UiO : Department of Informatics
University of Oslo

INF5442 – Image Sensor Circuits and Systems

Lecture 6 – Introduction to JPEG compression

6-October-2014

Motivation

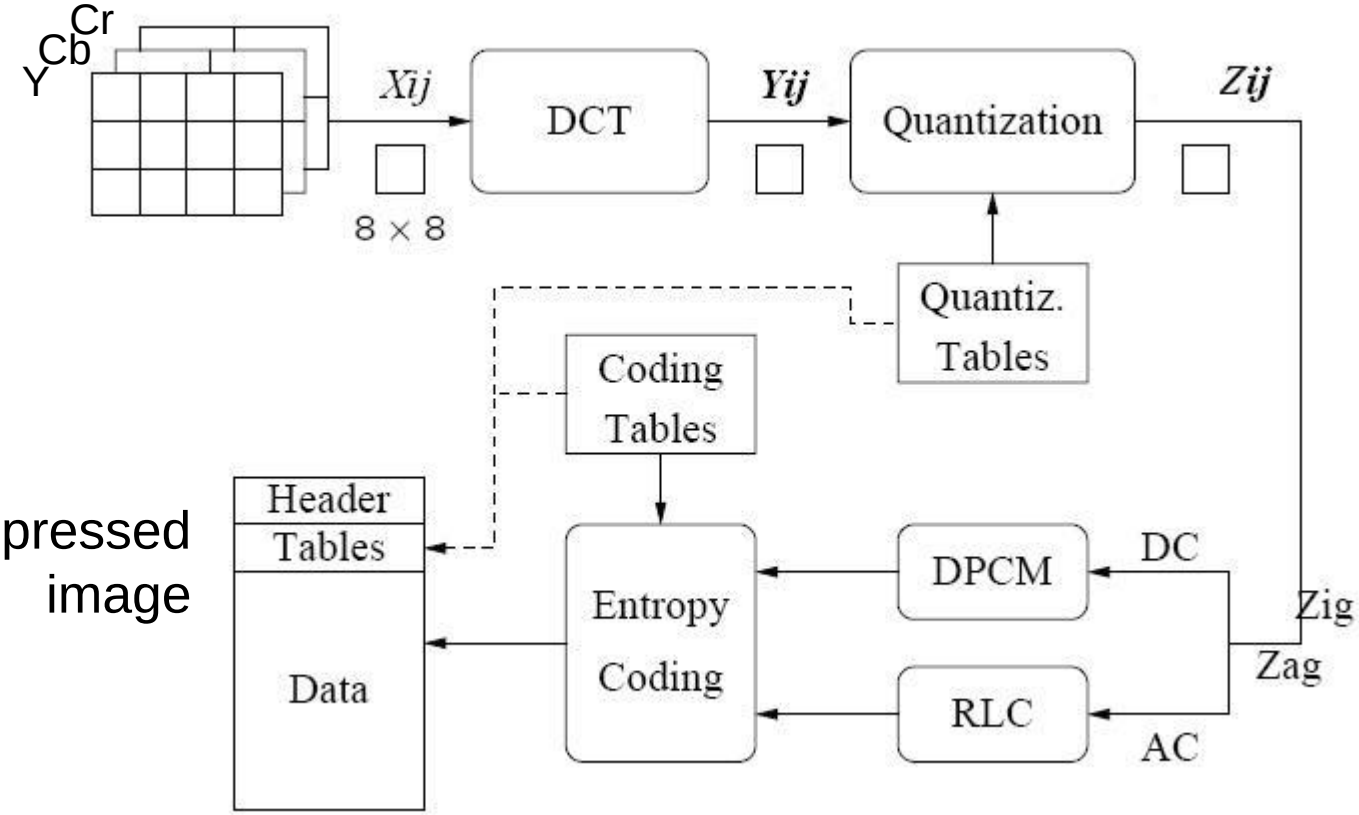
- Reduce output data bandwidth
- Enable higher video frame rate
- Reduce transmission power consumption
- Save image storage space on host side

Compression techniques used in JPEG

- Human visual system more sensitive to luma levels than chroma levels
  - Sub-sample chroma data
- Small changes between neighboring pixels
  - Transform into frequency domain which enables efficient coding schemes
- Human visual system more sensitive to low frequency than high frequency content
  - Round to zero HF contents that HVS cannot see

Conceptual diagram av JPEG encoder

Chroma sub sampling



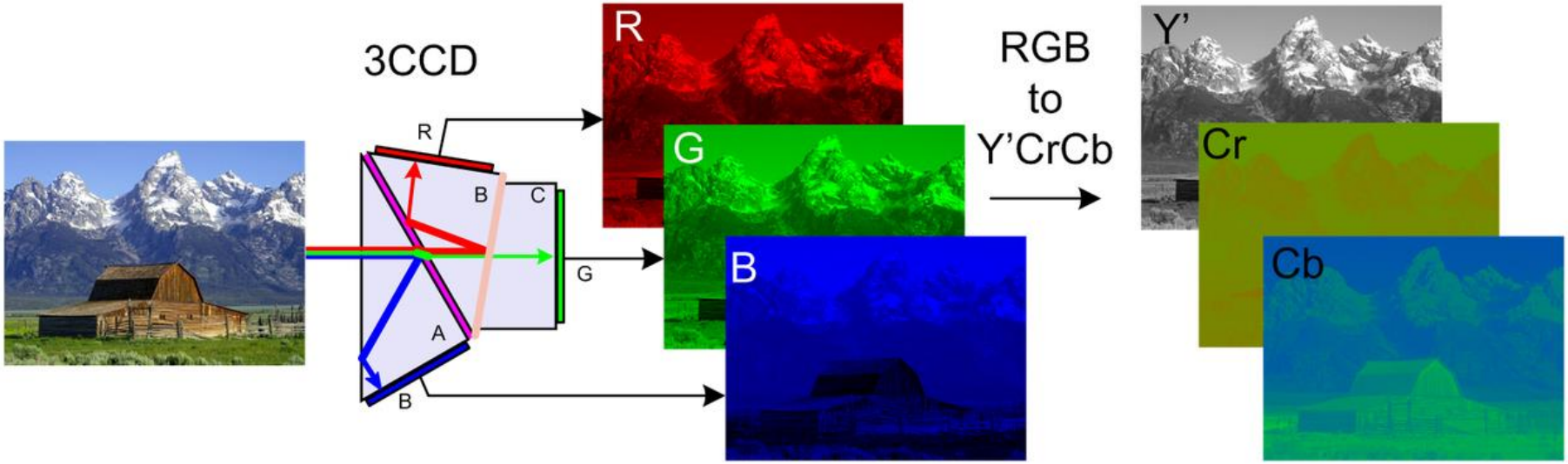
Compressed image

Step-1: RGB => YCbCr

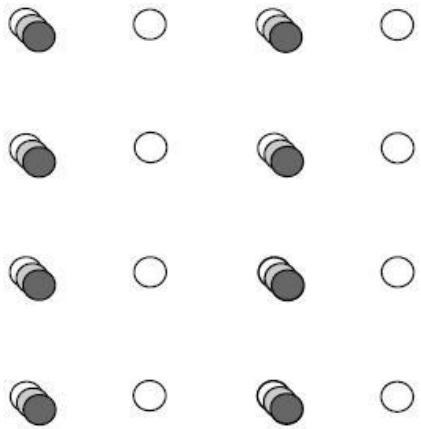
$$Y = 0.299\,R + 0.587\,G + 0.11B$$

$$Cb = 0.564\,(B - Y)$$

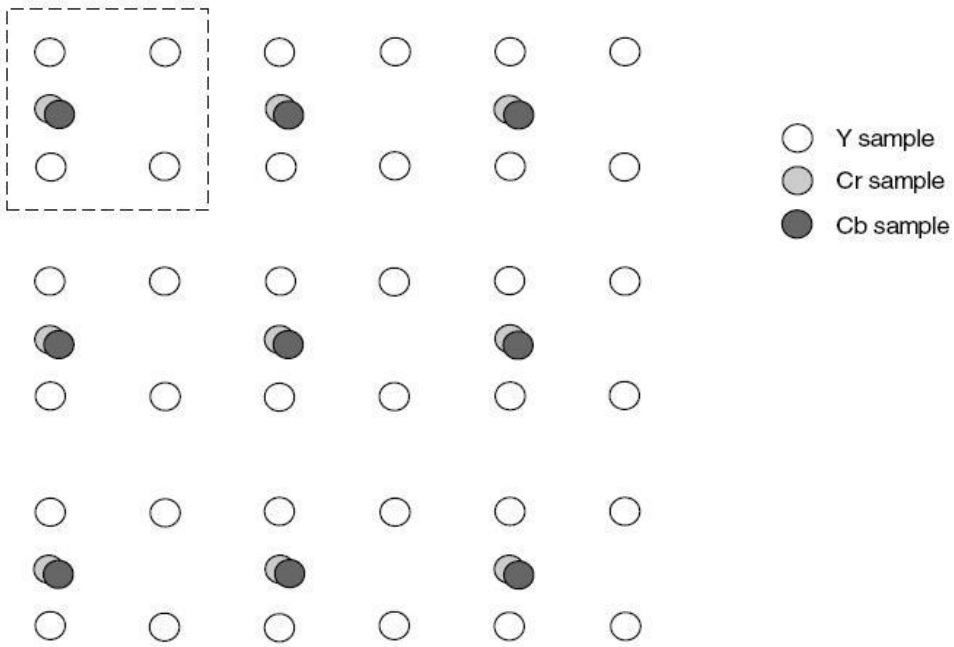
$$Cr = 0.713\,(R - Y)$$



Step-2: Sub-sample chroma information



4:2:2 sampling



4:2:0 sampling

- Selected chroma coding scheme written in JPEG header file

Step-3: divide up picture in macro blocks of 8x8 pixels

- Studies have shown that 8x8 is optimal block size
  - High correlation (redundancy) inside pixel cluster
  - Relatively inexpensive HW implementation (only 8 rows of memory required to process 8x8 matrix)

VGA example

VGA picture: 640x480 pixels

4:2:0 coding

- 4800 (80x60) luma macro blocks (Y)
- 2x1200 (40x30) chroma macro blocks (Cb, Cr)

200	202	189	188	189	175	175	175
200	203	198	188	189	182	178	175
203	200	200	195	200	187	185	175
200	200	200	200	197	187	187	187
200	205	200	200	195	188	187	175
200	200	200	200	200	190	187	175
205	200	199	200	191	187	187	175
210	200	200	200	188	185	187	186

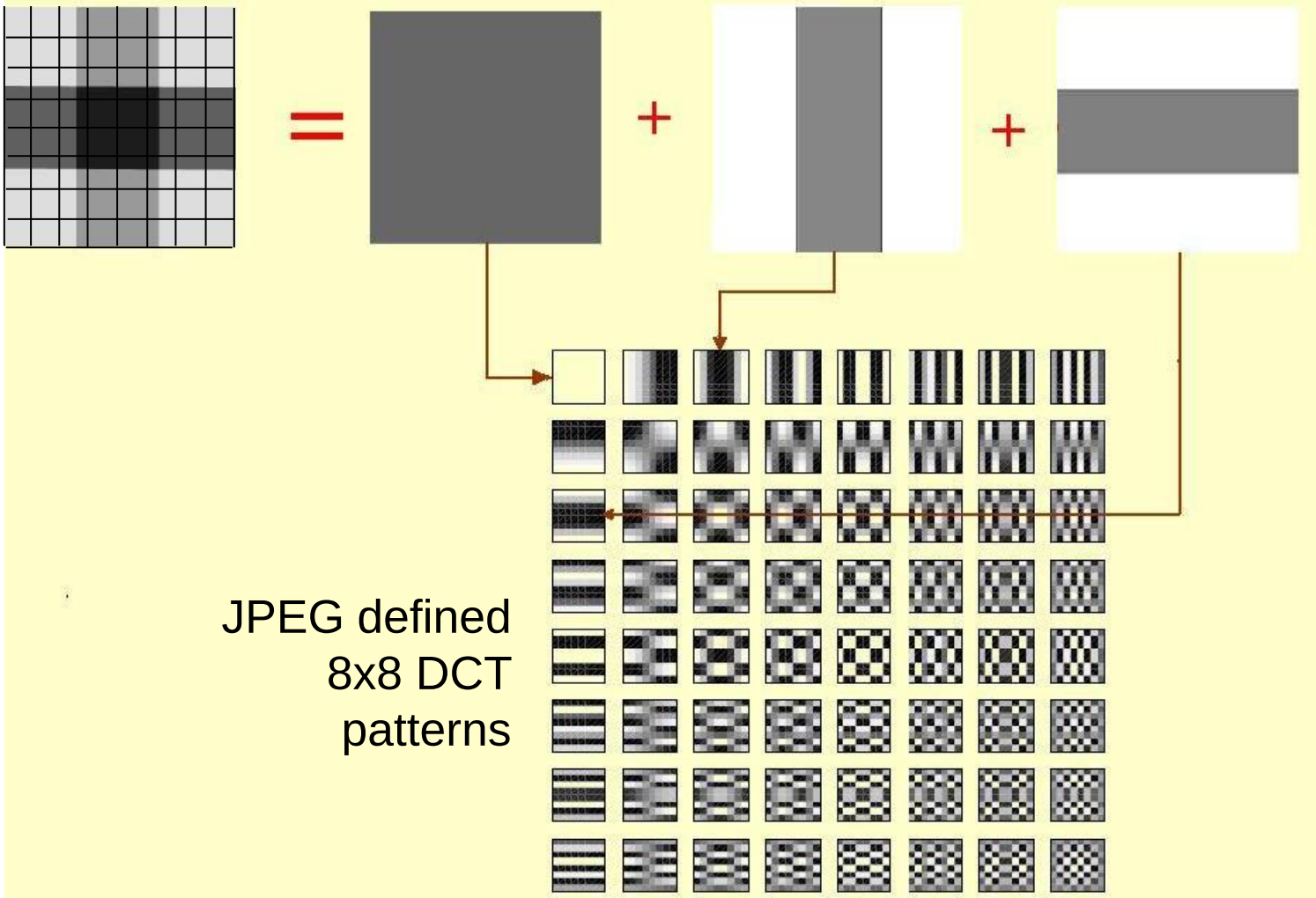
Step-4: DCT transformation

- Analogous to FFT where signal is represented in frequency domain
- Each macro block described as weighted sum of 64 jpeg-defined reference pictures
- Each reference picture has a unique frequency content
- Input (X_{ij}): 8x8 matrix (original picture)
- Output (Y_{ij}): 8x8 matrix (coefficients for each ‘frequency’)

$$DCT\ transformasjon: \quad Y_{ij} = A \cdot X_{ij} \cdot A^T$$

$$\mathbf{A} = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \sqrt{\frac{1}{2}}\cos\frac{\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{3\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{5\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{7\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{9\pi}{8} & \sqrt{\frac{1}{2}}\cos\frac{11\pi}{8} & \sqrt{\frac{1}{2}}\cos\frac{13\pi}{8} & \sqrt{\frac{1}{2}}\cos\frac{15\pi}{8} \\ \sqrt{\frac{1}{2}}\cos\frac{2\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{6\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{10\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{14\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{18\pi}{8} & \sqrt{\frac{1}{2}}\cos\frac{22\pi}{8} & \sqrt{\frac{1}{2}}\cos\frac{26\pi}{8} & \sqrt{\frac{1}{2}}\cos\frac{30\pi}{8} \\ \sqrt{\frac{1}{2}}\cos\frac{3\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{9\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{15\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{21\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{27\pi}{8} & \sqrt{\frac{1}{2}}\cos\frac{33\pi}{8} & \sqrt{\frac{1}{2}}\cos\frac{39\pi}{8} & \sqrt{\frac{1}{2}}\cos\frac{45\pi}{8} \\ \sqrt{\frac{1}{2}}\cos\frac{4\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{12\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{20\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{28\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{36\pi}{8} & \sqrt{\frac{1}{2}}\cos\frac{44\pi}{8} & \sqrt{\frac{1}{2}}\cos\frac{52\pi}{8} & \sqrt{\frac{1}{2}}\cos\frac{60\pi}{8} \\ \sqrt{\frac{1}{2}}\cos\frac{5\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{15\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{25\pi}{816} & \sqrt{\frac{1}{2}}\cos\frac{35\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{45\pi}{8} & \sqrt{\frac{1}{2}}\cos\frac{55\pi}{8} & \sqrt{\frac{1}{2}}\cos\frac{65\pi}{8} & \sqrt{\frac{1}{2}}\cos\frac{75\pi}{8} \\ \sqrt{\frac{1}{2}}\cos\frac{6\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{18\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{30\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{42\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{54\pi}{8} & \sqrt{\frac{1}{2}}\cos\frac{66\pi}{8} & \sqrt{\frac{1}{2}}\cos\frac{78\pi}{8} & \sqrt{\frac{1}{2}}\cos\frac{90\pi}{8} \\ \sqrt{\frac{1}{2}}\cos\frac{7\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{21\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{35\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{49\pi}{8} & \sqrt{\frac{1}{2}}\cos\frac{63\pi}{16} & \sqrt{\frac{1}{2}}\cos\frac{77\pi}{8} & \sqrt{\frac{1}{2}}\cos\frac{91\pi}{8} & \sqrt{\frac{1}{2}}\cos\frac{105\pi}{8} \end{bmatrix}$$

Conceptual diagram of DCT transform



DCT example

X_{ij}

200	202	189	188	189	175	175	175
200	203	198	188	189	182	178	175
203	200	200	195	200	187	185	175
200	200	200	200	197	187	187	187
200	205	200	200	195	188	187	175
200	200	200	200	200	190	187	175
205	200	199	200	191	187	187	175
210	200	200	200	188	185	187	186

$AX_{ij}A^T$

Y_{ij}

$$\begin{bmatrix} 515 & 65 & -12 & 4 & 1 & 2 & -8 & 5 \\ -16 & 3 & 2 & 0 & 0 & -11 & -2 & 3 \\ -12 & 6 & 11 & -1 & 3 & 0 & 1 & -2 \\ -8 & 3 & -4 & 2 & -2 & -3 & -5 & -2 \\ 0 & -2 & 7 & -5 & 4 & 0 & -1 & -4 \\ 0 & -3 & -1 & 0 & 4 & 1 & -1 & 0 \\ 3 & -2 & -3 & 3 & 3 & -1 & -1 & 3 \\ -2 & 5 & -2 & 4 & -2 & 2 & -3 & 0 \end{bmatrix}$$

HF content close to zero

Step-5: Quantization (lossy)

- Divide by quantisation matrix, Q, and round off decimals
- Level of lossyness defined by Q which is defined in JPEG header
- Coefficients at high frequencies can be rounded to zero without visible image artifacts

$$Z_{ij} = Round\left(\frac{Y_{ij}}{Q_{ij}}\right)$$

Luma:

$$Q = \begin{bmatrix} 16 & 11 & 10 & 16 & 24 & 40 & 51 & 61 \\ 12 & 12 & 14 & 19 & 26 & 58 & 60 & 55 \\ 14 & 13 & 16 & 24 & 40 & 57 & 69 & 56 \\ 14 & 17 & 22 & 29 & 51 & 87 & 80 & 62 \\ 18 & 22 & 37 & 56 & 68 & 109 & 103 & 77 \\ 24 & 35 & 55 & 64 & 81 & 104 & 113 & 92 \\ 49 & 64 & 78 & 87 & 103 & 121 & 120 & 101 \\ 72 & 92 & 95 & 98 & 112 & 100 & 103 & 99 \end{bmatrix}$$

Chroma:

$$Q = \begin{bmatrix} 17 & 18 & 24 & 47 & 99 & 99 & 99 & 99 \\ 18 & 21 & 26 & 66 & 99 & 99 & 99 & 99 \\ 24 & 26 & 56 & 99 & 99 & 99 & 99 & 99 \\ 47 & 66 & 99 & 99 & 99 & 99 & 99 & 99 \\ 99 & 99 & 99 & 99 & 99 & 99 & 99 & 99 \\ 99 & 99 & 99 & 99 & 99 & 99 & 99 & 99 \\ 99 & 99 & 99 & 99 & 99 & 99 & 99 & 99 \\ 99 & 99 & 99 & 99 & 99 & 99 & 99 & 99 \end{bmatrix}$$

Example

Original picture (X_{ij})

200	202	189	188	189	175	175	175
200	203	198	188	189	182	178	175
203	200	200	195	200	187	185	175
200	200	200	200	197	187	187	187
200	205	200	200	195	188	187	175
200	200	200	200	200	190	187	175
205	200	199	200	191	187	187	175
210	200	200	200	188	185	187	186

After DCT (Y_{ij})

515	65	-12	4	1	2	-8	5
-16	3	2	0	0	-11	-2	3
-12	6	11	-1	3	0	1	-2
-8	3	-4	2	-2	-3	-5	-2
0	-2	7	-5	4	0	-1	-4
0	-3	-1	0	4	1	-1	0
3	-2	-3	3	3	-1	-1	3
-2	5	-2	4	-2	2	-3	0

After quantization (Z_{ij})

32	6	-1	0	0	0	0	0
-1	0	0	0	0	0	0	0
-1	0	1	0	0	0	0	0
-1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

$Y'_{ij} = Z_{ij} \times Q_{ij}$

Reversing the process

Y'_{ij}

512	66	-10	0	0	0	0	0
-12	0	0	0	0	0	0	0
-14	0	16	0	0	0	0	0
-14	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

X'_{ij}

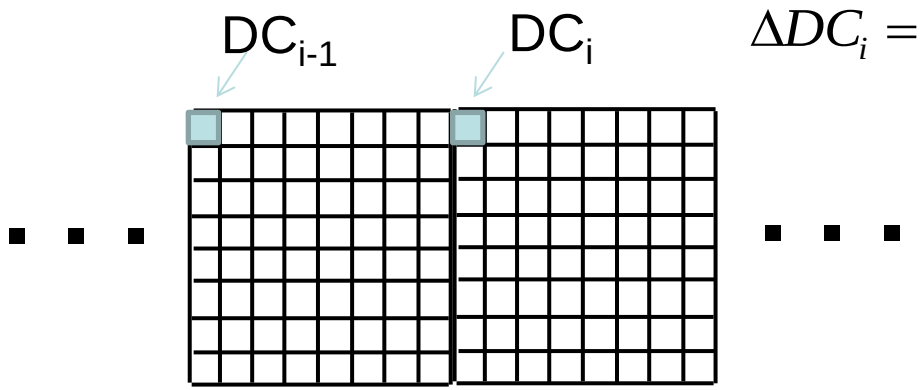
199	196	191	186	182	178	177	176
201	199	196	192	188	183	180	178
203	203	202	200	195	189	183	180
202	203	204	203	198	191	183	179
200	201	202	201	196	189	182	177
200	200	199	197	192	186	181	177
204	202	199	195	190	186	183	181
207	204	200	194	190	187	185	184

Step-6: Coding of DCT coefficients after quantization

- DC values (0,0 position) coded with Differential PCM (DPCM)
- AC values (all other positions) coded with Run Length Coding (RLC)

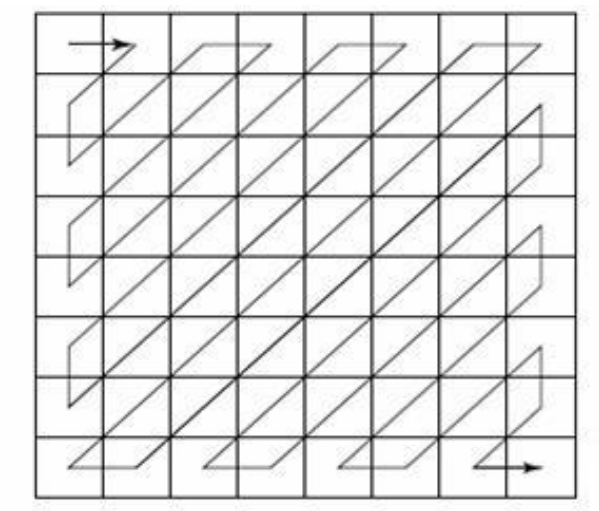
DPCM coding of DC-values

$$\Delta DC_i = DC_i - DC_{i-1}$$



Run Level Coding (RLC) of AC values

- Efficient coding method of all zeros in the matrix
- Diagonal (ZigZag) scanning of the matrix
  - Count zeroes (A) until non-zero value (B)
  - Transmit (A,B), and start counting zeros again



RLC example:

$$\begin{bmatrix} 32 & 6 & -1 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

(0, 32), (0, 6), (0, -1), (0, -1), (1,-1), (3, -1), (2, 1), (EOB)

EOB=End of block

Step-7: Entropy encoding

- Lossless
- Frequent codes represented with few bits
- Rare codes represented with many bits
- Also called Variable Length Coding (VLC)
  - Available VLC algorithms
    - Huffman coding (most common)
    - Adaptive Huffman coding
    - Shannon-Fano Algorithm
    - Arithmetic coding
- Jpeg header contains look-up table for selected VLC algorithm

Huffman coding of DC and AC coefficients

SSSS	DPCM difference	Additional bits (binary)
0	0	–
1	−1,1	0,1
2	−3,−2,2,3	00,01,10,11
3	−7,...,−4,4,...,7	000,...,011,100,...,111
4	−15,...,−8,8,...,15	0000,...,0111,1000,...,1111
⋮	⋮	⋮
16	32768	–

tables.jpg

Huffman coding of DC coefficients

SSSS	AC coefficients	Precision	
1	−1,1	8	12
2	−3,−2,2,3	8	12
3	−7,...,−4,4,...,7	8	12
4	−15,...,−8,8,...,15	8	12
5	−31,...,−16,16,...,31	8	12
6	−63,...,−32,32,...,63	8	12
7	−127,...,−64,64,...,127	8	12
8	−255,...,−128,128,...,255	8	12
9	−511,...,−256,256,...,511	8	12
10	−1023,...,−512,512,...,1023	8	12
11	−2047,...,−1024,1024,...,2047	8	12
12	−4095,...,−2048,2048,...,4095	8*	12
13	−8191,...,−4096,4096,...,8191		12
14	−16383,...,−8192,8192,...,16383		12
15	−32767,...,−16384,16384,...,32767		12*

tables.jpg

Huffman coding of AC coefficients

Some JPEG variants

- Progressive JPEG: picture stored as series of ‘scans’ that make the picture gradually sharper
- Lossless JPEG: no quantization
- JPEG 2000: ‘wavelet’ transformation instead of DCT

Other compression standards

- MPEG
- H.264
- Wavelet (e.g. JPEG-2000)
- fractal
- vector quantization

JPEG references

- W.B. Pennebaker and J.L. Mitchell, JPEG Still Image Data Compression Standard, International Thomson Publishing, Chapman & Hall, NY, 1992
- Digital Image Processing by R.C. Gonzalez and R.E. Woods
- http://www.wikipedia.org