Advanced Topics in Software Engineering: Performance Modelling and Evaluation

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The civil council ask you to develop a software architecture that...

- supports users in station selections while improving their satisfaction;
- guarantees a balanced use of resources;
- identifies anomalous situations.

An example...

Question...

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... study system behaviour and the impact of implementation choices on these scenarios.

Key Notions

A model can be constructed to represent some aspect of the dynamic behaviour of a system.

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Once constructed, such a model becomes a tool with which we can investigate the behaviour of the system.

The discrete event view

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The state of the system is characterised by variables which take distinct values and which change by discrete events, i.e. at a distinct time something happens within the system which results in a change in one or more of the state variables.

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Discrete event system

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Let $\{\ell_1, \ldots \ell_n\}$ be the bike stations in our system, we can count the number of bikes (resp. slots) B_{ℓ_i} (resp. S_{ℓ_i}) available at each station ℓ_i.

- When a bike is retrieved form ℓ_i, B_{ℓ_i} is decreased by 1 and S_{ℓ_i} increased;

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- When a bike is retrieved form ℓ_i, B_{ℓ_i} is decreased by 1 and S_{ℓ_i} increased;
- When a bike is returned at ℓ_i, B_{ℓ_i} is incremented and S_{ℓ_i} decremented.

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The use of discrete time or continuous time mainly depend on the levels of abstraction considered in the model.

Performance Modelling

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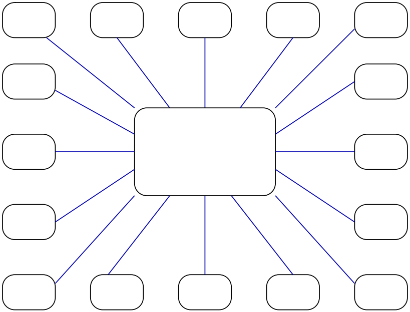
- Users typically want to optimise external measurements of the dynamics such as response time (as small as possible), throughput (as high as possible) or blocking probability (preferably zero);
- In contrast, system managers may seek to optimize internal measurements of the dynamics such as utilisation (reasonably high, but not too high), idle time (as small as possible) or failure rates (as low as possible).

Performance Modelling: Motivation



Capacity planning

- How many clients can the existing server support and maintain reasonable response times?

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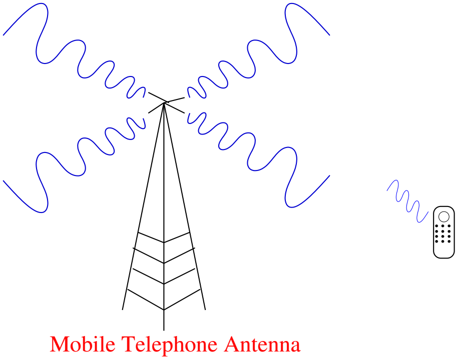

System Configuration

- How many frequencies do you need to keep blocking probabilities low?

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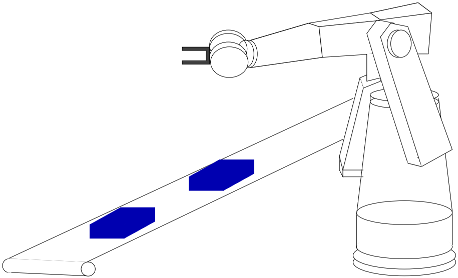
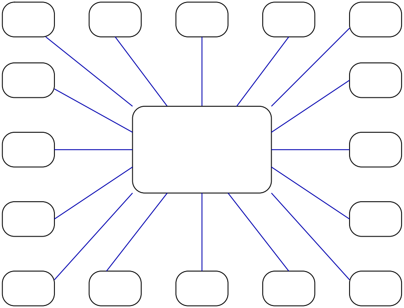


System Tuning

- What speed of conveyor belt will minimize robot idle time and maximize throughput whilst avoiding lost widgets?

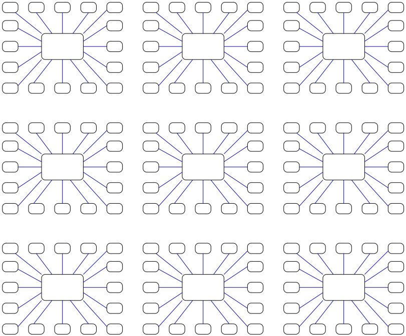
Performance Modelling: Response time analysis



Quality of Service issues

- Can the server maintain reasonable response times?

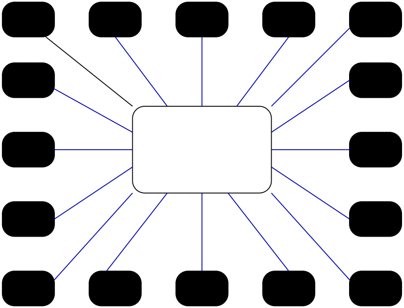
Performance Modelling: Capacity planning



Scalability and capacity planning issues

- How many times do we have to replicate this service to support all of the subscribers?

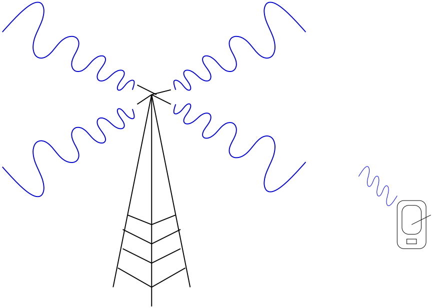
Performance Modelling: Scalability analysis



Robustness and scalability issues

- Will the server withstand a distributed denial of service attack?

Performance Modelling: Service Level Agreements



Service-level agreements

- What percentage of downloads do complete within the time we advertised?

Quantitative modelling

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Probability will be used to represent randomness (e.g. from human users) but also as an abstraction over unknown values (e.g. service times).

Probability Theory

Sample space

A sample space is an arbitrary non empty set Ω, containing of all possible outcomes or results of an experiment.

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Examples:

Toss of a coin: $\Omega_C = \{H, T\}$;

Toss of two coins: $\Omega_{2C} = \Omega_C \times \Omega_C = \{(H, H), (H, T), (T, H), (T, T)\}$;

Roll of a dice: $\Omega_D = \{1, 2, 3, 4, 5, 6\}$.

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Probability Theory

Probability measure

Let $\Sigma \subseteq 2^{\Omega}$, be a σ-algebra. A probability measure is a function $Pr : \Sigma \rightarrow [0, 1]$ associating elements in Σ with a real value in $[0, 1]$ such that:

- Pr is countably additive, if $\{A_i\}_{i \in I}$ is a countable collection of pairwise disjoint set, then:

$$Pr\left(\bigcup_{i \in I} A_i\right) = \sum_{i \in I} Pr(A_i)$$

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- the measure of the entire sample space is 1:

$$\Pr(\Omega) = 1$$

Probability Theory

Probability space

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Examples: Toss of a coin

We can consider the probability space $(\Omega_C, \Sigma_C, \Pr_C)$ such that:

- $\Pr_C(\{\}) = 0$;
- $\Pr_C(\{H\}) = \Pr_C(\{T\}) = \frac{1}{2}$;
- $\Pr_C(\{H, T\}) = 1$.

Probability Space: Some Properties

Let $(\Omega, \Sigma, \mathsf{Pr})$ be a probability space. The following properties hold:

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- For any $A, B \in \Sigma$:
$$\Pr(A \cup B) = \Pr(A) + \Pr(B) - \Pr(A \cap B)$$

Conditional Probability

Let $(\Omega, \Sigma, \Pr)$ be a probability space

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- If B is a precondition for A, then $\Pr(A \cap B) = \Pr(A)$.
- Two events are independent if knowledge of the occurrence of one of them tells us nothing about the probability of the other, i.e. $\Pr(A \mid B) = \Pr(A)$, or

$$\Pr(A \cap B) = \Pr(A) \times \Pr(B)$$

Random variables

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Let $(\Omega, \Sigma, \Pr)$ be a probability space, a random variable $X : \Omega \to \mathbb{R}$ is a measurable function from Ω to $\mathbb{R}$.

The probability that X takes value in a measurable set $S \subseteq \mathbb{R}$ is written as:

$$\Pr(X \in S) = \Pr(\{\omega \in \Omega | X(\omega) \in S\})$$

Distribution function

Let X a random variable on the probability space $(\Omega, \Sigma, \Pr)$, we define the distribution function F_X for each real $x \in \mathbb{R}$ by

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A random variable X is continuous if $p(x) = 0$ for all real x.

NB: If X is a continuous random variable, then X can assume infinitely many values, and so it is reasonable that the probability of its assuming any specific value we choose beforehand is zero.

Example: Dice Roll

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We can consider the probability space $(\Omega_{2D}, \Sigma_{2D}, \mathrm{Pr}_{2D})$ such that:

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The pms function p_X and the df F_X function can be defined as:

$$p_X(x) = \begin{cases} \frac{\min(x-1, 13-x)}{36} & 2 \leq x \leq 12 \\ 0 & \text{otherwise} \end{cases} \qquad F_X(x) = \sum_{y \leq x} p_X(y)$$

Mean, or expected value

If X is a discrete random variable with probability mass function $p(\cdot)$, we define the mean or expected value of $X \in S$, $\mu = E[X]$ by

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If X is a continuous random variable with density function $f(\cdot) = \frac{dF(\cdot)}{dx}$, we define the mean or expected value of X, $\mu = E[X]$ by

$$\mu = E[X] = \int_{-\infty}^{\infty} x \cdot f(x) dx$$

Variance

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The variance, $Var(X)$, gives us an indication of the “spread” of values:

$$Var(X) = E\left[(X - E[X])^2\right] = E\left[X^2\right] - E\left[X\right]^2$$

Random variables

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We can focus on the distribution function of a random variable without consider a specific probability space.

Exponential random variables, distribution function

The random variable X is said to be an exponential random variable with parameter λ ($\lambda > 0$) or to have an exponential distribution with parameter λ if it has the distribution function

$$F(x) = \begin{cases} 1 - e^{-\lambda x} & \text{for } x > 0 \\ 0 & \text{for } x \leq 0 \end{cases}$$

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Some authors call this distribution the negative exponential distribution.

Exponential random variables, density function

The density function $f = dF/dx$ is given by

$$f(x) = \begin{cases} \lambda e^{-\lambda x} & \text{if } x > 0 \\ 0 & \text{if } x \leq 0 \end{cases}$$

Mean, or expected value, of the exponential distribution

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Var(X) &= E\left[X^2\right] - E[X]^2 \\
&= \int_0^\infty x^2 \lambda e^{-\lambda x} dx - \left(\frac{1}{\lambda}\right)^2 \\
&= \frac{2}{\lambda^2} - \frac{1}{\lambda^2}
\end{aligned}
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Exponential inter-event time distribution

The time interval between successive events can also be deduced.

Let $F(t)$ be the distribution function of T, the time between events. Consider $\Pr(T > t) = 1 - F(t)$:

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The time interval between successive events can also be deduced.

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Memoryless property exponential distribution

The exponential distribution is said to have the memoryless property because the time to the next event is independent of when the last event occurred.

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This value is independent of t (and so the time already spent has not been remembered).

The Poisson distribution

The exponential distribution function is closely related to a discrete random variable, the Poisson distribution.

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The expectation of a Poisson random variable with parameter μ is also μ.

The Poisson random variable

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If we observe a Poisson process with parameter μ for some short time period of length h then:

- the probability that one event occurs is $\mu h + o(h)$.
- the probability that two or more events occur is $o(h)$.
- the probability that no events occur is $1 - \mu h + o(h)$.

Poisson vs exponential distributions

If we observe a Poisson process for a infinitesimal time period dt the probability that an event occurs is μdt.

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If the occurrence of events is governed by a Poisson distribution then the inter-event times are governed by an exponential distribution with the same parameter, and vice versa.

Therefore, if we know that the delay until an event is exponentially distributed then the probability that it will occur in the infinitesimal time interval of length dt, is μdt.

Exponential distributions: properties

Let X and Y two exponentially distributed random variables, with parameters λ_X and λ_Y respectively.

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Consider a stream of events which has events of two types — type A and type B — and assume that the probability that an event has type A is p_A and the probability it has type B is p_B ($p_A + p_B = 1$).

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Then if the inter-event time for any events is exponentially distributed with parameter λ, then the inter-event time for type A events is $p_A \times \lambda$ and similarly for type B events it is $p_B \times \lambda$.

To be continued...