

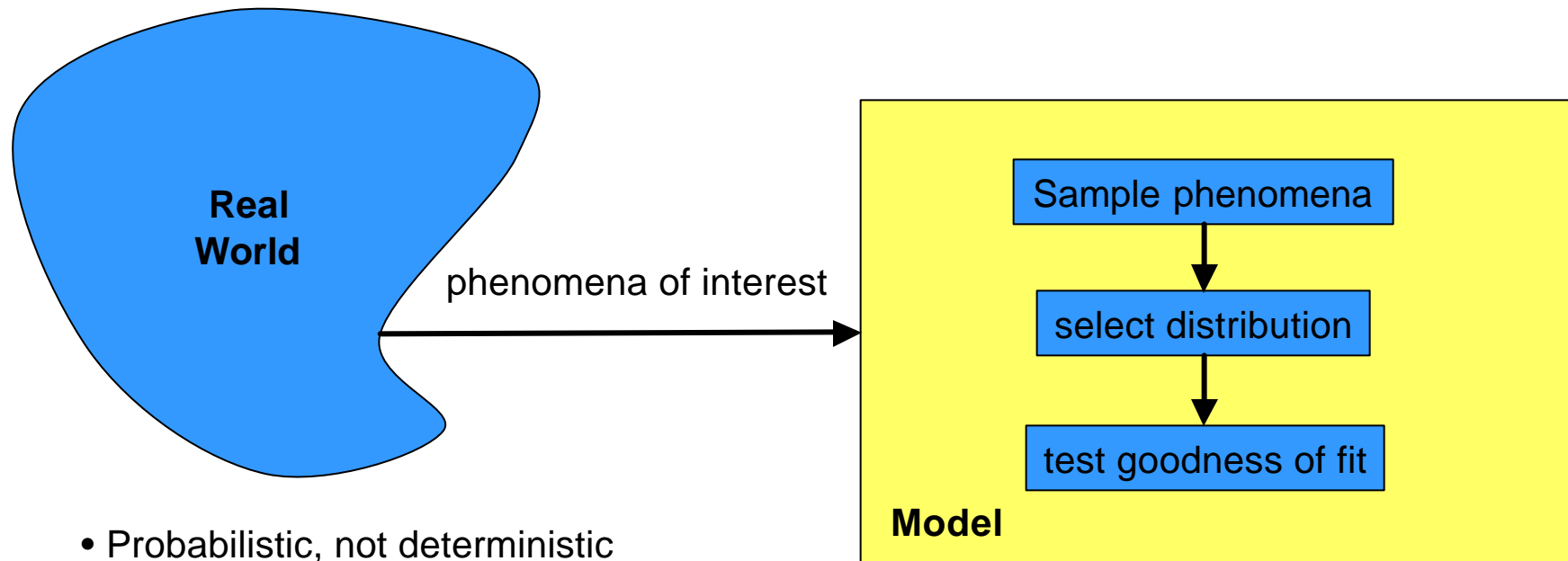
EE/CpE 345

Modeling and Simulation

Fall 2003

Class 4

Statistical Models in Simulation



Terminology/Concepts in Probability and Statistics

- Discrete Random Variables (X)

- The number of possible values of X is finite or countably infinite
- Example 5.1: The number of jobs arriving at a shop each week

- Number of jobs in a given week: X
- Possible values of X : The range space of X ,

$$R_X = \{1, 2, 3, \dots\}$$

- The probability that the R.V. X takes on the value x_i

- $p(x_i)$ is the probability that the R.V. X equals x_i $p(x_i) = P(X = x_i)$

- all event probabilities are non-negative $p(x_i) \geq 0 \quad \forall i$

- probabilities measure proportion
of event occurrences

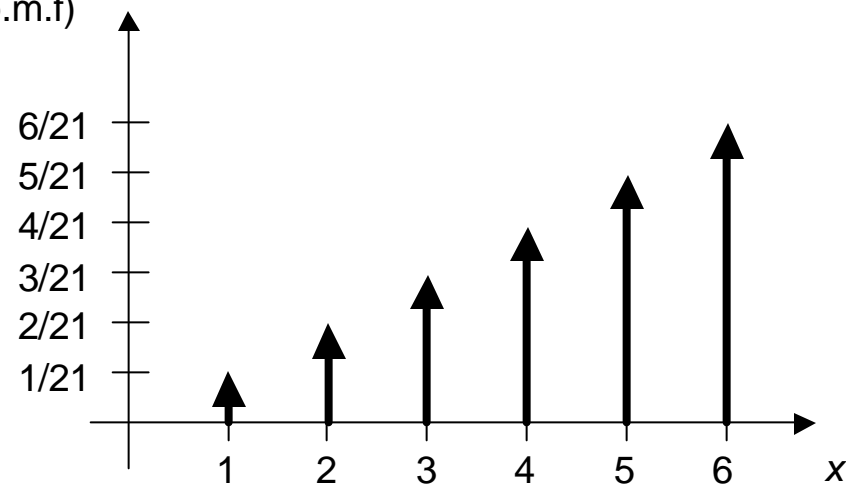
$$\sum_{i=1}^{\infty} p(x_i) = 1$$

Discrete Random Variables

- Example 5.2: Testing a single die
 - $R_X = \{1, 2, 3, 4, 5, 6\}$
 - Assume the die is loaded, with the probability of a given face showing proportional to the number of spots

x_i	1	2	3	4	5	6
$p(x_i)$	1/21	2/21	3/21	4/21	5/21	6/21

probability mass function (p.m.f)
 $p(x)$



Continuous Random Variables

- The Range Space R_X of the random variable X is an interval or collection of intervals

$$P(a \leq X \leq b) = \int_a^b f(x)dx$$

- $f(x)$ is the probability density function (p.d.f.)

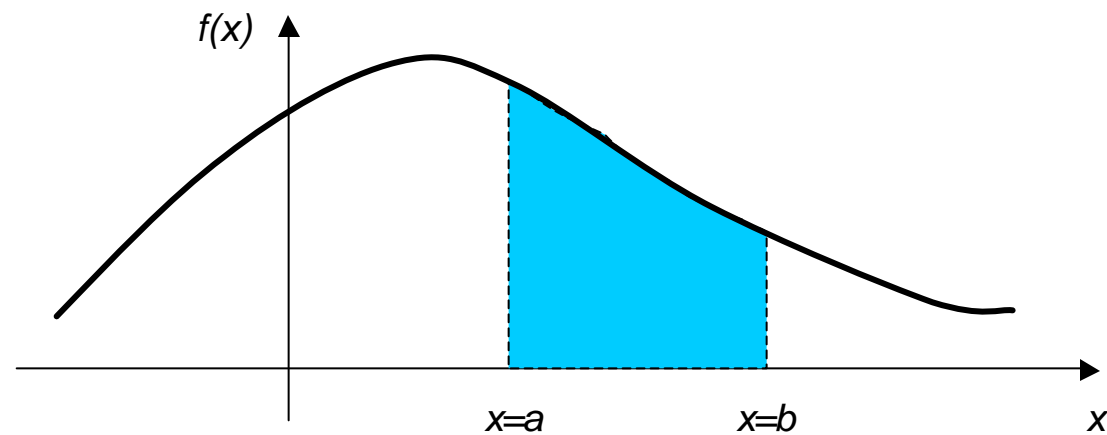
- The p.d.f. is nonzero within the Range Space
- The total area under the p.d.f. represents all possible events
- The p.d.f. is zero outside the Range Space

$$f(x) \geq 0 \quad \forall x \in R_X$$

$$\int_{R_X} f(x)dx = 1$$

$$f(x) = 0 \quad \forall x \notin R_X$$

Probability of events in an interval

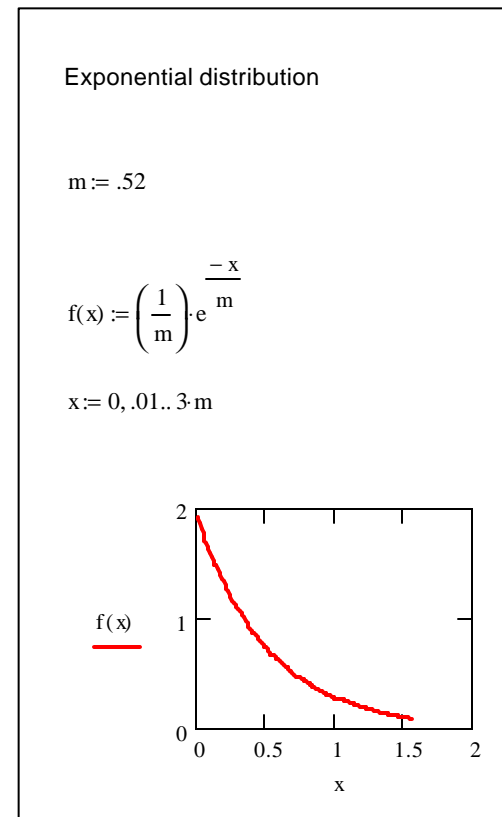


$$P(a < X < b) = \int_a^b f(x) dx = \int_{-\infty}^b f(x) dx - \int_{-\infty}^a f(x) dx$$

Continuous Random Variables

- Exponential distribution with mean m

$$f(x) = \begin{cases} \frac{1}{m} e^{-x/m} & x \geq 0 \\ 0 & \text{otherwise} \end{cases}$$



MathCad

Cumulative Distribution Function

- Measures probability that the R.V. X assumes a value less than or equal to x

– for discrete R.V.

$$F(x) = \sum_{\forall x_i \leq x} p(x_i)$$

– for continuous R.V.

$$F(x) = \int_{-\infty}^x f(t) dt$$

– Properties of $F(\cdot)$:

$$a < b \longrightarrow F(a) \leq F(b)$$

$$\lim_{x \rightarrow \infty} F(x) = 1$$

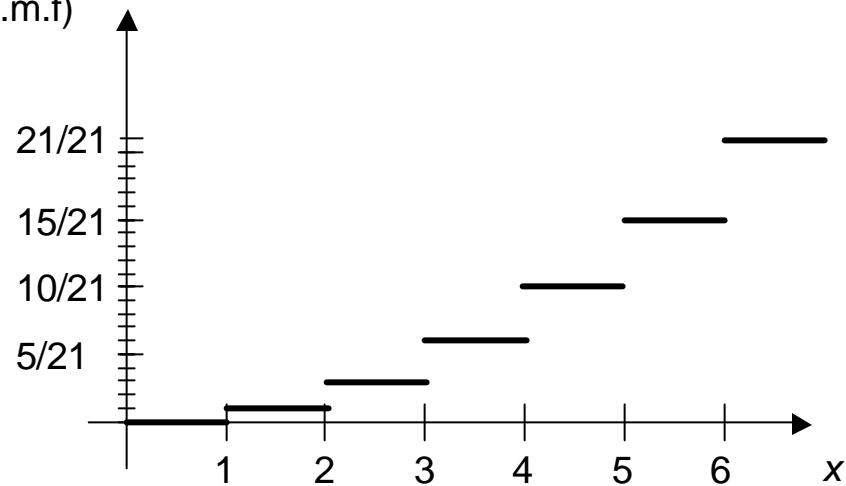
$$\lim_{x \rightarrow -\infty} F(x) = 0$$

C.D.F. Examples

- Loaded die

x_i	$(-8, 1)$	$[1, 2)$	$[2, 3)$	$[3, 4)$	$[4, 5)$	$[5, 6)$	$[6, 8)$
$p(x_i)$	0	$1/21$	$3/21$	$6/21$	$10/21$	$15/21$	$21/21$

probability mass function (p.m.f)
 $p(x)$

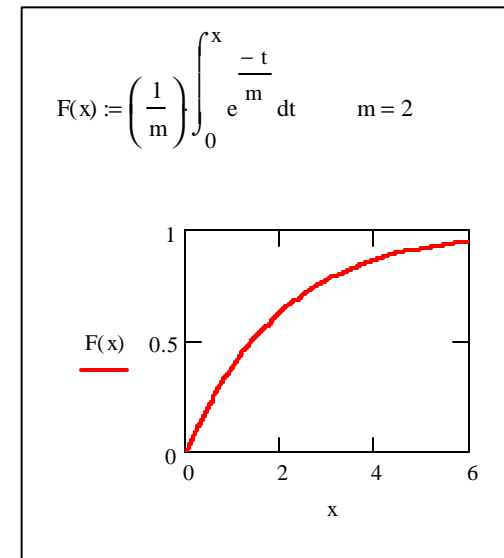


C.D.F. Examples

- Exponential distribution

$$F(x) = \frac{1}{m} \int_0^x e^{-t/m} dt = 1 - e^{-x/m}$$

- exponential distribution is easily evaluated, making it very popular for closed form solutions



Useful Parameters of R.V.s

- Expected Value

- if X is a R.V., the Expected Value (Expectation) is:

- Discrete case:

$$E(X) = \sum_{\forall i} x_i p(x_i)$$

- Continuous case:

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

- $E(X)$ is also called the mean, μ , or the 1st moment of X

- $E(X^n)$ is the n^{th} moment of X

$$E(X^n) = \sum_{\forall i} x_i^n p(x_i)$$

$$E(X^n) = \int_{-\infty}^{\infty} x^n f(x) dx$$

More Useful Parameters of R.V.s

- Variance

$$V(X) = E\left[\left(X - E[X]\right)^2\right] = \text{var}(X) = \mathbf{s}^2$$

$$V(X) = E(X^2) - [E(X)]^2$$

- Standard deviation

$$\mathbf{s} = \sqrt{V(X)}$$

- Mode - the value that occurs most often (discrete) or peak of p.d.f. (continuous).
- Bimodality - two peaks in the p.d.f.

Statistical Models

To address the statistical model to consider:

- What is the problem being addressed?
 - Queuing
 - Reliability/failure
 - Inventory
 - Communications systems behavior

- What is known about the process?
 - Completely random
 - Essentially constant with a random component
 - Constrained
 - non-negative
 - limited tails of distribution

- Tractable mathematical analysis

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Exponential distribution

unlimited tails

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unlimited tails

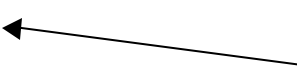
Gaussian/Normal distribution

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Truncated
Gaussian/Normal distribution
or small variance

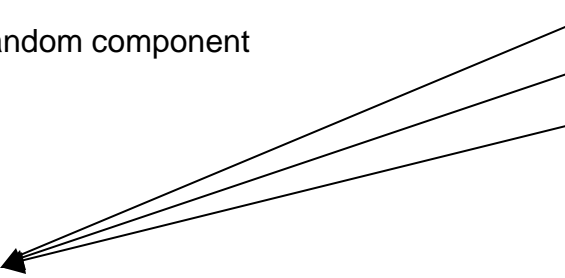


Statistical Models

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Normal
Exponential
Poisson



Discrete Distributions

- Bernoulli trials and binomial distributions
 - Consider an experiment (e.g., flipping a coin, receiving a bit) consisting of n trials which can be a success (1) or failure (0)
 - The n Bernoulli trials are called a Bernoulli process if the trials are independent
 - For one trial, the Bernoulli distribution is:

$$p(x) = \begin{cases} p & x=1 \\ 1-p = q & x=0 \\ 0 & \text{otherwise} \end{cases}$$

- Binomial distribution:
 - The number of successes in a Bernoulli process has a binomial distribution

$$p(x) = \begin{cases} \binom{n}{x} p^x q^{n-x} & x=0,1,2,\dots,n \\ 0 & \text{otherwise} \end{cases}$$

Discrete Distributions

- Geometric distribution
 - The number of Bernoulli trials before the first success

$$p(x) = \begin{cases} q^{x-1}p & x=1,2,\dots \\ 0 & \text{otherwise} \end{cases}$$

- Poisson distribution
 - Models arrival processes in queuing systems quite well
 - One of the few distributions that makes the mathematics tractable
 - mean and variance = α

$$p(x) = \begin{cases} \frac{e^{-a} a^x}{x!} & x=0,1,2,\dots \\ 0 & \text{otherwise} \end{cases}$$

Continuous Distributions

- Exponential distribution
 - Model completely random interarrival times
 - Model highly variable service times
 - λ is a rate: service rate, arrival rate
 - Distribution has long tail, useful for modeling component lifetime. λ is failure rate

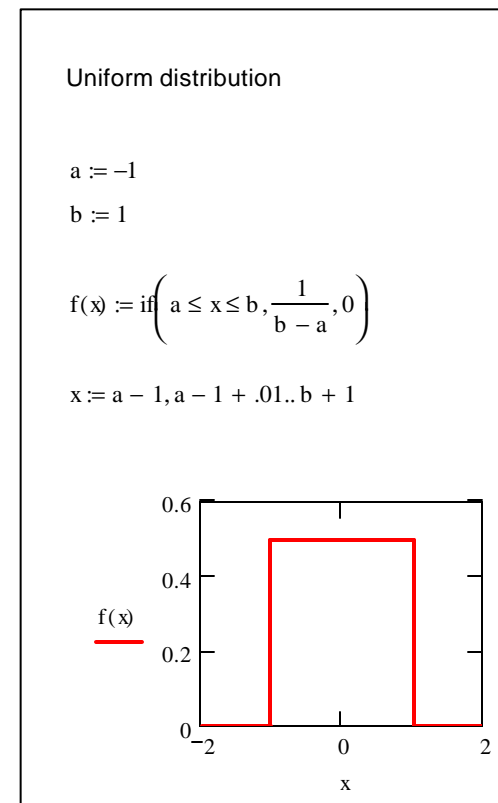
$$f(x) = \begin{cases} \lambda e^{-\lambda x} & x \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

Continuous Distributions

- Uniform distribution

- Easiest distribution to generate, serves as a basis for other R.V.s in simulation
- Uniform p.d.f.:

$$f(x) = \begin{cases} \frac{1}{b-a} & a \leq x \leq b \\ 0 & \text{otherwise} \end{cases}$$



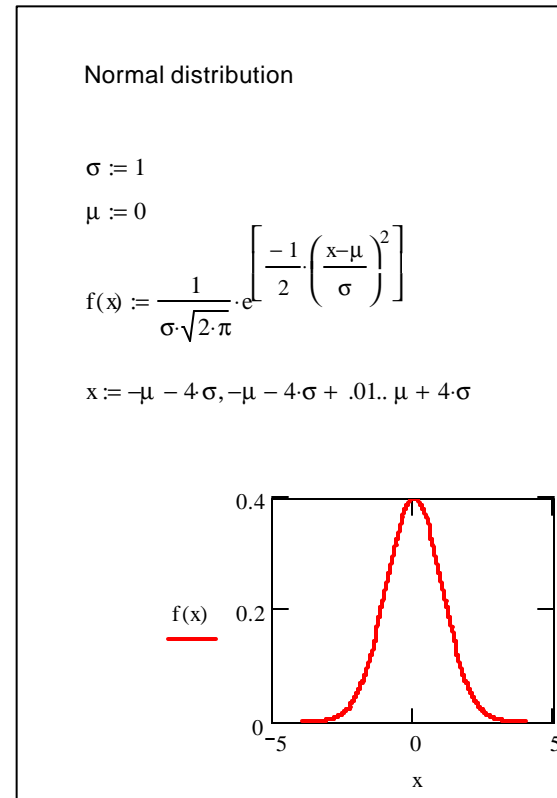
Continuous Distributions

- Erlang distribution
 - The Gamma p.d.f. is also known as the Erlang distribution of order k when $\beta=k$, an integer
 - With the “block calls dropped, exponential arrival rates and exponential holding times” assumptions, the Erlang distribution is used to predict the number of busy trunks in a telephone system.

Continuous Distributions

- Normal distribution (Gaussian distribution)
 - mean μ , variance σ^2

$$f(x) = \frac{1}{s\sqrt{2p}} e^{\left(-\frac{1}{2}\left[\frac{x-m}{s}\right]^2\right)}$$



Continuous Distributions

- Weibull distribution

$$f(x) = \begin{cases} \frac{\mathbf{b}}{\mathbf{a}} \left(\frac{x-\mathbf{u}}{\mathbf{a}} \right)^{\mathbf{b}-1} e^{-\left(\frac{x-\mathbf{u}}{\mathbf{a}} \right)^{\mathbf{b}}} & x \geq \mathbf{u} \\ 0 & \text{otherwise} \end{cases}$$

- location parameter v , scale parameter α , shape parameter β
- This distribution is a general case of many other distributions, e.g.,
 - with $\beta=1$ this is the exponential distribution with $\lambda=1/\alpha$

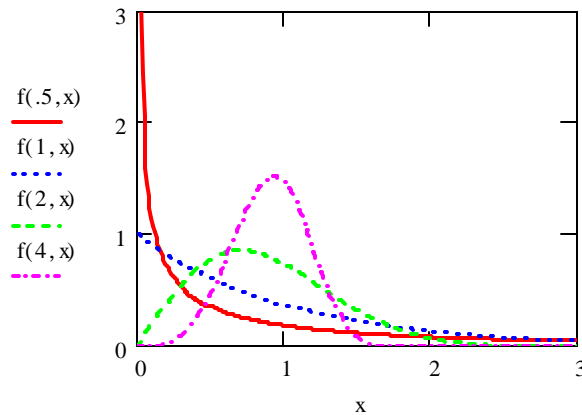
Continuous Distributions

Weibull distribution with $v=0$

$\alpha := 1$

$$f(\beta, x) := \frac{\beta}{\alpha} \left(\frac{x}{\alpha}\right)^{\beta-1} \cdot e^{-\left(\frac{x}{\alpha}\right)^\beta}$$

$x := 0, .01.. 3$



Error in text book, figure 5.20: $\alpha=1$, not .5

Continuous Distributions

- Rayleigh Distribution
 - Special case of Weibull distribution with $\alpha=2$

$$f(x) = \begin{cases} \frac{\mathbf{b}}{2} \left(\frac{x-\mathbf{n}}{2} \right)^{b-1} \exp \left[- \left(\frac{x-\mathbf{n}}{2} \right)^b \right] & x \geq \mathbf{n} \\ 0 & \text{otherwise} \end{cases}$$

- used to model multipath fading, radiation, wind speeds

Continuous Distributions

- Triangular distribution

$$f(x) = \begin{cases} \frac{2(x-a)}{(b-a)(c-a)} & a \leq x \leq b \\ \frac{2(c-x)}{(c-b)(c-a)} & b < x \leq c \\ 0 & \text{elsewhere} \end{cases}$$

Triangular distribution

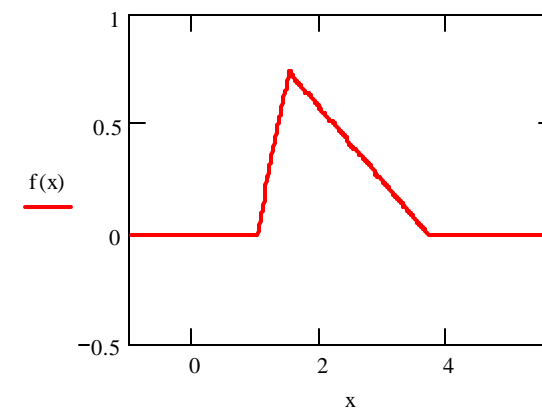
$$a := 1$$

$$b := 1.5$$

$$c := 3.7$$

$$f(x) := \text{if} \left[a \leq x \leq b, 2 \cdot \frac{(x-a)}{(b-a)(c-a)}, \text{if} \left[b < x \leq c, 2 \cdot \frac{(c-x)}{(c-b)(c-a)}, 0 \right] \right]$$

$$x := a - 2, a - 2 + .01, c + 2$$



Continuous Distributions

- Lognormal distribution

$$f(x) = \begin{cases} \frac{1}{\sqrt{2\pi s^2} x} e^{-\frac{(\ln x - m)^2}{2s^2}} & x > 0 \\ 0 & \text{otherwise} \end{cases}$$

- Shadow fading is often modeled as a lognormal process

Poisson Process

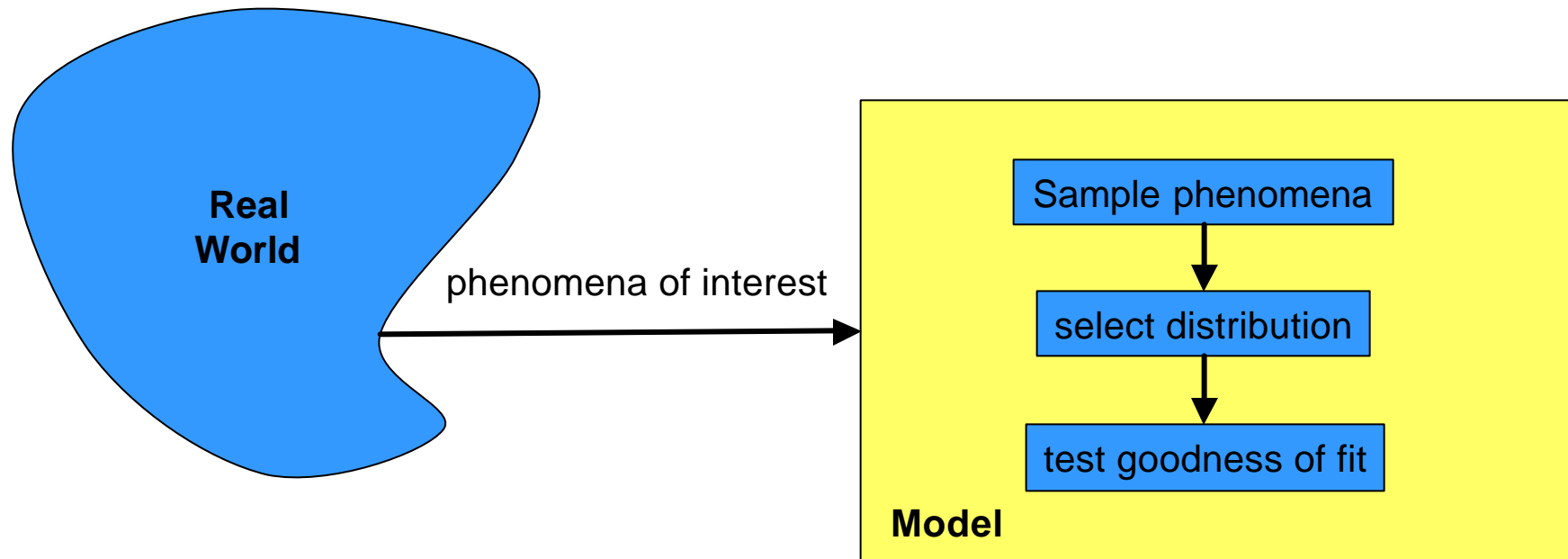
- A counting process $\{N(t), t=0\}$ is a Poisson process with mean rate λ if
 - arrivals occur singly
 - $\{N(t), t=0\}$ has stationary increments: The distribution of the number of arrivals between t and $t+s$ depends only on s , the length of the interval, and not on t , the starting point
 - $\{N(t), t=0\}$ has independent increments: The number of arrivals during non-overlapping time intervals are independent R.V.s

$$P[N(t) = n] = \frac{e^{-\lambda t} (\lambda t)^n}{n!} \quad \text{for } t \geq 0 \quad \text{and } n = 0, 1, 2, \dots$$

Poisson Process

- Properties of a Poisson Process
 - Random splitting
 - A Poisson process $\{N(t), t=0\}$ having rate λ
 - Each time an event occurs, it is arbitrarily be classified as either a type I (with probability p , $N_1(t)$) or type II (with probability $1-p$, $N_2(t)$) event
 - $N_1(t)$ and $N_2(t)$ are retain the property of being Poisson processes having rates λp and $\lambda(1-p)$
 - Pooling of two arrival streams
 - Given two independent Poisson processes
 - $N(t)=N_1(t)+N_2(t)$ is a Poisson process with rate $\lambda_1+\lambda_2$

Known vs. Empirical Distributions



- Situation A: You understand the processes that create random variability in observed phenomena. Pick the proper distribution, adjust parameters, and verify fit to data
- Situation B: You do not fully understand (or don't really care, or don't have the time to analyze) the processes that create random variability. Either
 - use sampled data to form an empirical distribution
 - pick a known distribution that is the best approximation

Homework 4

1. Chapter 5, p.199 problems 21 and 27