Wireless Communication Systems
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Lecture 6: Image

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Chap. 9 of “Fundamentals of Multimedia”
Some reference from http://media.ee.ntu.edu.tw/courses/dvt/15F/

Outline

- **Image concepts**
- Lossless JPEG
- JPEG
- Other JPEG Standards

Comparison between Audio and Image

- Audio
  - One-dimensional time-domain signals
  - Continuous analog signals or discrete digital signals

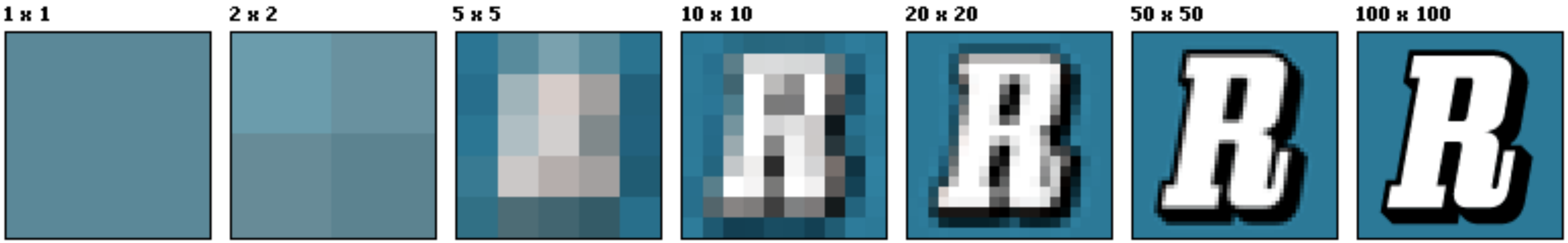
- Image
  - Digital image f(i,j)
  - Not defined over the time domain
  - Defined over the spatial domain
  - Two dimensions: rows and columns

Bitmap images

- Images consist of 2D pixels
  - Image resolution = Number of pixels
  - e.g., 1,600 x 1,200 or 800 x 600
- Commonly used in digital cameras, scanners, fax machines, etc
- Types
  - 1-bit images: Black & white binary image
  - 8-bit images: Grayscale images
    - Each pixel has a gray value between 0 and 255
  - 24-bit images: Color images
    - Three bytes represent RGB values in the range 0-255

Bitmap images

- **Sampling**
  - Resolution, number of pixels in x and y



Source: wikipedia

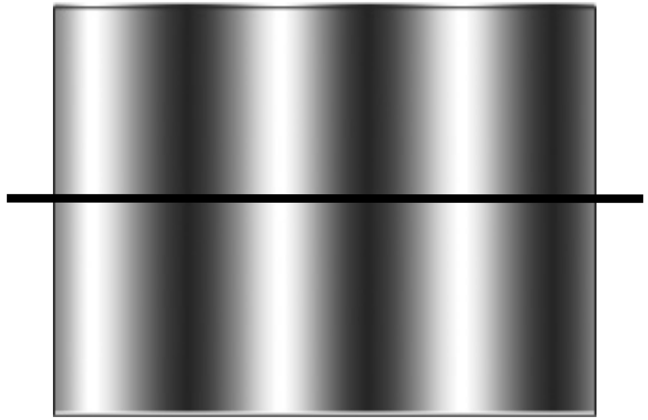
- **Quantization**
  - Bit-depth: Number of bits used to represent RGB

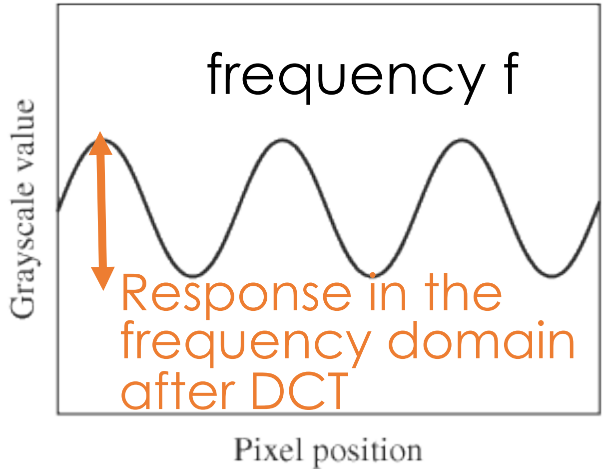
Waveforms

- **Spatial frequency** indicates how many times pixel values change across an image block

  → Can be convert to the frequency-domain using DCT

  → Say the frequency of the waveform is *f*. Then, the response (value) of the frequency *f* will be the amplitude of this waveform





Why Uses DCT?

- Leverage spatial redundancy to compress
  - If a pixel is red, its neighbors is likely red also
- Humans are less sensitive to very high-spatial frequency components
  - High-frequency components are usually close to zero
  - Hardly distinguishable even if set to 0
- Human are more sensitive to luminance than color
  - Transform RGB to YIQ or YUV
  - Reduce the size of color parts (UV)

JPEG

- Joint Photographic Experts Group
- Digital compression and coding of continuous-tone still images
- Also used to compress video frame-by-frame (Motion JPEG)
- Modes of operation
  - Sequential DCT
  - Progressive DCT
  - Sequential Lossless
  - Hierarchical

History of JPEG

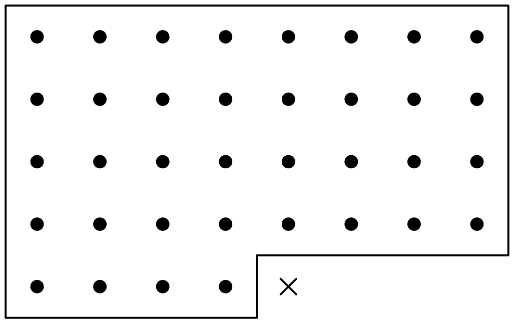
- Since 1986, joint meeting for *International Telecommunication Union (ITU)* and the *International Organization for Standardization (ISO)* to establish the standard for ***multilevel color still images.*** In 1987, the *International Electrotechnical Committee (IEC)* joined in.
- Known as JPEG, Joint Photographic Experts Group
- Schedules:
  - 1986, March, targets to Color still image—lossless and lossy
  - 1987, narrowed to three techniques: Adaptive DCT, DPCM with Adaptive Binary Arithmetic Coding, Progressive BTC
  - 1988, select the DCT-based method
  - 1988-1990, simulating, testing and documenting
  - 1991, draft
  - 1992, international standard
- Official document:
  - ISO/IEC international standard 10918-1(set requirements and guides) (-2, for compliance tests, -3, for extensions)
    - digital compression and coding of continuous-tone still images
  - ITU-T Recommendation T.81

Outline

- Image concepts
- **Lossless JPEG**
- JPEG
- Other JPEG Standards

Differential Pulse Code Modulation

- DPCM is a lossless predictive coding
- Use neighboring pixels to predict a pixel value
- Calculate the difference (error) between the weighted average and the pixel value x_m



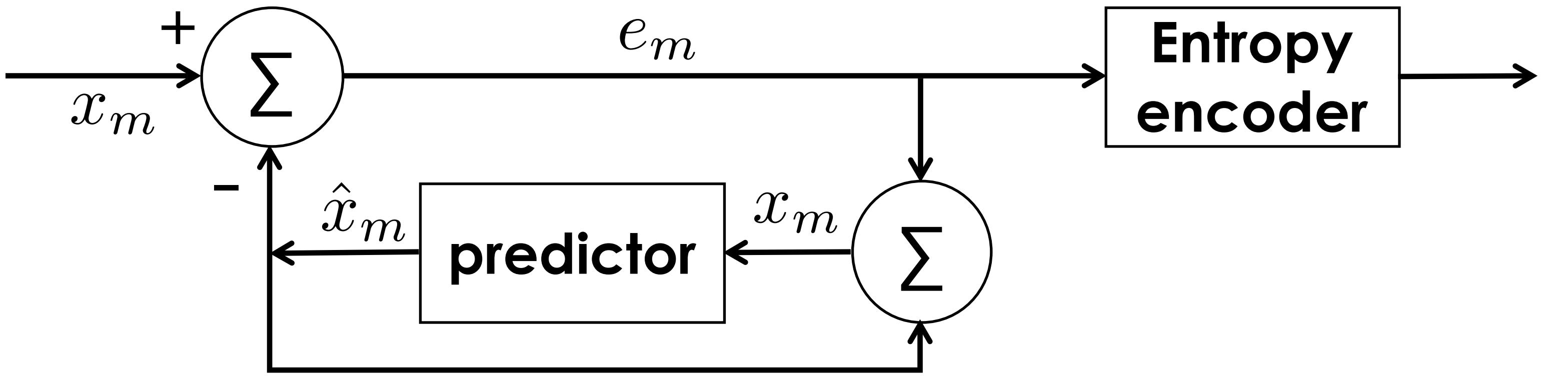
Region of causal predictor

$$\hat{x}_m = \sum_{i=0}^{m-1} \alpha_i x_i \Longrightarrow e = x_m - \hat{x}_m$$

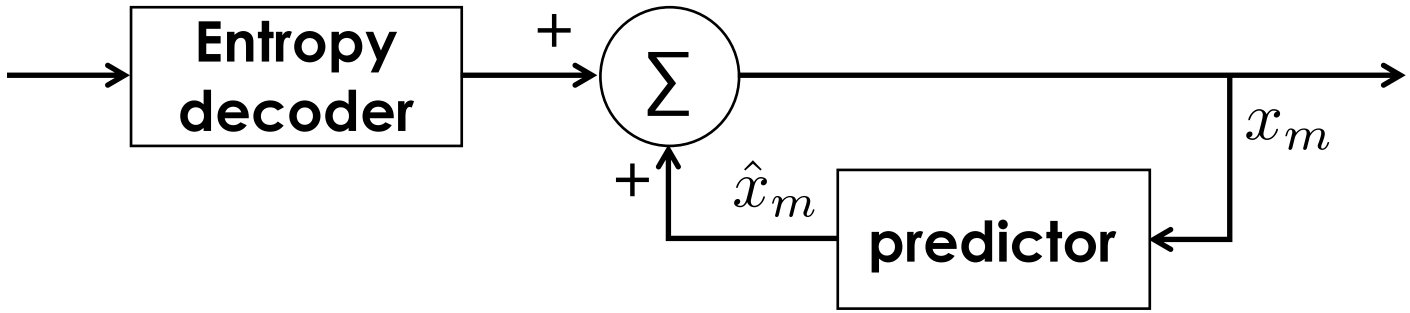
- Why taking the difference?
  - The variation (difference) of signals is usually much smaller than the amplitude of the signals
- Cons: error propagation

DPCM Encoding and Decoding

- Encode

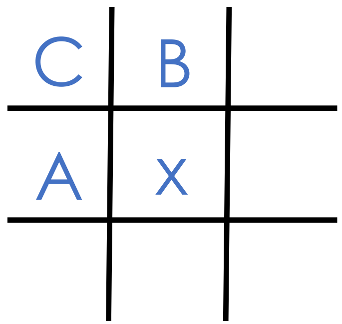


- Decode



Lossless JPEG Standards

- Use differential coding (DPCM) followed by a Huffman coder or an arithmetic coder
- The prediction residual for pixel x is $r = y - x$, where y can be any of the following functions
  1. y = 0
  2. y = A
  3. y = B
  4. y = C
  5. y = A + C - B
  6. y = A + (C – B)/2
  7. y = C + (A - B)/2
  8. y = (A + B)/2



- Pick the one outputting the smallest error
- The selection predictor should be sent to the decoder

Lossless JPEG – Example

- Let A =100, B=100, C=191, x = 180, y = (A+C)/2
- r = (100 +191)/2 - x = 145 – 180 = -35
- r = -35 = $(\mathbf{011100})_2$
  - belonging to class 6
- The Huffman code for 6 is **1110**
- Thus, the final code is **1110011100**

(Huffman code) (residual)

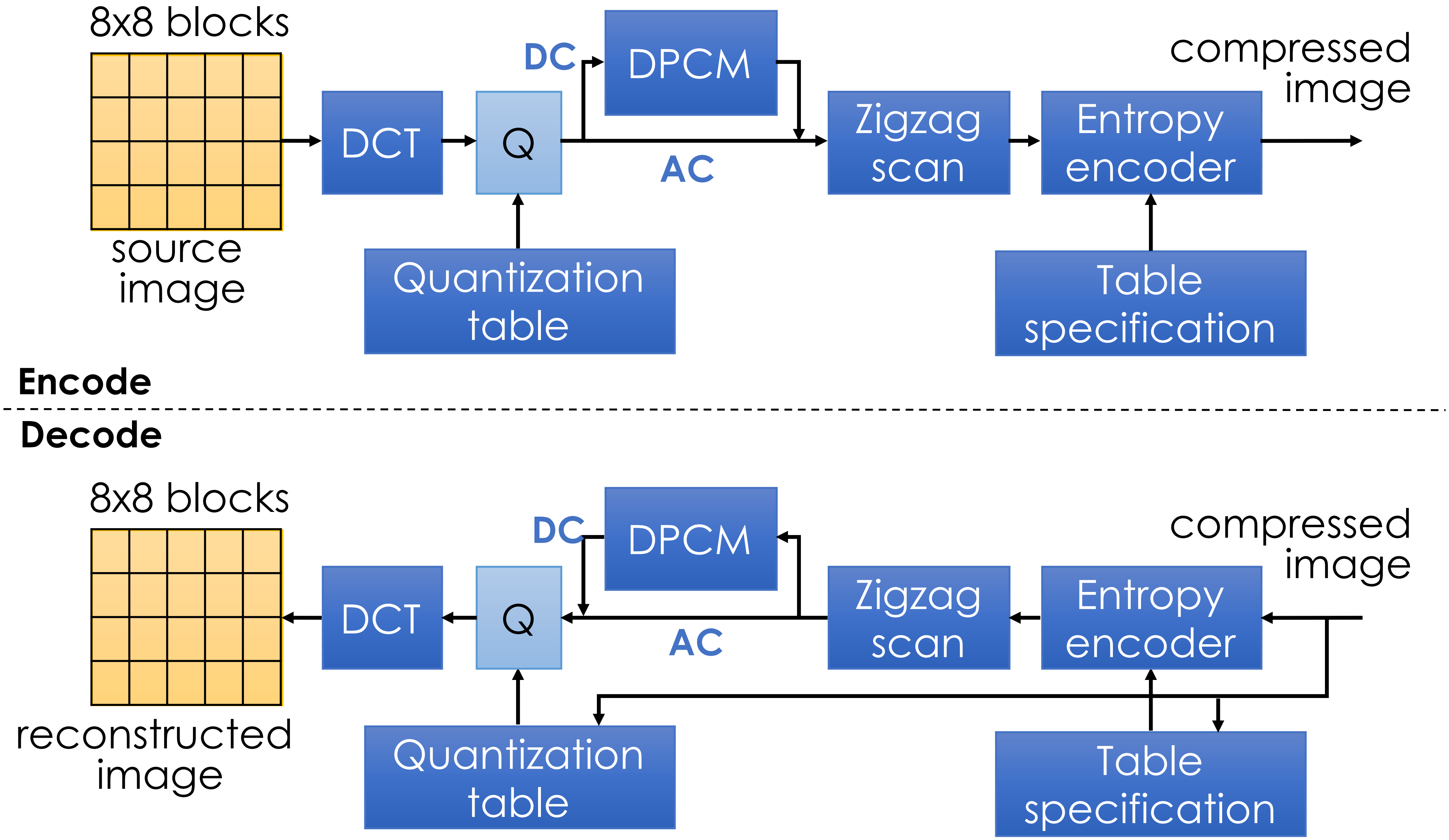
Q: Why Variable Length Coding?

Class	Error range
0	0
1	-1,1
2	-3, -2, 2, 3
3	-7, …, -4, 4, …, 7
4	-15, …, -8, 8, …, 15
5	-31, …, -16, 16, …, 31
6	-63, …, -32, 32, …, 63
7	-127, …, -64, 64, …, 127
8	-255, …, -128, 128, …, 255
9	-511, …, -256, 256, …, 511
10	-1023, …, -256, 256, …, 1023
11	-2017, …, -1024, 1024, …, 2047
12	-4095, …, -2048, 2048, …, 4095
13	-8191, …, -4096, 4096, …, 8191
14	-16383, …, -8192, 8192, …, 16383
15	-32767, …, -16383, 16383, …, 32767
16	-65535, …, -32768, 32768, …, 65535

Outline

- Image concepts
- Lossless JPEG
- **Sequential DCT-based JPEG**
- Other JPEG Standards

Sequential DCT-Based JPEG



Sequential DCT-Based JPEG

- Main Steps
  1. Transform RGB to YIQ or YUV (Optional)
  2. Subsample color components
  3. Divide the image to 8x8 blocks (faster for DCT)
  4. Perform DCT for each block
  5. Apply quantization (only step lead to losses)
  6. Perform zigzag ordering
  7. DPCM for DC and run-length encoding for AC
  8. Perform Entropy coding

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Chroma Subsampling

- Humans are less sensitive to color
  → subsample CbCr
- Subsample notation: *a:b:c*
  - From a 4x4 block: take ***a*** samples from Y, ***b*** samples from each CbCr top row, and ***c*** samples from each CbCr bottom row

4:1:1

Y CbCr	Y	Y	Y
Y CbCr	Y	Y	Y
Y CbCr	Y	Y	Y
Y CbCr	Y	Y	Y

4:2:0

Y CbCr	Y	Y CbCr	Y
Y	Y	Y	Y
Y CbCr	Y	Y CbCr	Y
Y	Y	Y	Y

4:2:2

Y CbCr	Y	Y CbCr	Y
Y CbCr	Y	Y CbCr	Y
Y CbCr	Y	Y CbCr	Y
Y CbCr	Y	Y CbCr	Y

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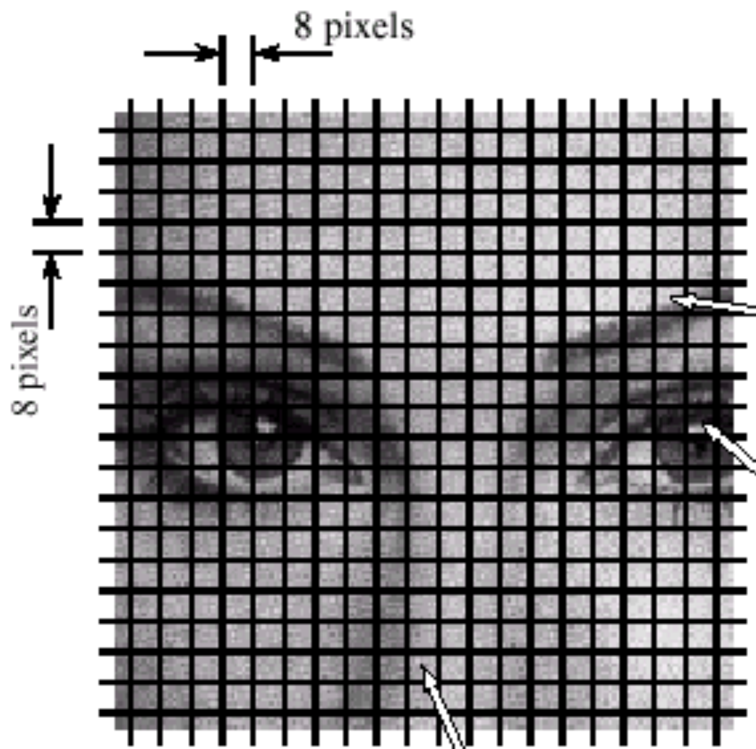


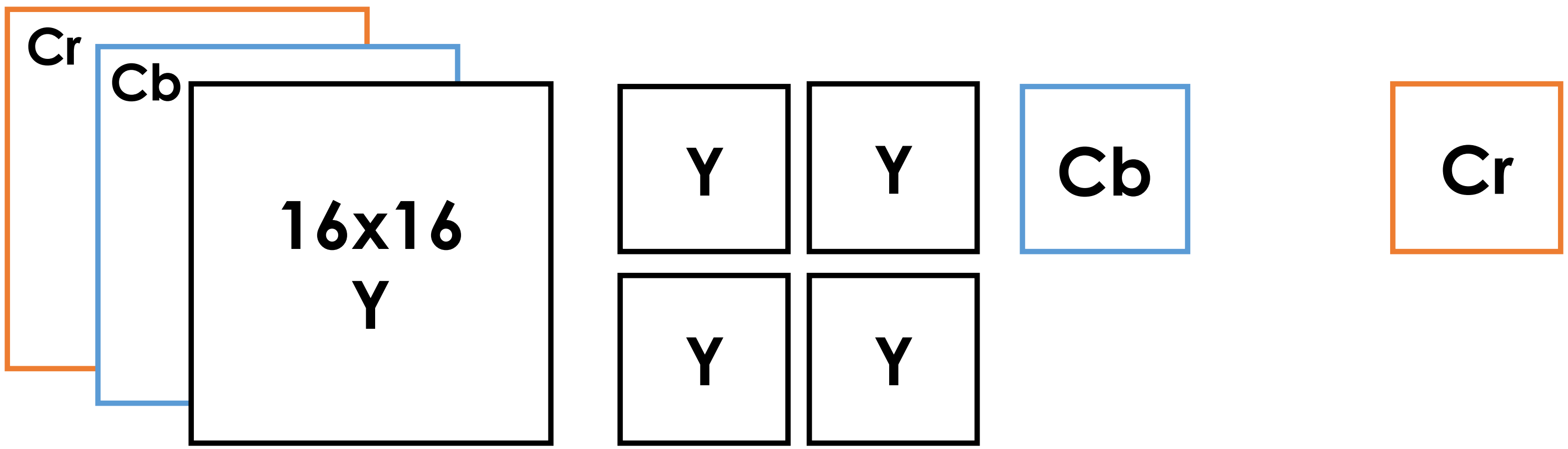
231	224	224	217	217	203	189	196
210	217	203	189	203	224	217	224
196	217	210	224	203	203	196	189
210	203	196	203	182	203	182	189
203	224	203	217	196	175	154	140
182	189	168	161	154	126	119	112
175	154	126	105	140	105	119	84
154	98	105	98	105	63	112	84

42	28	35	28	42	49	35	42
49	49	35	28	35	35	35	42
42	21	21	28	42	35	42	28
21	35	35	42	42	28	28	14
56	70	77	84	91	28	28	21
70	126	133	147	161	91	35	14
126	203	189	182	175	175	35	21
49	189	245	210	182	84	21	35

154	154	175	182	189	168	217	175
154	147	168	154	168	168	196	175
175	154	203	175	189	182	196	182
175	168	168	168	140	175	168	203
133	168	154	196	175	189	203	154
168	161	161	168	154	154	189	189
147	161	175	182	189	175	217	175
175	175	203	175	189	175	175	182

Subsampling and Macroblocks

- With subsampling, we create 8x8 blocks as follows
  - For example of 4:2:0
  - Divide an image into 16x16 macroblocks
  - Four blocks for Y (no subsampling)
  - Subsample blocks for CbCr
  - Four 8x8 Y blocks and one 8x8 CbCr block



Sequential DCT-Based JPEG

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Quantization

- Main source of quality losses
- Reduce the total number of bits needed for a compressed image

$$\hat{F}(u,v) = \text{round}\left(\frac{F(u,v)}{Q(u,v)}\right)$$

$\hat{F}(u,v)$: quantised DCT coefficient

$F(u,v)$: original DCT coefficient

$Q(u,v)$: 8-bit quantisation matrix entry

- Since $Q(u,v)$ is large, the magnitude and variance of $\hat{F}(u,v)$ are much smaller than those of $F(u,v)$

Default Quantization Tables

- Low-frequency components have smaller Q values
  → introduce less losses
- Tables specified from psychophysical studies
  - Maximizing the compression ratio
  - Minimizing perceptual losses

For luminance

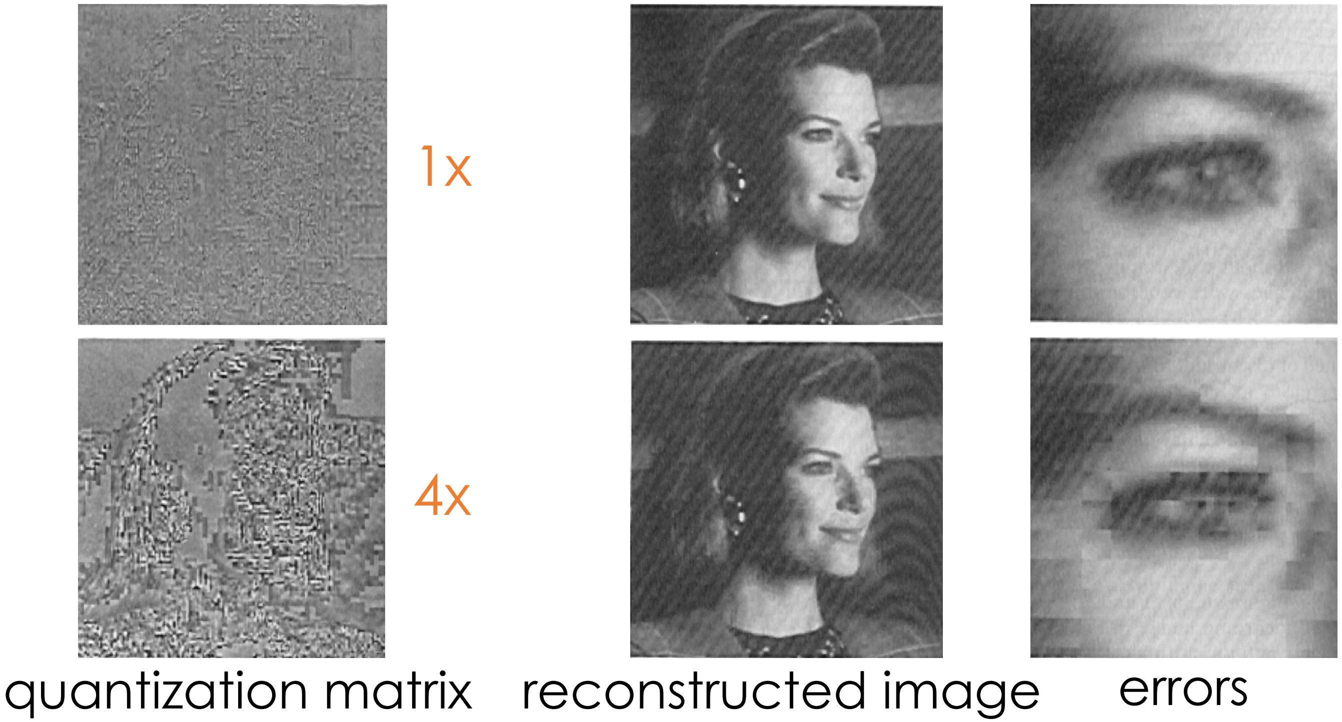
16	11	10	16	24	40	51	61
12	12	14	19	26	58	60	55
14	13	16	24	40	57	69	56
14	17	22	29	51	87	80	62
18	22	37	56	68	109	103	77
24	35	55	64	81	104	113	92
49	64	78	87	103	121	120	101
72	92	95	98	112	100	103	99

For chrominance

17	18	24	47	99	99	99	99
18	21	26	66	99	99	99	99
24	26	59	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

Adaptive Quantization

- Allow Spatially adaptive quantization
  - Quantization matrix can be scaled block
  - Improve performance by up to 30% as compared to non-adaptive quantization



Sequential DCT-Based JPEG

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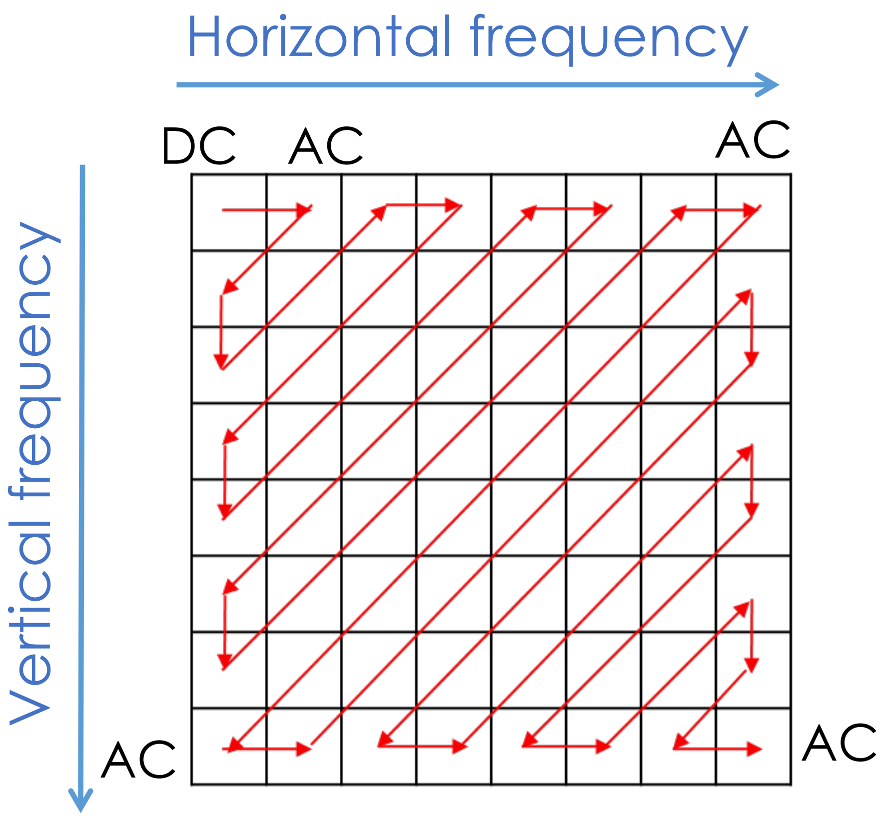
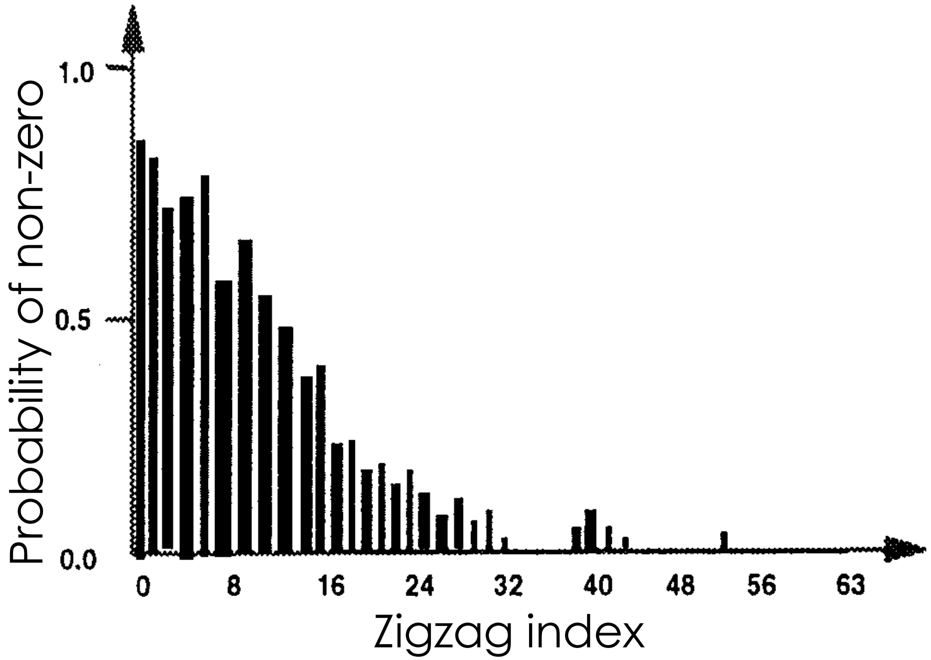
Zigzag Scanning

- Why Zigzag?
  - Sort from low frequency to high frequency
  - Longer string of 0's in the tail (high frequency components)





Sequential DCT-Based JPEG

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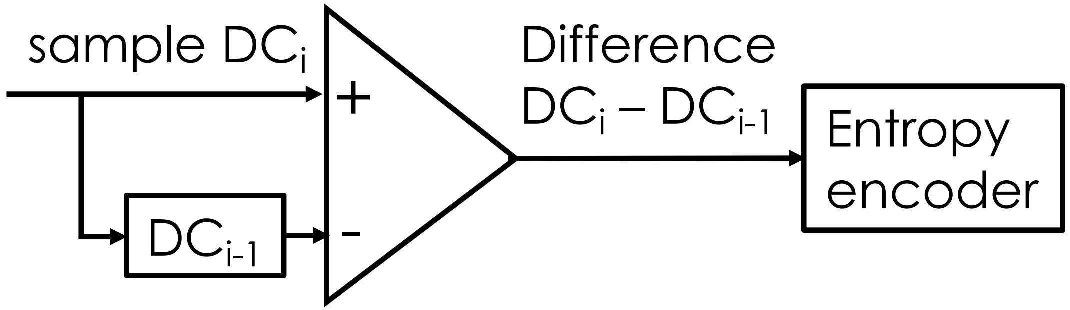
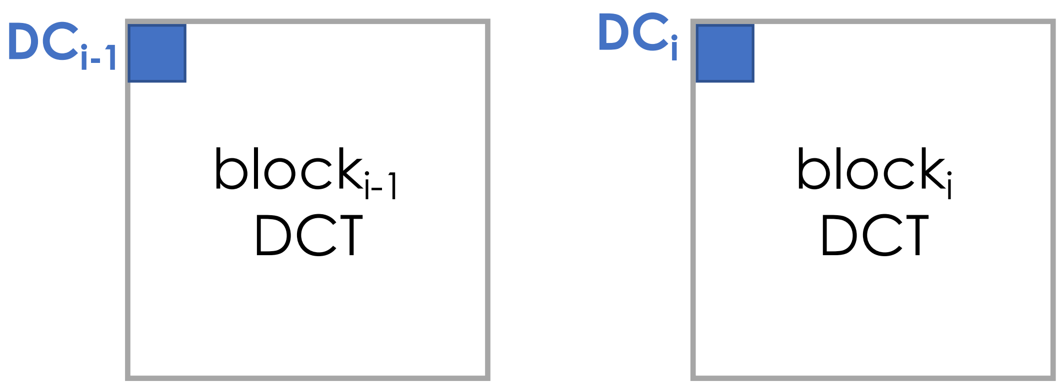
Predictive Coding for DC

- Use DPCM (differential pulse code modulation)
- **Use the DC of the previous block to predict the DC of the current block**





Predictive Coding for DC

- Why DPCM?
  - DC coefficient is relatively large as compared to AC coefficients
  - DC = average intensity of a block
  - Intensity of nearby blocks usually does not change drastically

- Example:
  - DC coefficients of the first five blocks:
    150, 155, 149, 152, 142
  - DPCM produces 150, 5, -6, 3, -8 for entropy coding
  - → difference is much smaller

Run-Length Coding for AC

- Since many of AC coefficients are 0, represent them by (#-zero-to-skip, next-non-zero-value)
  - Example: given the quantized frequency coefficients

    (32, 6, -1, -1, 0, -1, 0, 0, 0, -1, 0, 0, 1, 0, 0, … 0)

    32 → DC

  - Skip the DC and convert the AC coefficients to

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

  - (0, 0) is a special pair indicatind end-of-block after the last nonzero AC coefficient

Sequential DCT-Based JPEG

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  2. Subsample color components
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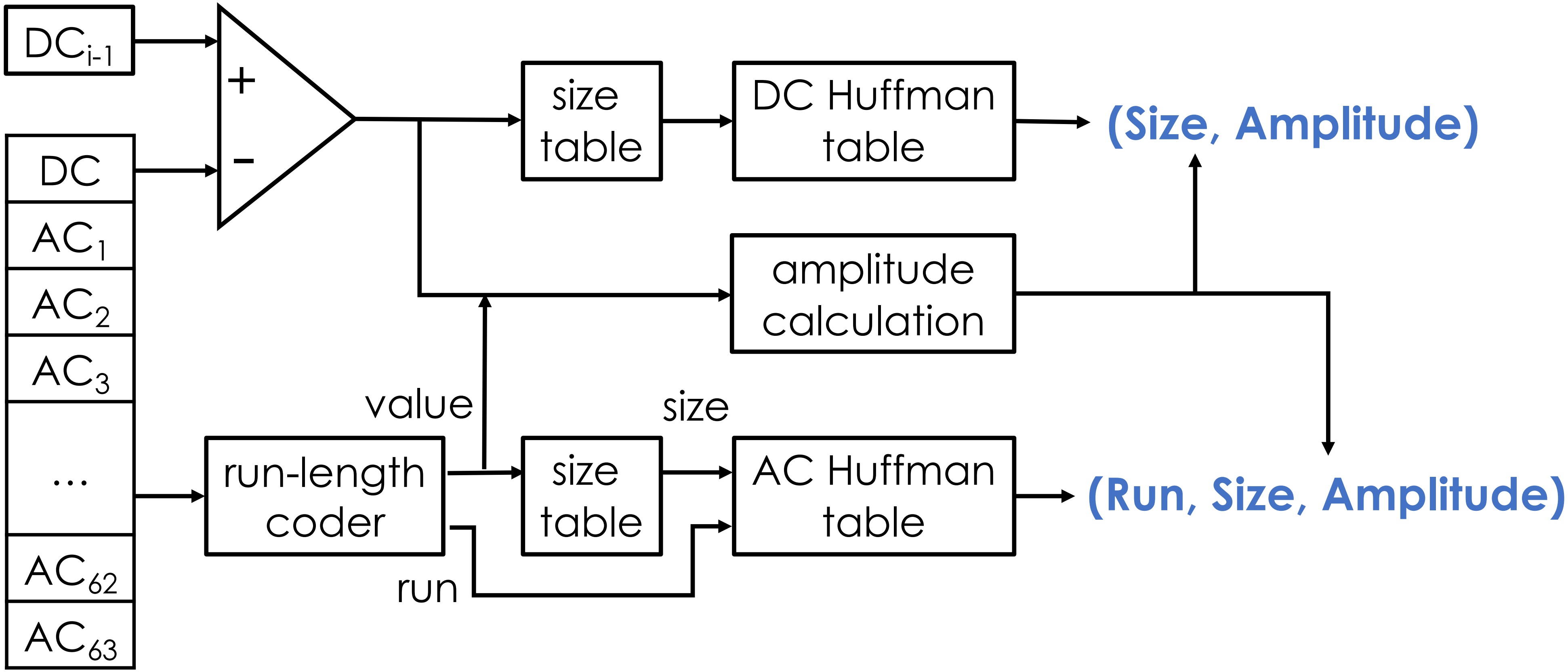
  5. Apply quantization
  6. Perform zigzag ordering
  7. DPCM for DC and run-length encoding for AC
  8. Perform Entropy coding

Entropy Coding

- Huffman coding or Arithmetic coding (less used)
- Huffman coder
  1. Find intermediate symbol sequence
  2. Convert the intermediate symbol sequence into the binary sequence using Huffman table
- DC → **(size, amplitude)**
  - **Size**: how many bits are needed to represent the coefficient (Huffman code, i.e., variable length code → frequent patterns need less bits)
  - **Amplitude**: actual binary bits (Not Huffman code, just convert the DC coefficient to 1's complement)
- AC → **(run, size, amplitude)**

Huffman Coding in JPEG



DCT coefficients are in zigzag order

Example of Sequential JPEG

- Original

52	55	61	66	70	61	64	73
63	59	66	90	109	85	69	72
62	59	68	113	144	104	66	73
63	58	71	122	154	106	70	69
67	61	68	104	126	88	68	70
79	65	60	70	77	68	58	75
85	71	64	59	55	61	65	83
87	79	69	68	65	76	78	94

- After level shift by -128

-76	-73	-67	-62	-58	-67	-64	-55
-65	-69	-62	-38	-19	-43	-59	-56
-66	-69	-60	-15	16	-24	-62	-55
-65	-70	-57	-6	26	-22	-58	-59
-61	-67	-60	-24	-2	-40	-60	-58
-49	-63	-68	-58	-51	-60	-70	-53
-43	-57	-64	-69	-73	-67	-63	-45

Example of Sequential JPEG

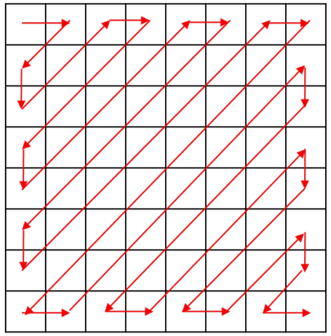
- After DCT

-415	-29	-62	25	55	-20	-1	3
7	-21	-62	9	11	-7	-6	6
-46	8	77	-25	-30	10	7	-5
-50	13	35	-15	-9	6	0	3
11	-8	-13	-2	-1	1	-4	1
-10	1	3	-3	-1	0	2	-1
-4	-1	2	-1	2	-3	1	-2
-1	-1	-1	-2	-1	-1	0	-1

- After quantization

-26	-3	-6	2	2	0	0	0
1	-2	-4	0	0	0	0	0
-3	1	5	-1	-1	0	0	0
-4	1	2	-1	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

Example of Sequential JPEG



- After zigzag scan

  -26 -3 1 3 -2 -6 2 -4 1 -4 1 1 5
  0 2 0 0 -1 2 0 0 0 0 0 -1 -1 EOB

- After DPCM of DC coefficient (assuming previous DC value of -17)

  -9 -3 1 3 -2 -6 2 -4 1 -4 1 1 5
  0 2 0 0 -1 2 0 0 0 0 0 -1 -1 EOB

- After RLC

  -9 (0, -3) (0, 1) (0, 3) (0, -2) (0, -6) (0, 2) (0, -4) (0, 1) (0, -4)
  (0, 1) (0, 1) (0, 5) (1, 2) (2, -1) (0, 2) (5, -1) (0, -1) EOB

- After VLC

  1010110 0100 001 0100 0101 100001 0110 100011 001
  100011 001 001 100101 11100110 110110 0110 11110100
  000 1010

Coefficient Coding

DC Category (SSSS)	AC Category (SSSS)	Coefficient
0	N/A	0
1	1	-1,1
2	2	-3,-2,2,3
3	3	-7,…,-4,4,…,7
4	4	-15,…,-8,8,…,15
5	5	-31,…,-16,16,…,31
6	6	-63,…,-32,32,…,63
7	7	-127,…,-64,64,…,127
8	8	-255,…,-128,128,…,255
9	9	-511,…,-256,256,…,511
10	10	-1023,…,-512,512,…,1023
11	11	-2047,…,-1024,1024,…,2047
12	12	-4095,…,-2048,2048,…,4095
13	13	-8191,…,-4096,4096,…,8191
14	14	-16383,…,-8192,8192,…,16383
15	N/A	-32767,…,-16384,16384,…,32767

DC Table

- For luminance

Size	length	code word
0	2	0 0
1	3	0 1 0
2	3	0 1 1
3	3	100
4	3	101
5	3	110
6	4	1110
7	5	11110
8	6	111110
9	7	1111110
10	8	11111110
11	9	111111110

- For chrominance

Size	length	code word
0	2	0 0
1	2	0 1
2	2	1 0
3	3	110
4	4	1110
5	5	11110
6	6	111110
7	7	1111110
8	8	11111110
9	9	111111110
10	10	1111111110
11	11	11111111110

AC Table

- For luminance

Run/Size	length	code word
0/0	4	1010 (EOB)
0/1	2	0 0
0/2	2	0 1
0/3	3	100
0/4	4	1011
0/5	5	11010
0/6	7	1111000
…	…	…
F/0	11	11111111001
…	…	…
F/A	16	1111111111111110

- For chrominance

Run/Size	length	code word
0/0	2	0 0 (EOB)
0/1	2	0 1
0/2	3	100
0/3	4	1010
0/4	5	11000
0/5	5	11001
0/6	6	111000
…	…	…
F/0	10	1111111010
…	…	…
F/A	16	1111111111111110

Example for AC Coding

- The sequences are: 0,0,0,0,0,0,-18
  - RLC = (6, 5, 01101) means *run* is 6, size 5, and amplitude 01101 (-18)
  - huffman coded for (6/5) is 1101, then the codeword for -18 is 110101101
- Special Cases:
  - The run length value may be larger than 15. In that case, JPEG uses the symbol (15/0) to denote a run-length of 15 zeros followed by a zero. Such symbol can be cascaded as needed; however, the codeword for the last AC must have a nonzero amplitude
  - If after a nonzero AC value all the remaining coefficients are zero, then the special symbol (0/0) denotes an end-of-block(EOB)

Outline

- Image concepts
- Lossless JPEG
- JPEG
- **Other JPEG Standards**

Operation Modes of JPEG

- Sequential DCT-based encoding
  - Image blocks are coded in a scan-like sequence, from left to right and from top to bottom
- Progressive DCT-based encoding
  - The coding is completed in multiple scan, the first scan yields the full image but without all the details, which are provided in successive scans.
  - Two procedures:
    - Spectral Selection (decoder side only)
    - Successive Approximation (codec)
- Lossless encoding
    - Predictive coding only
- Hierarchical encoding

Summary

- Image concepts
  - Different between analog and digital images
  - Waveforms of an image
- Lossless JPEG
  - Use *Differential Pulse Code Modulation (DPCM)* to reduce the size
- JPEG
  - Blocks and color subsampling
  - Convert each block to frequency responses using DCT
  - Quantization (matrix-based)
  - ZigZag ordering (try to collect 0s as a long list)
  - DPCM for DC and run-length coding for AC
  - Huffman coding (table lookup)
- Other JPEG Standards