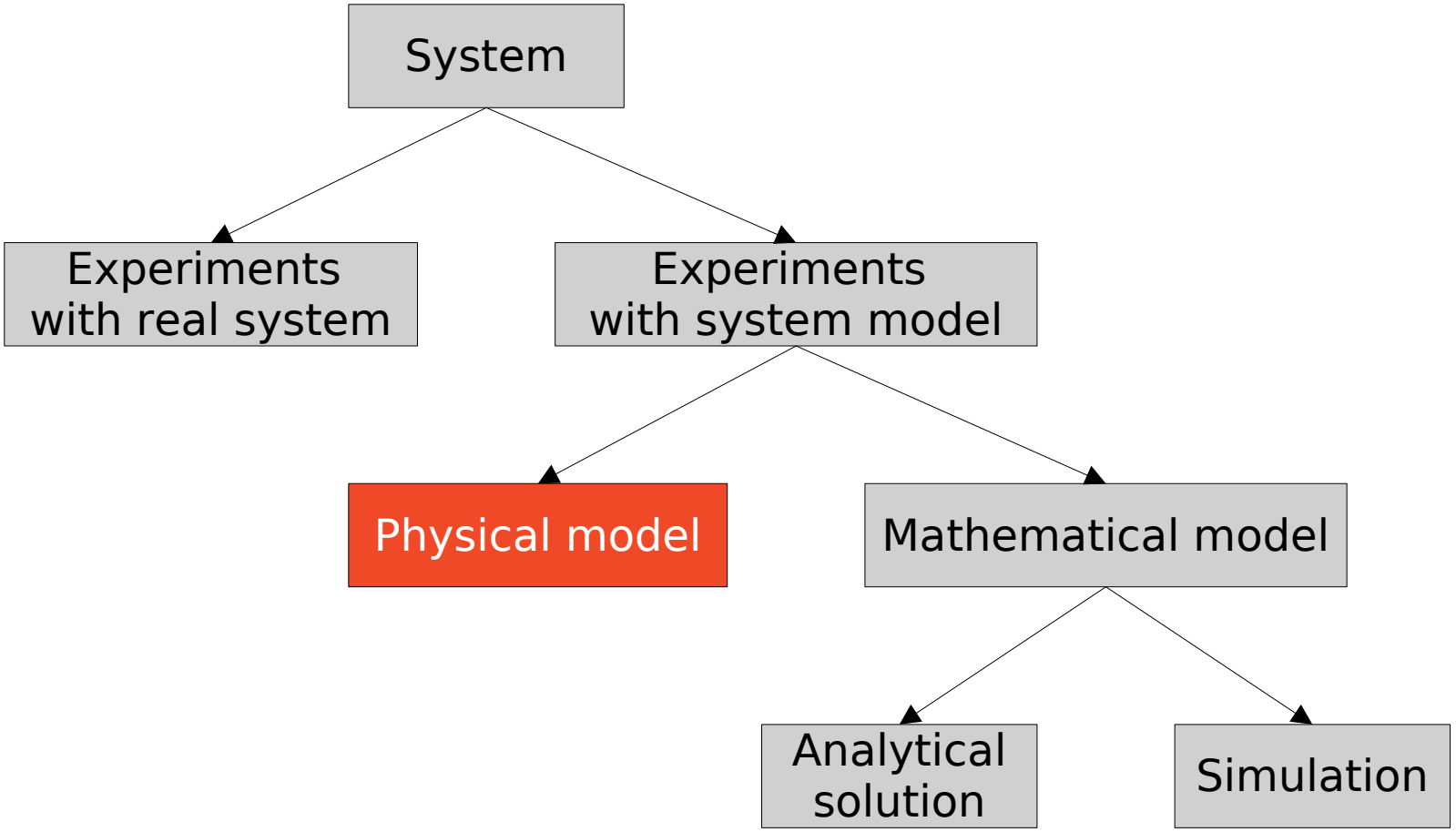

Types of test

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- Functional testing
  - System behaves as expected
- Activity testing
  - System works under normal conditions
- Endurance testing
  - System can scale under (limited) pressure
- Stress testing
  - Limits of the system
- (Benchmarking)
  - Performance under standardized load

Functional testing

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- Functional testing
- Definition of expected behavior
  - Test suite with known results
- Execution of tests
  - Checking expected results
  - Checking error catching
  - Checking for timeouts
  - Bugs/Regressions
- Example:
  - Unit testing

Activity testing

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- Activity testing
- Typical workload
- Normal operation set
- Identification of problems
  - Beyond unit testing
- Example
  - Testing from users
  - Small production deployment

Endurance testing

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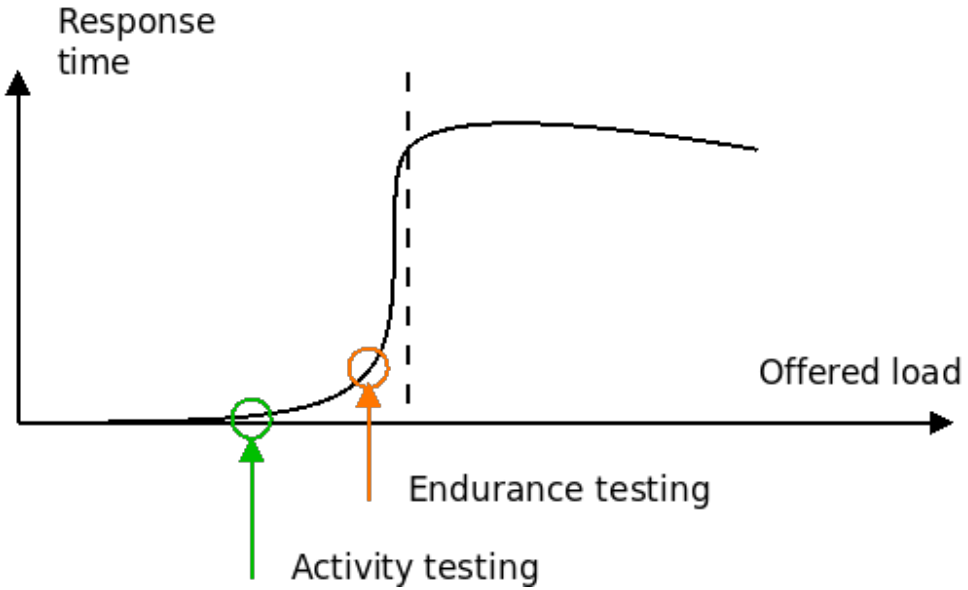
- Endurance testing
- High load → system under stress
- Main focus
  - Is the system still working on rush hours?
  - What-If scenarios
  - *what happens if load increases by 20%?*



Endurance testing

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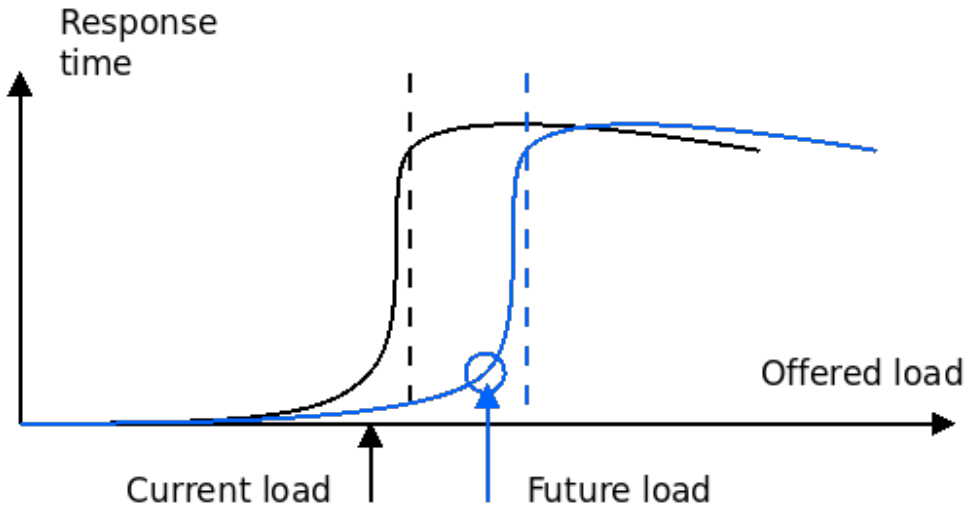
- Endurance testing
- Goals
  - Evaluate scalability
  - Input for capacity planning
- System is under stress
  - *But it is expected to cope with the new conditions*



Stress testing

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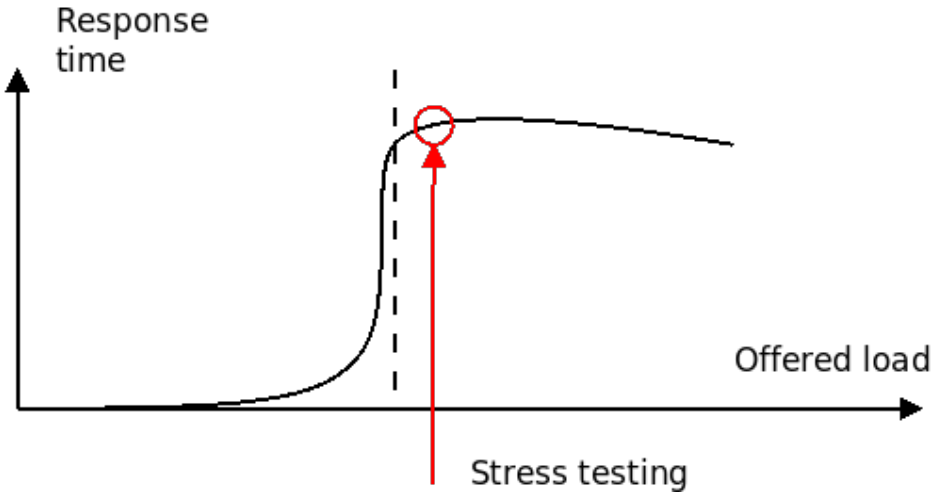
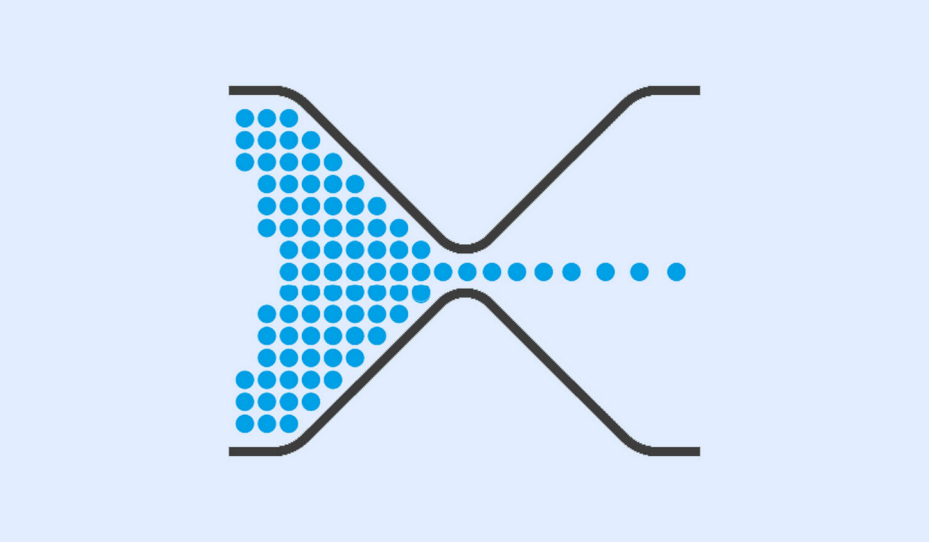
- Stress testing
- System is taken to the limit
  - We aim to create failures
- Main focus
  - What is the maximum load?
  - Where are the system bottlenecks?
  - Presence of trashing?





Example

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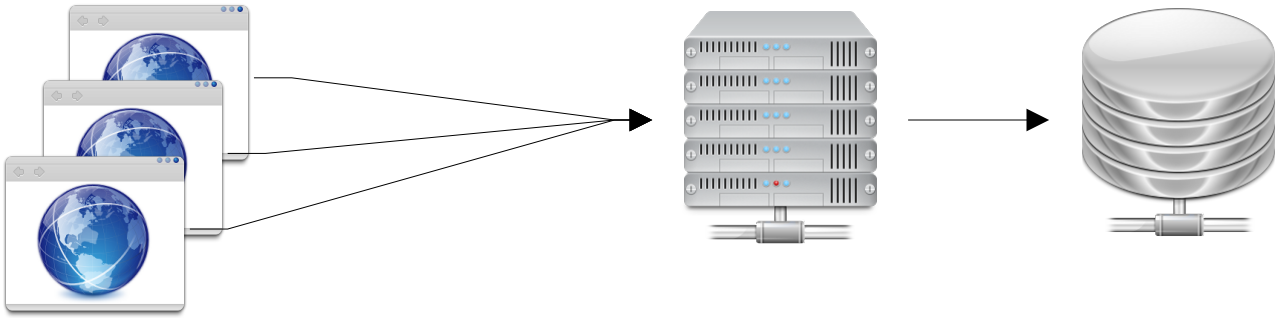
- Example:
- 2-tier Web server
  - DBMS: up to 100 req/s
  - Web server: up to 500 req/s
  - 50% of Web page requests require access to DB
- What is the maximum throughput?
- Where is the bottleneck?



Example

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- Example:
- Incoming load of 500 req/s
  - Web server saturates
  - DBMS receives 500*0.5 = 250 req/s > 100 req/s
- Incoming load of 200 req/s
  - Web server utilization: 60%
  - DBMS is saturated (load = 100 req/s)
- Conclusion
  - Max load is 200 req/s
  - Bottleneck is DBMS

Trashing

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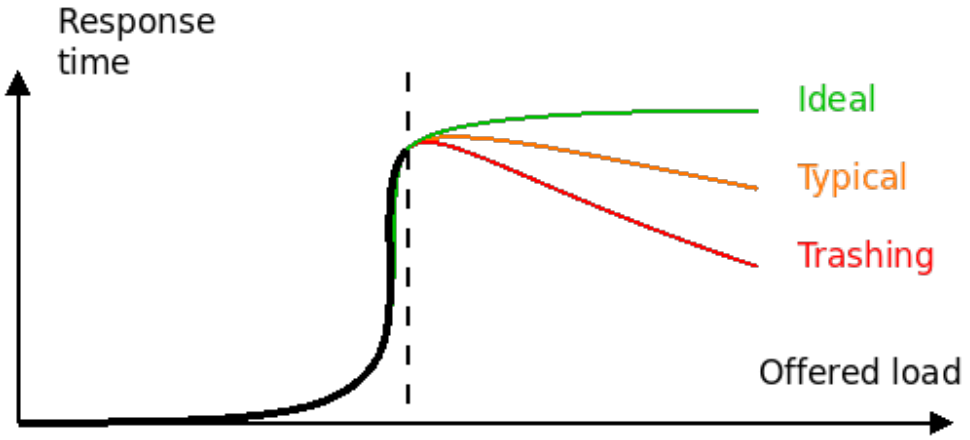
- Stress testing
- Possible behavior
  - Ideal saturation
  - Trashing
  - Intermediate behavior
- Impact of thrashing
  - Cache locality disrupted
  - Resource contention



Benchmarking

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- Performance evaluation requires a workload
- How can I compare my working condition with other scenarios?
- How can I select the best option of every experiment under different workload conditions?
- Need for a standard

Benchmarking

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- Dictionary definition
  - *A point of reference by which something can be measured*
  - *(not necessary related to computers)*
- Computer industry definition
  - *A set of conditions against which a product or system is measured*
  - *A set of performance criteria which a product is expected to meet*
- Critical concepts:
  - Point of reference
  - Benchmark is related to measurement

Benchmarking

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- Load testing
- Evaluating performance
- Realistic workload conditions
- Refers to specific application scenario
- Results cannot be compared outside the specific application

- Benchmarking
- Evaluating performance
- Using workload conditions
  - Well-defined
  - Standardized
- Results can be compared between different systems

Benchmarking

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- Types of benchmark
- Toy benchmark
- Real programs

} Not very representative

- Synthetic benchmarks

} Slightly better, prone to abuse

- Benchmark based on real applications

} Much better

Toy benchmark

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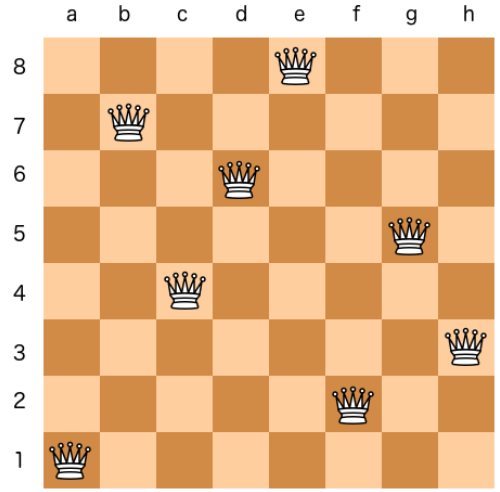
- Toy benchmark
- Small algorithms
- Examples:
  - Quicksort
  - Matrix operations
  - 8 queens problem
- Simple to build
- Easy to run
- Not very representative
  - *Who runs 8-queen problem in daily work?*

$$U = \begin{bmatrix} u_{1,1} & u_{1,2} & u_{1,3} & \cdots & u_{1,n} \\ & u_{2,2} & u_{2,3} & \cdots & u_{2,n} \\ & & \ddots & \ddots & \vdots \\ & & & \ddots & u_{n-1,n} \\ 0 & & & & u_{n,n} \end{bmatrix}$$



Real programs

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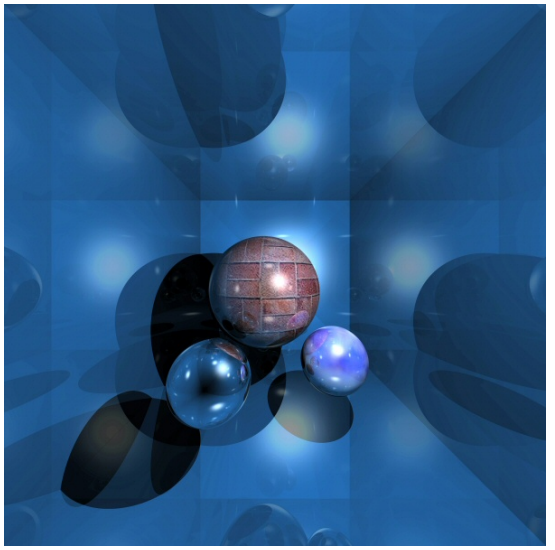
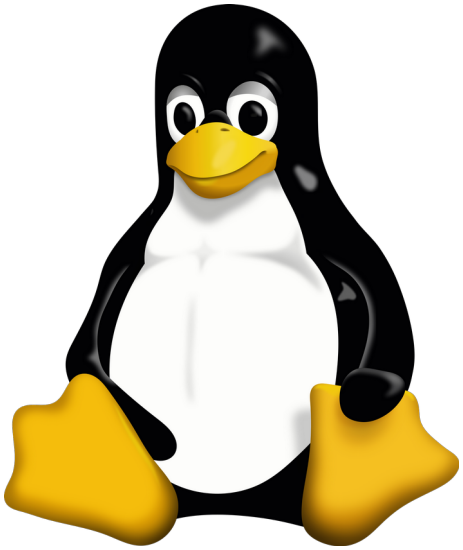
- Real programs
- Run a well known software on a platform
- Time for the task is a measure of system performance
- Examples
  - Ray tracing SW
  - Compiling the linux kernel





Real programs

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- Some common problems
- Not every software works on every platform
  - Porting issues of gcc toolchain
- Optimization problems
  - Driver issues for some GPU
- Not clear if the workload is
  - Significant
  - General to draw meaningful conclusions
- If multiple SW are used
  - How to weight them properly?

Synthetic benchmark

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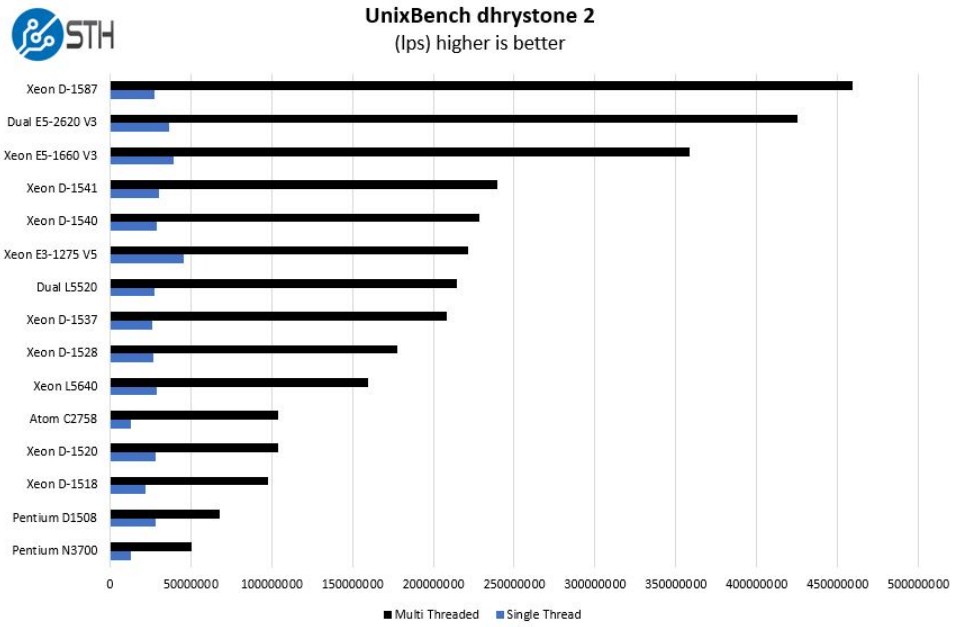
- Synthetic benchmarks
- Based on common operations in software
- Typically focused on some limited aspect of HW architecture
- Dhrystone
  - Integer math performance
- Whetstone
  - Floating point performance



Benchmark abuse

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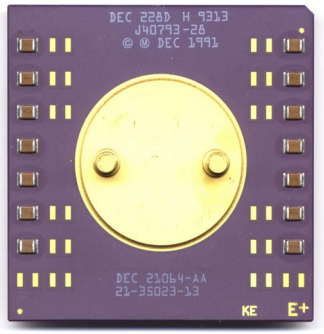
- Cases of benchmark abuse
  - Marketing impact of benchmark results
- Hardware architecture optimized for benchmark performance
  - Multiply-and-sum instruction (Power PC architecture)
- Compiler optimization
  - Unroll-loops in benchmark code
  - Jump optimization (Alpha CPU)
- Benchmark can be
  - Binary (pre-compiled)
  - Source (to compile)



Benchmark abuse

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- Some common tricks
- Use home-brewed benchmark, give no reference
- Show only a subset of suites with better performance
- Modify benchmark source code
- Use only part of the benchmark tests
- Use timing of measures to manipulate overheads
  - E.g., discard first runs to mask cache misses
  - Measure only some overheads that make competitors look bad
- Everything should be clearly stated and motivated

A dirty trick

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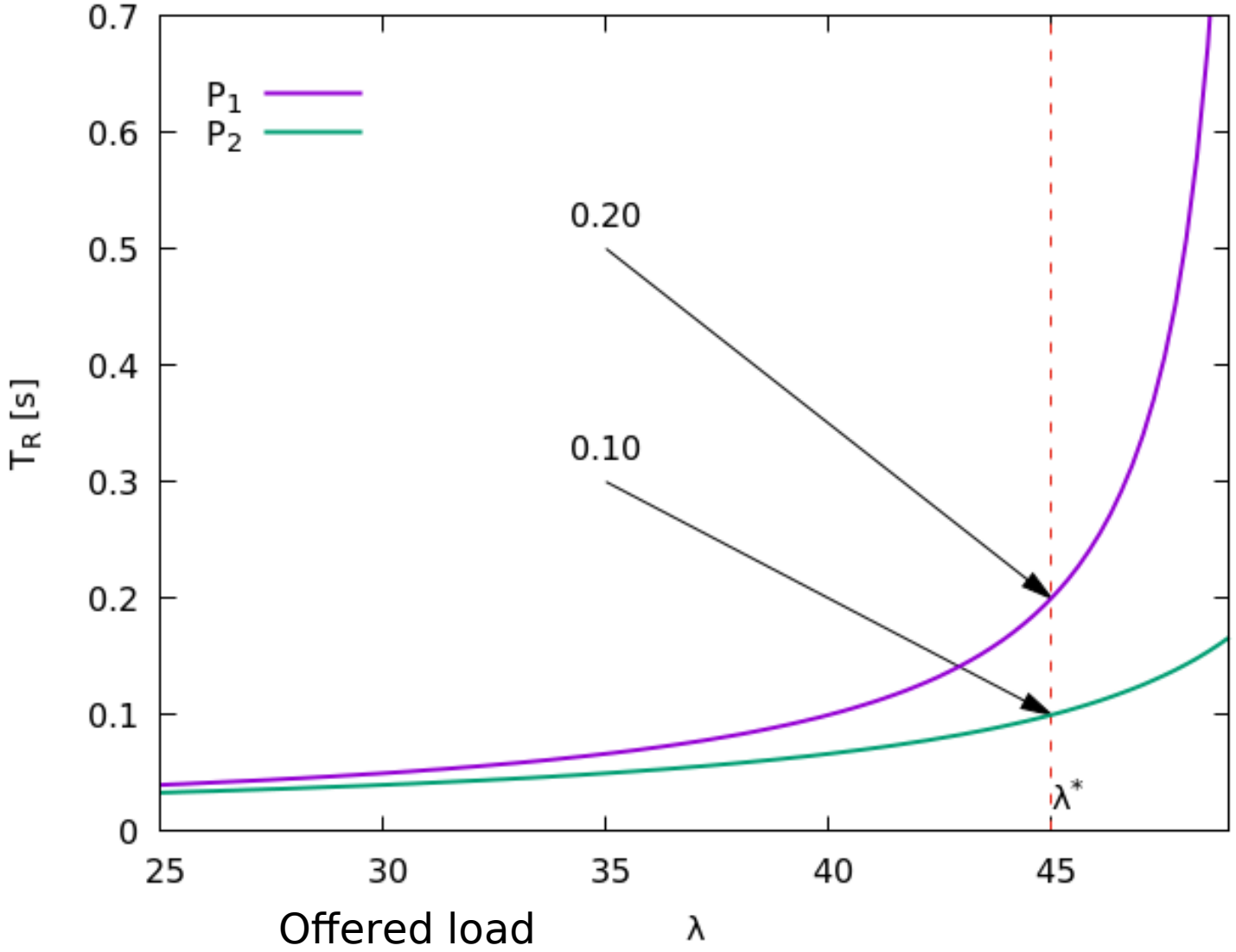
- Let's turn Mr. Hyde for an example
- We want to sell a new CPU
  - Slightly faster than competitors
  - Expensive

- Need good advertisement
  - ~~Pay 50% more for a 10% performance increase~~
- We can *tune* our benchmark
  - When system is heavily loaded small changes in power make the difference in response time
  - Pay 50% more for 2× faster

A dirty trick



A dirty trick

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- We will see the model detail later
- Lessons to bring home
  - Understanding performance model is important
  - Knowing benchmark test conditions is vital
- Now back to Dr. Jekill mode

Real applications

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- Benchmark based on real applications
- Goals:
  - Make benchmark representative of real problems
  - Provide open source code and clear performance measurements
- Compare with previous types of benchmark
  - Full application (not just algorithms)
  - Representative problems (not just kernel compiling)
  - More than ALU testing (not just Int or FP math)
  - Fully standardized scenarios

Standards

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- Old-school benchmarks
  - SPEC
  - TPC
- More cloud-friendly benchmarks
  - SPEC
  - Yahoo YCSB
  - PerfKit Benchmarker

SPEC Web

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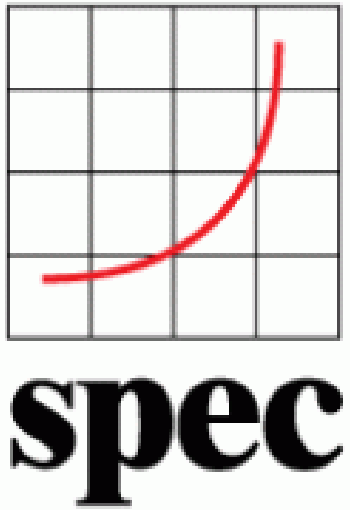
- Developed by SPEC
  - System Performance Evaluation Consortium
  - Non-profit group developing several benchmark
- Representative workload
  - Web requests based on log traces
  - Logs from NCSA, HP, ...



SPEC Web

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- Workload
  - 4 classes of files
  - Poisson file size distribution in classes
- Scaling
  - N. directory in data set ×2 as data set size ×4
  - Requests evenly distributed on dirs
- Emulated Users model
  - On-off model
  - Think time for pages

Fraction [%]	Size
35%	0 – 1 KB
50%	1 – 10 KB
14%	10 – 100 KB
1%	100 KB – 1 MB

- Support for levels of burstiness
- Architecture:
  - One controller
  - Multiple clients
  - One server

SPEC Web

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- Evolution of benchmark
- Different directory size
- Support for HTTP/1.1
  - Keep-alive requests (70%)
  - Cookies
- Support fo dynamic content
- Support for advertisement based on user-id cookie
- Zipf file popularity model

Fraction [%]	Type
70.00%	Static GET
12.45%	Dynamic GET
12.60%	Dynamic GET+ Ad
4.80%	Dynamic POST
0.15%	Dynamic GET + CGI

TPC

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- TPC:
  - Transaction Processing Performance Council
- Several classes of benchmarks:
- TPC-W:
  - Web-based benchmark
- TPC-D
  - Database benchmark
- Each benchmark is based on a test application

TPC

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- TPC-W
- Dynamic Web site (changes with version)
  - Book store (like Amazon)
  - Auction system (like ebay)

- Auction system inspired by RUBiS benchmark
  - Rice University Bidding System
  - Auction in Java and PHP

TPC-W

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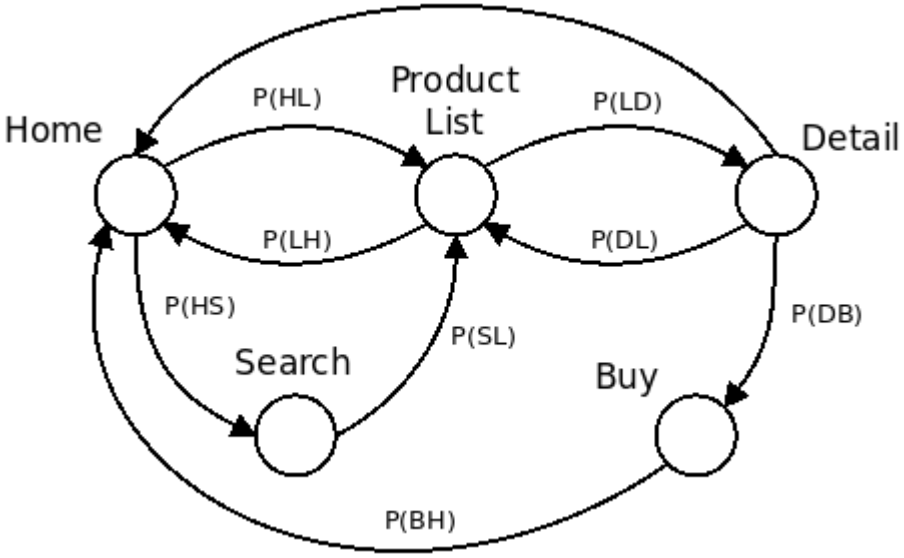
- Definition of workload
  - Several dynamic web pages
  - Database size (product catalog)
- Definition of user behavior
  - User defined as stochastic FSM
  - Each page is a state
  - Probability of passing from a page to another
- Population of users
- Multiple workload mixes (browsing/shopping/...)



SPEC-Cloud

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- SPEC-Cloud
- IaaS-oriented benchmark
- Focus on
  - Scalability
  - Elasticity
- Test:
  - Scalability → load increases without creating errors
  - Elasticity → load changes, SLA preserved

YCSB

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- YCSB
  - Yahoo Cloud Serving Benchmark
- Developed by Yahoo!
- Focus on Cassandra Database
- Available on github
- Test of transactions on a DB
  - Replicated
  - NoSQL

tjake/**YCSB-test**

Yahoo! Cloud Serving Benchmark

0 Contributors | 0 Issues | 2 Stars | 1 Fork

YCSB

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- Access to Key-Value storage
- Multi-phase benchmark
- Baseline phase
  - Run once the application
- Elasticity+Scalability phase
  - Re-run application with varying workload intensity
  - Collect measures
  - Compare with baseline

YCSB

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- Scalability metric
  - Throughput speedup compared to baseline
- Elasticity metric
  - Performance deviation from baseline
- Other metrics
  - Instance provision time (time to deploy new VM)
  - Instance run success (percentage of successful runs)
  - Provisioning success (percentage of new instance successfully deployed)

PerfKit Benchmarker

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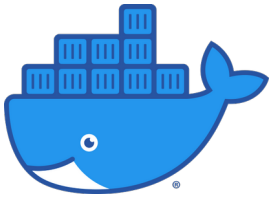
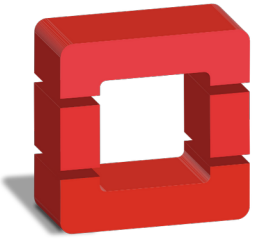
- Google tool
- Comparison of cloud solutions
  - Focus on network performance
- PKB features
  - Automatic setup and tear-down
  - Support for Docker and Open Stack
  - Most common workloads supported





openstack
CLOUD SOFTWARE

PerfKit Benchmarker

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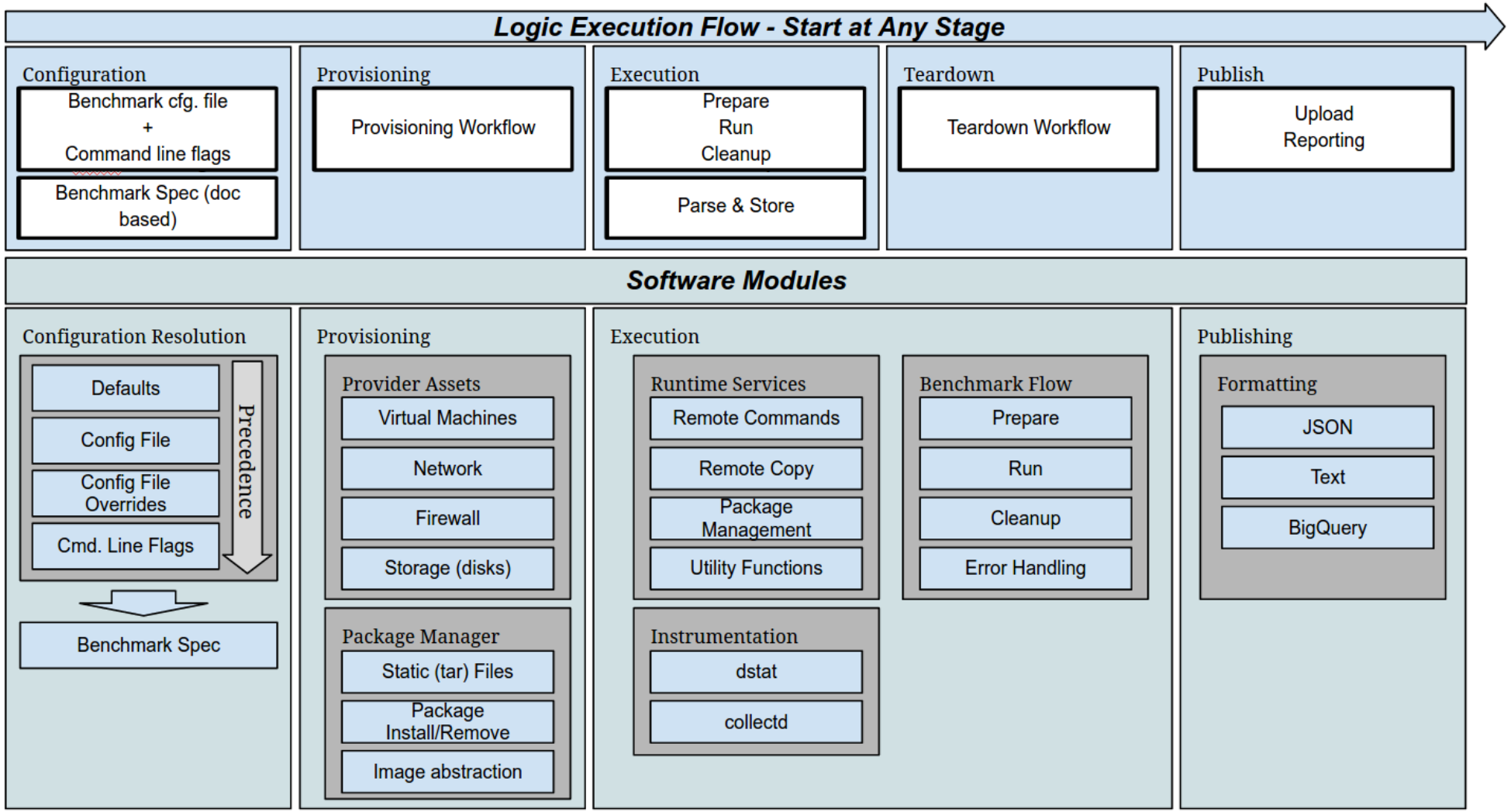

Benchmark architecture

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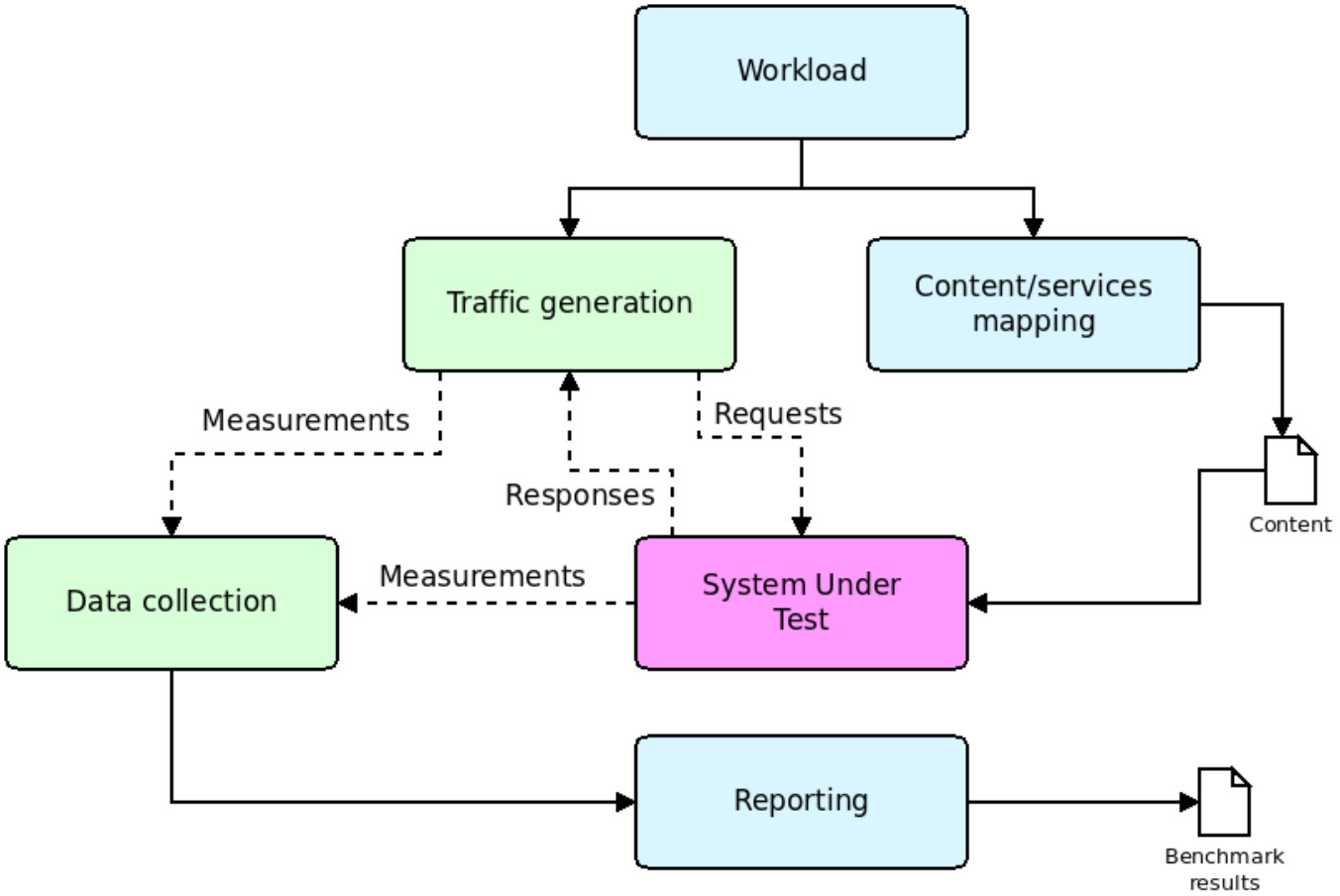
- Most examples seen share a common architecture
- Declined based on the goals of the performance study



Mathematical models

Possible approaches

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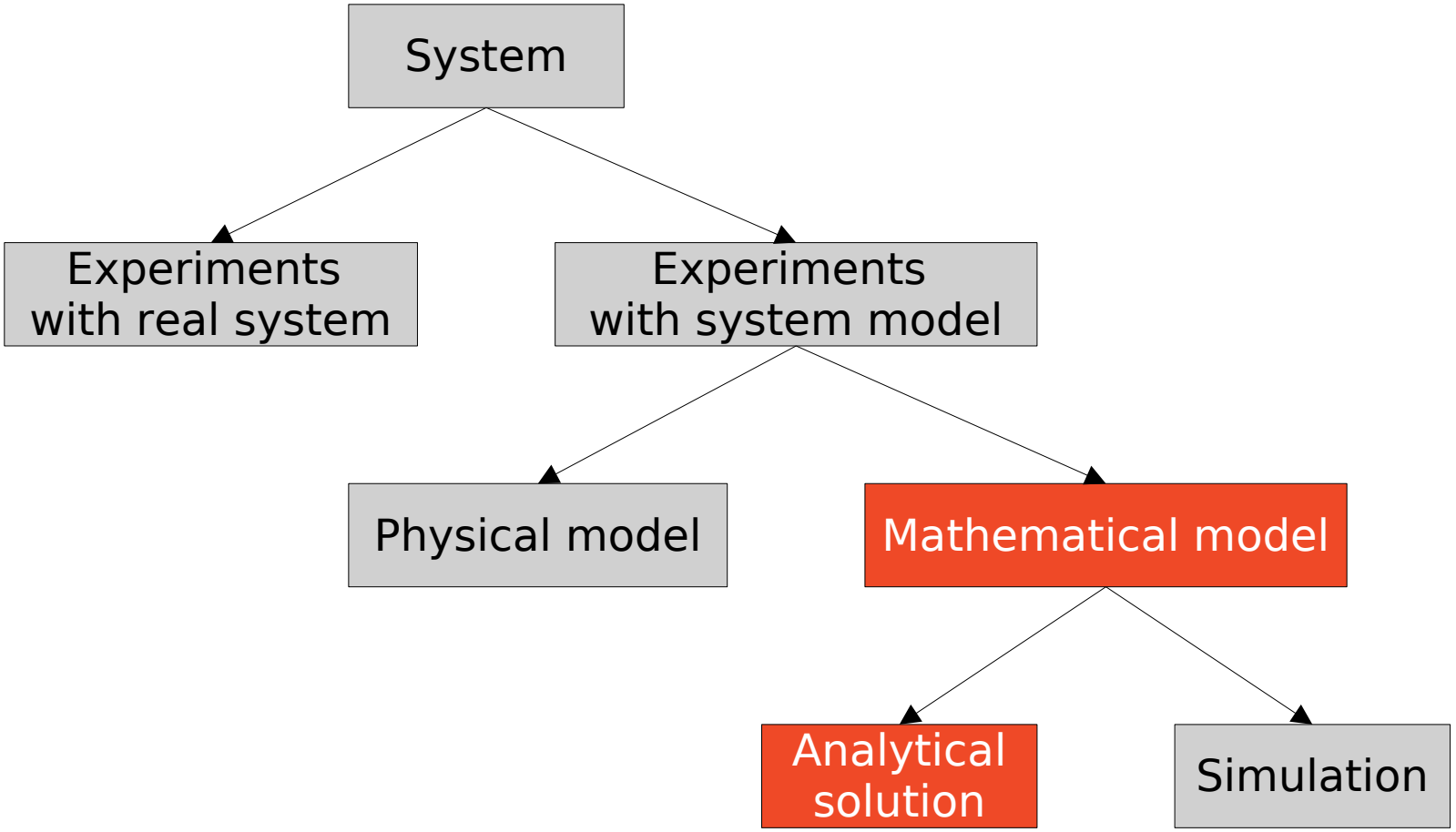

A simple example

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- Multi-tier Web server
- Main contributions of response time:
  - Network
  - Front-end node
  - Middle-tier node
  - Back-end node
- Each node response time:
  - CPU time
  - Storage time (data retrieval)
  - Communication (LAN)

Network model

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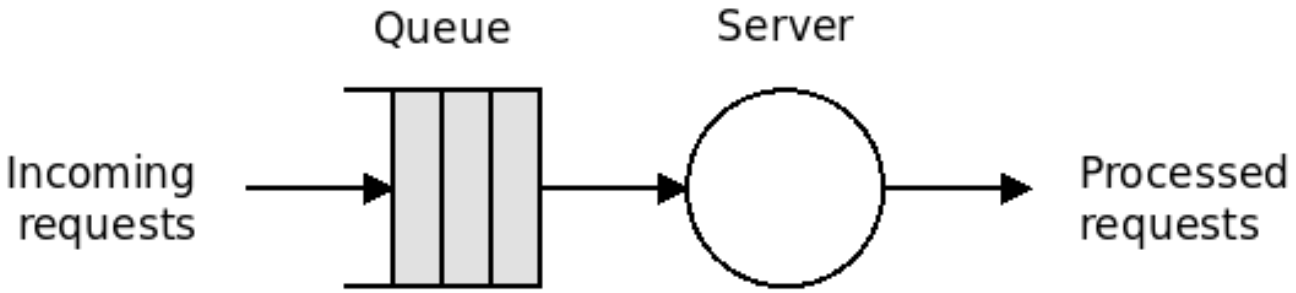
- Queuing model
- Example: network
  - Input: Incoming packets to be delivered
  - Output: delivered packets
  - Network is busy during transmission
  - Packets wait in routers queues



Nodes model

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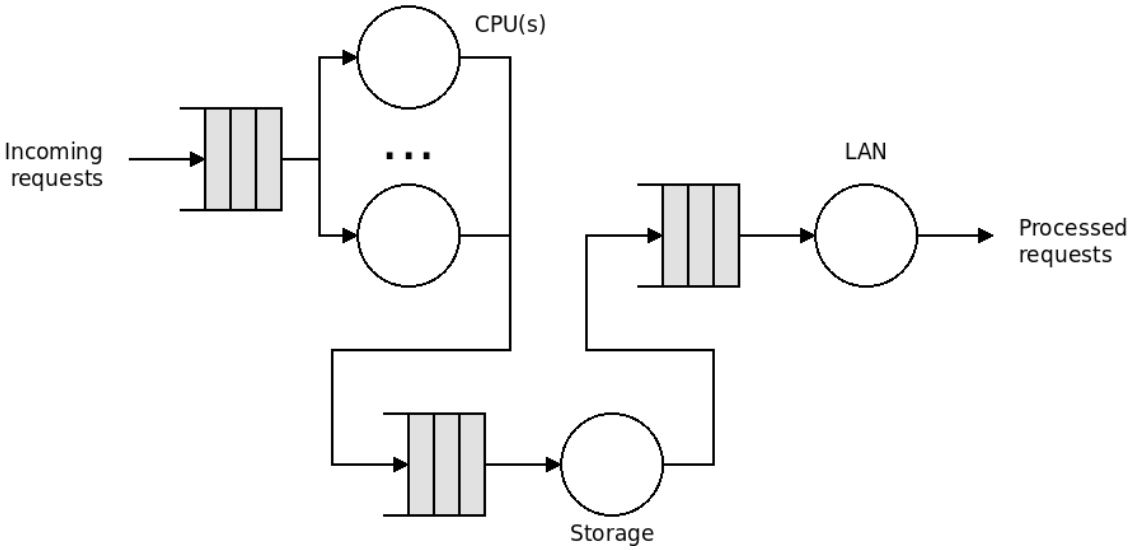
- Node model
  - CPU (multiple parallel servers for multi-core arch.)
  - LAN
  - Storage
- Each resource as a queue model



Big picture

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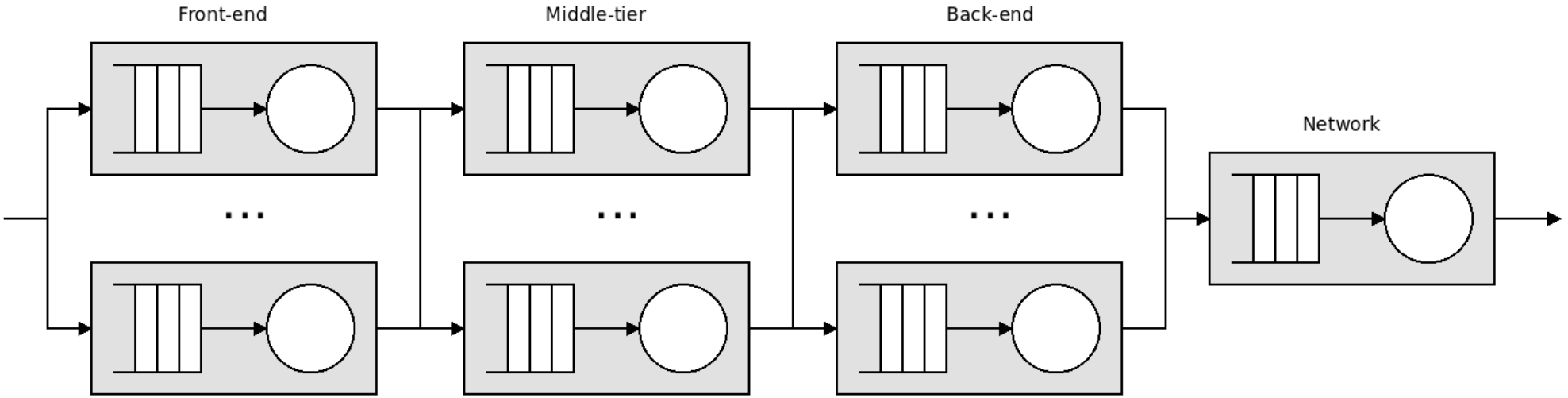
- Complex model
- Several queues
- Same questions
  - Where is the bottleneck?
  - How to address it?



Modeling the problem

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- Focus on a single node
  - Queues: CPU, storage, LAN
  - 1 server per each resource
- Workload
  - S_i: average service time at i-th resource ($1/\mu$)
  - W_i: average waiting time at i-th queue
  - λ_i: arrival rate at i-th queue

Modeling the problem

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- Performance metrics
  - R_i: average response time at i-th queue
  - X_i: throughput of i-th queue
  - X_0: overall system throughput
- Number of jobs at a resource
  - N_{iw}: requests in waiting queue at i-th resource
  - N_{is}: number of requests being serviced [0,1] (or [0,m])
  - N_i: number of requests at i-th resource

Utilization law

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- B_i the time the serve is busy in observation period τ
- C_i completed requests in period τ
- Utilization $U_i = B_i/\tau$
  - But $X_i = C_i/\tau$
  - Hence $1/\tau = X_i/C_i$
  - $U_i = B_i * X_i/Ci = (B_i/C_i) * X_i = S_i * X_i$
- In a steady state: $X_i = \lambda_i * S_i$
  - Often used notation: $\rho=\lambda/\mu$
- In a multiple server queue (with m servers)
  - $U_i = (X_i/m) * S_i$

Little's law

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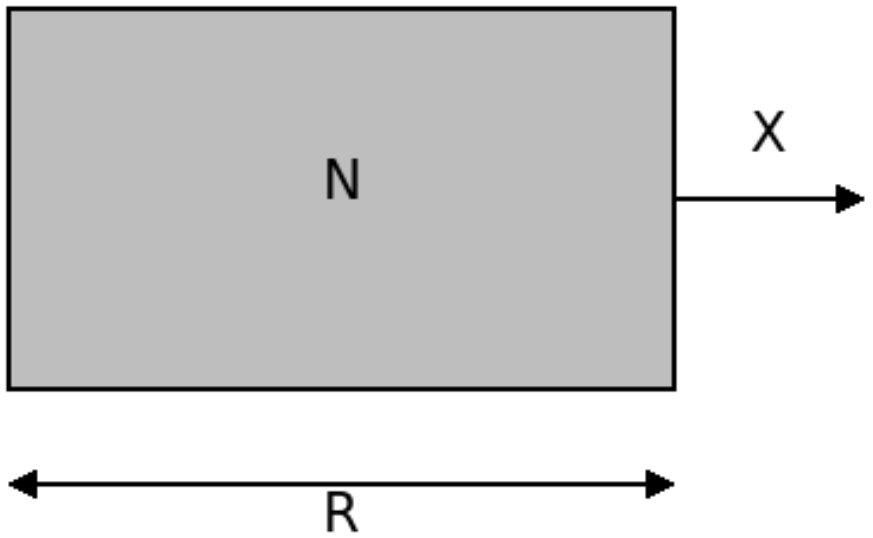
- System as a black box
  - N requests inside
  - X rate of outgoing requests (throughput)
  - R time spent within the system



Little's Law

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- General formulation:
  - $N=X*R$
- Applied to our problem:
  - Waiting: $N_{iw} = X_i * W_i$
  - Service: $N_{is} = X_i * S_i$
  - Response: $N_i = X_i * R_i$

Open/Closed loop models

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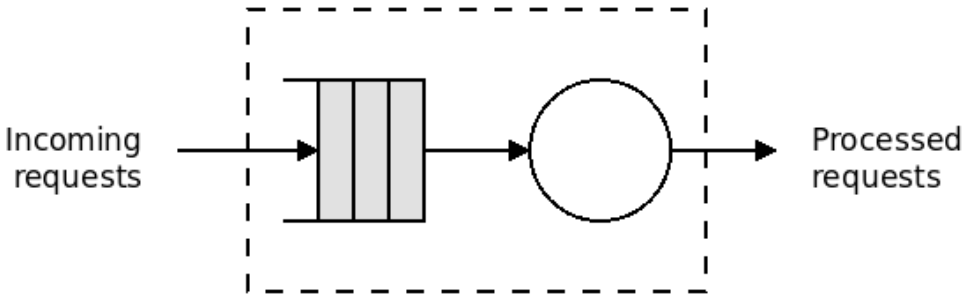
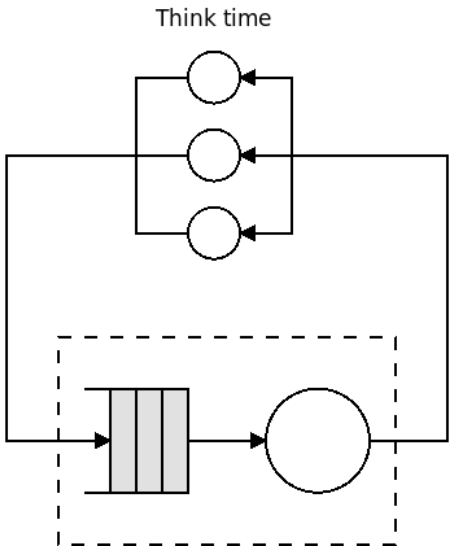
- Open loop:
  - Potentially infinite population of users
  - Requests come in and go out form system
- Closed loop:
  - Finite population of users
  - Requests circle through the system
  - Think time of users





Response time law

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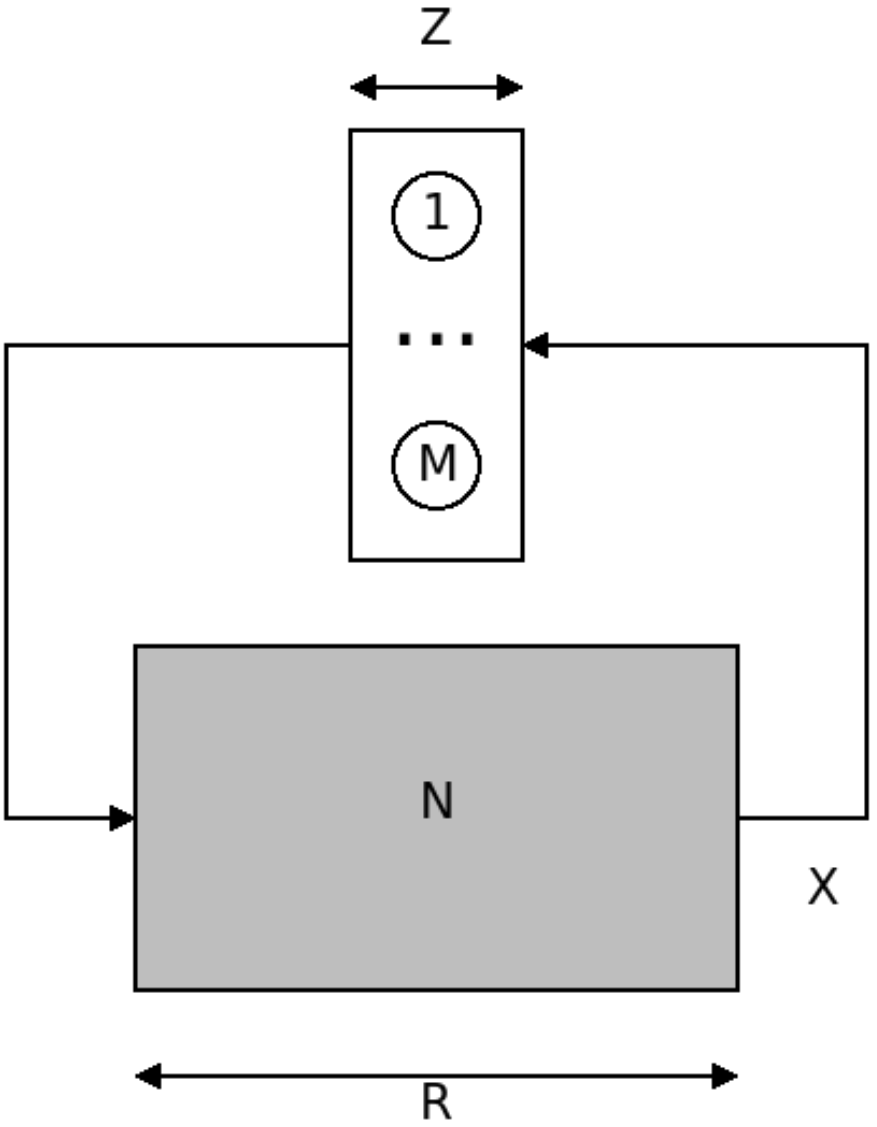
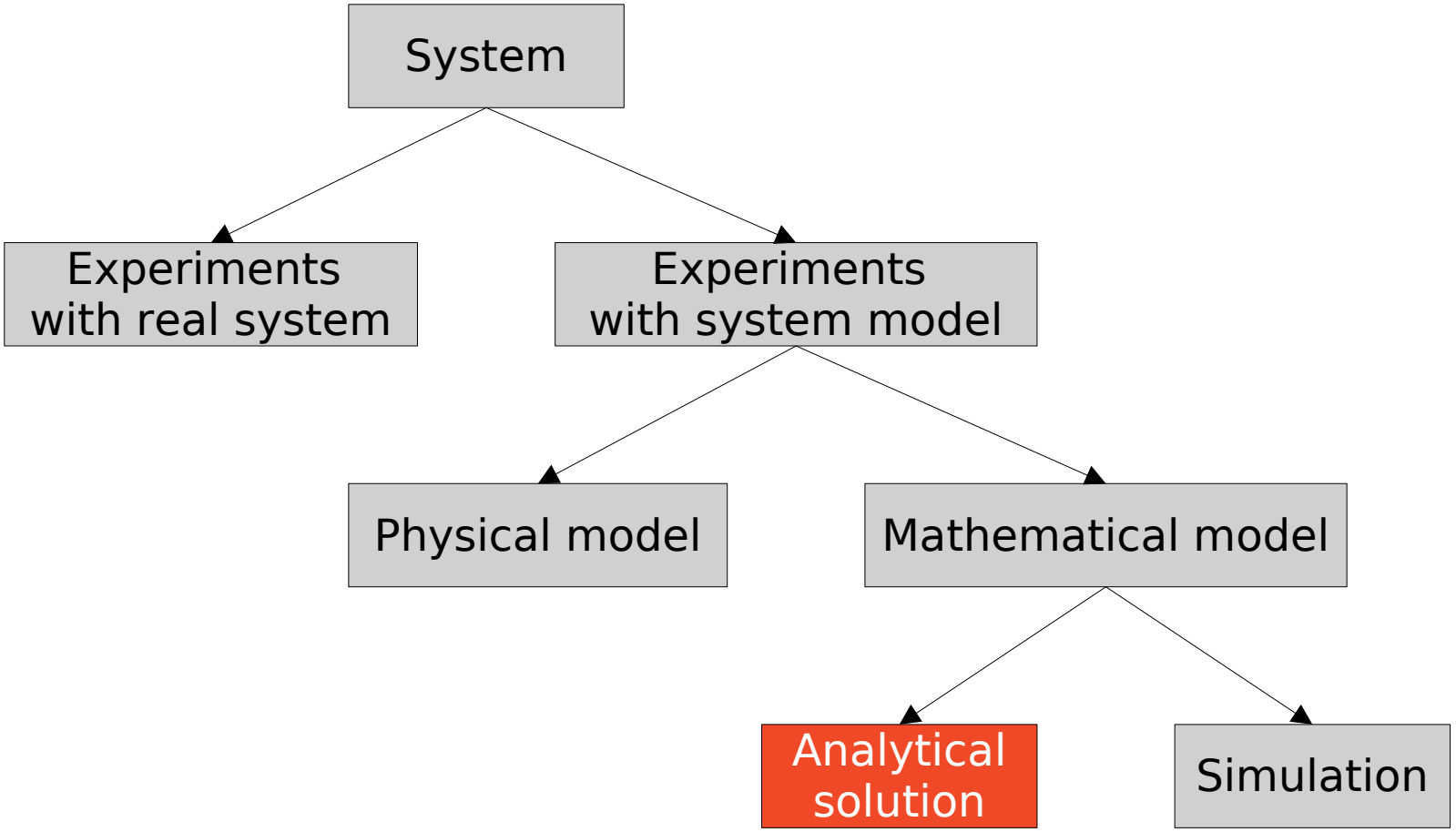
- Overview:
  - System with a population of M users
  - Think time Z
- Closed loop formulation of little's law
  - R+Z = M/X



Queuing theory

Possible approaches



Stochastic process

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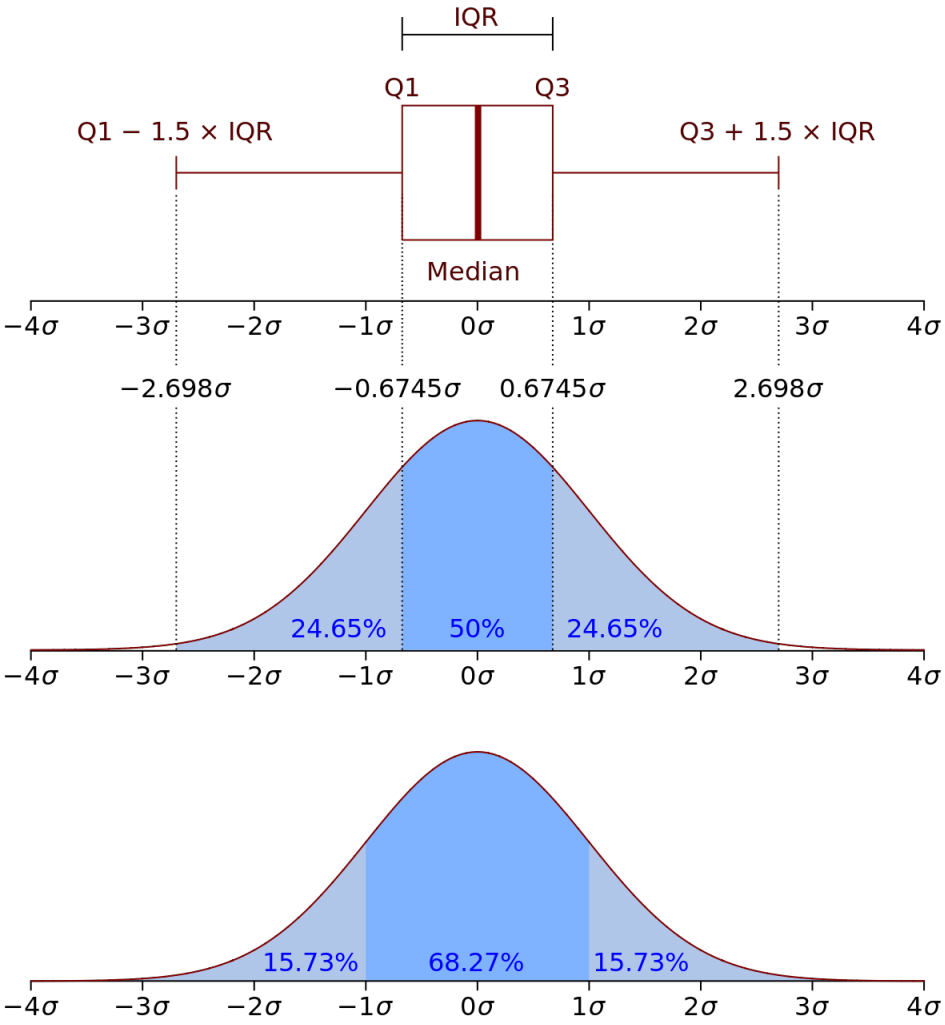
- Stochastic process
  - A process driven by random behavior
  - Defines a family f random (aleatory) variables
- Aleatory variable
  - Can be described by its statistical properties
  - e.g., PDF



System overview

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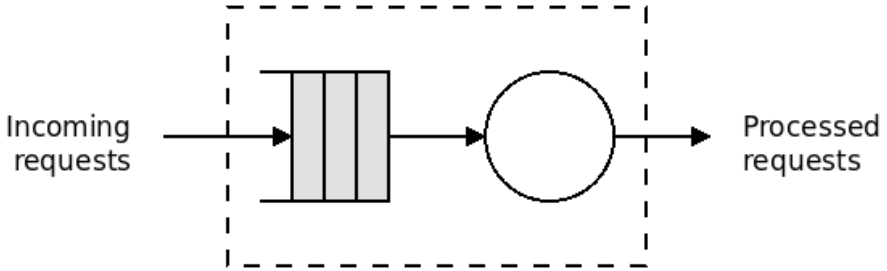
- Open loop
- Incoming job
  - Stochastic process
  - Inter-arrival time is a random variable
- Processed requests
  - Stochastic process
  - Processing time is another random variable



Some definitions...

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- System definition
  - {Arrival}/{Process}/{# Servers}/{Queue Len}…
  - e.g.: M/M/1/∞ (M/M/1 for short)
- Some stochastic processes:
  - M → Poisson (memory-less)
  - D → Deterministic
  - E_K → Erlang distribution
  - G → Generic
- Poisson process are easy to model
  - Use of Markov Chain (the M in the process)

Poisson process

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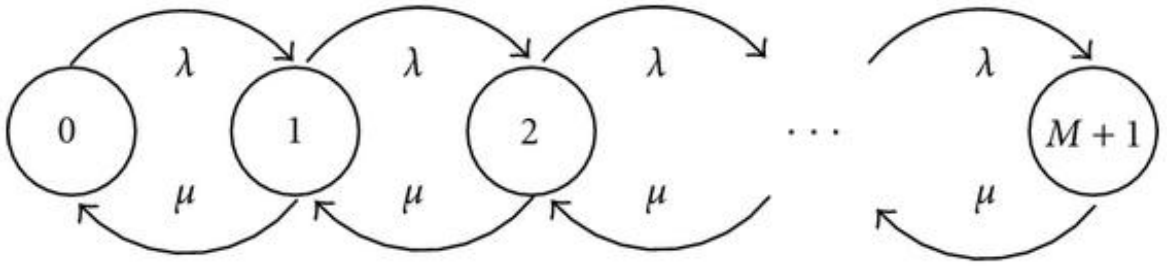
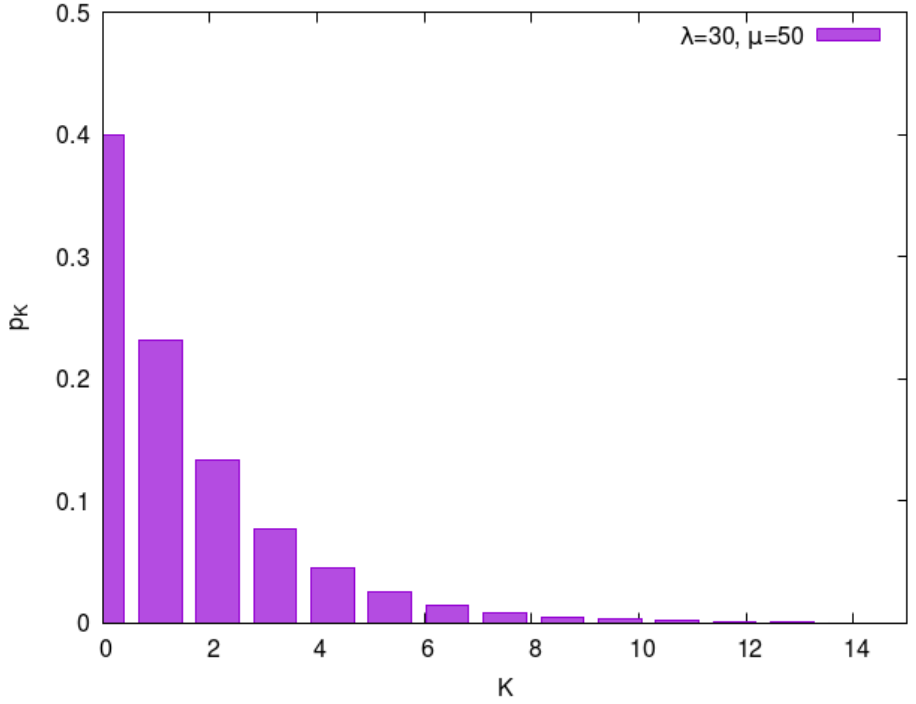
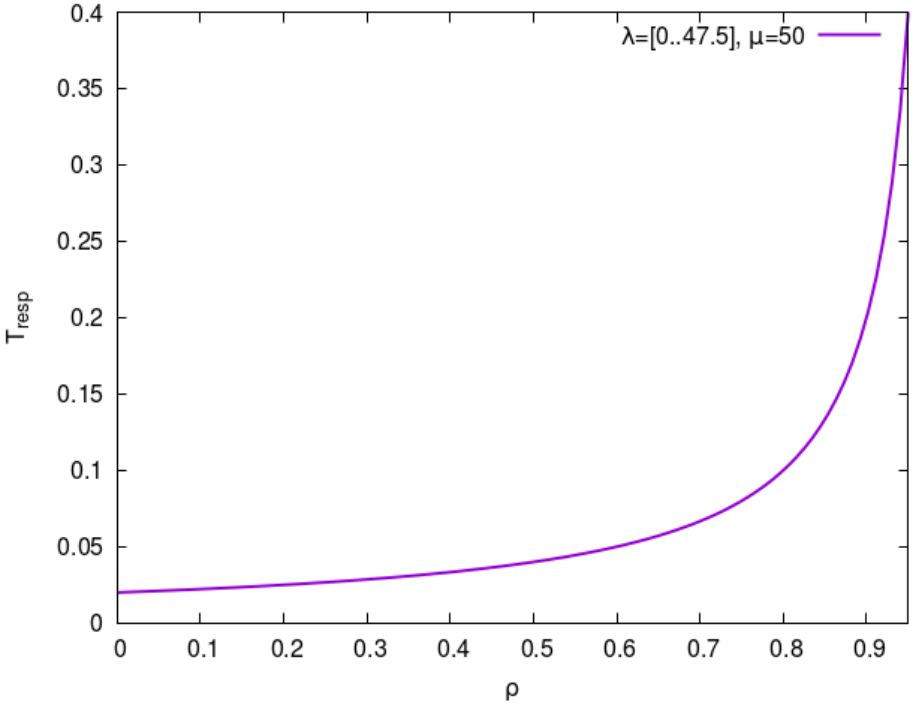
- Status:
  - Elements in system
- Poisson process:
  - Rates do not depend on status
  - Arrival rate: λ
  - Leave rate: μ
  - Utilization: $\rho = \lambda / \mu$
  - Probability to be in state k: $p_k = (1 - \lambda/\mu)(\lambda/\mu)^k = (1-\rho)\rho^K$



Poisson process





- Overview of Poisson process:
  - Infinite queue size
  - Probability of being state K
  - Response time as function of arrival rate: $T_{resp} = 1/(\mu - \lambda)$

Other useful formulas

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- PASTA Theorem (M/G/1 systems)
- Pollaczek-Khinchin Formula

$$\begin{cases} \mathrm{E}[W] = \dfrac{\lambda \mathrm{E}[S^2]}{2(1-\rho)} = \dfrac{1+C_v^2}{2} \cdot \dfrac{\rho}{1-\rho} \cdot \mathrm{E}[S] \\ \mathrm{E}[T] = \mathrm{E}[S] + \dfrac{\lambda \mathrm{E}[S^2]}{2(1-\rho)} = \left(1 + \dfrac{1+C_v^2}{2} \cdot \dfrac{\rho}{1-\rho}\right) \cdot \mathrm{E}[S] \end{cases}$$

- E[W]: average waiting time
- E[T]: average response time
- E[S]: average service time (1/μ)

Other useful formulas

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- Allen-Cuneen approximation (G/G/N systems)

$$W_M = \frac{P_{cb,N}}{\mu N(1-\rho)}\left(\frac{C_S^2 + C_D^2}{2}\right), \qquad P_{cb,N} \approx \begin{cases} (\rho^N + \rho)/2 & \text{if } \rho \geq 0.7 \\ \rho^{\frac{N+1}{2}} & \text{otherwise.} \end{cases}$$

- W_M Average waiting time
- $P_{cb,N}$ Probability that all servers are busy
- C_S, C_D, Coefficient of variation
  - arrival (C_S)
  - Service (C_D)
  - Coefficient of variation = Std. Dev / Average

A dirty trick (reprise)

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- Let's turn Mr. Hyde for an example
- We want to sell a new CPU
  - Slightly faster than competitors
  - Expensive

- Need good advertisement
  - ~~Pay 50% more for a 10% performance increase~~
- We can *tune* our benchmark
  - When system is heavily loaded small changes in power make the difference in response time
  - Pay 50% more for 2× faster

A dirty trick (reprise)

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- We need to find the right load λ^*
  - Goal: 2× gain on response time
- Real advantage
  - Throughout speedup is K
  - Competitor processor: 50 req/s
  - Our processor: 55 req/s → K=1.1
- Assume a simple setup:
  - Poisson request arrival
  - Poisson service

Challenge

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- How to model the problem?
- How to find λ^*?
- Volunteers?

A dirty trick (reprise)

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- We model the systems as M/M/1 systems
- Processor P1 (slow):
  - $\mu_1 = \mu$
  - $T_1(\lambda) = 1/(\mu-\lambda)$
- Processor P2 (our, fast):
  - $\mu_2 = K\,\mu$
  - $T_2(\lambda) = 1/(K\mu-\lambda)$
- P2 is 2x faster at λ^*
  - $T_1(\lambda^*) = 2\,T_2(\lambda^*)$

A dirty trick (reprise)

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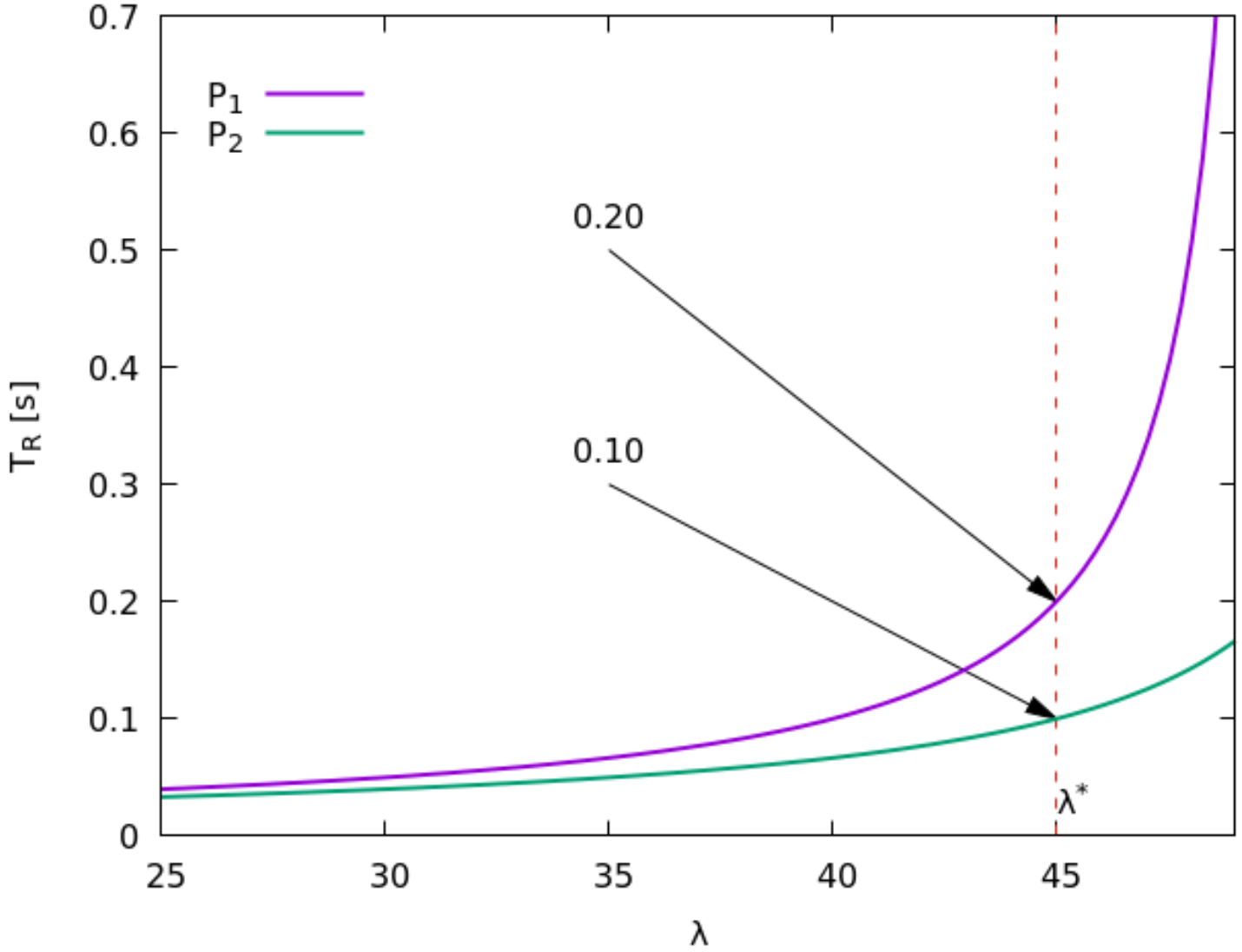
- Solution is easy:
  - $\lambda^* = (2-K)\mu$
- We can now plot the results

A dirty trick



Other exercises

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- We have an incoming load $\lambda > \mu$
- We want to scale-up our system → K servers
- Assumption:
  - Requests can be distributed uniformly over servers
- How many servers do I need to avoid overload?
- Assumption
  - I have a maximum response time T_{SLA}
- How many servers do I need to meet the SLA?
- Volunteers welcome

Failures

Availability

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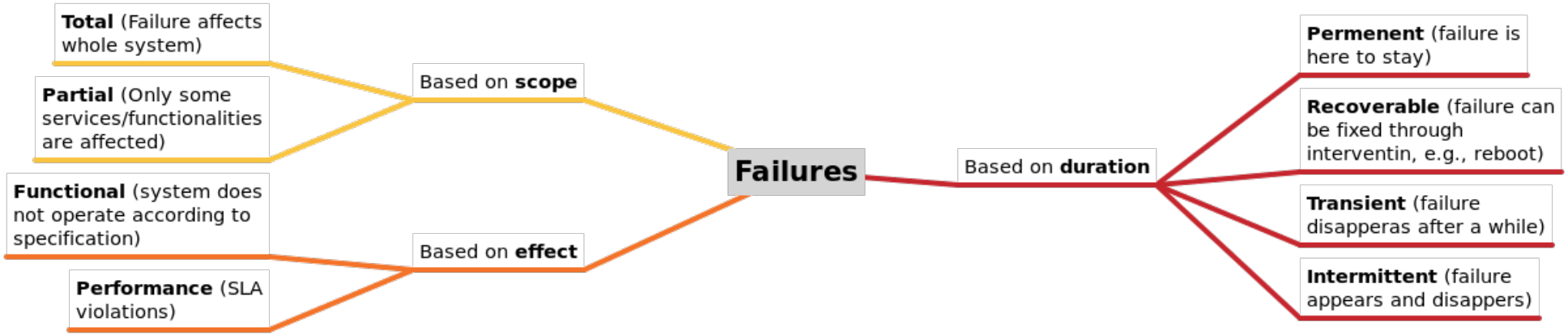
- Being available → not being in a failure state
- Classification of failures
  - Several criteria



Failures

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- Classification based on Duration
- Permanent
  - Failure is here to stay
- Recoverable
  - It is possible to return online after intervention (e.g., restart, reboot)
- Transient
  - Failure disappears after a while
- Intermittent
  - Failure that appears and disappears

Failures

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- Classification based on Effect
- Functional
  - The system does not operate according to its functional specifications
  - “System is not working right”
- Performance
  - System works but not in a timely fashion
  - SLA violations

Failures

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- Classification based on Scope
- Total
  - Failure affects the whole system
- Partial
  - Only some services/functionalities are affected

Failure metrics

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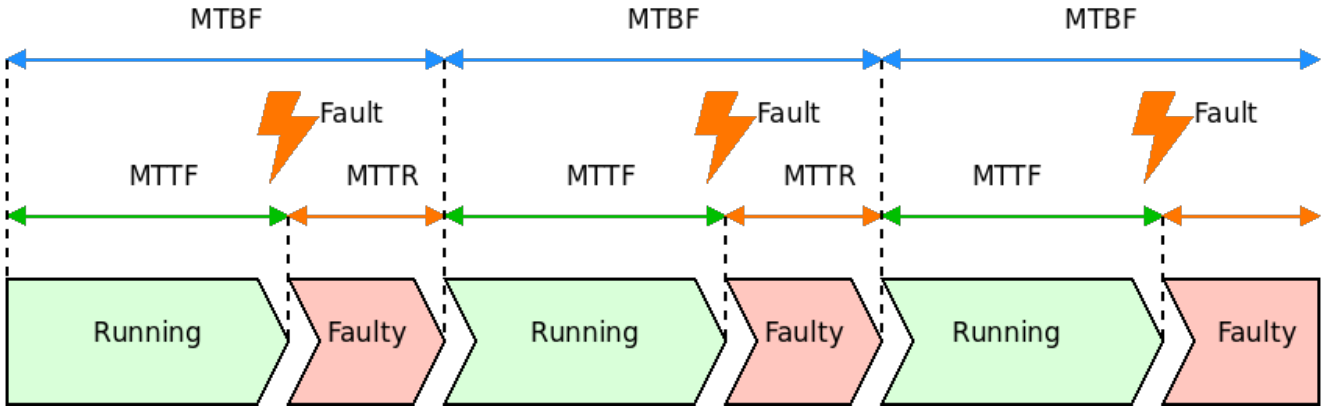
- MTBF
  - Mean Time Between Faults
- MTTF
  - Mean Time To Fault
- MTTR
  - Mean Time To Repair
- MTBF=MTTF+MTTR



Availability classes

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Availability Class	Availability	Unavailable [min/y]	System Type
1	90.0%	52560 (36d)	Unmanaged
2	99.0%	5256 (3.6d)	Managed
3	99.9%	526 (8.8h)	Well-managed
4	99.99%	52.6	Fault-tolerant
5	99.999%	5.3	Highly Available
6	99.9999%	0.53	Very Highly Available
7	99.99999%	0.053	Ultra Available

- Availability
  - Fraction of time when the system is operational
  - Availability A=MTTF/MTBF

Availability and reliability

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- Availability
  - Probability that a system is available at time t
- Reliability
  - Probability that a system works correctly during a period τ
- If the observation period τ is long enough Availability and Reliability converge to the same value

Fault-tolerance checklist

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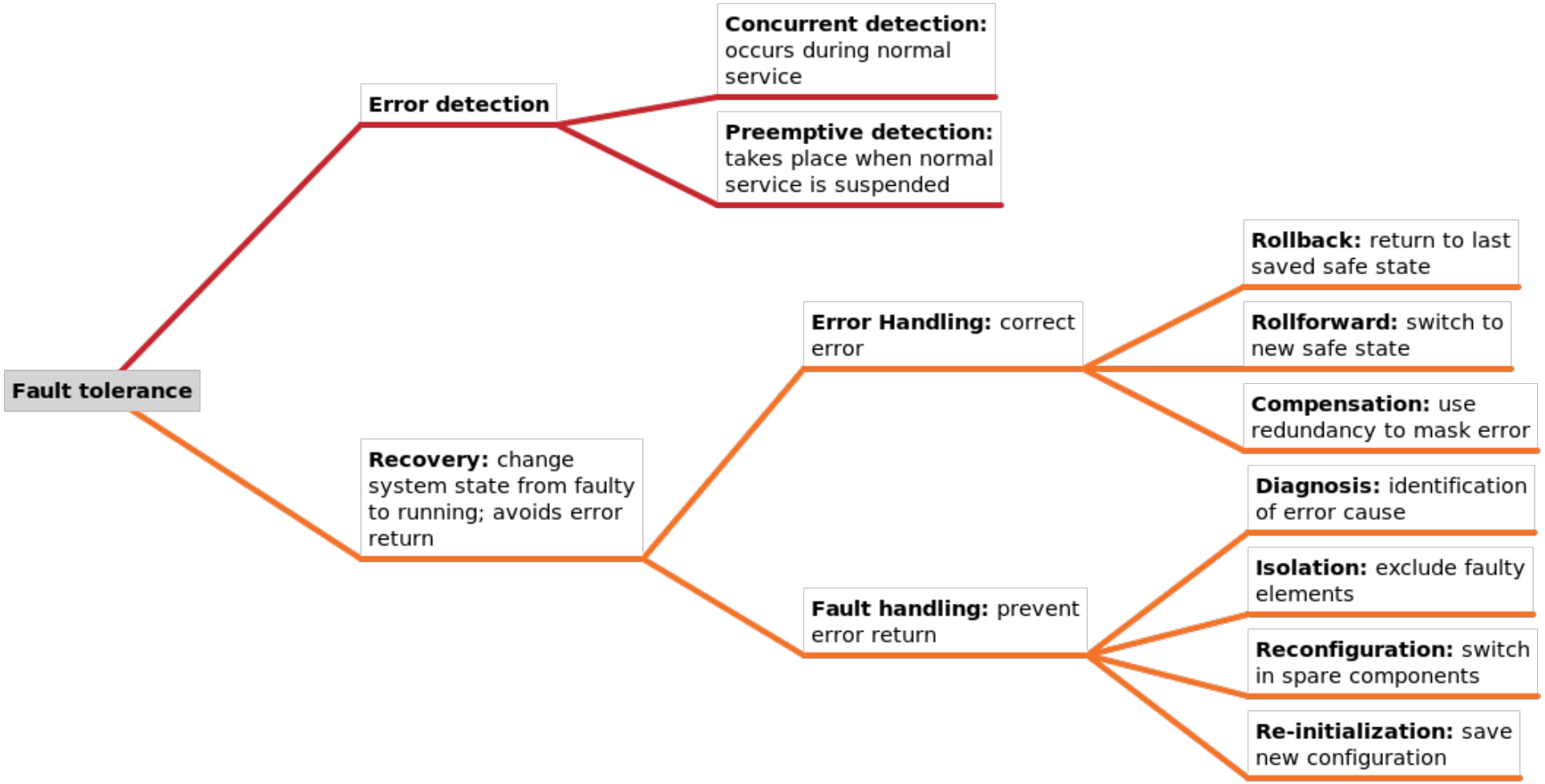

Some figures

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- Data Center problems in one year
  - ~0.5 overheating (power down most machines in <5 mins, ~1-2 days to recover)
  - ~1 PDU failure (~500-1000 machines suddenly disappear, ~6 hrs to come back)
  - ~1 rack-move (plenty of warning, ~500-1000 machines powered down, ~6 hrs)
  - ~1 network rewiring (rolling ~5% of machines down over 2-day span)
  - ~20 rack failures (40-80 machines instantly disappear, 1-6 hours to get back)
  - ~5 racks go wonky (40-80 machines see 50% packet loss)
  - ~8 network maintenances (might cause ~30-minute random connectivity losses)
  - ~12 router reloads (takes out DNS and external vIPs for a couple minutes)
  - ~3 router failures (have to immediately pull traffic for an hour)
  - ~dozens of minor 30-second blips for dns
  - ~1000 individual machine failures (2-4% failure rate, machines crash at least twice)
  - ~thousands of hard drive failures (1-5% of all disks will die)

Combining reliability

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- Given N sub-systems
  - Each subsystem I has a failure probability r_i
- What is the overall failure probability?
  - Depends on how systems interacts
- Serial systems
- Parallel systems

Serial systems

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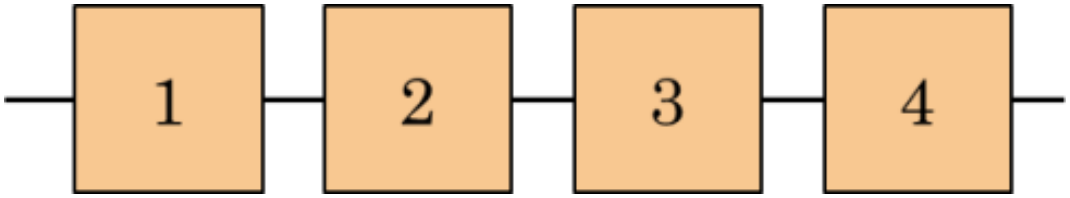
- Global failure → one sub-system failed
  - Like Christmas lights
- System reliability:
  - $R=\prod r_i$
- Systems fails if one sub-system fails
- System is available if every sub-system is available



Parallel systems

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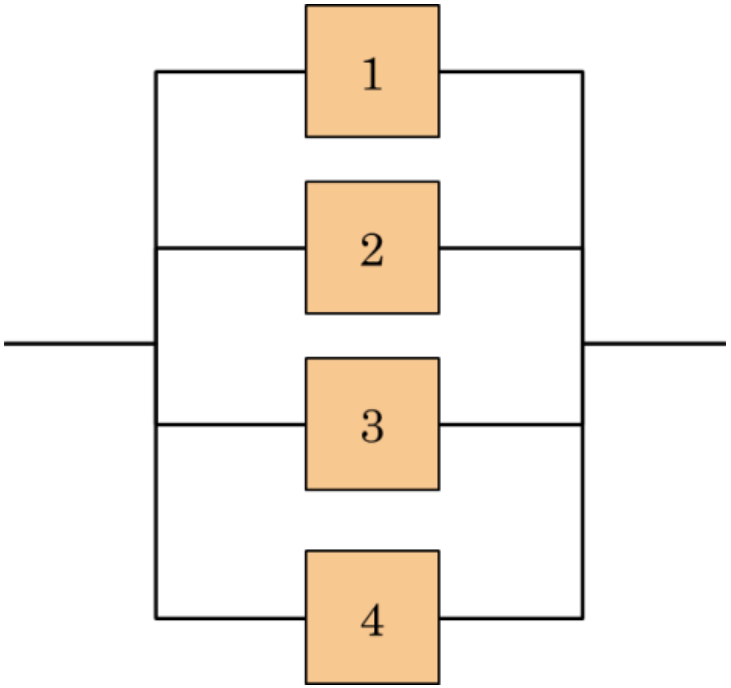
- Global failure → every sub-system failed
- System reliability:
  - $R=1-\prod(1-r_i)$
- System is available if at least one sub-system is available



Some questions

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- Given subsystem with identical reliability
- In a parallel system
  - How many subsystem do I need to guarantee a reliability of X?
- In a serial system
  - What is the maximum number of subsystem to guarantee a reliability of X?
- Volunteers?

CAP Theorem

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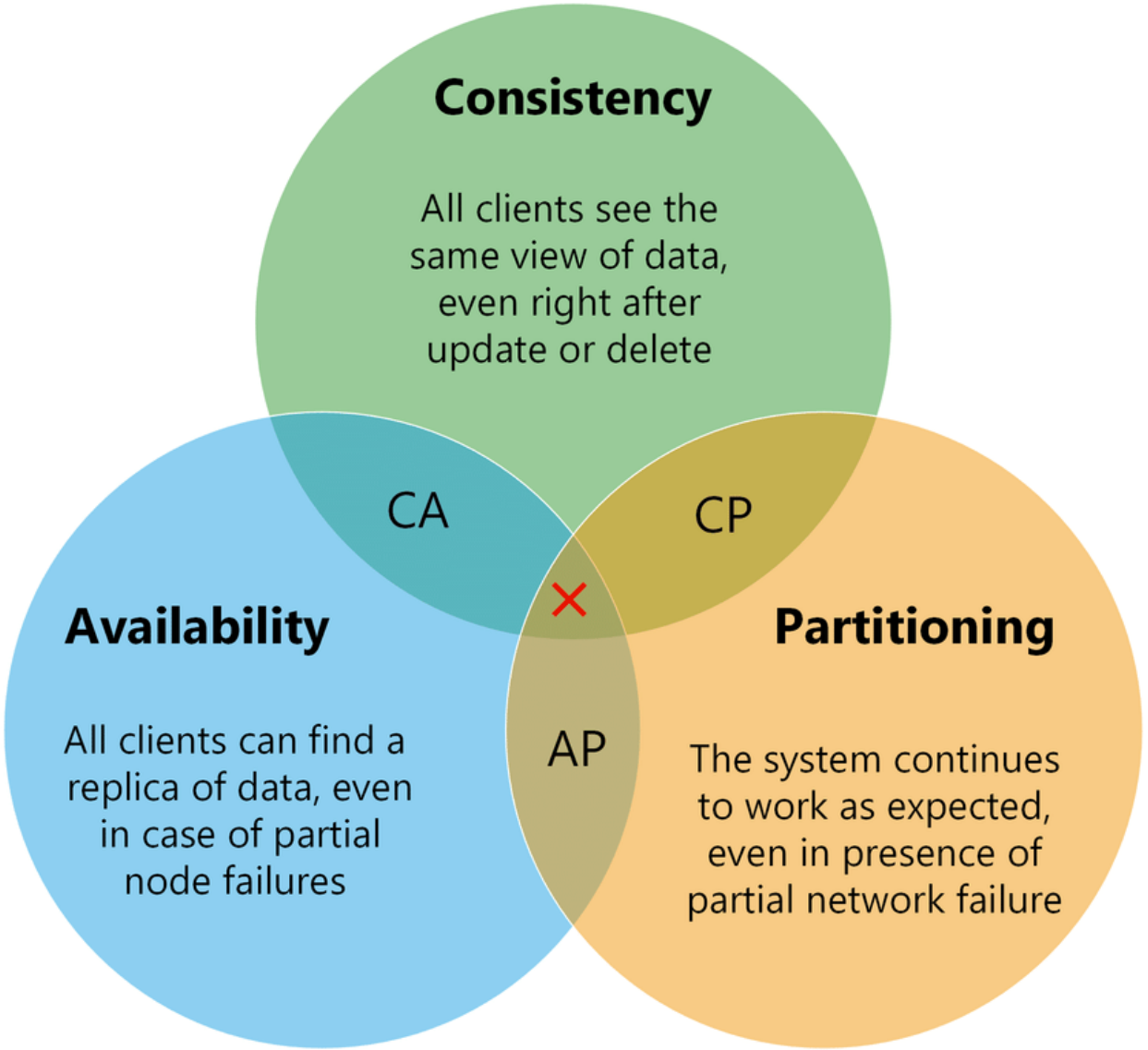
- CAP
  - Consistency/Availability/Partition-tolerance
- Consistency: Every read return data from most recent write
- Availability: Every request returns a non-error response
- Partition-tolerance: The system works also in case of network partitions (messages lost or delayed)
- CAP theorem
  - Can choose only 2 out of 3 properties

CAP Theorem


Consistency
All clients see the same view of data, even right after update or delete
CA
CP
Availability
All clients can find a replica of data, even in case of partial node failures
AP
Partitioning
The system continues to work as expected, even in presence of partial network failure

Some useful hints

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- Look out for bottlenecks
- Look out for single points of failure
- Keep it simple and stupid (KISS) 
  - Centralized control is simple!
- If it is not tested, don't rely on it
- Testing is not easy
  - Hundreds of services
  - Loosely couples services
  - Thousand of machines
  - How to deal with it?

Additional information

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- Some useful readings:
- D. Menascé, V. Almeida,
  “Capacity Planning for Web Services”
- K. Trivedi, A. Bobbio,
  “Reliability and Availability Engineering”
- K. Trivedi “Probability and Statistics with Reliability, Queuing, and Computer Science Applications”

Workload forecasting

Forecasting

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- Forecast:
  a statement of what is judged likely to happen in the future, especially in connection with a particular situation,
- Trying to understand how workload is evolving
- A critical part of capacity planning

A good forecast

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- Not just a number but a set of scenarios
  - optimistic/average/pessimistic
- May involve many parameters of workload
  → Not just a change in workload intensity
- Examples:
  - Session arrival rate
  - Requests per session
  - Think time between interactions
  - Probability ratio in multiple services (workload mix)
  - Response size

Steps for forecasts

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- Defining objectives (what are we trying to predict?)
- Select information sources
  - Interviews
  - Reports
  - Historical data
- Gather data (quantitative/qualitative)
- Build models
- Forecast
- Validation

Qualitative forecast

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- Typically based on human sources
- Can be useful to build a reference scenario
- Examples:
- Interviews with end users
  - Questionnaires to a large set of people
- Collecting opinions of experts
  - More free-format interview
- Analysis of technological trends
  - Access to specialized reports

Validation

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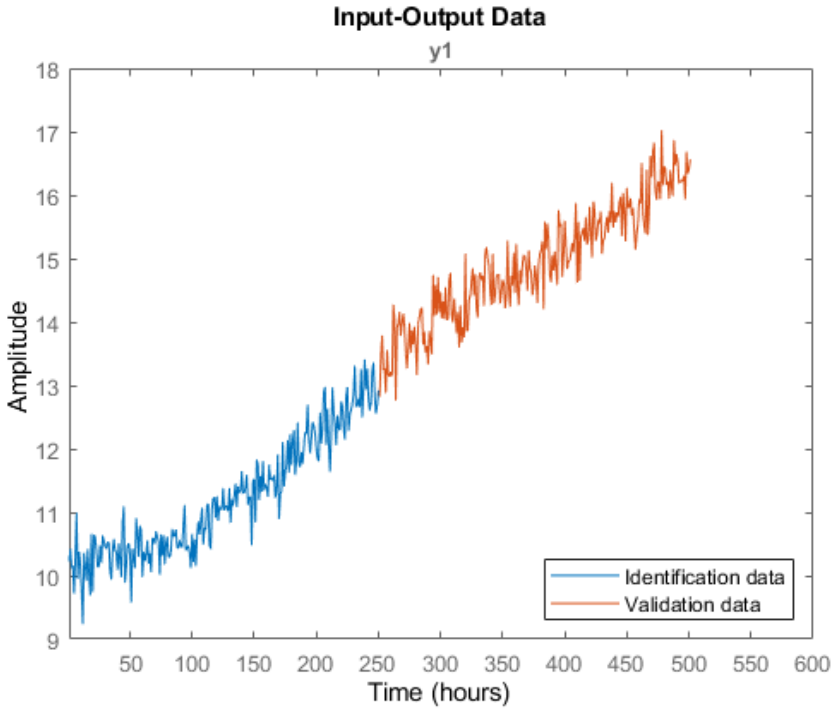
- Can use part of historical data
- Apply forecast to past
- It should describe the present
- Similar to Training/Validation process in ML



Historical data analysis

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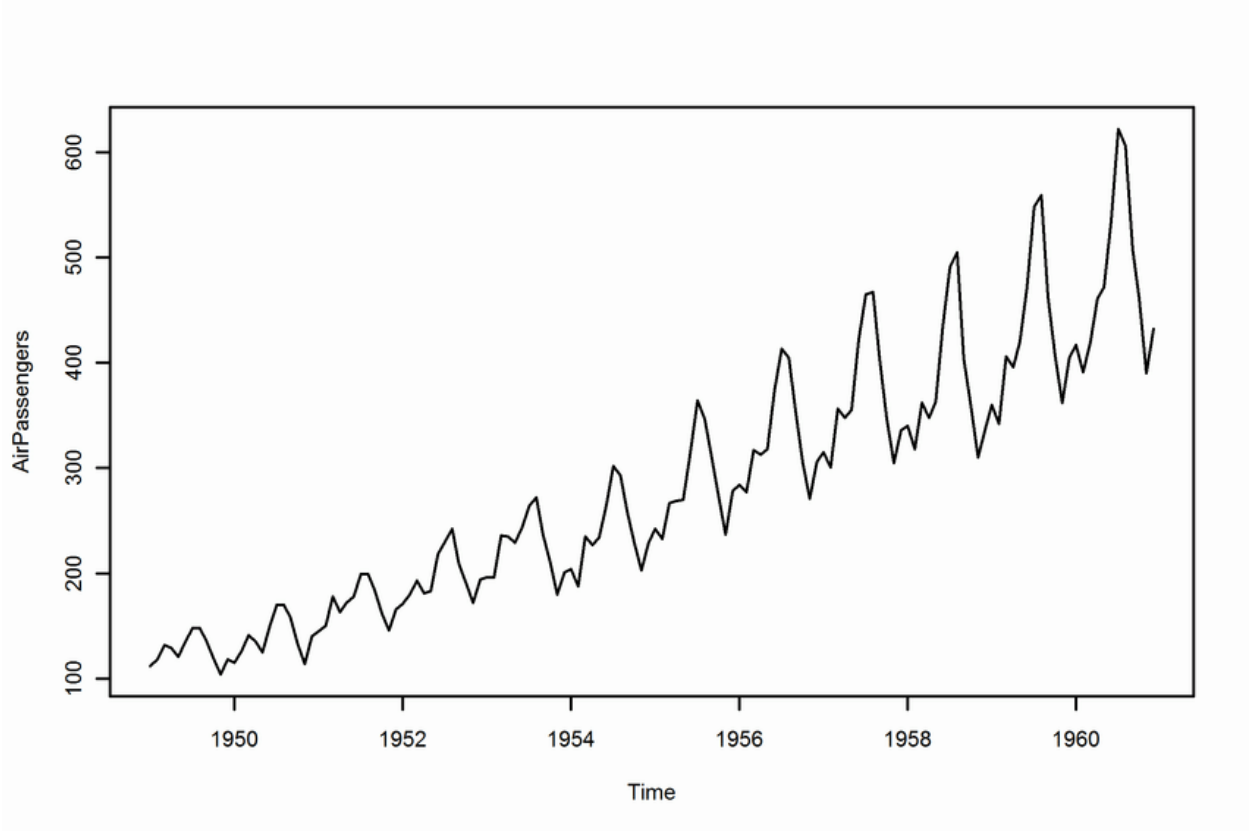
- Identify trends in time series
  - Linear trend
  - Periodic components



Error measures

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- Mean error
  - $ME=\Sigma_t(Y_t-F_t) / n$
- Mean square error
  - $MSE=\Sigma_t(Y_t-F_t)^2 / n$
- Sum of square error
  - $SSE=\Sigma_t(Y_t-F_t)^2$

Linear regression methods

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- Interpolation function
  - $Y=a+bX$
- Minimize square error (Least Square method)
  - $b= (n\Sigma_t(Y_tX_t) - (\Sigma_tX_t)(\Sigma_tY_t))/(n\Sigma_t(X_t)^2 - (\Sigma_tX_t)^2)$
  - $a= avg(Y)-b(avg(X)$

How predictable is a series?

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- Typical test:
- Autocorrelation
  - Correlation between:
    - Time series X(t) and
    - Time series X(t-lag)
  - Evaluation as a function of lag
- Slow autocorrelation decay:
  - easy to predict
- Fast autocorrelation decay:
  - highly irregular time series
- Spikes for a specific lag value
  - Periodic behavior