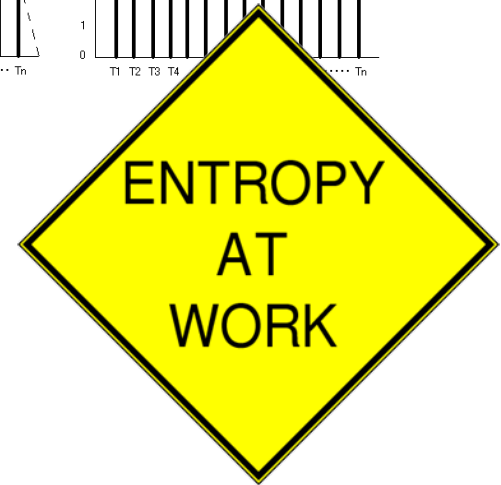
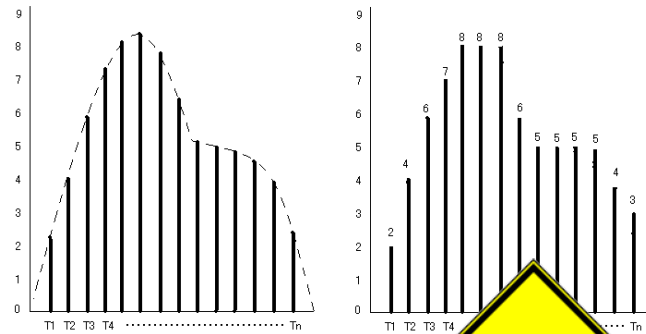
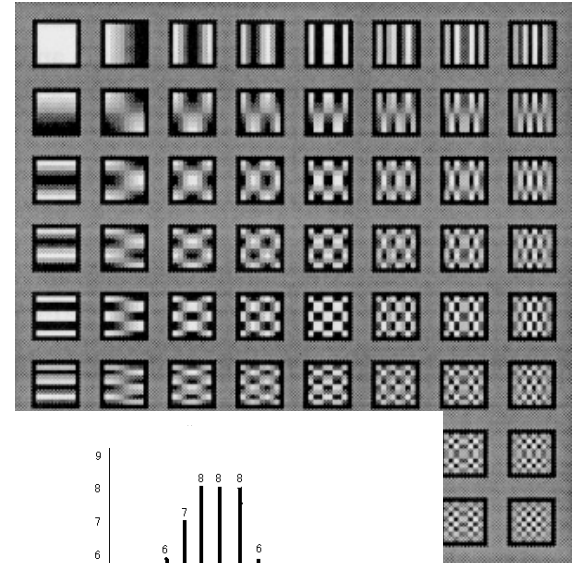


Basics of DCT, Quantization and Entropy Coding

Nimrod Peleg
Update: April 2009



Discrete Cosine Transform (DCT)

- First used in 1974 (Ahmed, Natarajan and Rao).
- Very close to the **Karunen-Loeve*** (KLT) transform (or: **Hotelling**** Transform), that produces un-correlated coefficients
- Coefficients can be quantized using visually-weighted quantization values.
- A fast algorithm is available and similar to **FFT**.

* Named after **Kari Karhunen** and **Michel Loève**

** Named after **Harold Hotelling**

DCT Based Compression

- **HVS** response is dependent on spatial frequency.
- We decompose the image into a **set of waveforms**, each with a particular **spatial frequency**
- DCT is a **real** transform.
- DCT **de-correlating** performance is very good.
- DCT is **reversible** (with Inverse DCT).
- DCT is a **separable** transform.
- DCT has a **fast** implementation (similar to FFT)

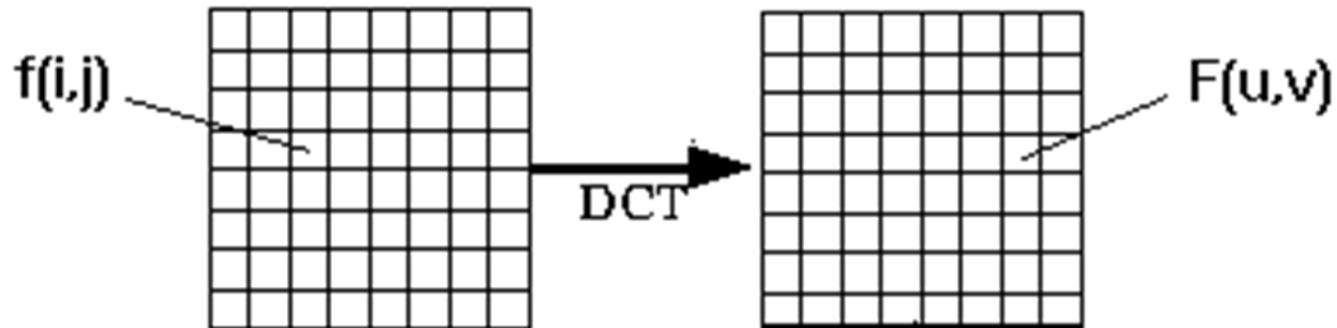
1D DCT* Transform: 

$$F(u) = \left(\frac{2}{N}\right)^{1/2} \sum_{i=0}^{N-1} A(i) \cos\left[\frac{\pi u}{2N}(2i+1)\right] f(i)$$
$$A(i) = \begin{cases} 1/\sqrt{2} & \text{for } i=0 \\ 1 & \text{Otherwise} \end{cases}$$

*: one of four definitions !

DCT (Discrete Cosine Transform)

- The DCT helps separate the image into parts (or spectral sub-bands) of differing importance, with respect to the image's visual quality.



2D - DCT

- Image is processed one **8x8 block** at a time
- A 2-D DCT transform is applied to the block:

$$F(u, v) = \frac{C(u)C(v)}{4} \sum_{x=0}^7 \sum_{y=0}^7 f(x, y) \cos\left(\frac{(2x+1)u\pi}{16}\right) \cos\left(\frac{(2y+1)v\pi}{16}\right)$$

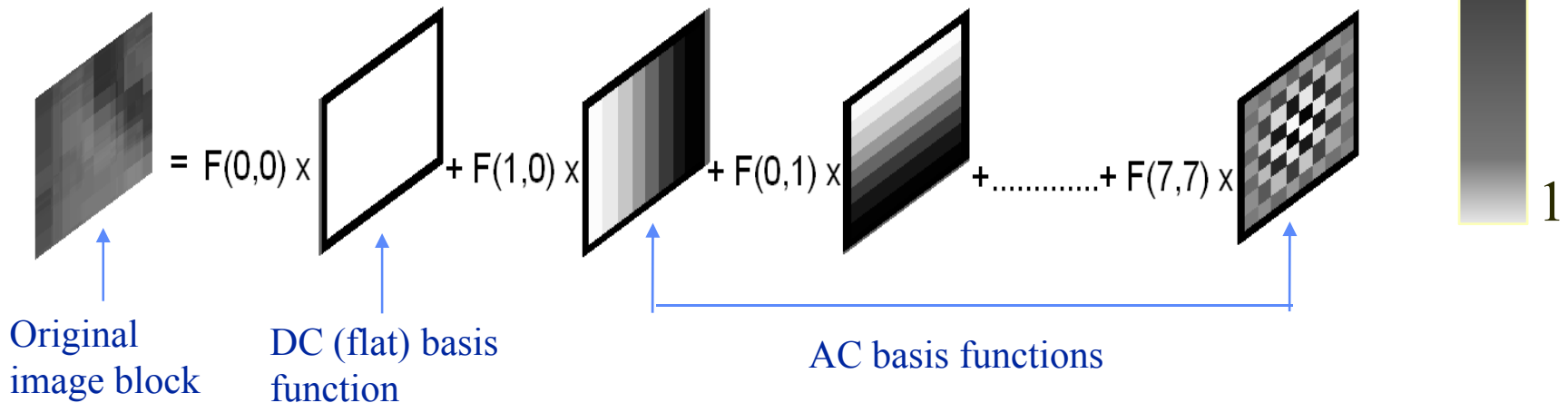
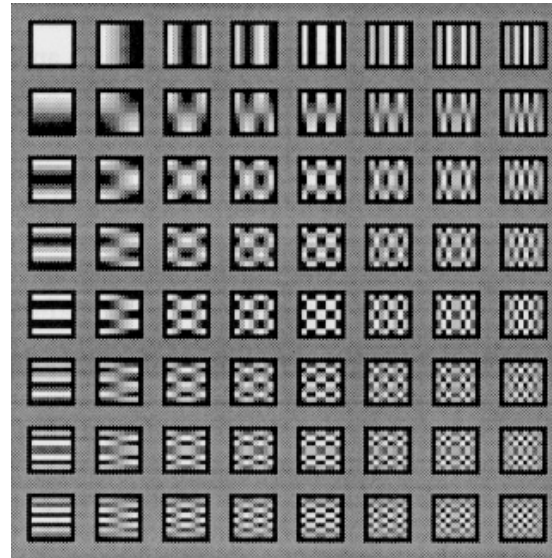
DCT coefficients

$$C(n) = \begin{cases} \frac{1}{\sqrt{2}} & n = 0 \\ 1 & n \neq 0 \end{cases}$$

Samples

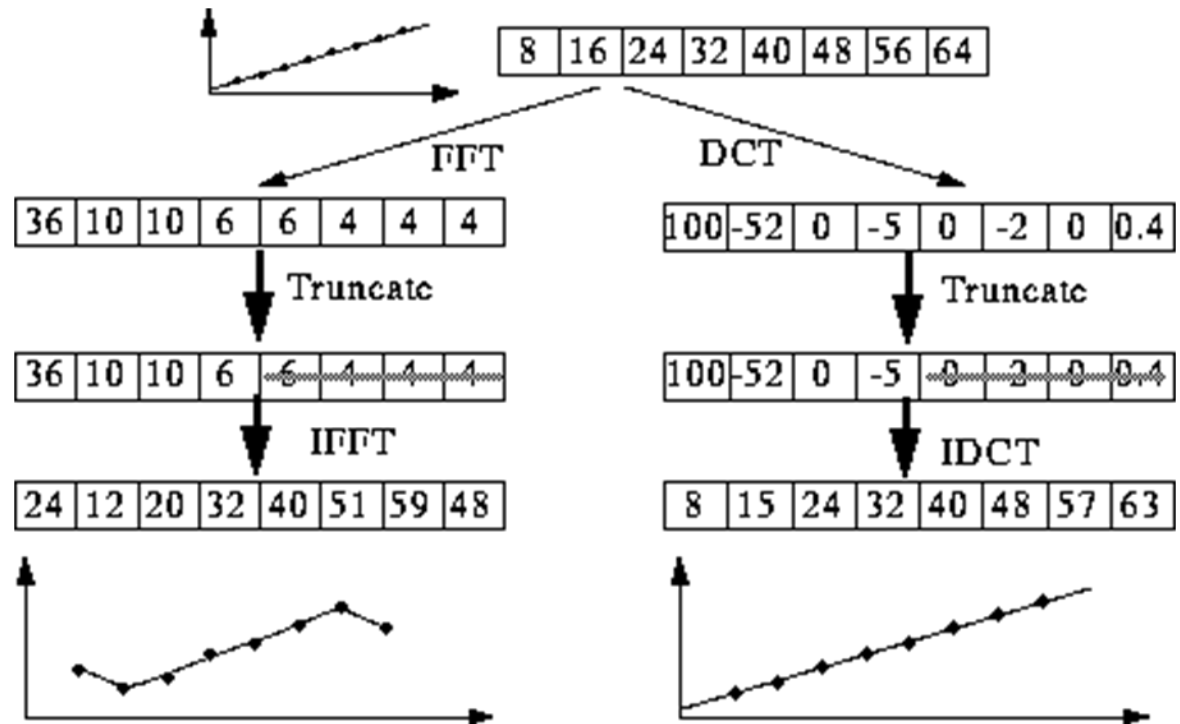
- Perform nearly as well as the ideal K-L transform
- Closely related to the DFT transform
- Computationally efficient

2D-DCT Basic Functions



Why DCT and not FFT?

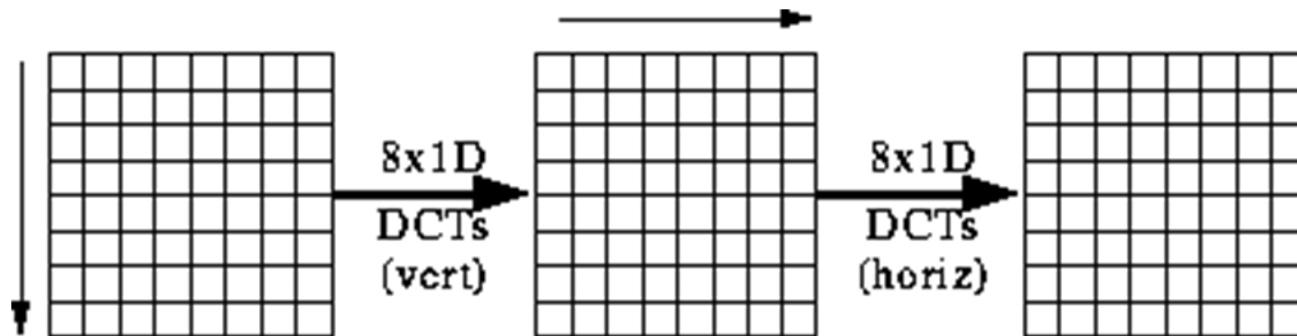
- DCT is similar to the Fast Fourier Transform (FFT), but can approximate lines well with **fewer coefficients**



A better
“De-Correlator”:
Concentrates energy
In the
“lower Frequencies”

Computing the 2D DCT

- Factoring reduces problem to a series of 1D DCTs:
 - apply 1D DCT (Vertically) to Columns
 - apply 1D DCT (Horizontally) to resultant Vertical DCT
 - Or alternatively Horizontal to Vertical.

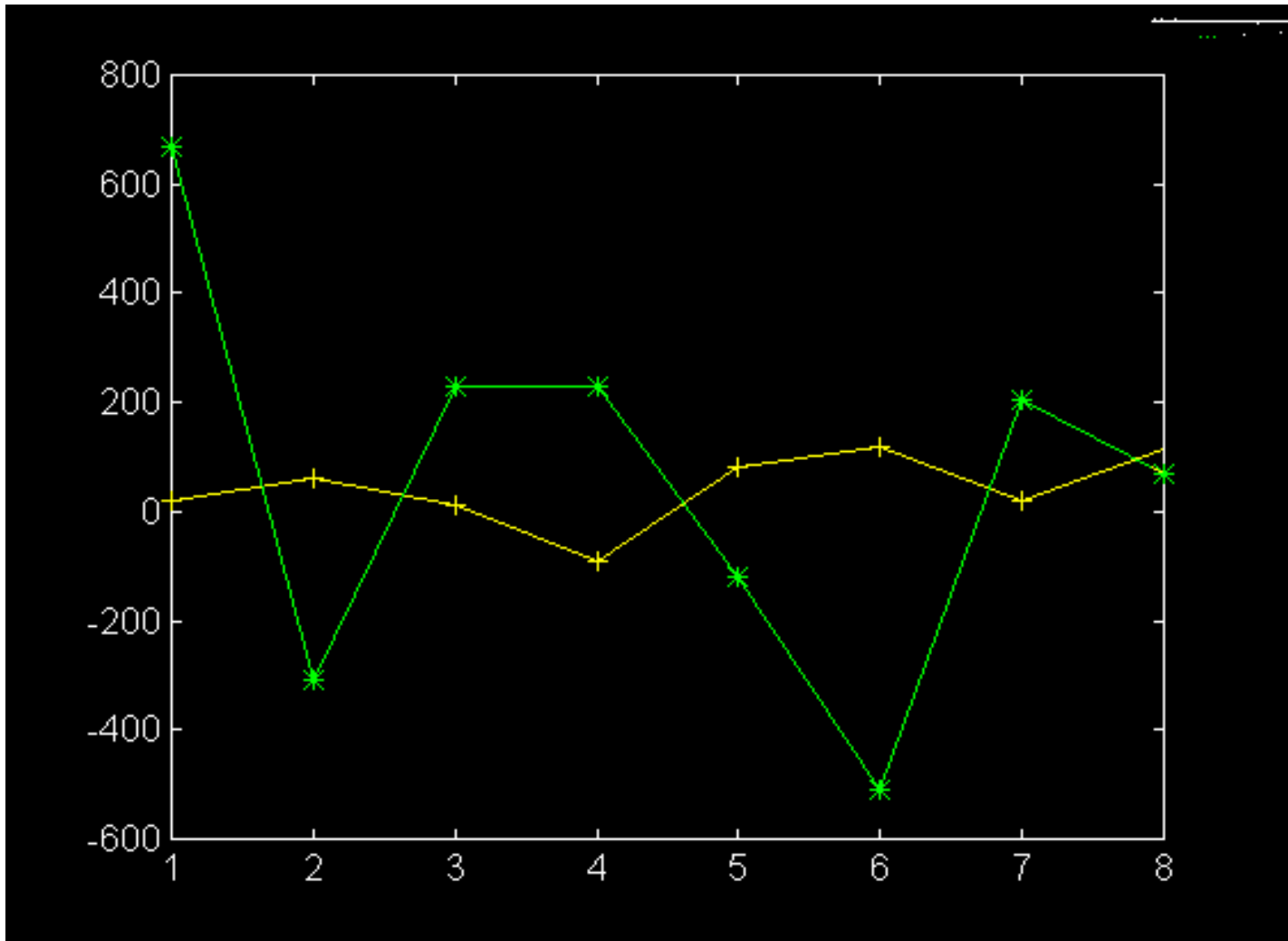


Most software implementations use **fixed point arithmetic**.
Some fast implementations approximate coefficients so all
multiplies are **shifts and adds**.

World record is 11 multiplies and 29 adds. (C. Loeffler, A. Ligtenberg and G. Moschytz, "Practical Fast 1-D DCT Algorithms with 11 Multiplications", Proc. Int'l. Conf. on Acoustics, Speech, and Signal Processing 1989 (ICASSP '89), pp. 988-991)

1-D DCT Correlation Removal

(original signal : yellow, DCT: green)



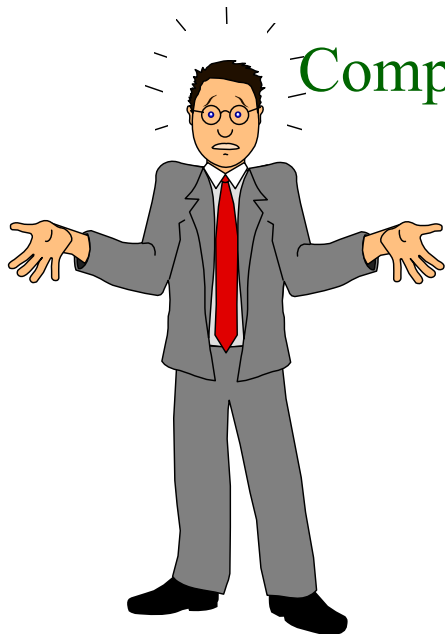
And in numbers...

Original Values

20 60 10 -90 80 120 20 115

DCT

Compression ???



DCT Coeff. Values (Not normalized)

670.0000 -308.3878 229.6567 231.0802
-120.2082 -509.6407 203.3661 69.0309

And the Answer ...



Quantization of DCT Coeff.

- Quantization **reduces accuracy** of the coefficients representation when converted to integer.
- This **zero's** many high frequency coefficients.
- We measure the **threshold for visibility** of a given basis function (coefficient amplitude that is just detectable by human eye).
- We divide (*Quantize*) the coefficient by that value (+ appropriate **rounding to integer**).

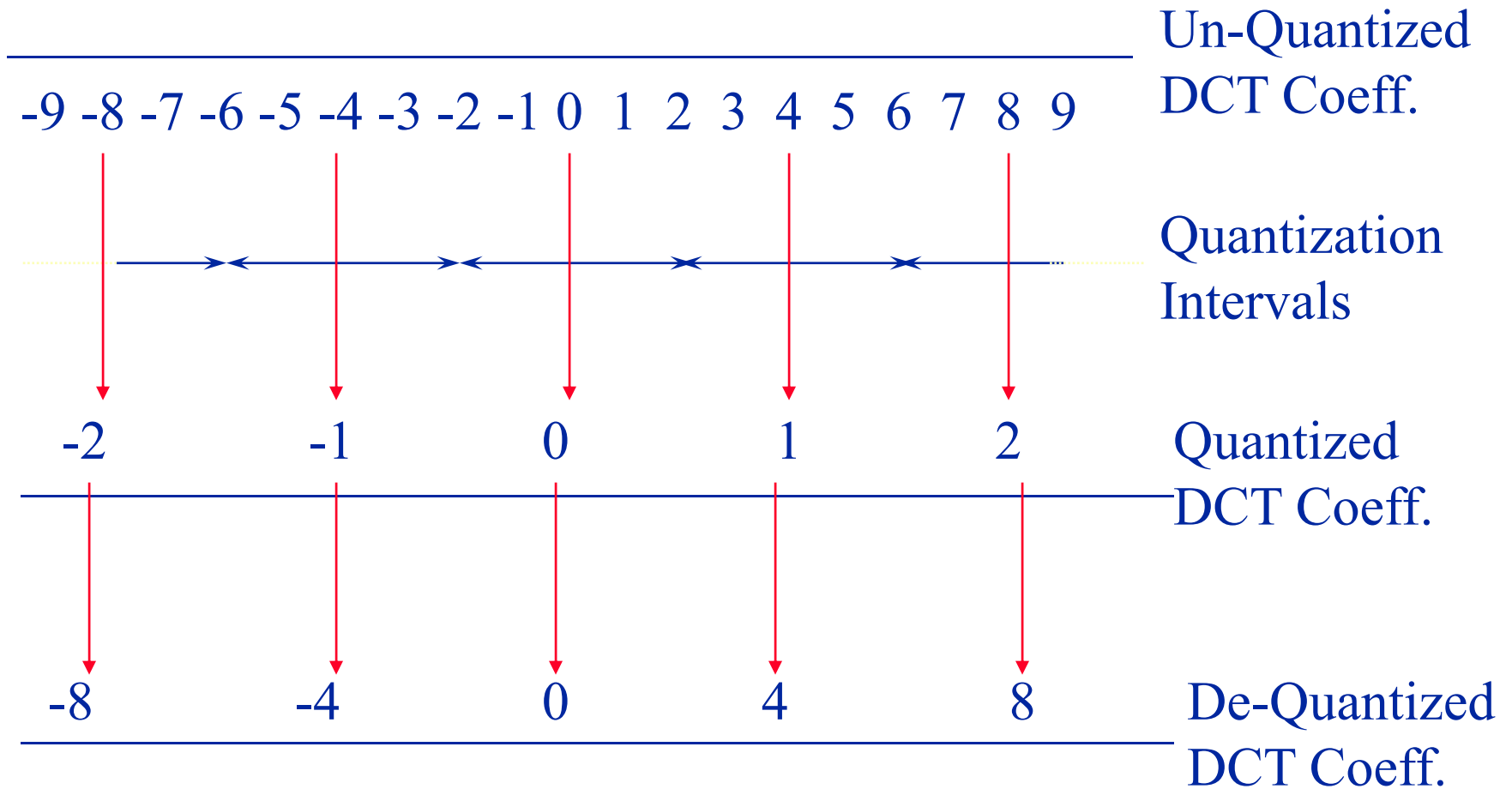
What is Quantization ?

- Mapping of a continuous-valued signal value $x(n)$ onto a limited set of discrete-valued signal $y(n)$: $y(n) = Q [x(n)]$

such as $y(n)$ is a “good” approximation of $x(n)$

- $y(n)$ is represented by a limited number of bits
- We define Decision levels and Representation levels

Inverse Quantization



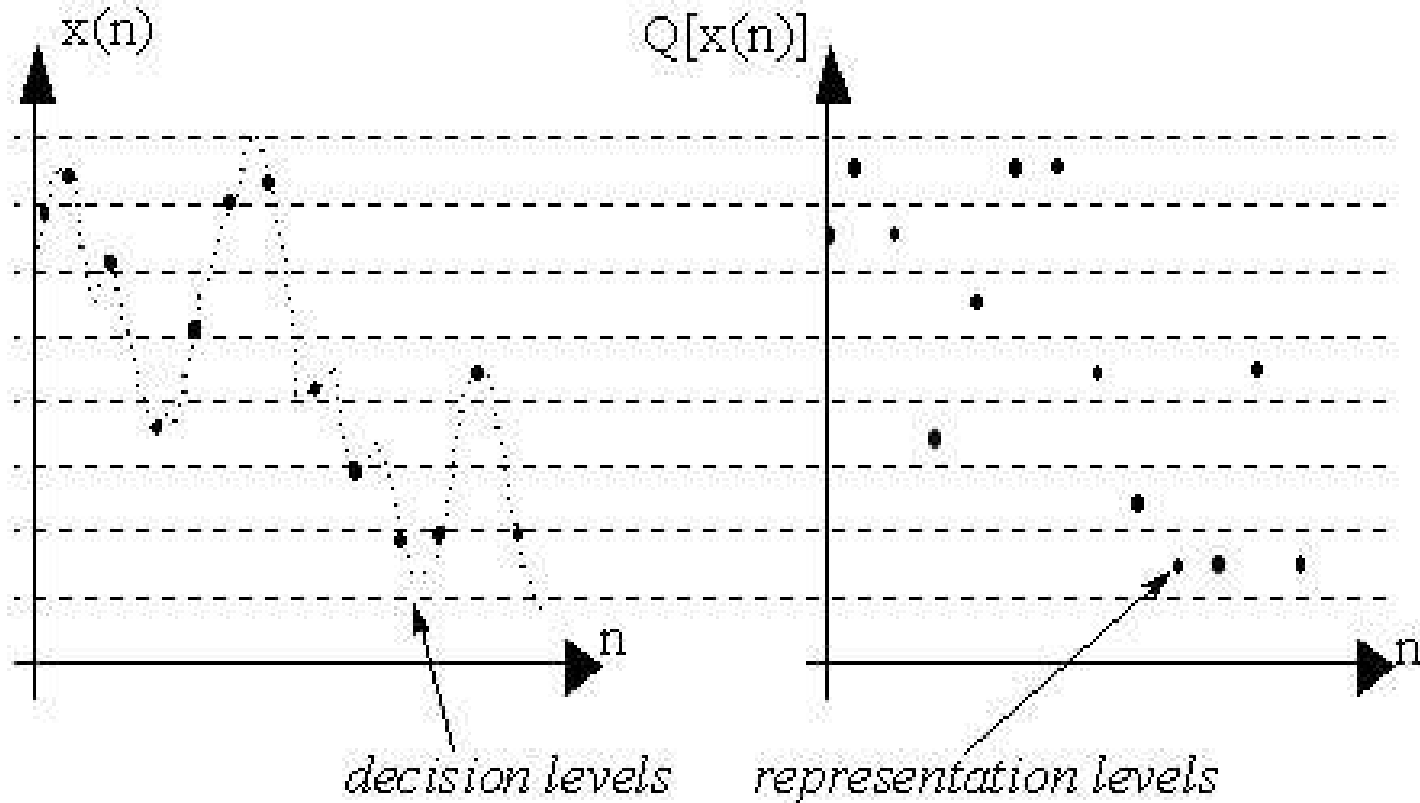
Inverse Quantization (Cont'd)

Note that:

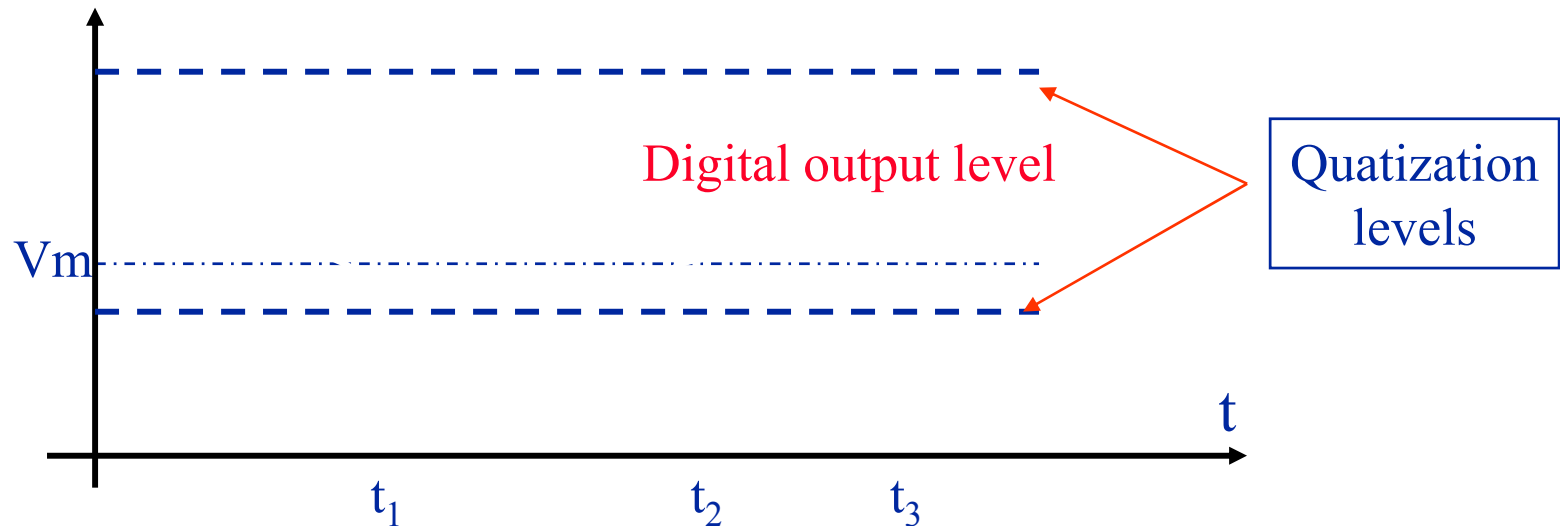
- **Quantization factor** is 4 (for the given example)
 - A half of the Q-factor (i.e 2 for the above) is added to coefficient magnitude before it is divided and truncated
 - done in JPEG
- **Linear quantization**: for a given quantization value, steps are uniform in size
- 8-bit sample transforms to **11-bit quantized DCT** coefficients, for Q value of 1
 - for an 8-bit sample, quantization value of 16 produces 7-bit DCT coefficients)

Decision levels Vs. Representation levels

Quantization Process - I



Quantization Process



V_m is the Average value ('dc') of V_{in} , and far away from the digital output level

• **e.g. , this can be heard in audio !**

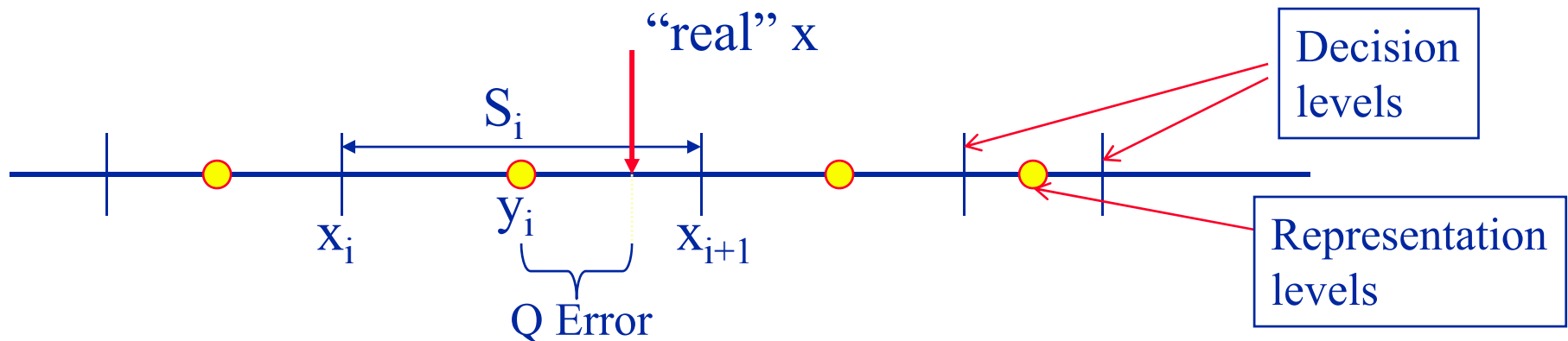
Pseudo random noise can save the need for more quantization levels (Dithering)

Quantization Definition & Error

- Given a signal $x(t)$, divide x amplitude into L non-overlapping intervals S_k :

$$S_k = \{x \mid x_k < x \leq S_{k+1}\} \quad k=1, 2, \dots, L$$

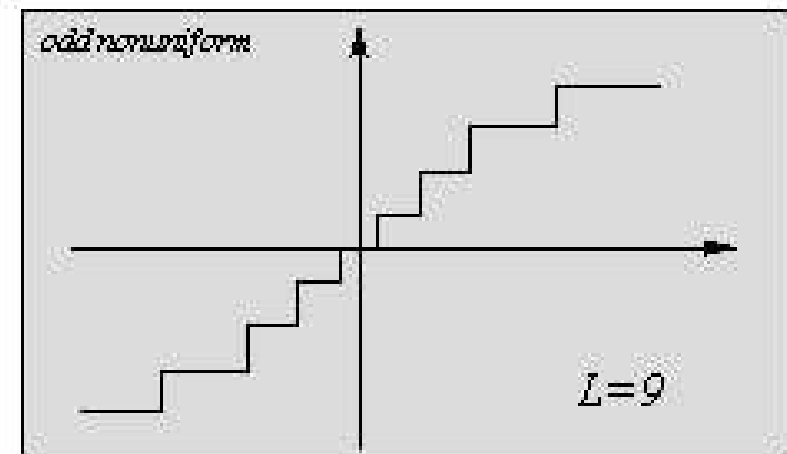
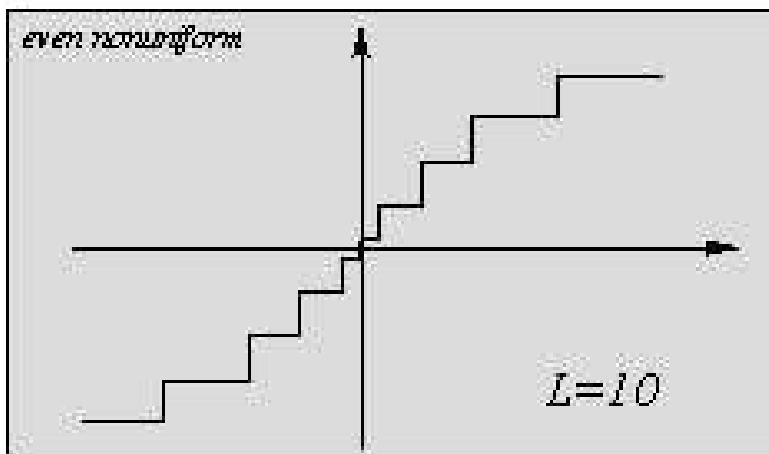
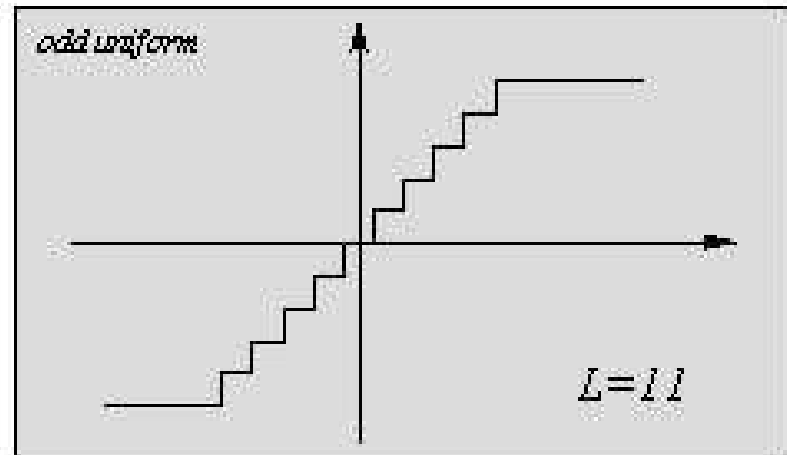
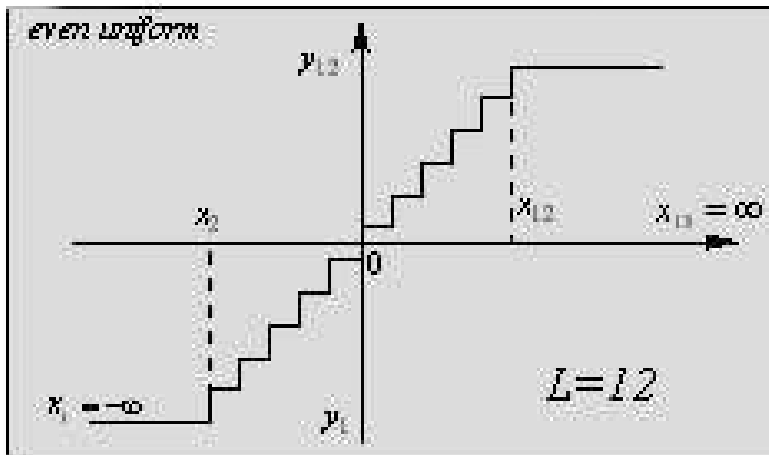
- If x is in the area of S_i than it is represented by y_i and a Quantization Error is introduced



Typical Quantizers - I

- The signal is assumed to be **symmetrical around zero**, so, quantizers are usually designed to be symmetrical about the origin
- Options:
 - Odd/Even number of levels
 - Uniform or Non-uniform
 - Optimized (or not) for Probability Density Function (PDF)

Typical Quantizers - I



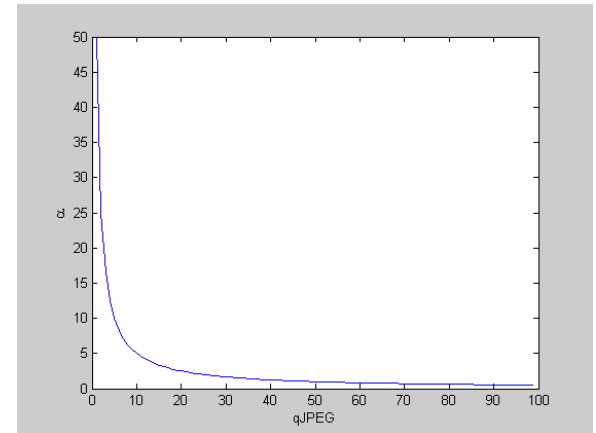
Luminance Q-Table

| | | | | | | | |
|----|----|----|----|-----|-----|-----|-----|
| 16 | 11 | 10 | 16 | 24 | 40 | 51 | 61 |
| 12 | 12 | 14 | 19 | 26 | 58 | 60 | 55 |
| 14 | 13 | 16 | 24 | 40 | 57 | 69 | 56 |
| 14 | 17 | 22 | 29 | 51 | 87 | 80 | 62 |
| 18 | 22 | 37 | 56 | 68 | 109 | 103 | 77 |
| 24 | 35 | 55 | 64 | 81 | 104 | 113 | 92 |
| 49 | 64 | 78 | 87 | 103 | 121 | 120 | 101 |
| 72 | 92 | 95 | 98 | 112 | 100 | 103 | 99 |

Quality Factor

- For other **quality factors**, the elements of these quantization matrices are multiplied by the compression factor α , defined as:

$$\alpha = \begin{cases} \frac{50}{q_JPEG} & 1 \leq q_JPEG \leq 50 \\ 2 - \frac{2q_JPEG}{100} & 51 \leq q_JPEG \leq 99 \end{cases}$$



- The minimum legal $\alpha \cdot Q(u,v)$ is 1
 - This cannot be a **lossless compression !!!**

Quantization table and **quality factor** are not specified in the Standard – just recommended (Annex K)

Notes on Q-Tables

- Visibility measured for:
 - 8x8 DCT basis functions
 - Luminance resolution: 720x576
 - Chrominance resolution: 360x576
 - Viewing distance: 6 times screen width
- Noticeable artifacts on high-quality displays, since little is known about visibility thresholds when more than one coefficient is zero (simultaneously)

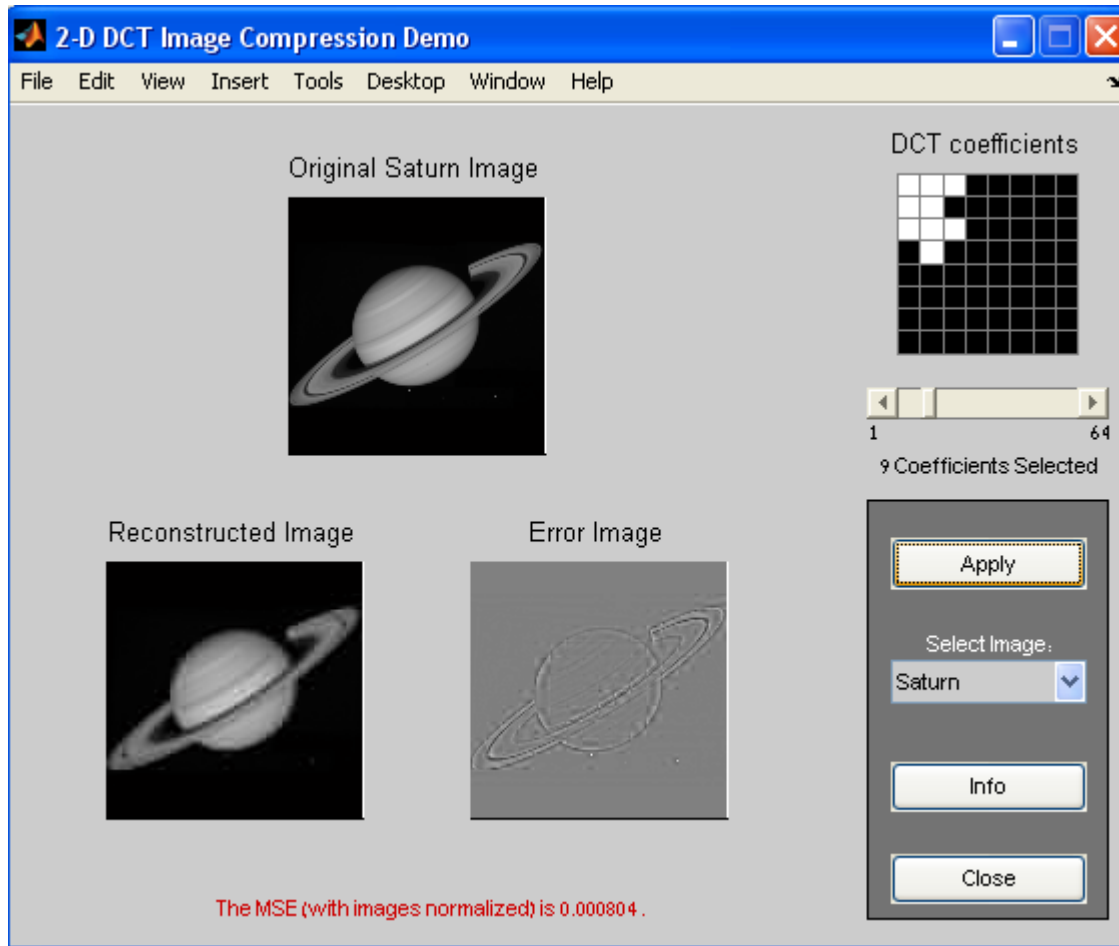
More About JPEG DCT Process

- **Zero-shift on input samples** to convert range from 0:255 to -128:127, reduces internal precision requirements in DCT calculations.
- DCT is always done on **8x8 blocks**:
 - **Spatial frequencies** in the image and of the cosine basis are not precisely equivalent.
 - “**Blocking artifacts**” appear if not enough AC coeff. are taken.

DCT Computational Complexity

- Straightforward calculation for 8x8 block: each coeff. needs 64 multiplies and 63 additions. Quantization requires one more addition and a division.
- Fast algorithm requires 1 multiply and 9 additions.
- Modern pipelined processors architectures makes the calculation very economic and fast.

Erasing DCT Coefficients: a Matlab demo

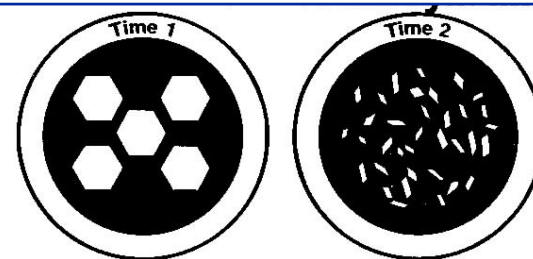


- Run the script: “dctdemo.m”
- **Zero** coefficients and see the effect

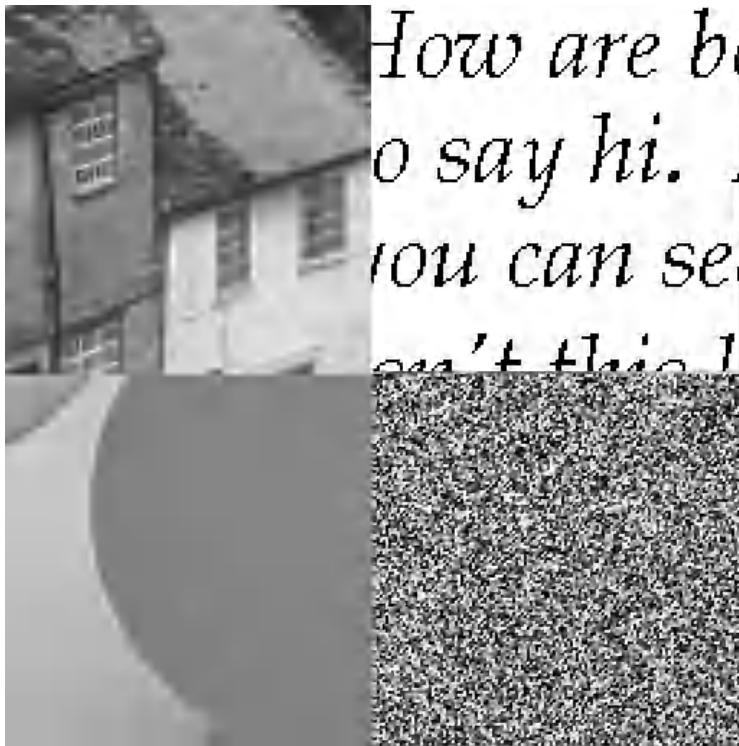
Entropy Coding: VLC



Second law of Thermodynamics



ENTROPY (simplicity) increases
in closed system



אנטרופיה:

רמת אי-הסדר במערכת

בתרמודינמיקה:

מדד לכמות האנרגיה שאינה זמינה לעבודה

Entropy Encoding

- Amount of information in a symbol: $F = \log_2 \frac{1}{P_i}$

- Entropy of an Image:

“Average amount of information”

- A source with M possible symbols, With a uniform distribution:

$$H_1 = - \sum_{i=1}^M P_i \log_2 P_i \quad [\text{bit}]$$

- Shannon Theorem:

H= minimum number of bits to code the source

The Shannon Theorem

- Shannon (1948) showed that for the coding of a discrete (independent) source, a uniquely decodable binary code exists, with average codeword length : $H(Y(n)) \leq \text{Save}$

- Shannon also showed that for this source, a binary prefix code (such as Huffman) exists, and holds: $\text{Save} \leq H(Y(n)) + 1$

The Shannon Theorem (Cont'd)

- If N independent symbols are taken together we get: $S_{ave} \leq H(Y(n)) + 1/N$
- For very large N , S_{ave} is very close to the entropy, but the practical problems become severe:
 - *coding delay*
 - *complexity*
 - *size of VLC tables*

k-th order entropy

1/2

- For an ‘alphabet’ A (set of symbols):

$$H_k = -\frac{1}{k} \sum_{x_1, \dots, x_k \in A^k} P(x_1, \dots, x_k) \log_2 P(x_1, \dots, x_k) \quad [\text{bit}]$$

- The important property of the entropy is:

$$\log_2 |A| \geq H_k(X) \geq H_{k+1}(X) \geq 0$$

- The expected value (per-letter in ‘A’ !) is always greater than or equal to entropy:

$$\frac{E\{L(X_1, \dots, X_n)\}}{n} \geq H_n(X)$$

Shannon, Theorem 1

k-th order entropy

2/2

- Shannon, Theorem 2

There exists a coding algorithm such that:

$$\frac{E\{L(X_1, \dots, X_n)\}}{n} < H_n(X) + \frac{1}{n}$$

- Important to remember:

for a “**memoryless**” source (symbols are independent): entropy of any order is equal to the first order entropy !

Influence of block length

- Does theorem 2 mean that for memory-less source, we can reach entropy by 1-symbol blocks?

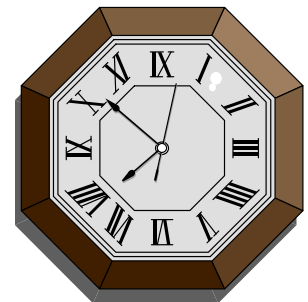
Consider a binary source with entropy : $H_1=0.4$
According to the above, the lower bound is $H_1 + 1/n$,
with $n=1$ we get : $0.5 + 1 = 1.5$ bpp

But ...

we can easily do it with 1 bpp

Huffman Coding

- The symbol with the **highest probability is assigned the shortest code** and vice versa.
- Codewords length is not fixed (**VLC**)
- A codeword cannot be a prefix for another codeword (**Self Synchronized Code**)



Huffman Coding Example

| Symbol | P _i | | Huffman | Binary | |
|--------|----------------|--|----------|--------------|-----|
| Q1 | 0.4 | | 1 | 000 | |
| Q2 | 0.2 | | 1 | 011 | 001 |
| Q3 | 0.12 | | 0 | 001 | 010 |
| Q4 | 0.08 | | 1 | 0101 | 011 |
| Q5 | 0.08 | | 0 | 0100 | 100 |
| Q6 | 0.08 | | 1 | 0001 | 101 |
| Q7 | 0.03 | | 1 | 00001 | 110 |
| Q8 | 0.01 | | 0 | 00000 | 111 |

Huffman Coding Example (Cont'd)

- Source Entropy (H_0):
$$H = -\sum_{i=1}^M P_i \log_2 P_i = 2.45$$

- Huffman Rate:
$$R = \sum P_i L_i = 2.52$$

- No Coding: 3 bps

- Compression Ratio:
$$2.52/3 = 0.84$$

- Problems:
 - Sensitive to BER
 - Statistics Dependent
 - Not Unique

Other Coding Techniques

- Run-Length

Coding of strings of the same symbol

(Used in JPEG)

- Arithmetic (IBM)

Probability coding (A JPEG Option)

- Ziv-Lempel (LZW)

Used in many public/commercial application

such as ZIP etc.. (LZ Demo - Java Applet)

(<http://www.cs.sfu.ca/cs/CC/365/li/squeeze/LZW.html>)

So...how JPEG do it ?

- The theoretical **entropies of each quantized DCT** sub-band are known.
- In practice this would be a poor way to code the data because:
 - **64 separate entropy codes** would be required, each requiring many extra states to represent run-length coding of zeros.
 - The statistics for each code are likely to **vary significantly** from image to image.
 - To **transmit the code table** for each sub-band as header information would involve a large coding overhead.
 - Coding the sub-bands separately does not take account of the **correlations** which exist between the positions of the **non-zero coefficients** in one sub-band with those of nearby sub-bands.

Coding the DC Coefficients

- The size of the differences can in theory be up to $\pm(255 \times 8) = \pm 2040$ if the input pixels occupy the range -128 to +127 (The DCT has a gain of 8 at very low frequencies)
- Hence the **Huffman code table** would have to be quite large.
- JPEG adopts a much smaller code by using a form of floating-point representation, where *Size* is the base-2 exponent and *Additional Bits* are used to code the polarity and **precise amplitude**
- There are only **12 Sizes** to be Huffman coded, so specifying the **code table** can be very simple and require relatively few bits in the header: 16 header bytes + 12 codes = 28 bytes for the DC table.

The DC Codes

| DC Coef Difference | Size | Typical Huffman codes for Size | Additional Bits (in binary) |
|------------------------------|------|--------------------------------|---------------------------------|
| 0 | 0 | 00 | - |
| -1,1 | 1 | 010 | 0,1 |
| -3,-2,2,3 | 2 | 011 | 00,01,10,11 |
| -7,...,-4,4,...,7 | 3 | 100 | 000,...,011,100,...,111 |
| -15,...-8,8,...,15 | 4 | 101 | 0000,...,0111,1000,...,1111 |
| | | | |
| -1023,...-512,512,...,1023 | 10 | 1111 1110 | 00 0000 0000,...,11 1111 1111 |
| -2047,...-1024,1024,...,2047 | 11 | 1 1111 1110 | 000 0000 0000,...,111 1111 1111 |

- Only **Size** needs to be Huffman coded in the above scheme: within a given Size, all the input values have sufficiently similar probabilities
- Each coded Size is followed by the appropriate number of **Additional Bits** to define the sign and magnitude of the coefficient difference exactly

The Run-Size Technique

- The remaining **63 quantized AC-coefficients** usually contain many zeros and so are coded with a combined run-amplitude Huffman code.
- The codeword represents the **run-length of zeros** before a non-zero coefficient *and* the **Size** of that coefficient.
- This is followed by the **Additional Bits** which define the coefficient amplitude and sign precisely.
- This 2-dimensional Huffman code (**Run, Size**) is efficient because there is a strong correlation between the Size of a coefficient and the expected Run of zeros which precedes it: small coefficients usually follow long runs; larger coefficients tend to follow shorter runs.

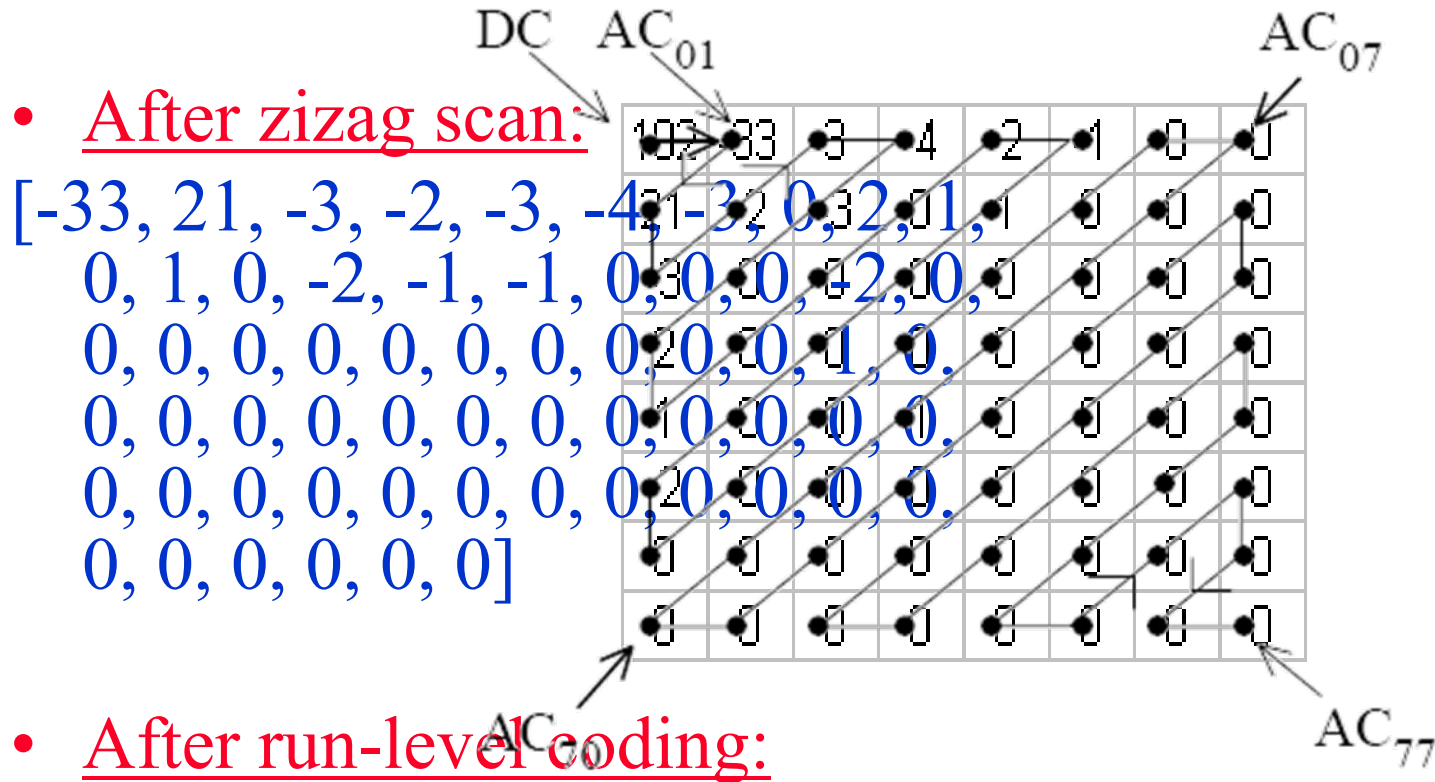
The AC Run-Size Table

- To keep the code table size n below 256, only the following Run and Size values are coded: Run=1→15 ; Size=1→10
These require 150 codes.
- Two extra codes, corresponding to (Run,Size) = (0,0) and (15,0) are used for EOB (End-of-block) and ZRL (Zero run length).
- EOB is transmitted after the last non-zero coef in a 64-vector.
It is omitted in the rare case that the final element is non-zero.
- ZRL is transmitted whenever Run>15: a run of 16 zeros which can be part of a longer run of any length.
 - Hence a run of 20 zeros followed by -5 would be coded as:
(ZRL) (4,3) 010

The AC Huffman Table

| (Run,Size) | Code Byte (hex) | Code Word (binary) | (Run,Size) | Code Byte (hex) | Code Word (binary) |
|-------------------|------------------------|---------------------------|-------------------|------------------------|---------------------------|
| (0,1) | 01 | 00 | (0,6) | 06 | 1111000 |
| (0,2) | 02 | 01 | (1,3) | 13 | 1111001 |
| (0,3) | 03 | 100 | (5,1) | 51 | 1111010 |
| (EOB) | 00 | 1010 | (6,1) | 61 | 1111011 |
| (0,4) | 04 | 1011 | (0,7) | 07 | 11111000 |
| (1,1) | 11 | 1100 | (2,2) | 22 | 11111001 |
| (0,5) | 05 | 11010 | (7,1) | 71 | 11111010 |
| (1,2) | 12 | 11011 | (1,4) | 14 | 111110110 |
| (2,1) | 21 | 11100 | | | |
| (3,1) | 31 | 111010 | (ZRL) | F0 | 11111111001 |
| (4,1) | 41 | 111011 | | | |

Run-Level Coding



(0,-33) (0,21) (0,-3) (0,-2)
 (0,3)(0,-4) (0,-3) (1,2) (0,1)
 (1,1) (1,-2) (0,-1) (0,-1) (3,-2)
 (11,1)

A Coding Example (Cont'd)

- If the DC value of the previous block was 44, then the **difference is -2**. If Huffman codeword for *size=2* is **011** then the codeword for the DC is: **01101**
- Using Annex K in the JPEG for the luminance AC coeff., we receive the following codewords:

A Coding Example (Cont'd)

| <u>Value</u> | <u>Run/Size</u> | <u>Huffman</u> | <u>Ampl.</u> | <u>Total bits</u> |
|--------------|-----------------|----------------|--------------|-------------------|
| 16 | 0/5 | 11010 | 10000 | 10 |
| -21 | 0/5 | 11010 | 01010 | 10 |
| 10 | 0/4 | 1011 | 1010 | 8 |
| -15 | 0/4 | 1011 | 0000 | 8 |
| 3 | 3/2 | 111110111 | 11 | 11 |
| -2 | 0/2 | 01 | 01 | 4 |
| 2 | 1/2 | 11011 | 10 | 7 |
| -3 | 0/2 | 01 | 00 | 4 |
| 2 | 5/2 | 11111110111 | 10 | 13 |
| -1 | 0/1 | 00 | 0 | 3 |
| EOB | 0/0 | 1010 | | 4 |

A Coding Example (Cont'd)

- Compression results:
 - DC coeff. : 5 bits
 - AC coeff. : 82 bits
 - Average bitrate: $87/64 = 1.36$ bit/pixel
 - Starting from 8 bpp resolution, the compression ratio is : $8/1.36 = 5.88$

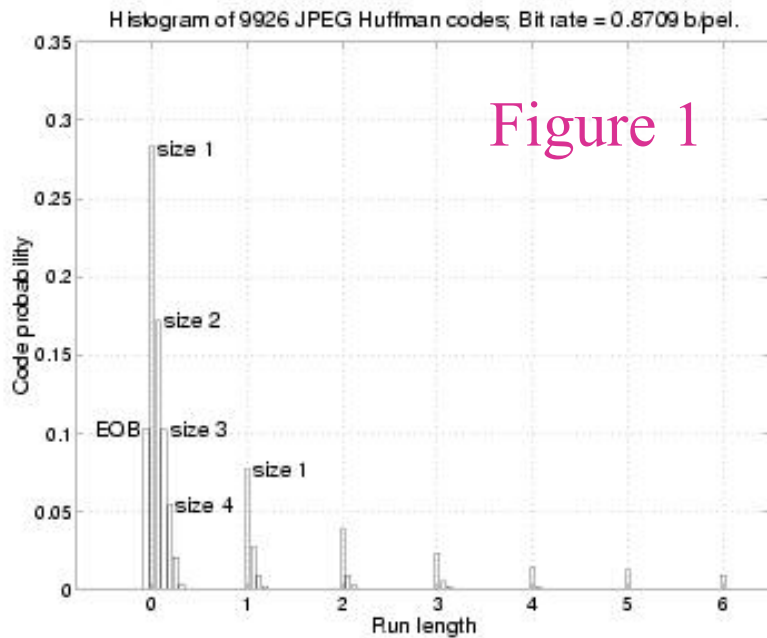
A Coding Example (Cont'd)

- Run-length coding contribution:

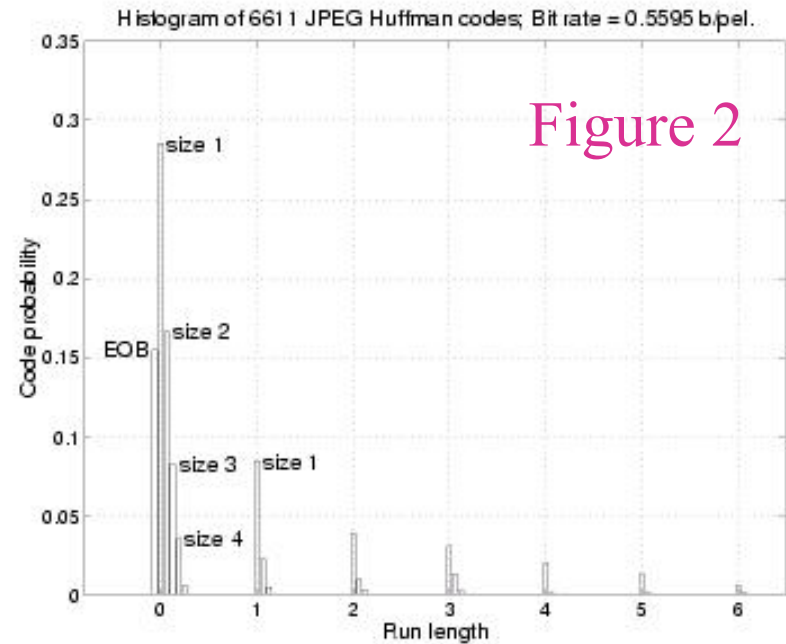
Direct Huffman coding of DC differentials [-2047, 2047] and AC differentials [-1023, 1023] requires code tables with 4,095 and 2,047 entries respectively.

By Huffman coding only the *(run, size)* pairs, tables are reduced to 12 and 161 entries respectively

(Run,Size) and Quantization



Histogram of the (Run,Size) codewords for the DCT of Lenna, quantised using Q_{lum} .



Histogram of the (Run,Size) codewords for the DCT of Lenna, quantised using $2Q_{lum}$.

The bin number represents the decoded byte value

(Run,Size) and Quantization Cont'd

- Note the strong **similarity between the histograms**, despite the fact that **figure 2** represents only 2/3 as many events.
- Only the **EOB probability changes significantly**
 - because its probability goes up as the number of events (non-zero coefficients) per block goes down.
- It turns out that the **(Run,Size) histogram remains relatively constant** over a wide range of images and across different regions of each image.
 - This is because of the strong correlation between the run lengths and expected coefficients sizes.
- The number of events per block varies considerably depending on the **local activity in the image**, but the probability distribution of those events (except for EOB) changes much less.


(Run,Size) and Quantization Cont'd

Comparing the mean bit rates to code Lenna for the two quantization matrices with the theoretical entropies:

| Q matrix | Mean Entropy (b/pel) | JPEG Bit Rate (b/pel) | JPEG efficiency |
|-------------|----------------------|-----------------------|-----------------|
| Q_{lum} | 0.8595 | 0.8709 | 98.7% |
| 2 Q_{lum} | 0.5551 | 0.5595 | 99.21% |

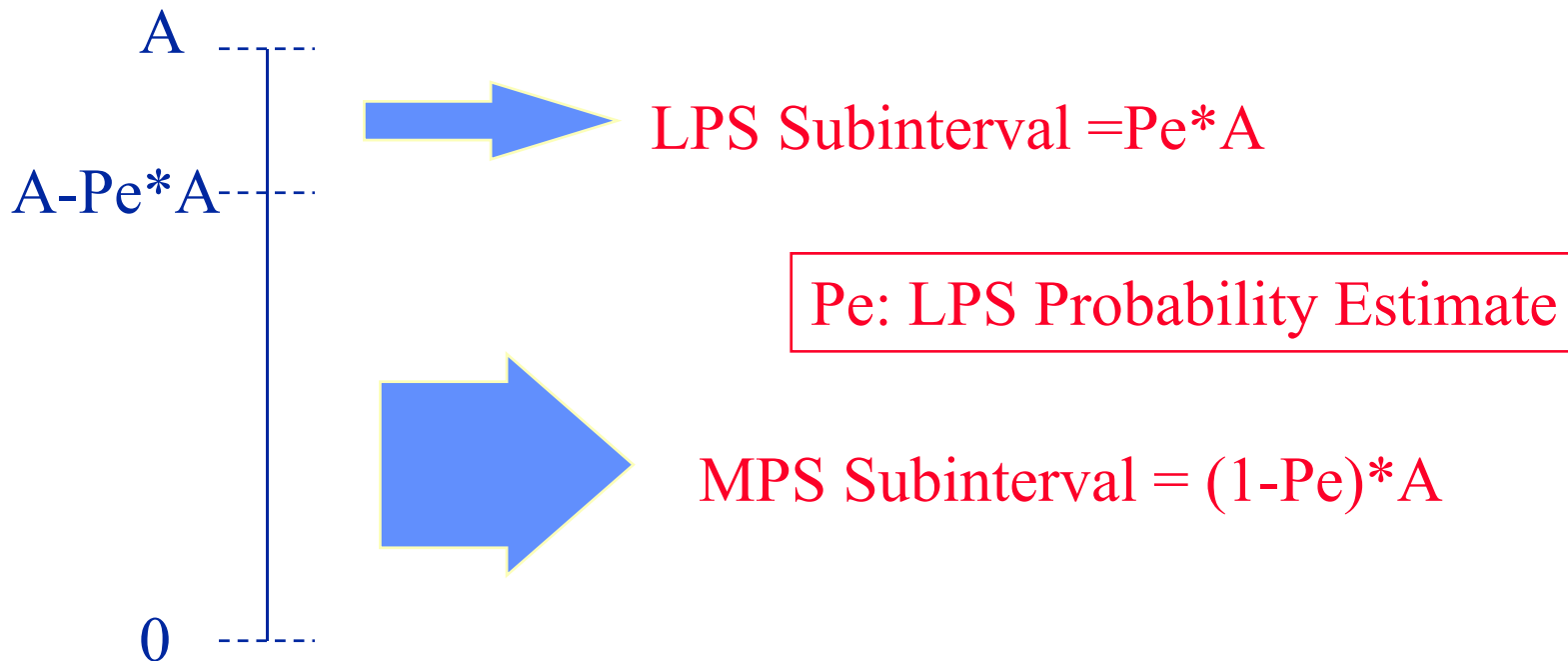
- We see the **high efficiency** of the (Run,Size) code at two quite different compression factors. This tends to apply over a wide range of images and compression factors and is an impressive achievement.
- There is very little efficiency loss if a **single code table** is used for many images, which can avoid the need to transmit the 168 bytes of code definition in the header of each image. Using the recommended **JPEG default luminance tables** (Annex K.3.3) the above efficiencies drop to 97.35% and 95.74% respectively.

Arithmetic Coding

- Used in both JPEG and JBIG
- Also known as **QM-Coder** (A “child” of well-known Q-Coder)
- A **Binary coder** (1 or 0 symbols only)
- descriptor is decomposed into a tree of binary decisions
- Rather than assigning intervals to the symbols it assigns intervals to the **most** and **less** probable symbols (MPS, LPS) ... 

Arithmetic Coding (Cont'd)

➔ ...Then orders the symbols such that the LPS sub-interval is above the MPS:



Arithmetic Coding (Example)

Assume quad-dictionary:

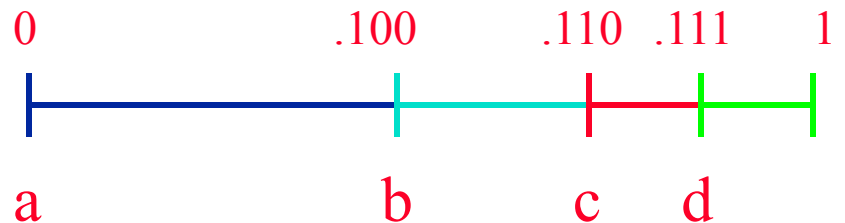
a ($P_a=1/2 \rightarrow .100$)

b ($P_b=1/4 \rightarrow .010$)

c ($P_c=1/8 \rightarrow .001$)

d ($P_d=1/8 \rightarrow .001$)

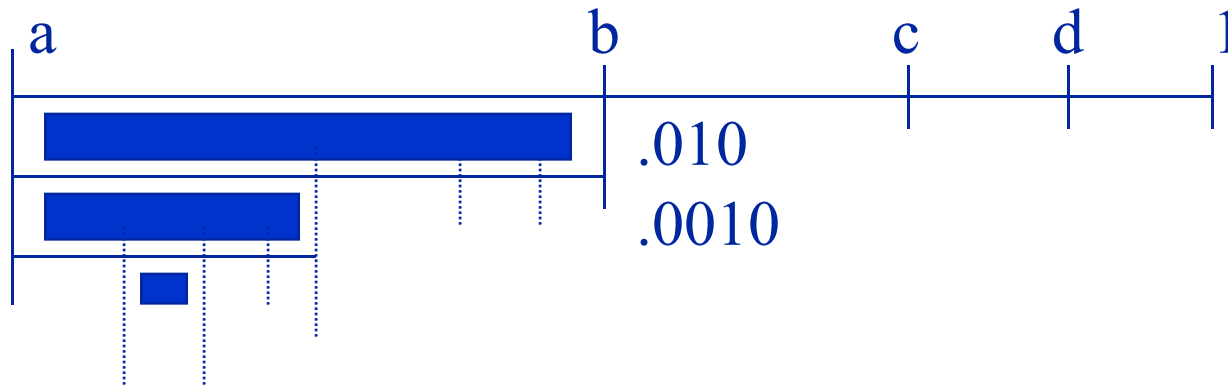
Codewords as joints of units interval



- This is an accumulative probability function : $F(x) = \sum_{k=0}^x p(k) = p(0) + p(1) + \dots + p(x)$
- Each “code point” is the probability sum of previous probabilities
- The length of the interval on the right side of the point is equal to probability of the symbol
- Intervals in our case: $[0, 0.1)$, $[0.1, 0.11)$,

Arithmetic Coding (Example)

Successive Subdivision
of unit interval: *a a b ...*



$$\text{New_Code} = \text{Current_Code} + A * P_i$$

A: interval length

P_i : probability

$$\text{New_A} = \text{Current_A} + P_i$$

Arithmetic Coding Main Problems

- Needs ‘infinite precision’ for interval A
- Needs a multiplication for interval subdivision: $A * P_e$
- Results about 10% better than Huffman but more complicated

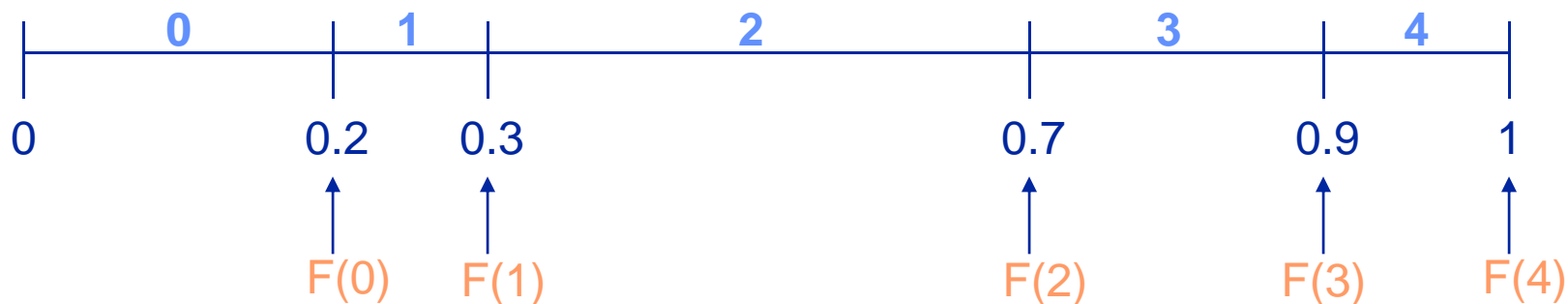
A Coding Example

- The accumulative distribution function of the random variable X with optional values $\{0,1,2,3,4\}$ are:

| X | $P(x)$ | $F(x)$ |
|-----|--------|-------------------------|
| 0 | 0.2 | 0.2 |
| 1 | 0.1 | $0.2+0.1=0.3$ |
| 2 | 0.4 | $0.2+0.1+0.4=0.7$ |
| 3 | 0.2 | $0.2+0.1+0.4+0.2=0.9$ |
| 4 | 0.1 | $0.2+0.1+0.4+0.2+0.1=1$ |

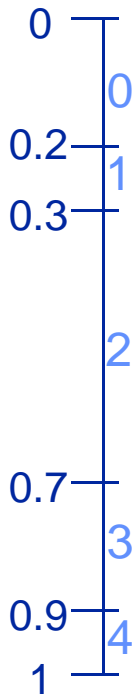
A Basic coding and decoding algorithm

- We have n open segments $[a,b)$, where n is the size of the alphabet we use:



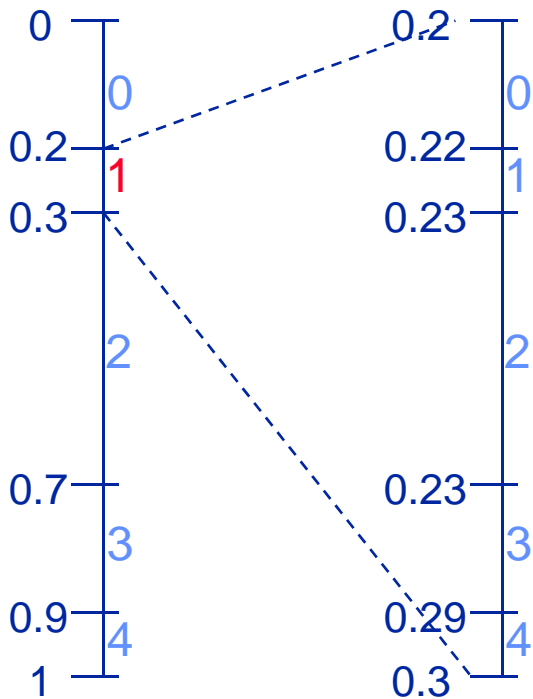
A Coding Example: 1/5

- We'll represent the “message” “1432” using the accumulative distribution function we have:



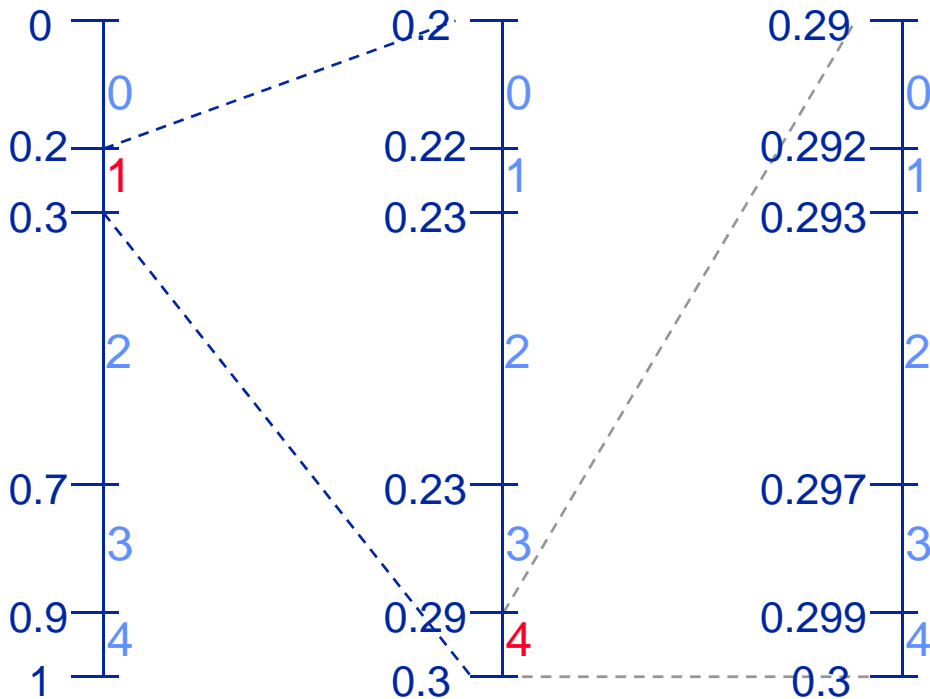
A Coding Example: 2/5

- We'll represent the “message” “1432” using the accumulative distribution function we have:
- **First letter: 1**



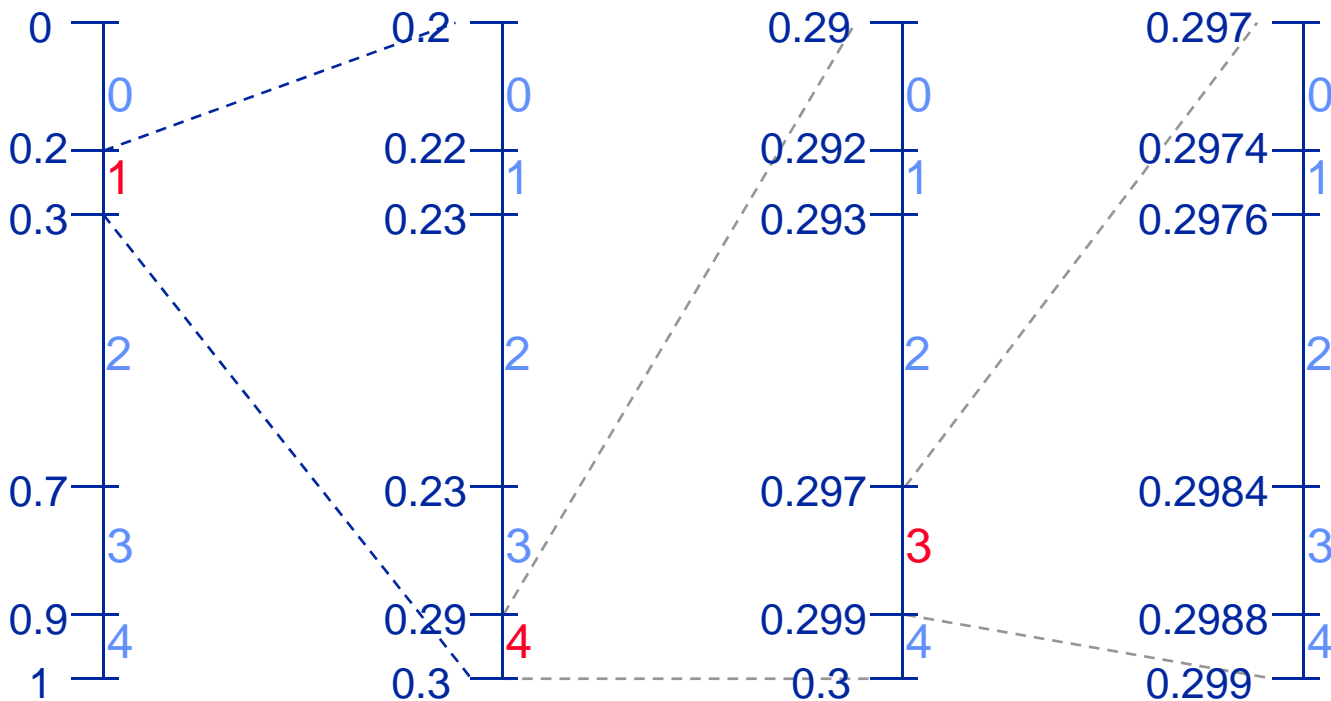
A Coding Example: 3/5

- We'll represent the “message” “1432” using the accumulative distribution function we have:
- **Second letter: 4**



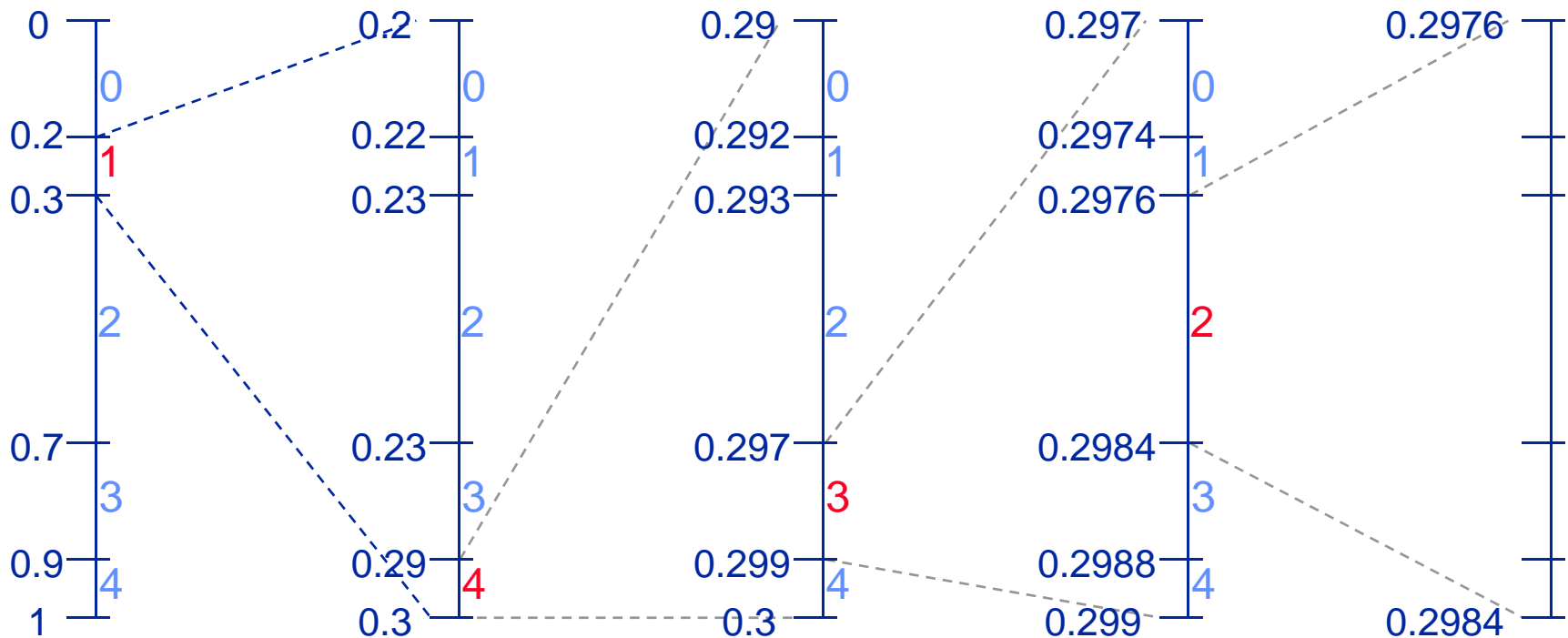
A Coding Example: 4/5

- We'll represent the “message” “1432” using the accumulative distribution function we have:
- **Third letter: 3.**



A Coding Example: 5/5

- We'll represent the "message" "1432" using the accumulative distribution function we have:
- **Fouth letter: 2**

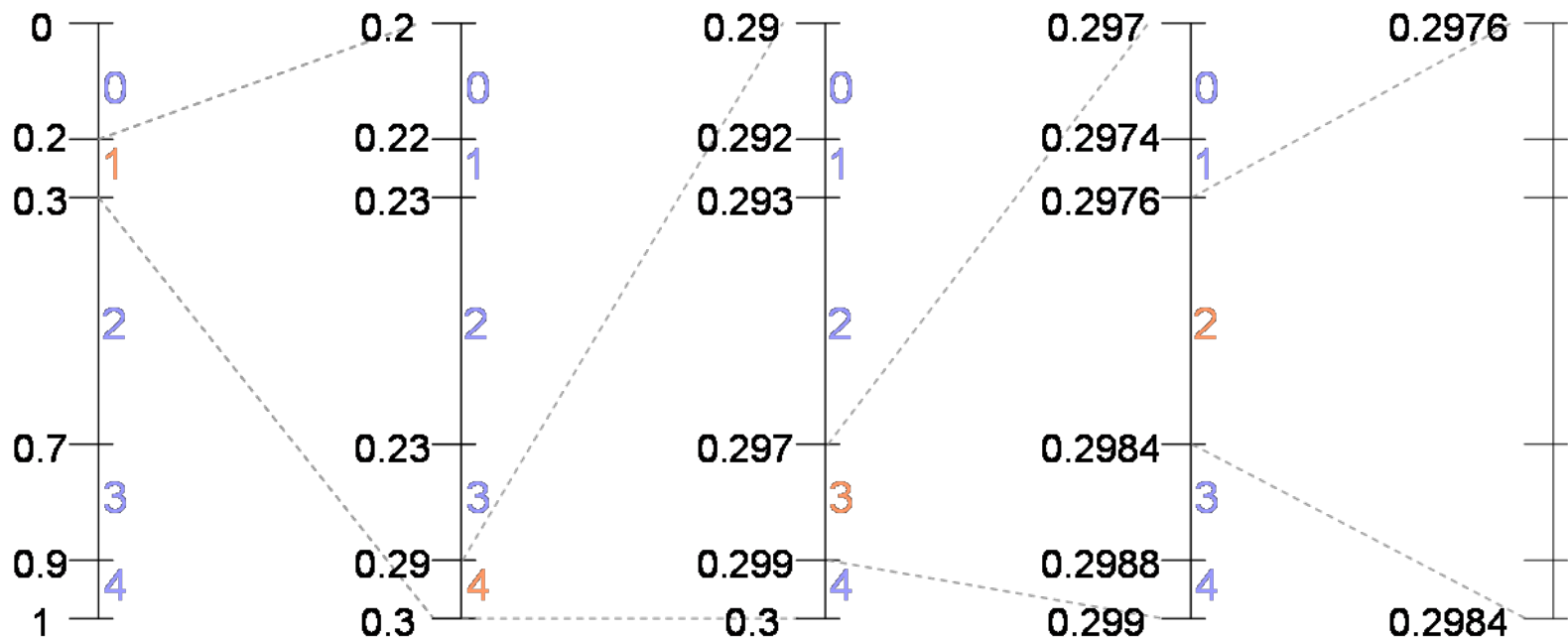


Choosing the coding word

- The string “1432” should be represented by a binary word in the boundary $[0.2976, 0.2984)$
- For simplicity, let's choose the middle point: 0.298
- $0.298_{10} = 0.0100110001001001101110\dots_2$
- It can be shown that we need $\lceil -\log p \rceil + 1$ bit to represent the **exact** message, where p is the boundary size, in our case: $p = 0.0008$, so we need 12 bits
- Since the two zeros at the end mean nothing we can use a shorter string: 0.0100110001

Decoding Procedure

We just need to “open” the boundary where 0.298 is in, the same way we encoded it, letter by letter.



Mathematical Formulation

- Through every step we are inside the boundary [$low, high$)
- We begin in the area $[0,1)$ so we initialize with $low=0, high=1$
- Every step, we get x , and need to calculate the
- next boundary limits $low', high'$
- $F(x)$ is the accumulative distribution function

$$low' = low + (high - low) \cdot F(x - 1)$$

$$high' = low + (high - low) \cdot F(x)$$

Pro's

- Adaptive : optional, even “on-the-fly”, using symbols probability or other mathematical model
 - No need to send **side information** !
- The coding algorithm is **not depended on the probability (or other) model**
- Very efficient ...

And Con's ...

- Computational **complexity**: need floating point arithmetic
- Sensitive to **BER**
- Decoding can't be **parallelized**
- **Not progressive**: no output until the whole message is coded
- Message length or “**end-of-message**” sign are needed

Advanced Algorithms

- **Progressive**: we want to have the output start before the “end-of-message”
 - There are coding/decoding “predictive” algorithms
- **Fixed point** arithmetic
 - There are fixed point and table based methods

An excellent reference...

- By Ilan Sutskever,
can be found in the course web site