Űrkommunikáció
Space Communication
2023/1.

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Organization Issues

- Lectures (14 Semester week)
  - Recording is forbidden
  - Questions during lecture are welcome
  - Slides will be uploaded after the lectures
- 1 Midterm Exam (Score>50%) and Final Exam
  - probably on VIK Moodle tool
  - Multiple choice questions and numerical tasks
- References:
  - J. G. Proakis, M. Salehi: Communication Systems Engineering (Prentice Hall, 2002)
  - Th. M. Cover, J. A. Thomas: Elements of Information Theory (Wiley, 2006)
  - H. L. Van Trees: Detection, Estimation, and Modulation Theory, Vol I (Wiley)

Hungarian references

- Dallos György: Tantárgyi segédlet a Hírközléselmélet című tárgyhoz (2006) http://www.hit.bme.hu/~dallos/hirkelm/
- Frigyes I.: Hírközlő rendszerek (Műegyetemi Kiadó, 2001)
- Csibi S.: Információ közlése és feldolgozása (Tankönyvkiadó, 1980)

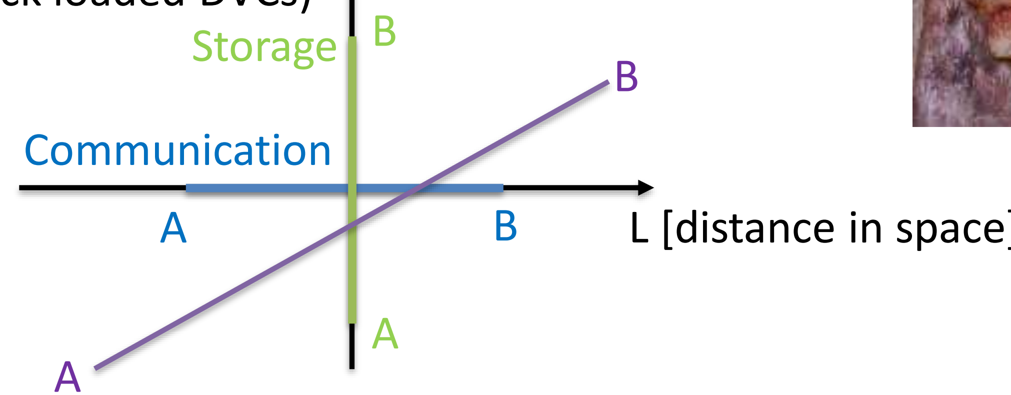
The goal of Communication

To transfer ***information / news*** form the
- information ***Source*** to the
- ***Sink*** of information get through a
- communication ***Channel***.

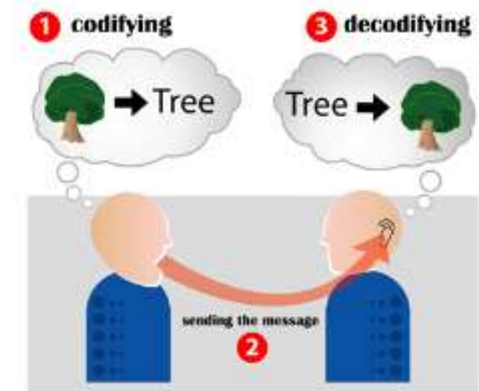
The channel is influenced / corrupted by natural and/or artificial
- ***Noise***
- ***Interference***
- ***Fading*** of the signal bearing the information
- Sketch on a disc, etc.

Transfer information between two points A and B separated in
- ***time*** (info storage) or
- ***space*** (info communication)
- (or both: e.g. a truck loaded DVCs)

Space-Time diagram



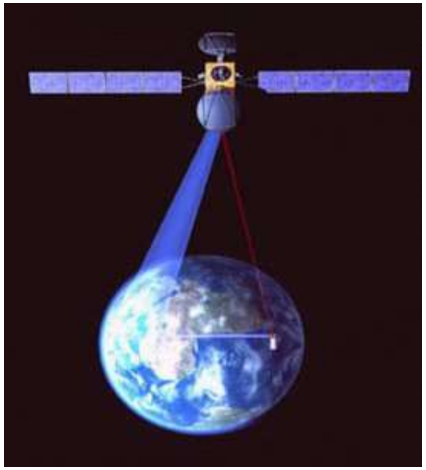
Transferring info in space



Transferring info in time

Form Wikipedia

Pont-pont összeköttetések



1. Föld-Föld (terrestrial links)
2. Föld-Műhold (satellite links)
3. Műhold-Műhold

<u>A műholdas rádióátvitel előnyei a földihez képest:</u>

- Nagyobb lefedettséget biztosít
- Egy műhold számos földi állomás között képes kapcsolatot létesíteni

<u>Hátrányok:</u>

- Az áthidalandó távolság igen nagy. A Föld-műhold-Föld szakasz együttes késleltetése nagyságrendileg 500 ms. (Egy összeköttetés legfeljebb egy műholdas szakaszt tartalmazhat)

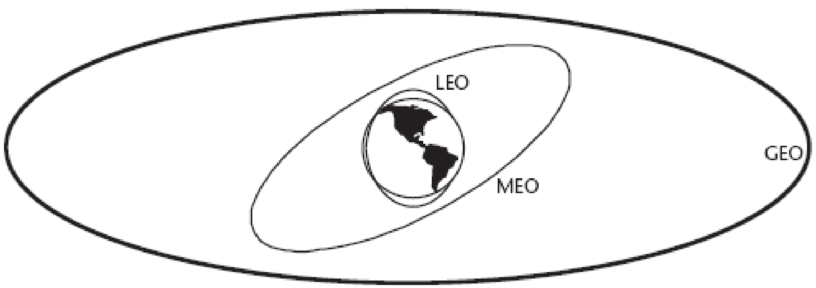
<u>A pont-pont jellegű vezeték nélküli összeköttetések előnyei a vezetékes rendszerekhez képest:</u>

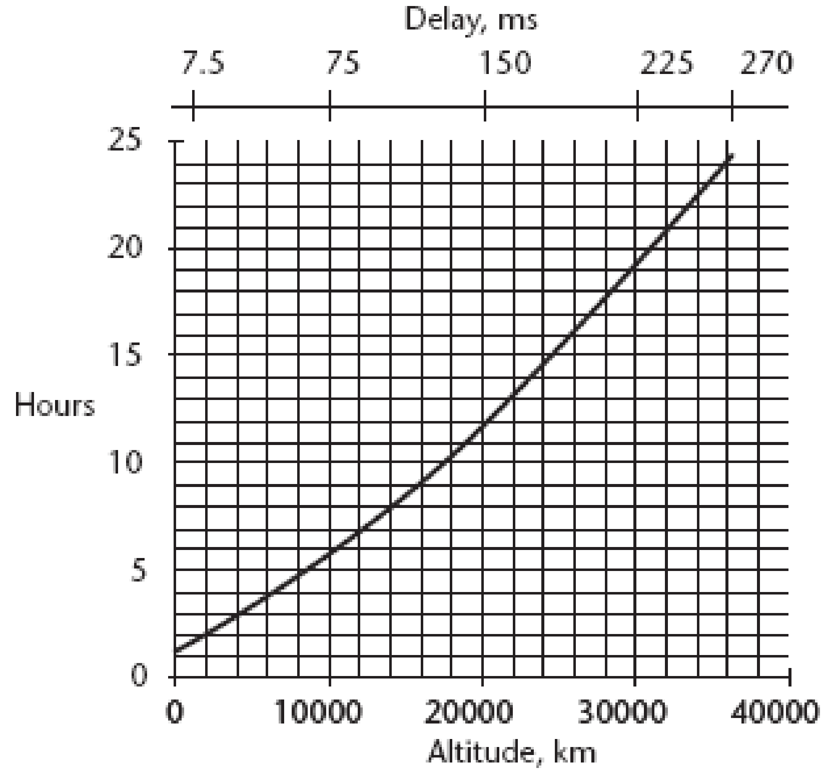
- kiesés (vezetékszakadás)
- olcsóbb, gyors telepítés

<u>Hátrányok:</u>

- kapacitásuk korlátozottabb
- kevésbé védettek a meteorológiai jelenségek, vagy más összeköttetések interferenciái ellen

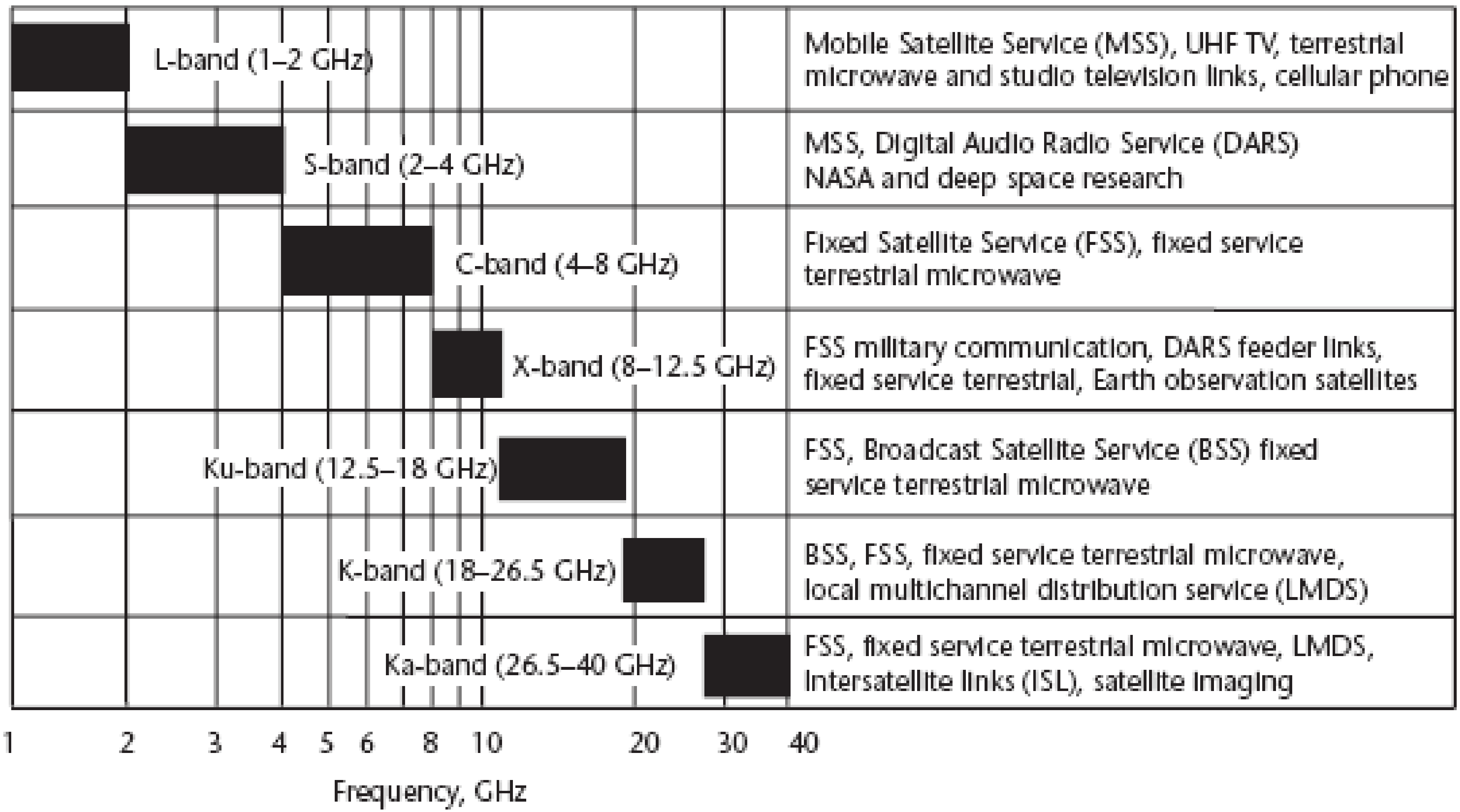
Csatorna - késleltetés



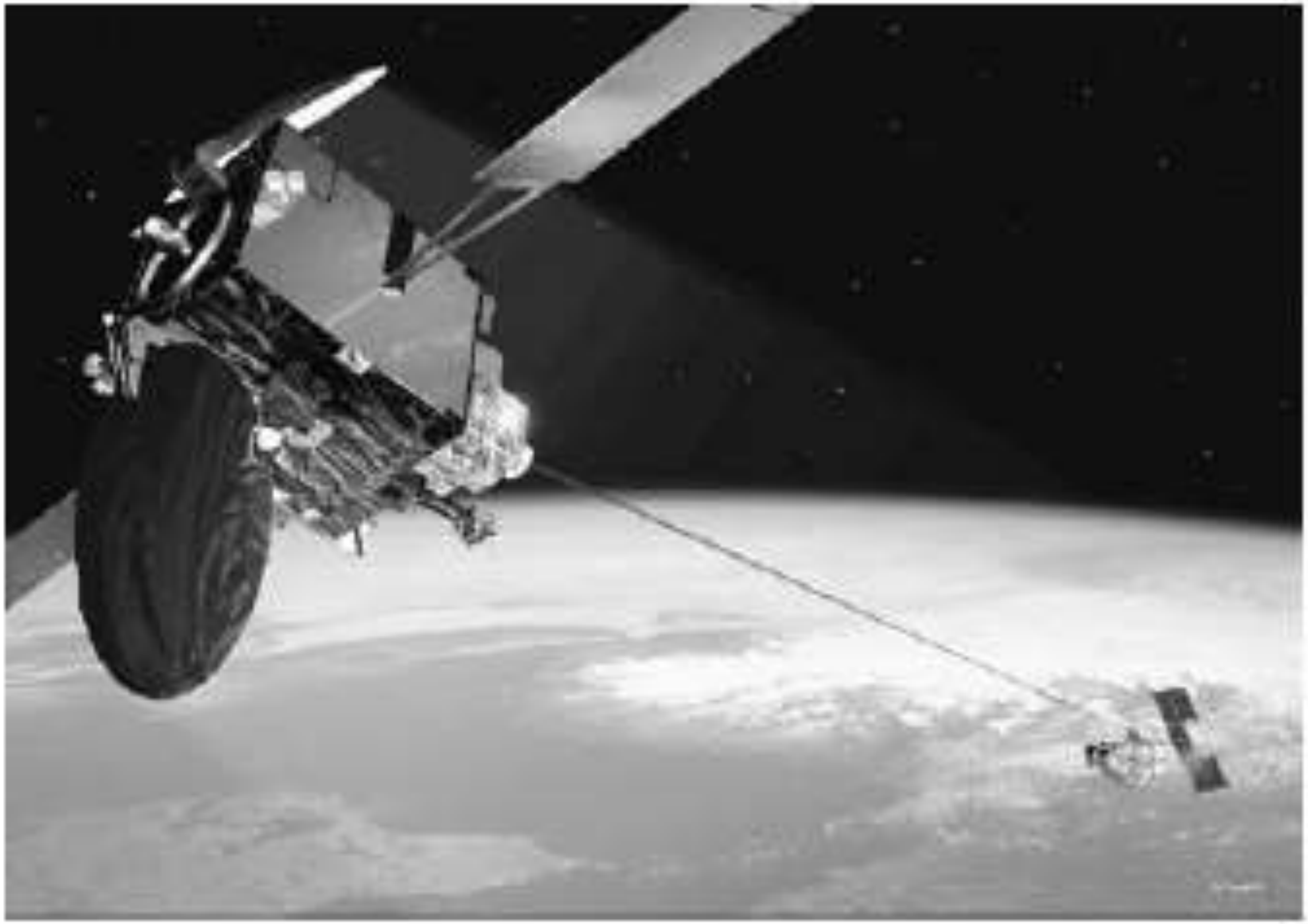


The respective altitude ranges are 500 to 900 km for LEO, 5,000 to 12,000 km for MEO, and 36,000 km for GEO. One-way (single-hop) propagation delay.

Frekvenciasávok (ITU) - Szolgáltatások



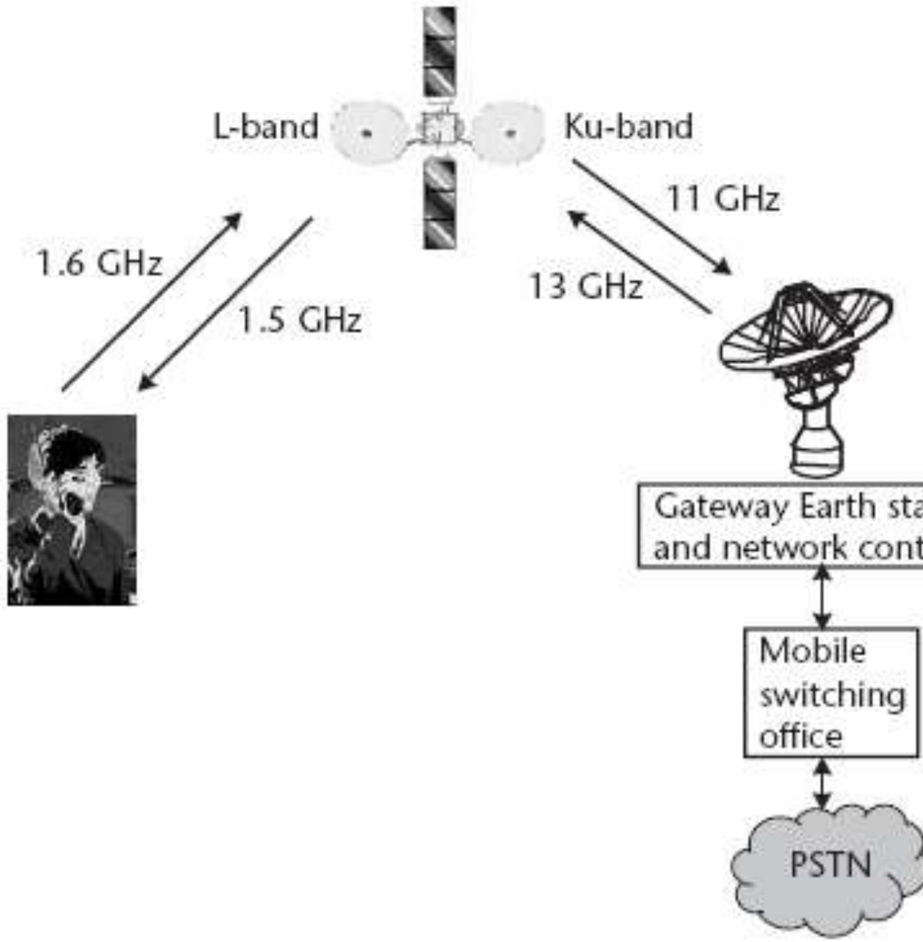
Rádiócsatorna - Szabadtér



MSS

Thuraya 1 provides high-power mobile satellite links to handheld terminals. (Courtesy of Boeing Satellite Systems.)

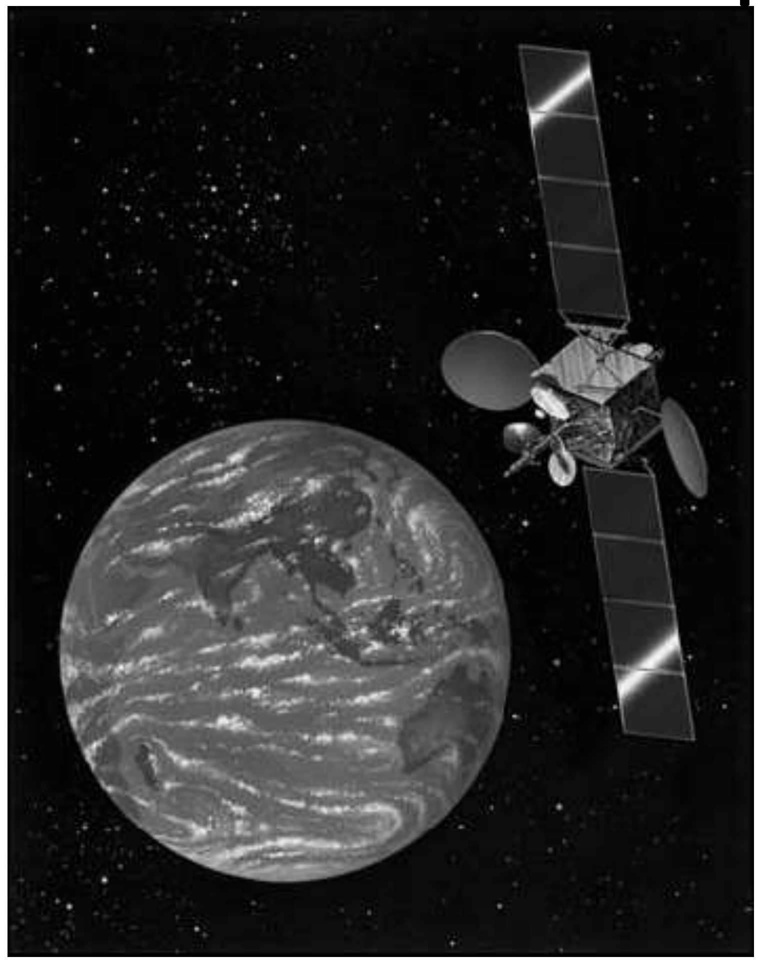
The mobile-to-fixed duplex link



VSAT – BSS with one transponder

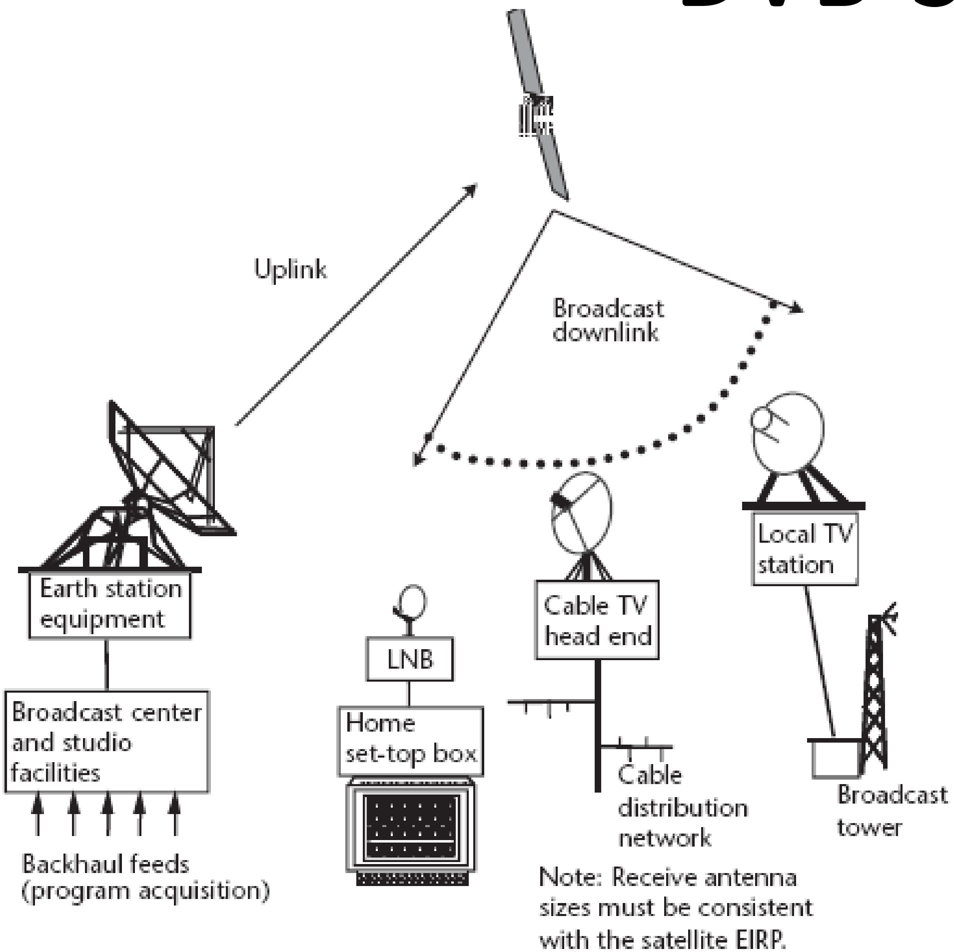
The Measat 1 satellite provides services to Malaysia and throughout Southeast Asia. Total payload power of such satellites reaches 1 kW

VSAT – BSS with 48 transponders



AsiaSat 3C is a hybrid C/Ka satellite with a total of 48 transponders.
Total payload power of such satellites reaches 15 kW

DVB-S


Uplink
Broadcast
downlink
Earth station
equipment
Broadcast center
and studio
facilities
Backhaul feeds
(program acquisition)
LNB
Home
set-top box
Cable TV
head end
Cable
distribution
network
Local TV
station
Broadcast
tower
Note: Receive antenna
sizes must be consistent
with the satellite EIRP.

VSAT

Source and Sink of Information

The (almost) ***analog signals*** of the real (or artificial, therefore ***digital***) world around us

Produced – (Source of Info)

- A: by the nature (Waves in the whole spectrum, light, sound, etc…)
- A,D: by humans (speech, music, text (series of symbols - digital), painting, etc…)
- D,A: by artificial sensors (camera, microphone, thermometer, antenna - EM waves, radar, analog voltmeter, etc.).
- D: artificially (Digital devices PC, Machine Type Communication MTC, Vehicle-to-Infrastructure V2I, etc…)

Sensed - (Sink of Info)

- A: by human sensors (we can see, hear, smell, touch – temperature, pressure, taste)
- D: by artificial devices (TV, PC, MTC, etc…)

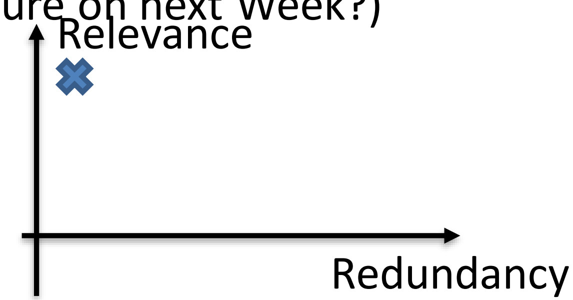
Information bearing signals varying randomly, because constant or deterministic signals we already known.

(Is this a news for you: There will be a Space Communication lecture on next Week?)

Mathematical model: *stochastic processes*

Relevance and Redundancy - Efficient communication

(songs of whales –not so relevant for human; green background)



Communication Channel

We will deal with technical / engineering aspects of communications and not with the social aspects (like how to introduce ourselves or make a discussion with others).

Physical Channels by different types of information transfer

- Information ***storage media***: DIN A4 sheet of paper (~1000 Symbols/Letters stored by 8 bit/symbol = 8 kbit), CD, DVD, magnetic tape, papyrus of the ancient Egypt's, etc.
- ***Wired communication channels:*** twisted pair of coper cable, optical cable, coax cable, wave guide of EM waves, etc.
- ***Wireless communication channels***: EM wave propagation, laser, fluctuating air pressure, etc.

We will deal with ***digital communication systems*** because digital signals/symbols are ***better protected / less influenced by the disturbing effects of the communication channels*** (we can better differentiate between 0 and 1 as between two analog signal) and because modern systems are (almost) digital.

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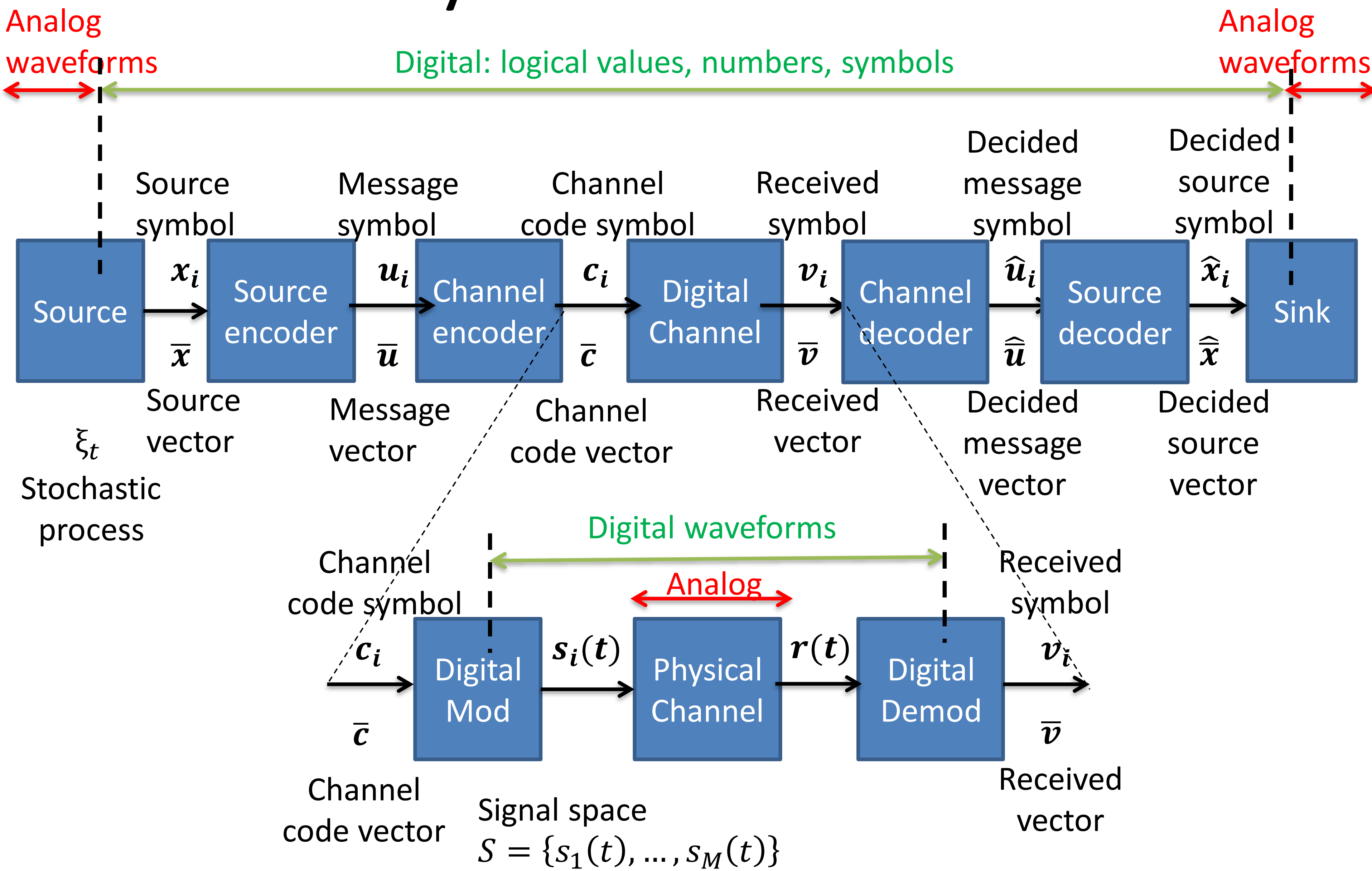
System overview



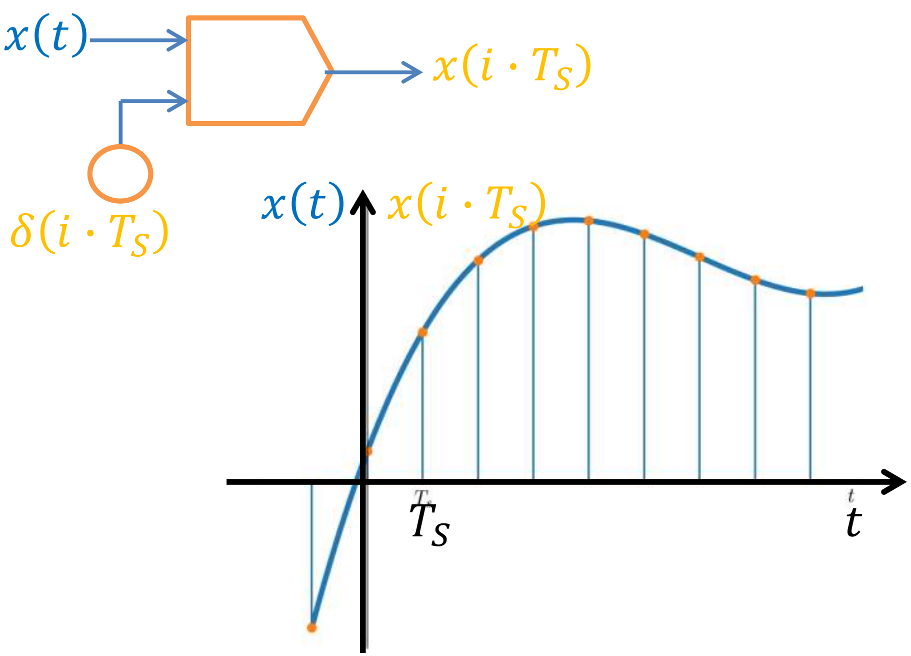
Analog to Digital (A/D) and Digital to Analog (D/A)

A/D: Two steps – ***Sampling*** and ***Quantization***

D/A: Time domain – ***Interpolation***
Frequency domain – ***Low-pass filtering***

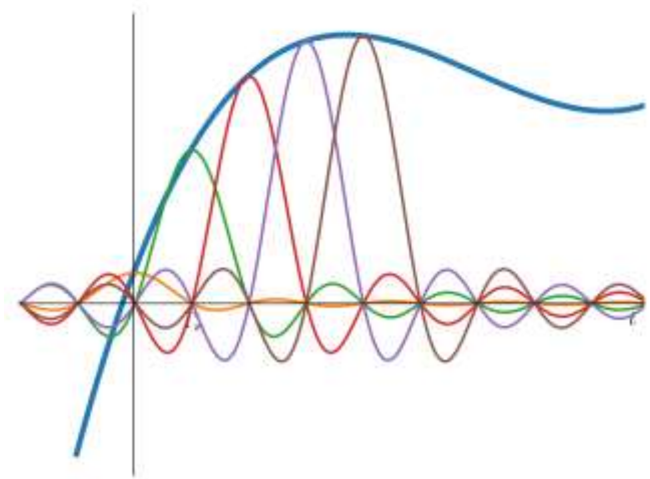
Shannon's sampling theorem: If the analog signal $x(t)$ is bandlimited with ***B*** and its absolute-valued integral exits, then $x(t)$ is uniquely represented (can be reconstructed free from distortion) by its samples $x(i \cdot T_S)$ taken at a rate $f_S \geq 2 \cdot B$ or equivalently taken at discrete time points separated by $T_S = 1/f_S \leq 1/2B$.
$f_N = 2 \cdot B$ is called Nyquist rate.

Sampling:



Interpolation formula:

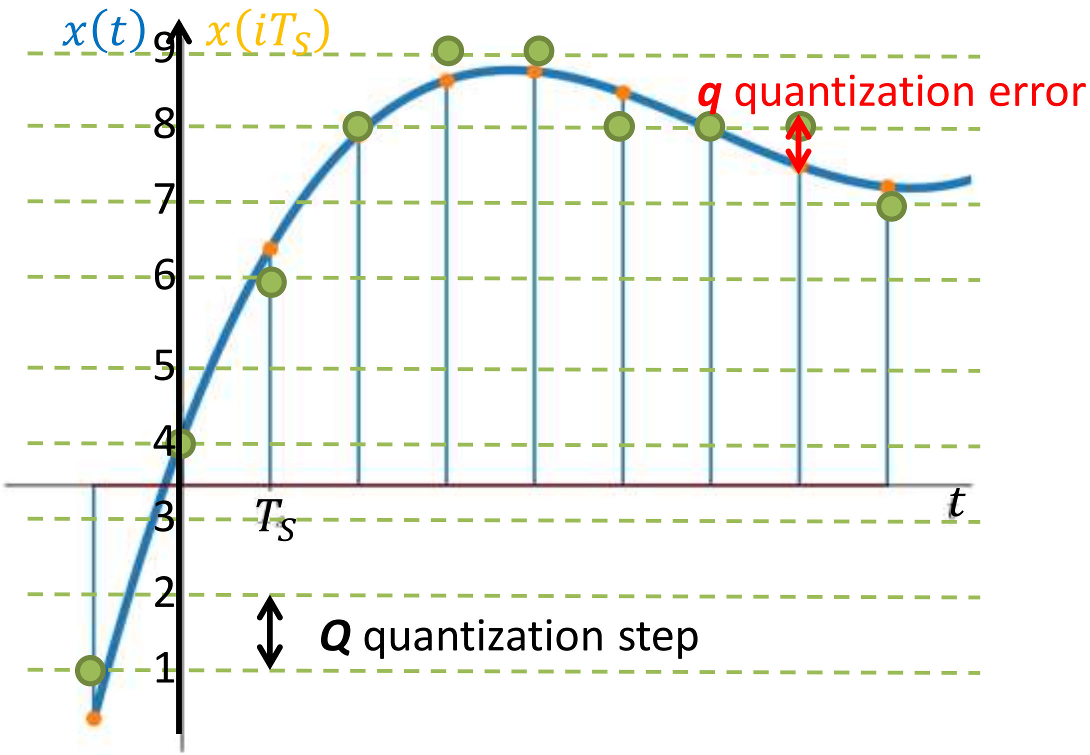
$$x(t) = \sum_{i=-\infty}^{\infty} x(i \cdot T_S) \cdot \frac{\sin 2\pi B(t - i \cdot T_S)}{2\pi B(t - i \cdot T_S)}$$



Analog to Digital (A/D) and Digital to Analog (D/A)

Linear Quantization

$d(iT_S) =$....,1,4,6,8,9,9,8,8,8,7,...



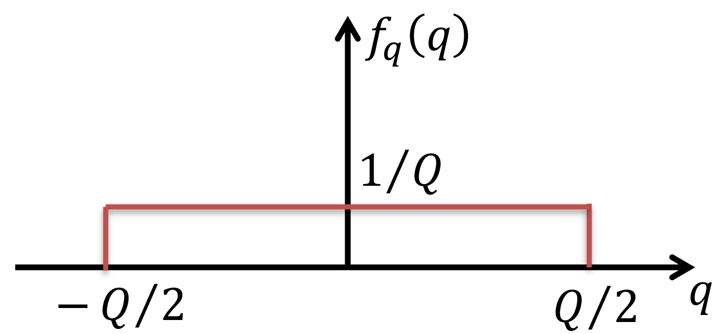
Quantization error is limited for all i

$$-Q/2 \le q(iT_S) < Q/2$$

Random errors causing quantization noise.

$$x(iT_S) = d(iT_S) - q(iT_S)$$
$$x(iT_S) + q(iT_S) = d(iT_S)$$

Assuming uniform distribution:



Power of quantization noise – Relevance? Question of Q:

$$P_q = \int_{-Q/2}^{Q/2} q^2 f_q(q) dq = \frac{1}{Q}\int_{-Q/2}^{Q/2} q^2 dq = \frac{1}{Q}\left[\frac{q^3}{3}\right]_{-\frac{Q}{2}}^{Q/2} = \frac{1}{3Q}\left[\frac{Q^3}{8} - \left(-\frac{Q^3}{8}\right)\right] = \frac{Q^2}{12}$$

Meaning and Measuring of Information

- What is Information?
  - News, new knowledge, surprise, wonder, message, …?
  - We know what is not: Things, that are constant, not changing, well known by us, if we do not surprise, when the event happens, …
- How to measure?
  - We need a ***quantitative measure*** to express the amount of Information for example to be able to compare different systems regarding their efficiency in storage and/or transmission of Information.

The first time to deal quantitatively with the elusive concept of Information was by Ralph Vinton Lyon ***Hartley***: "Transmission of Information", BSTJ, 1928:

Form Wikipedia

- "Reception of a symbol provides information only if there had been other possibilities for its value beside that which was received."

In other words:

- A symbol can give information only if it the value of a ***random variable*** (RV).
- Communication systems should be ***transmitting random quantities***, not reproduce sinusoidal signals.

Hartley's measure of Information

- Consider single symbol X whit D possible values: $X = \{x_1, x_2, \cdots, x_D\}$
- How many Information we gather by observing ***X***?
- The Information conveyed by ***N*** such a symbols must be ***N*** times as much as that conveyed by just one symbol.

Number of Observation	Number of possibilities	Amount if Information
1^{st}	D	$\mathrm{Info}(X)$
2^{nd}	D^2	$2 \cdot \mathrm{Info}(X)$
⋮	⋮	⋮
N^{th}	D^{N}	$\mathrm{N} \cdot \mathrm{Info}(X)$

- Because

$$\log_a\left(D^{\mathrm{N}}\right) = N \cdot \log_a(D) \Leftrightarrow \mathrm{N} \cdot \mathrm{Info}(X)$$

- This suggests that

$$Info(X) = \log_a(D)$$

Hartley: "The base selected for the logarithm fix the size of the unit of Information."

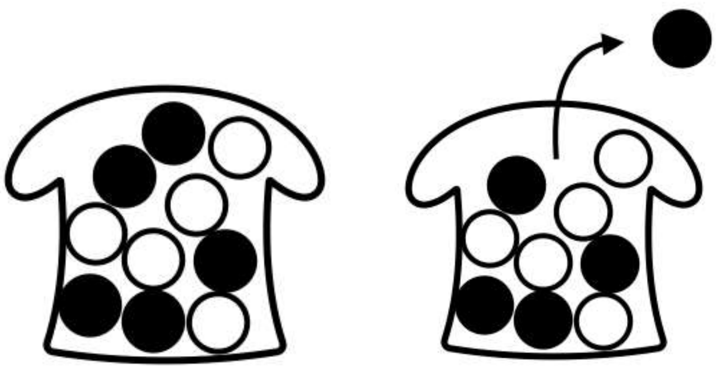
- If the base a=2, we call Hartley's **unit for Information [bit].**
- Honoring Hartley, if a=10, then the name of the unit [Hartley] (very rarely used).
- If the base a=*e*, we call the **unit for Information [nat].** $1\ [nat] \approx 1{,}443\ [bit]$

Weakness of Hartley's measure

It ignores the ***different probabilities*** of the various values of the random variable X.

Consider the random experiment: get out a ball randomly from a hat.
The ball is the symbol X, the number of possibilities is two: **X={Black, White}, applying a=2**
Hartley's Accordingly:

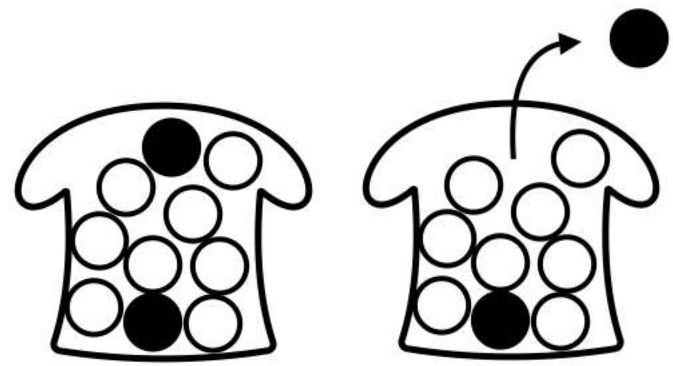
$$Info(X) = \log_{a=2}(D = 2) = ld(2) = 1\ [bit]$$



Case A: Same number of Black and White.

Our ***"surprise" is the same*** by each outcome.

$$Info(X) = \frac{5}{10} ld\left(\frac{10}{5}\right) + \frac{5}{10} ld\left(\frac{10}{5}\right) = 1[bit]$$



Case B: Different number of Black and White.
We are ***rather sure in advance, that white*** ball will be the result (8 times out of 10), our ***"surprise" is higher by black*** (from 10 just 2).

$$Info(X) = \frac{8}{10} ld\left(\frac{10}{8}\right) + \frac{2}{10} ld\left(\frac{10}{2}\right) \cong 0{,}72\ [bit]$$

Shannon's measure of Information

Twenty Years After …..

Claude Elwood ***Shannon***: "A Mathematical Theory of Communication", BSTJ, 1948:

The amount of ***Information should be reciprocally proportional to the probability*** of a random event of a discrete random variable.

Forrás: ww.techzibits.com

Consider a discrete random variable X whit n possible values:

$$X = \{x_1, x_2, \cdots, x_n\}$$

With a Probability Distribution Function (PDF):

$$p(X) = \{p(x_1), p(x_2), \cdots, p(x_n)\}$$

- Definition: ***Self Information*** of a random event x_i:

$$\mathrm{I}(x_i) = ld\ \frac{1}{p(x_i)} = -ld\ p(x_i)\ [bit, Shannon]$$

$\mathrm{I}(x_i)$ is the amount of Information given in [bit] unit gathered by observing x_i.

- Definition: ***Entropy*** of a discrete random variable X:

$$\mathrm{H}(X) = E\{I(x_i)\} = \sum_{i=1}^{n} p(x_i) \cdot I(x_i) = \sum_{i=1}^{n} p(x_i) \cdot ld\ \frac{1}{p(x_i)}\ \left[\frac{bit}{symbol}\right]$$

$\mathrm{H}(X)$ is the Entropy (or uncertainty) is the expected (average) value of the self Information of the events.

Some examples

- Self-Information of a ***certain event***

$$p(x) = 1 \leftrightarrow \mathrm{I}(x) = ld\ \frac{1}{p(x)} = ld\ 1 = 0$$

- Self Information of an ***event that never happens***

$$p(x) = 0 \leftrightarrow \mathrm{I}(x) = ld\ \frac{1}{p(x)} =?\ div\ by\ 0!$$

However, we can calculate the limit, when $p(x) \rightarrow 0$:

$$\lim_{p(x)\to 0} p(x) \cdot ld\ \frac{1}{p(x)} \underset{q=1/p(x)}{\Longleftrightarrow} \lim_{q\to\infty} \frac{1}{q} ld\ q = \lim_{q\to\infty} \frac{1}{q}\frac{\ln q}{\ln 2} = \frac{1}{\ln 2} \lim_{q\to\infty} \frac{\dot{\ln q}}{\dot{q}} = \frac{1}{\ln 2} \lim_{q\to\infty} \frac{1}{q} = 0$$

- We can ***imagine the Entropy*** as the average number of questions (whit binary answer: Yes, or No) needed to find out a character in a word.

Let's try it! I have a word of 4 characters in my mind. You should find it out by questions (e.g. Is the second character A? Answer: Y/N)! The a-priori probabilities of possible characters:

p(A)=1/3, p(B)=1/6, p(C)=1/6, p(D)=1/4, p(E)=1/12

H(X)=1/3ld(3)+1/6ld(6)+1/6ld(6)+1/4ld(4)+1/12ld(12)= 2,1887… [bit/symbol]

	1st char.	2nd char.	3rd char.	4th char.	Solution	No. of questions	Average
1st word							
2nd word							
3rd word							

The Entropy is bounded

Theorem: If the discrete random variable X has ***n*** possible values, then

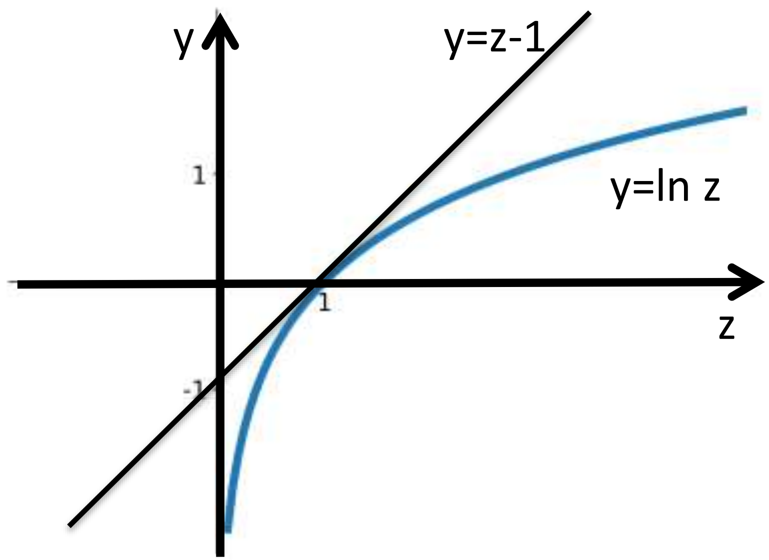
$$\mathbf{0 \leq H(X) \leq \boldsymbol{ld\ n} = \boldsymbol{H_0(X)}}$$

- Proof lower bound:

$$0 \leq p(x_i) \leq 1 \ \ \forall i$$

$$ld\ p(x_i) = \frac{1}{\ln 2} \ln p(x_i) \ \ \forall i$$

$$H(X) = -\sum_{i=1}^{n} p(x_i) \frac{1}{\ln 2} \ln p(x_i) \geq 0 \ \left[\frac{bit}{symbol}\right]$$



- Proof upper bound:

$$\mathrm{H}(X) \leq ld\ n$$

$$\mathrm{H}(X) - ld\ n \leq 0$$

$$\overbrace{\frac{1}{\ln 2} \sum_{i=1}^{n} p(x_i) \ln \frac{1}{p(x_i)}}^{H(x)} - \overbrace{\frac{1}{\ln 2} \sum_{i=1}^{n} p(x_i) \ln n}^{ld\ n} =$$

$$= \frac{1}{\ln 2} \sum_{i=1}^{n} p(x_i) \ln \underbrace{\frac{1}{n \cdot p(x_i)}}_{z} \leq \frac{1}{\ln 2} \sum_{i=1}^{n} p(x_i)[z-1] = \frac{1}{\ln 2} \sum_{i=1}^{n} p(x_i) \left[\frac{1}{n \cdot p(x_i)} - 1\right] =$$

$$= \frac{1}{\ln 2} \left[\underbrace{\sum_{i=1}^{n} \frac{1}{n}}_{1} - \underbrace{\sum_{i=1}^{n} p(x_i)}_{1}\right] = 0$$

The Entropy ***H(X) has a maximum*** by $z = 1 = \frac{1}{n \cdot p(x_i)} \ \forall i$

$\boldsymbol{p(x_i) = 1/n}, \ \forall \boldsymbol{i}$ → ***Uniformly distributed random variable has maximum Entropy.***