EE653: Lecture 1

Sept. 1 2005

EE653: Cross-Layer design for wireless networks

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EE653: Cross-Layer design for wireless networks
Course outline

- Goal: Learn to design wireless systems with a different, new perspective
- Cross-layer → account for interaction of protocols among layers
  - Physical layer
  - MAC Layer
  - Network Layer
- What we need to know
  - Layered architecture versus cross-layer design
  - Characterize wireless systems → users coexistence, interference
    - Physical layer → noise, fading, interference
    - MAC layer → congestion/spectrum sharing
    - Network layer → high level management of interference – depending on the network architecture
  - Cross-Layer Design – interactions among interference management protocols and joint design

Course structure and requirements

- First half of the class – lectures – background information
- Second half – seminar discussing papers on cross-layer design
  - Invited lecture from industry – practical perspective on cross-layer design

- Course requirements
  - Homework: 20%
  - Paper presentation: 10%
  - Midterm: 35%
  - Project: 35%

Introduction to Communication Networks

- Def: A communication network is a collection of devices interconnected by communication paths.
  - Each device is called a node in the network
  - A node can be:
    - Computer, PDA, cell phone, telephone, sensor (humidity, motion, light, etc.)

- Network hardware:
  - Two important dimensions for classifying networks: ***transmission technology*** and ***scale***

Transmission Technology:

1. Broadcast networks

2. Point-to-point networks

1. Broadcast networks

- have a single communication channel that it is shared by all devices in the network.
- Short information messages (packets) are sent by any device and received by all others.
- An address field within a packet specifies for whom it is intended. Upon receiving a packet, a device checks the address field. If the packet is intended for itself, it processes the packet, otherwise the packet is just ignored.
- A packet can also be addressed to all destination nodes in the network, using a special code in the address field.
- Transmission to a subset of nodes, also possible: multicast
  - 1 bit indicates multicasting
  - (n-1) bits: group address
  - All receiving devices must subscribe to the multicast group

2. Point-to-point networks

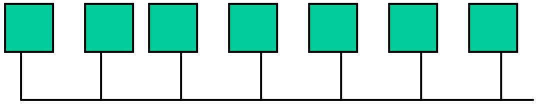
- each packet – unique source and destination nodes
- a communication path must be established
- *direct communication* – physical link between the two nodes exists
- *multi-hop communication* – nodes communicate with each other using intermediate nodes
- many alternate routes may exist

Question: Which one is the best route?

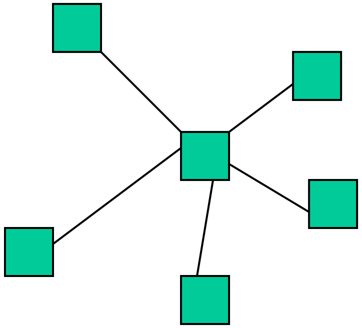
Answer: From what point of view?

- select cost criteria: e.g., distance, bandwidth, energy, etc.
- routing algorithms
    - optimize the various criteria

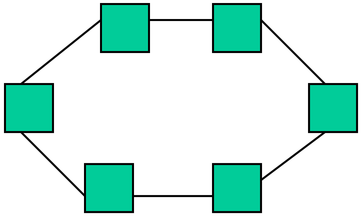
- Point-to-point networks: topology
  - Bus
    - Usually used for wireline computer networks



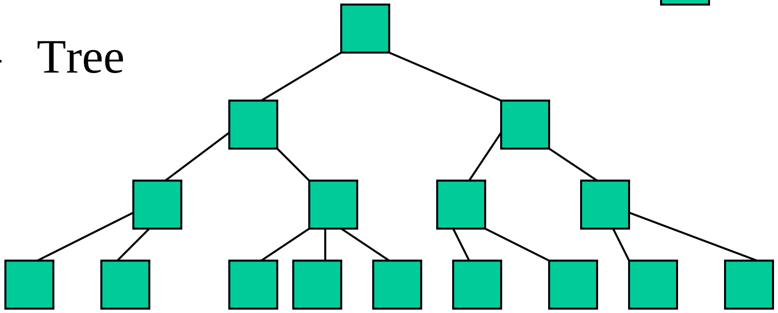
  - Star
    - e.g. cellular, wireless LAN



  - Ring
    - Seldom used today



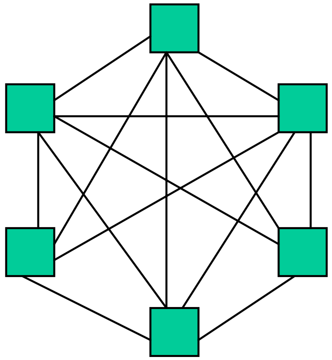
  - Tree



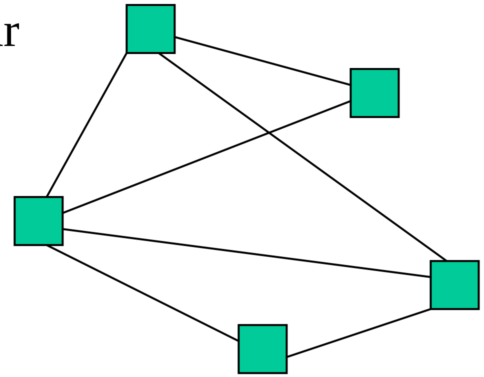
A tree topology connects multiple star networks to other star network:
- “star bus topology”

- Point-to point network topology (continued)

  – Complete



  – Irregular



Ad hoc networks

Definition: An ad hoc network is a collection of wireless devices which Spontaneously form temporary networks without the aid of any infrastructure, or centralized management.

- the communication is peer-to-peer, it does not go through an access point or central controller

Note: Any of the links in the above topologies may be

- **simplex** (unidirectional)
- **half-duplex** (both directions but not simultaneously)
- **full-duplex** (both directions, simultaneously)

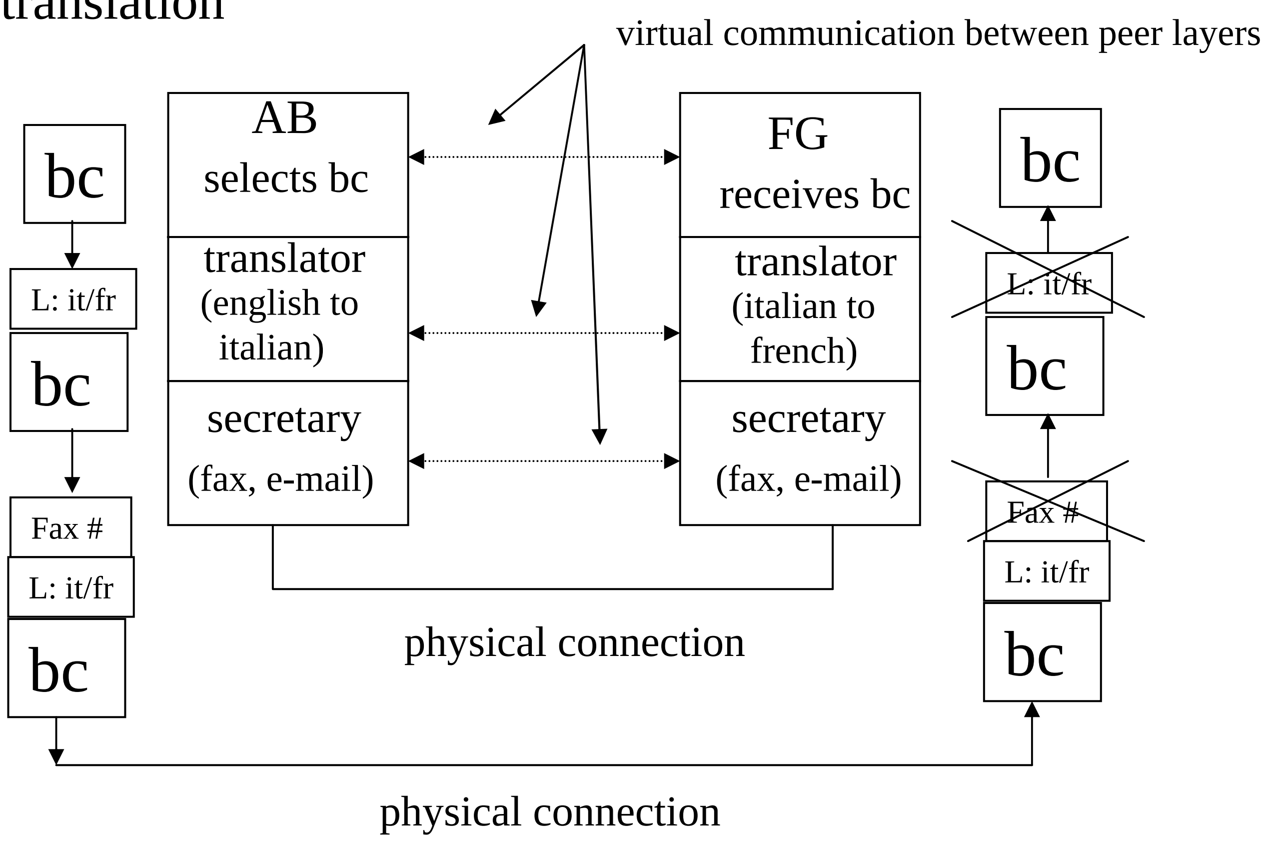
- From the scale point of view, networks can be classified into:
  - Local Area Networks (LAN) – building, campus
  - Metropolitan Area Networks (MAN) – city
  - Wide Area Networks (WAN) – country, continent
  - Internet – planet

Layered Protocol Architecture

- Networks are organized as a series of layers (or levels), each one built upon the one below it.
  - Main reason: reduce complexity – "divide and conquer" approach; split the network into smaller modules with different functionalities and deal with more manageable design and implementation.
- The purpose of each layer – offer certain services to the higher layers, shielding those layers from the details of how the services are implemented.

Def: The set of layers and protocols is called a network architecture.

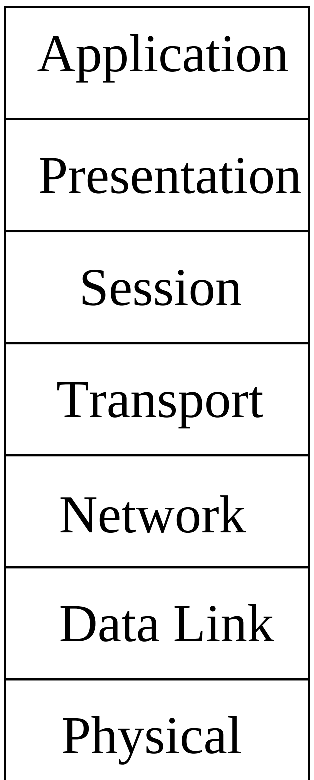
- Each layer *n* communicates only with its peer using a set of rules and conventions – collectively known as ***layer n protocol***
- **Birthday card example**
  - American business man (AB) wants to send a birthday card (bc) to his French girlfriend (FG) in french, and uses an agency for translation



- **Layer 1 protocol:** fax
  - agreed upon by the peer processes in layer 1
  - Can be changed (in common agreement) without informing other layers
- **Layer 2 protocol:** choice of language for intermediate translation
  - Italian might be replaced with Danish or Finish, without informing other layers
- Each process adds information intended only for its peer, not passed upward to the layers above.
- In a computer network: each layer adds its own header and possible a trailer to the packet.
- A list of protocols used by a certain system: **protocol stack**
- **Important properties of the layered architecture:**
  - **Each layer should perform a well defined function**
  - **The layers' boundaries should be chosen to minimize the information flow across the interfaces**
  - **Tradeoff number of layers**
    - **Too small: too many distinct functions in a common layer**
    - **Too large: too complex architecture**

OSI Reference Model
(Open Systems Interconnection)

- Seven layers model
  - Note: Many existing networks have somewhat different layers than the OSI model.



1) Physical Layer

Function: Transmits raw bits over a communication channel: ***unreliable bit pipe***

Main design issues:

- how to represent “0” and “1”
- bit duration
- type of transmission (simplex, duplex)
- how to initiate/terminate connection, etc.

2) **Data link layer**

- Raw unreliable pipe -> line that appears free of transmission errors in the network layer
- Breaks input data into data frames:
  - Adds overhead bits – computing the check sum for each frame: error detection and correction
  - Acknowledgement for lost frames: ARQ protocols (Automatic Repeat Request)
  - Some form of flow regulation also included
- For **multi-access communication**: many users compete for access to a common shared channel (medium) – this is the case of wireless
  - Add MAC (Medium Access Control) sub layer – deals with access control over the shared channel

3) **Network layer**

Function: controls the network operation.

Examples from wireless: routing, admission control, power control, base station assignment (handoff).

4) **The transport layer**

- true source-to-destination (end-to-end) layer

Main function: splits the data from session layer into smaller pieces and ensures that all these message pieces arrive correctly at the other side.

- error checking mechanisms and data flow control
- provides services for both the “connection-mode” transmission and connectionless transmission
- if connection mode and packet network, packets may need to be re-ordered (e.g. TCP/IP)
- TCP can be mapped into the transport layer

Connection – oriented service: modeled as the telephone system: establish connection, use it and then close it. Acts like a tube; order of packets is preserved.

Connectionless service: modeled after the postal system. Each packet carries the full destination address and it is routed independently. Packets may arrive out of order!

5) **The session layer**

- enhanced services: e.g. remote login, remote file transfer

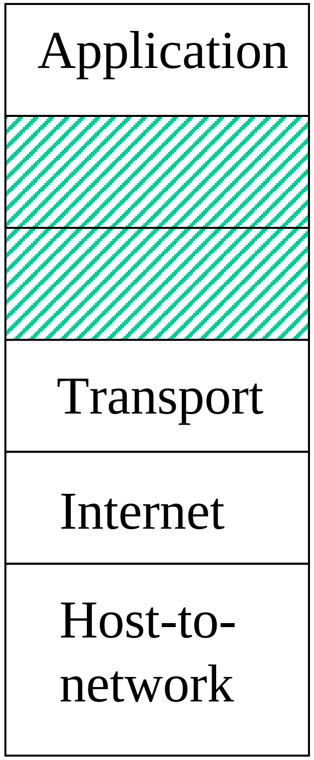
6) **The presentation layer**

- syntax and semantics of the information transmitted
  e.g., encoding data using a standard format.

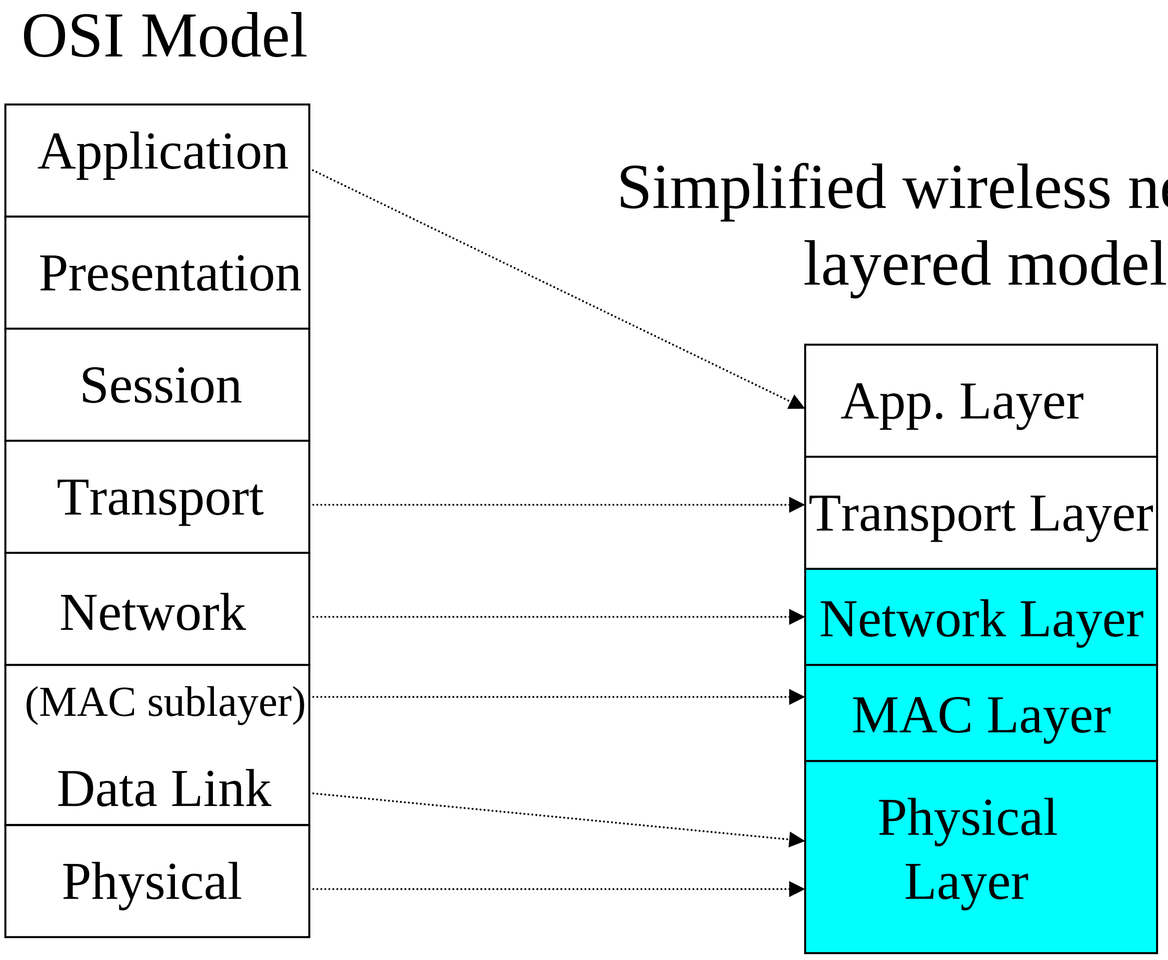
7) **Application layer**

- a variety of commonly used protocols

TCP/IP reference model



Our simplified model for wireless systems



- Advantages of layered design → modularity
  - Simplicity
  - Easy debugging
  - Easy to standardize
  - Flexibility to deploy new protocols (easy upgradeable)

- Any disadvantage?
- Underlying assumption: layers can be optimized independently
  - Is this always true for wireless?
  - Is it efficient?
  - What is the alternative?
  - What are the tradeoffs involved?
- Answer: wireless networks don’t come with links
  - Channel quality dynamically changes with fading and interference
  - Certain QoS required
  - Alternate solution: cross-layer design

→ interference management

- **Cross-Layer Design**
  - Birthday card example revisited:
  - AB has multiple options:
    - Add media clip
    - Add flowers
    - Has QoS requirements: cost and transmission delay
  - Translator's agency have dynamically varying price for different services depending on the current load
  - Similarly, the secretary has dynamically varying costs, based on the current dispatching of the couriers
  - AB exchanges information with the lower layers to optimize cost and delay, while trying to get the best service → **Cross-layer design**

- Cross-layer design advantages:
  - Exploits the interactions between layers
  - Promotes adaptability at all layers based on information exchange between layers
  - In wireless networks: tight interdependence between layers

- Cross-layer design disadvantages
  - Hard to characterize the interactions between protocols at different layers
  - Joint optimization across layers may lead to complex algorithms
  - Potential to destroy modularity

- ***Note: Understanding and exploiting the interactions between different layers is the core of the cross-layer design concept.***

- ***Several questions need to be clarified before these interactions can be successfully exploited:***
  - Does cross-layer design mean that we have to throw away the OSI reference model ?
  - Do we still need a network architecture ?
  - Is cross-layer design suitable for all types of wireless networks and all types of applications?

- Common misconception:

  Layered approach must be completely eliminated and all layers must be integrated and jointly optimized

  - clearly impractical
  - leads to spaghetti code
  - disaster in terms of implementation, debugging, upgrading and standardization

Solution: holistic view of wireless networking

- maintains the layered approach, while accounting for interactions between various protocols at different layers.

→ "loose-coupling" design

Probability review

- Discrete random variables
  - Notation X
  - Number of possible values for X is finite or countable infinite

Example 1. X = number of jobs arriving at a shop in a given week

- possible values of X = range space of X

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

- the probability that X takes the value x_i = $p(x_i) = P(X = x_i)$

- cannot take negative values:

$$p(x_i) \geq 0, \text{ for all } i$$

- $p(x_i)$ measures the frequency with which event x_i *occurs*

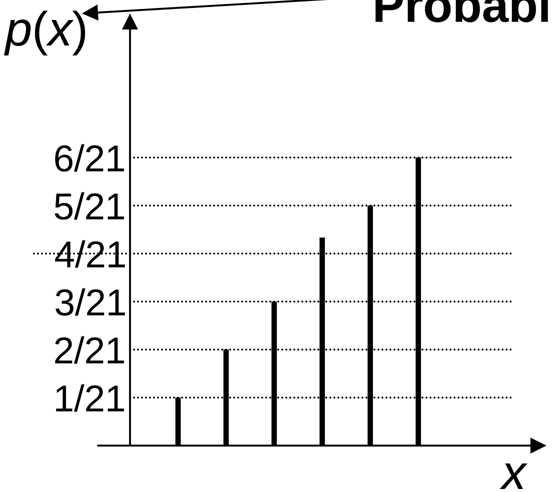
$$\sum_{i=1}^{\infty} p(x_i) = 1$$

Discrete random variables

- Example. Tossing a die experiment
  - Assume the die is loaded, with the probability of one face showing up, proportional to the number of spots on the die

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

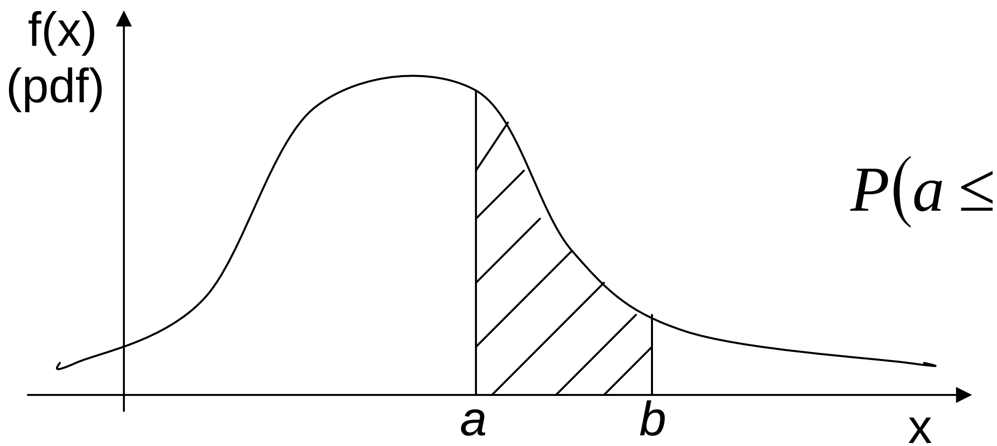
Probability mass function (*pmf*)



What would be the *pmf* for a regular die ?
- every face shows with equal probability

Continuous random variables

- If the random variable can take values in a continuous interval (or a collection of intervals) – X = continuous random variable
- Characterized by the probability density function (pdf)



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

Properties:

(a) $f(x) \ge 0 \quad \forall x \in R_X$

(b) $\int_{R_X} f(x) = 1 \quad \forall x \in R_X$

(c) $f(x) = 0, \ if \ x \notin R_X$

Example for continuous random variable

- Driving time from Hoboken to Philadelphia
  - Is this characterized by a known *pdf* ?
  - Empirical distribution
  - What would be some obvious measures that you would use to characterize the driving time
    - **(a) On *average* will be about 2 hours → statistical mean**
    - **(b) 90% of the time, it will take between 1h 45 min and 2 h 10 min.**
    - **(c) What is the spread (variance) from the mean driving time?**

(b)

$$P(105\,\text{min} \le X \le 130\,\text{min}) = \int_{105}^{130} f(x)dx = 0.9$$

Mean and Variance

- Mean = expected value (expectation) $E(X) = \mu = 1^{st}$ *moment of X*
  - Discrete case:

$$E(X) = \sum_{i \in R_X} x_i \, p(x_i)$$

  - Continuous case:

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

  - $E(X^n) = n^{th}$ *moment of X*

$$E(X^n) = \sum_{i \in R_X} x_i^n \, p(x_i) \quad \text{discrete}$$

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

Mean and variance - cont

- Variance – measure of the spread (variation) of possible values of X around the mean

$$\sigma^2 = \mathrm{var}(X) = V(X) = E[(X - E(X))^2] = E(X^2) - [E(X)]^2$$

- Standard deviation

$$\sigma = \sqrt{\mathrm{var}(X)}$$

- Mode – peak of the pdf or pmf

Cumulative Distribution Function (CDF)

- Measures the probability that X has a value less or equal to x
  - Discrete r.v.

$$F(x) = \sum_{i, x_i \le x} p(x_i)$$

  - Continuos r.v.

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

- Properties of CDF function:

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

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

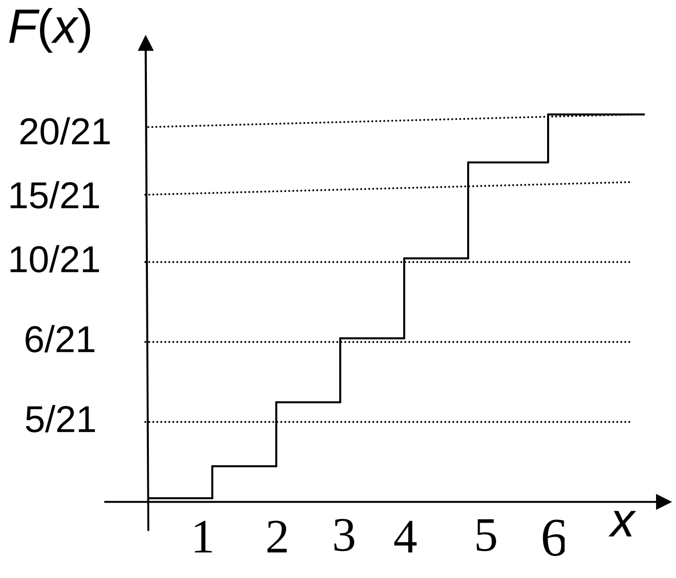
$$a < b \Rightarrow F(a) \le F(b)$$

CDF example

- Loaded die

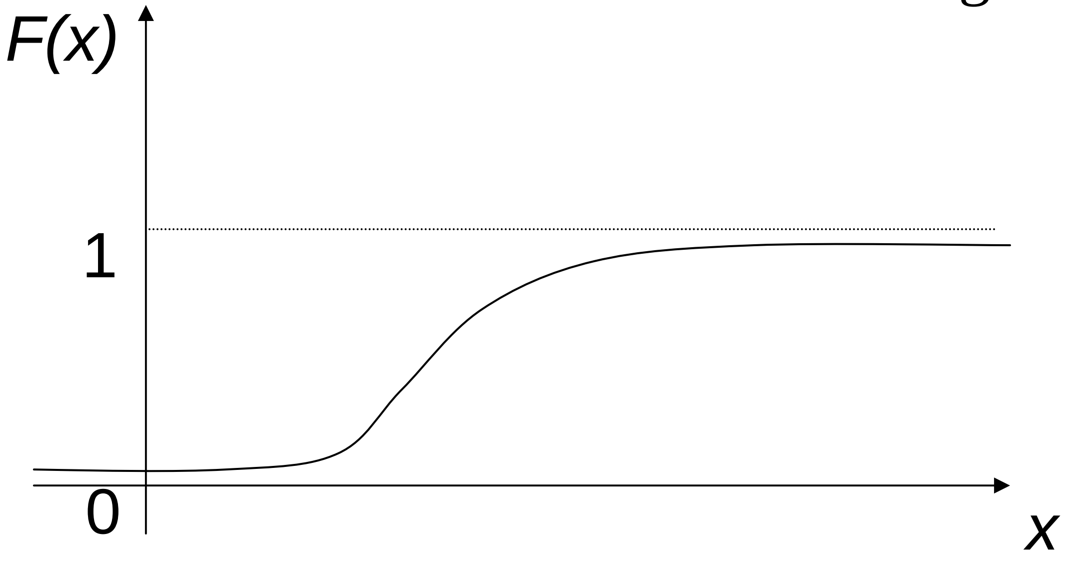
x_i	1	2	3	4	5	6
$p(x_i)$	1/21	2/21	3/21	4/21	5/21	6/21

x	(-∞,1)	[1,2)	[2,3)	[3,4)	[4,5)	[5,6)	[6, ∞)
F(x)	0	1/21	3/21	6/21	10/21	15/21	21/21



Continuous CDF example

- Based on the three properties, a generic CDF for a continuous r.v. should look like in the figure



Discrete Distributions

- Bernoulli trials
  - Consider an experiment, consisting of n trials, which can be a success (1) or a failure (0)
    - E.g. coin flipping, receiving a bit, etc.
  - The n Bernoulli trials are called a Bernoulli process, if
    - The trials are independent

$$p(x_1, x_2, \ldots, x_n) = p(x_1)p(x_2)\ldots p(x_n)$$

    - Probability of success remains constant from trial to trial
  - For one trial, the Bernoulli distribution is

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

$$E(X) = 0 \cdot q + 1 \cdot p = p$$

$$\mathrm{var}(X) = E\left(X^2\right) - E(X)^2 = $$

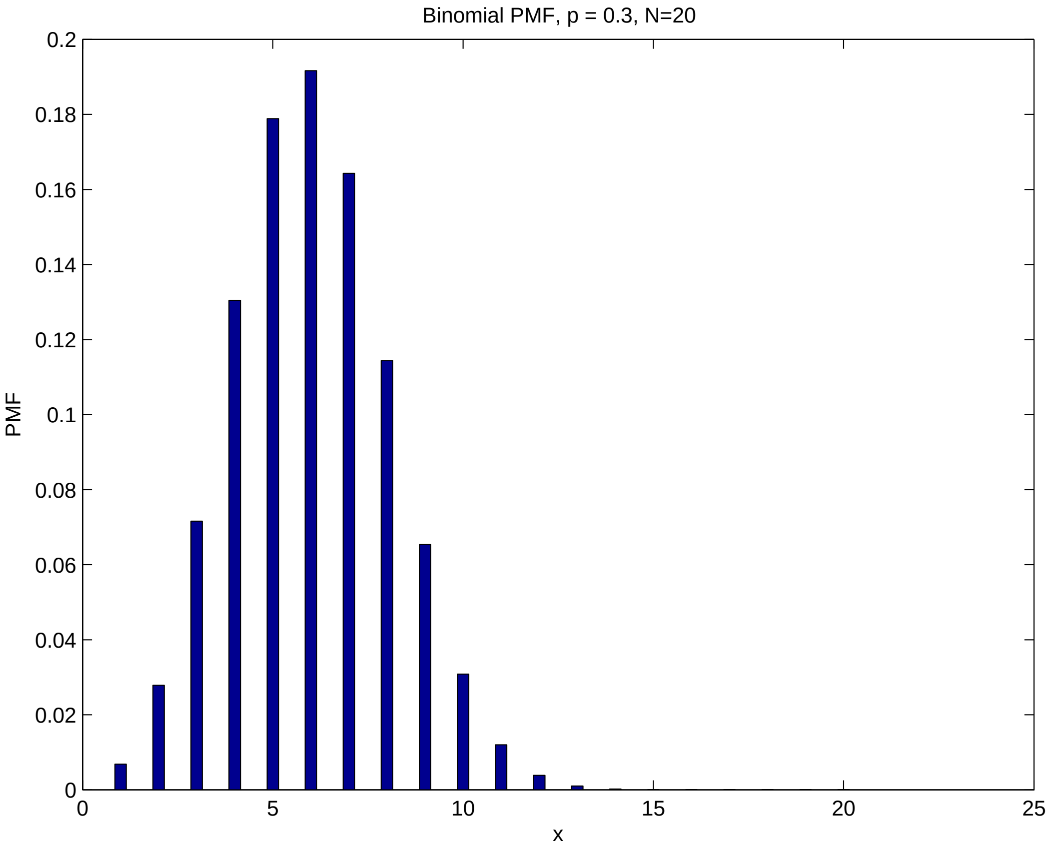
$$= \left[0^2 \cdot q + 1^2 \cdot p\right] - p^2 = p(1 - p)$$

Discrete distributions - cont

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

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

$$E(X) = np$$
$$\mathrm{var}(X) = npq$$



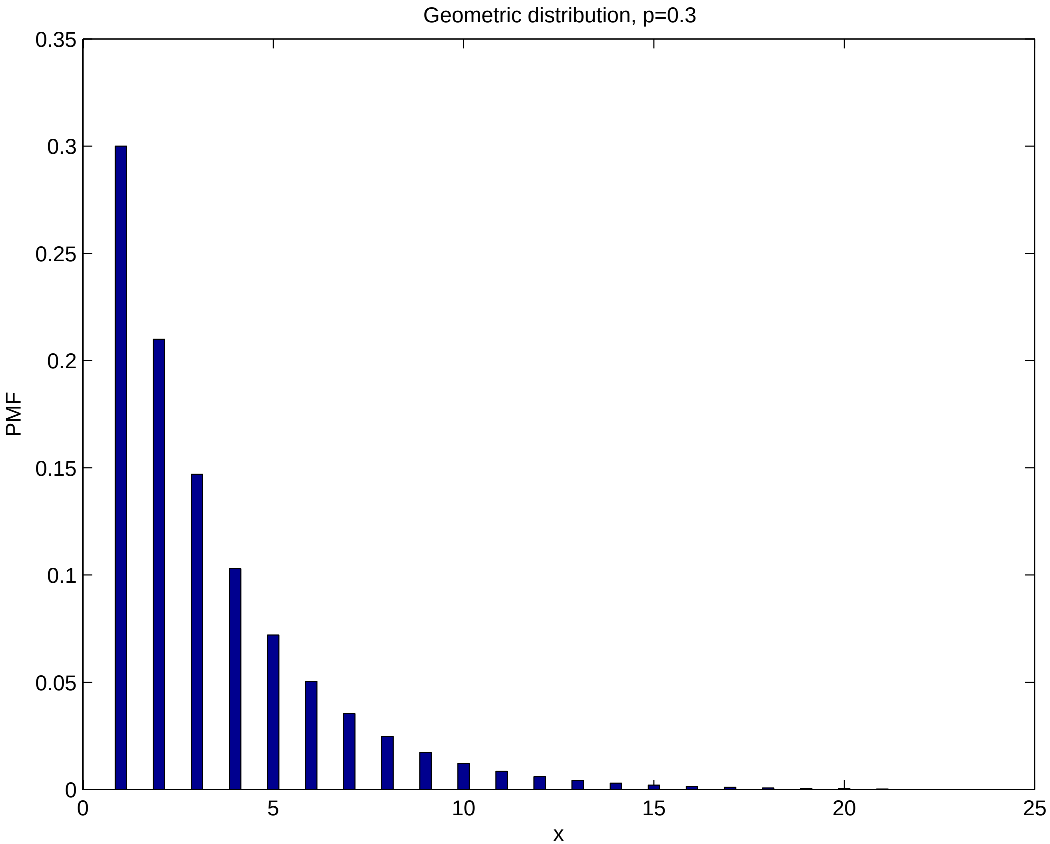
Discrete distributions - cont

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

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

$$E(X) = \frac{1}{p}$$

$$\mathrm{var}(X) = \frac{q}{p^2}$$

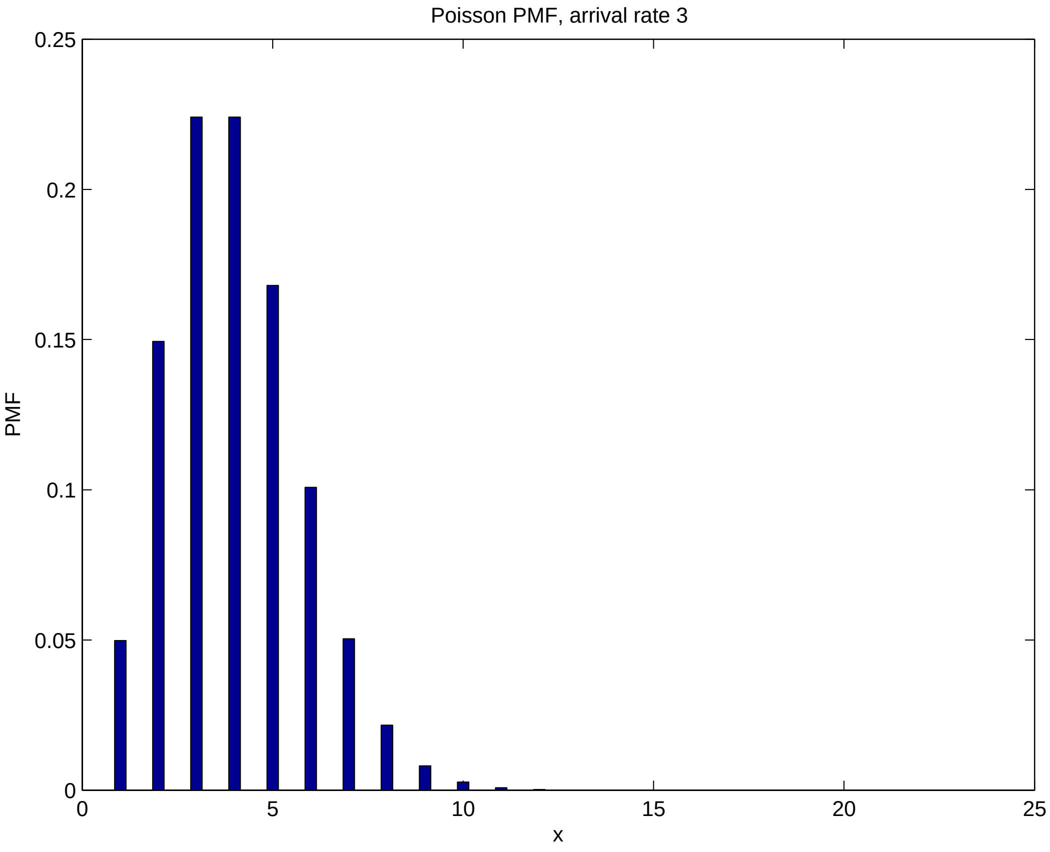


Discrete distributions - cont

- Poisson distribution
  - Very often used – good model for arrival processes

$$p(x)=\begin{cases}\dfrac{e^{-\lambda}\lambda^{x}}{x!} & x=0,1,2,\ldots\\ 0 & ow\end{cases}$$

$$E(X)=\text{var}(X)=\lambda$$



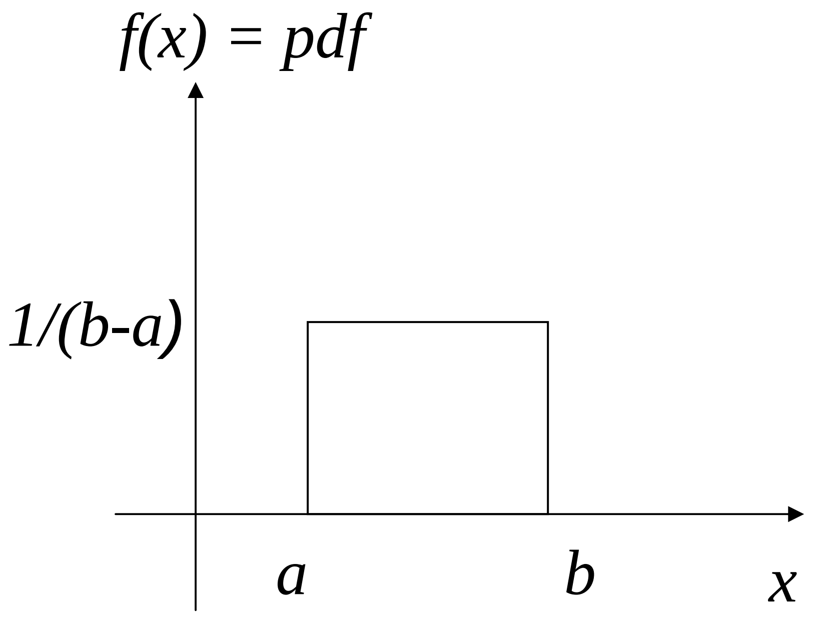
Continuous Distributions

- Uniform distribution
  - Very easy to generate (recall rand() function), is used for generating other types of r.v.s

$$f(x)=\begin{cases}\frac{1}{b-a} & a\le x\le b\\ 0 & ow\end{cases}$$

$$E(X)=\frac{a+b}{2}$$

$$\mathrm{var}(X)=\frac{(b-a)^2}{12}$$



Continuous Distributions – Cont.

- Exponential distribution
  - Used to model inter-arrival times and service times for queues
  - Has long tail – useful for modeling component lifetime, e.g. life of a light bulb

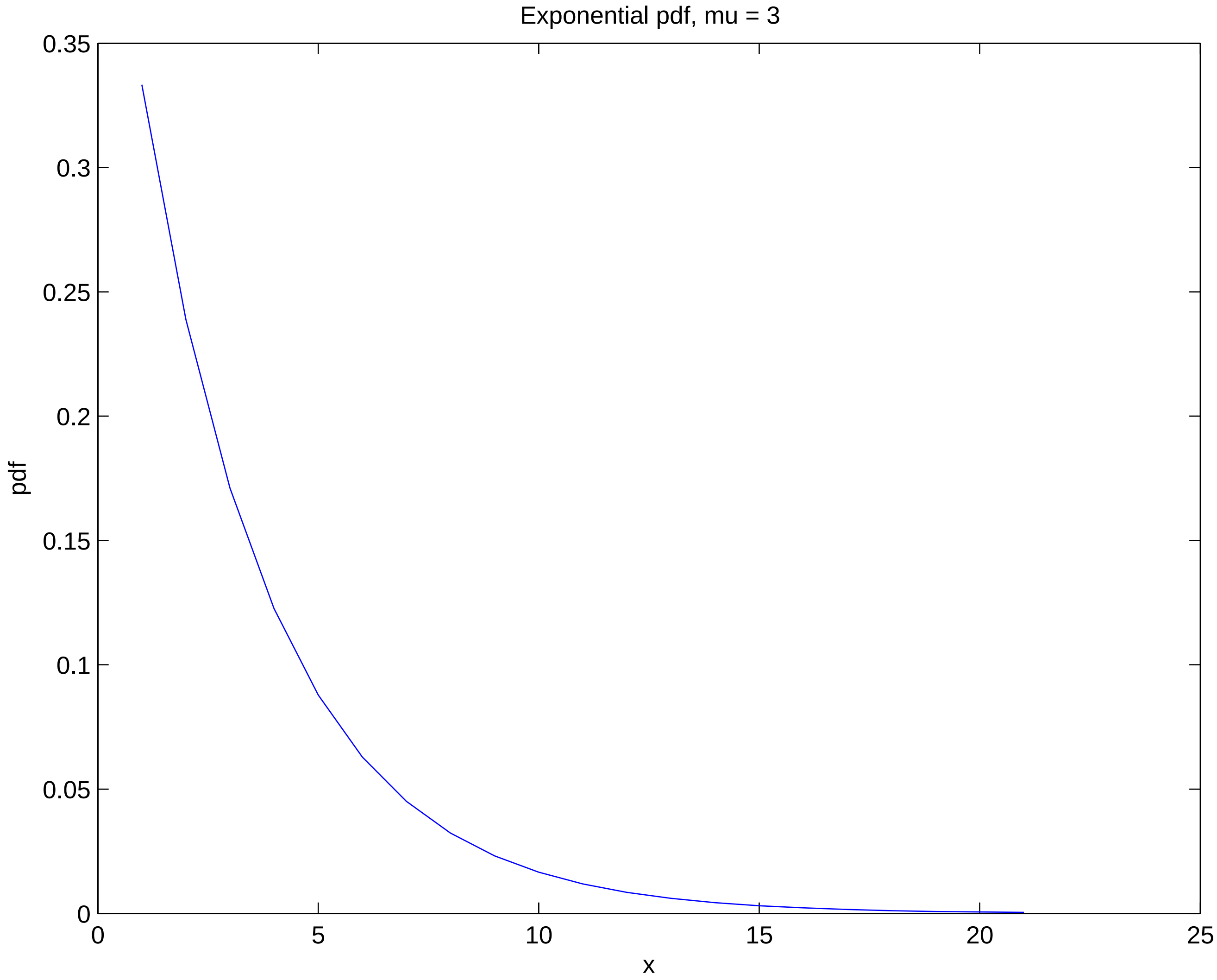
$$f(x) = \begin{cases} \lambda e^{-\lambda x} & x \geq 0 \\ 0 & ow \end{cases}$$

$$E(X) = \frac{1}{\lambda}$$

$$\text{var}(X) = \frac{1}{\lambda^2}$$

λ is a rate: e.g. arrival rate, service rate, failure rate, etc…

Exponential distribution

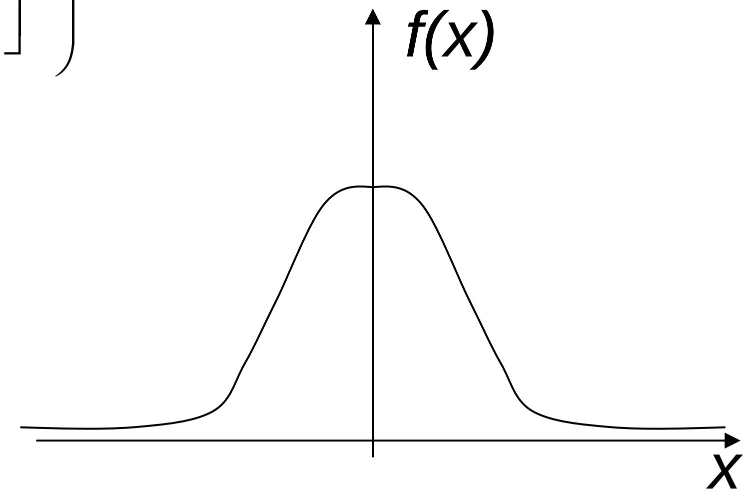


Continuous Distributions – Cont.

- Normal distribution (Gaussian distribution)
  - Widely used: model of thermal noise in circuits, communications
  - Mean μ, variance σ^2

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\left(-\frac{1}{2}\left[\frac{x-\mu}{\sigma}\right]^2\right)}$$

  - Mode and mean are equal



$$F(x) = P(X \le x) = \Phi\left(\frac{x-\mu}{\sigma}\right)$$

$$\Phi(z) = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt$$ - tabulated

More details about the exponential distribution

pdf: $$f(x)=\begin{cases}\lambda e^{-\lambda x} & x\geq 0\\ 0 & ow\end{cases}$$

$$E(X)=\frac{1}{\lambda}$$

$$\operatorname{var}(X)=\frac{1}{\lambda^2}$$

λ is a rate: e.g. arrival rate, service rate, failure rate, etc…

- Some important properties:
  - Memory-less property: $P(X>s+t\,|\,X>s)=P(X>t)$

conditional probability: for two events A, B:

$$P(A,B)=P(A\,|\,B)P(B)=P(B\,|\,A)P(A)$$

We can then show the memory-less property of the exponential r.v.

$$P(X>s+t\,|\,X>s)=\frac{P(X>s+t,X>s)}{P(X>s)}=\frac{P(X>s+t)}{P(X>s)}=\frac{e^{-\lambda(s+t)}}{e^{-\lambda s}}=e^{-\lambda t}$$

Example for exponential distribution

- Suppose a bus arrives at a bus station, such that the inter-arrival time between buses is exponential distributed with mean $\mu = 10$ minutes.
- Suppose that you already have waited for the bus for 10 minutes. Questions:
  - What is the probability that you will still have to wait for at least another 15 minutes?

$$P\left(X > 10+15 \mid X > 10\right) = P(X > 15) = \int_{15}^{\infty} 0.1e^{-0.1x}dx = -e^{-0.1x}\Big|_{15}^{\infty}$$

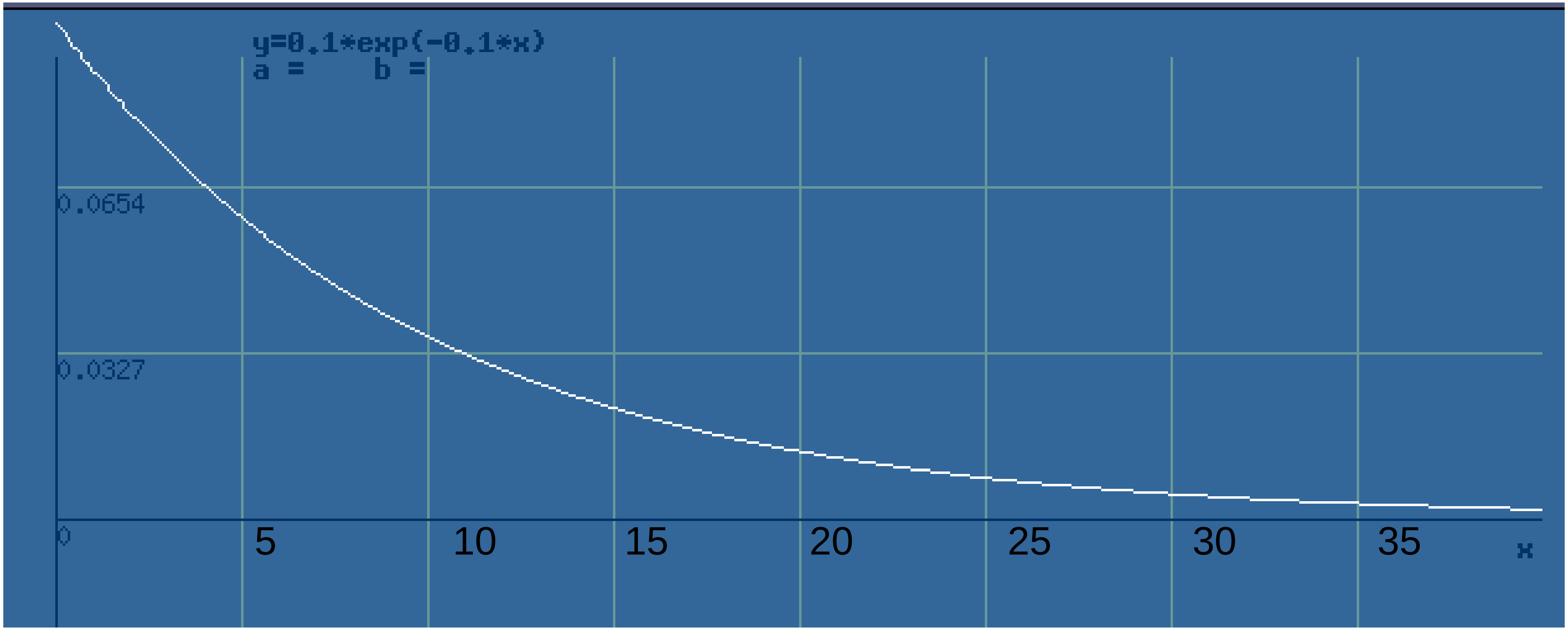
$$= e^{-0.1 \cdot 15} = 0.22$$

  - What is the probability that you will still have to wait less than 5 minutes?

$$P\left(X < 10+5 \mid X > 10\right) = P(X < 5) = 1 - \int_{5}^{\infty} 0.1e^{-0.1x}dx = 0.39$$

Exponential distribution pdf

Exponential: λ= 0.1; μ = 10



Source for the plot: http://www.wessa.net/math.wasp

Relation with Poisson r.v.

- If the interval between generation of events (e.g. arrival, service) is an exponential r.v. with mean $\mu = 1/\lambda$, then the event generation process is a Poisson process, with mean λ.
  - Example: If buses arrive at the station at intervals that are exponentially distributed, the arrival process for the buses is Poisson.
    - Questions: If the mean time between arrivals is $\mu = 10$ minutes,
      - (1) What is the probability that a traveler has to wait for the bus for more than 15 minutes?
      - (2) What is the probability that at most 2 busses will arrive in the station within the first ½ hour?

(1) $$P(t > 15) = e^{-0.1 \cdot 15} \approx 0.22$$

(2) $$P(N \le 2) = \sum_{i=0}^{2} \frac{e^{-0.1 \cdot 30} \cdot 3^i}{i!} \approx 0.049 + 0.15 + 0.22 = 0.4195$$

Poisson process

- A counting process {*N(t), t* $\geq$ *0* } (*N(t) represents the number of events that occurred in the interval* [0, t)) is a Poisson process if
  - *Arrivals occur one at a time*
  - *{N(t), t* $\geq$ *0 } has stationary increments: the distribution of the number of arrivals for the interval t+s, depends only on the length of the observation interval s, and is independent on the initial starting point t*
  - *{N(t), t* $\geq$ *0 } has independent increments: the number of arrivals for non-overlapping time intervals are independent random variables.*
  - *The probability of n arrivals in the interval* [0, t) *is given as*

$$P\left(N(t)=n\right)=\frac{e^{-\lambda t}(\lambda t)^n}{n!},\ t>0,\ n=0,1,2,...$$

Some useful properties of the Poisson process

- Random splitting
  - If a Poisson arrivals process with rate λ is split using a coin flipping (probability of a head = p) into two types of arrivals A and B, the resulting arrival processes are also Poisson with rates

$\lambda_A = \lambda p,$ and $\lambda_B = \lambda(1-p)$, respectively

- Pooling of two or more arrival streams
  - If n arrival streams are pooled together, the resulting arrival process will be Poisson, with the rate equal to the sum of the rates of the individual processes.

$$\lambda_p = \sum_{i=1}^{n} \lambda_i$$

More on random variable distributions

- Poisson and exponential random variables are extensively used for queueing theory analysis and modeling of queueing systems
- If you add *k* independent exponential random variables, with rate λ, the resulting random variable has an Erlang distribution of order *k:*

$$f(x) = \frac{\lambda^k e^{-\lambda x} x^{k-1}}{(k-1)!}, \qquad \text{x} \geq 0$$

- *For k=1 → exponential*
- *CDF:*

$$F(x) = 1 - \sum_{i=0}^{k-1} \frac{(\lambda x)^i e^{-\lambda x}}{i!}$$

- *Mean and variance:* $E(X) = \frac{k}{\lambda}; \;\; \mathrm{var}(X) = \frac{k}{\lambda^2}$

Gamma distribution

- The gamma distribution generalizes the Erlang distribution

$$f(x) = \frac{\lambda^{\alpha} e^{-\lambda x} x^{\alpha-1}}{\Gamma(\alpha)}, \qquad x \geq 0,$$

$$\text{where, } \Gamma(\alpha) = \int_0^{\infty} t^{\alpha-1} e^{-t} dt, \;\; \Gamma(\alpha) = (\alpha-1)\Gamma(\alpha-1)$$

- Some properties:

$$\Gamma(1/2) = \sqrt{\pi}$$

$$\text{if } \alpha \text{ integer, } \Gamma(\alpha) = (\alpha-1)!$$

Rayleigh and Lognormal Distributions

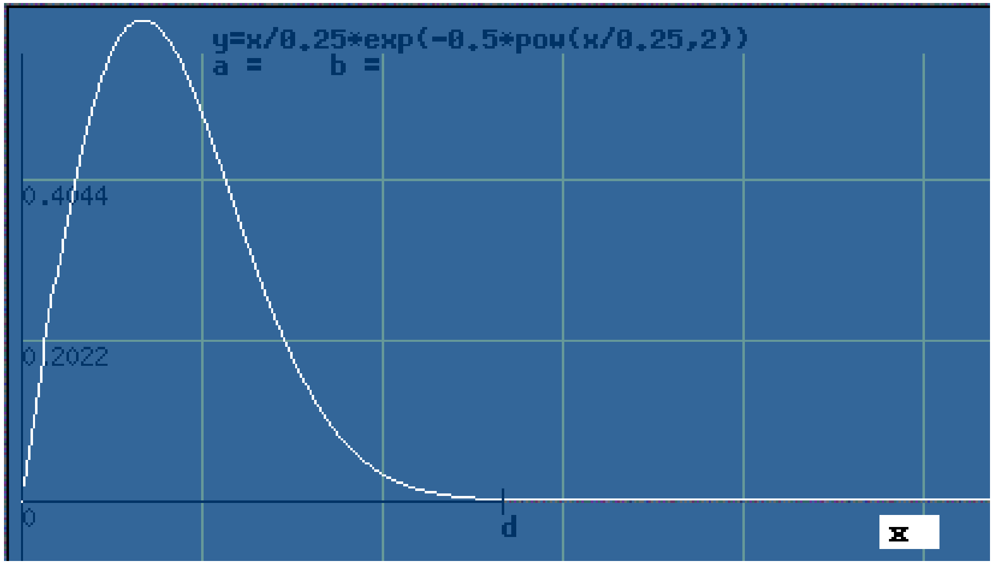
- Both are used in wireless communications for modeling different types of fading experienced by the radio transmission
  - Fast fading: modeled by the Rayleigh distribution (appears as an effect of the motion)
  - Slow fading: modeled by the Lognormal distribution (appears as an effect of the environment)

Rayleigh distribution

$$f(x) = \frac{x}{p}\exp\left(-\frac{x^2}{2p}\right), \mathrm{x} \geq 0$$

$$E(X) = \sqrt{\frac{\pi}{2}p}\ ; \quad \mathrm{var}(X) = \frac{4-\pi}{2}\mathrm{p}$$

Rayleigh: p = 0.25



http://www.wessa.net/math.wasp

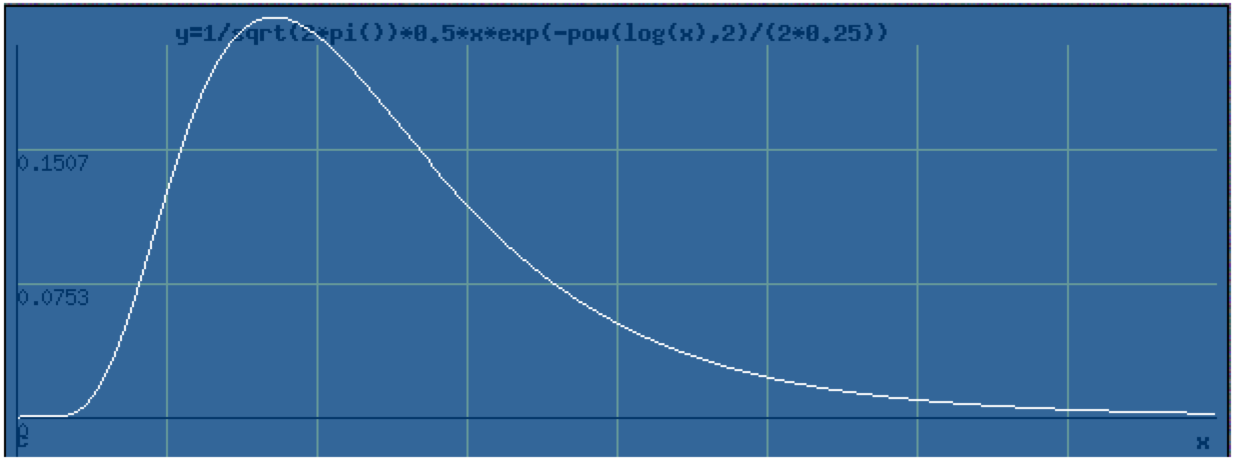
Lognormal distribution

- pdf: $f(x) = \frac{1}{\sqrt{2\pi}\sigma x} \exp\left[-\frac{(\ln x - \mu)^2}{2\sigma^2}\right], \quad x > 0$
- If X is lognormal, ln(X) is normal distributed with mean μ and variance σ^2
- Mean and variance for the lognormal distribution

$$\mu_L = e^{\mu + \sigma^2/2}$$

$$\sigma_L^2 = e^{\sigma^2 + 2\mu}\left(e^{\sigma^2} - 1\right)$$

Lognormal: μ=0, σ = 0.5



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