JPEG 2000 Standard - Overview

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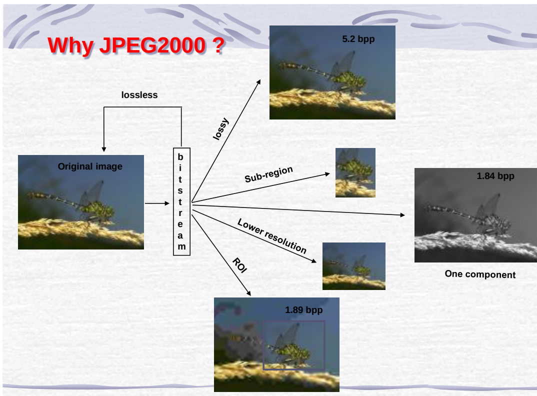
<Outline>

- *JPEG2000 Background & Overview*
- **Part I JPEG2000 Coding**
  - **Multi-Component Transform**
  - **Discrete Wavelet Transform (DWT)**
  - **Dead-Zone Quantization**
  - **Tier one coding**
    - **Bit Plane Coding (BPC)**
    - **Binary Arithmetic Coding (BAC)**
  - **Tier two coding**
  - **Bit-Rate Control**
  - **Region of Interest (ROI)**

Modes of current JPEG

- Sequential Lossless mode
  - decoded image is exact replica of the original
- Sequential DCT based mode
  - the simplest and widely used algorithm in this mode is the "Baseline JPEG"
- Progressive DCT based mode
  - encodes image in multiple scans
- Hierarchical Mode
  - encodes at multiple resolution

Why JPEG2000 ?

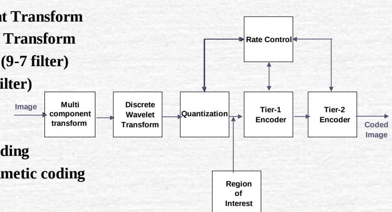


JPEG 2000 Standard

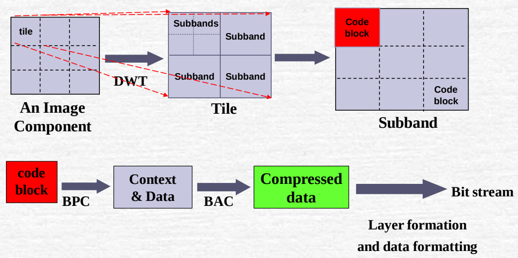
- **Part I : Core Coding System**
- **Part II : Extensions**
- **Part III : Motion JPEG 2000**
- **Part IV : Conformance Testing**
- **Part V : Reference Software**
- **Part VI : Compound image file format**
- **More parts are coming…**

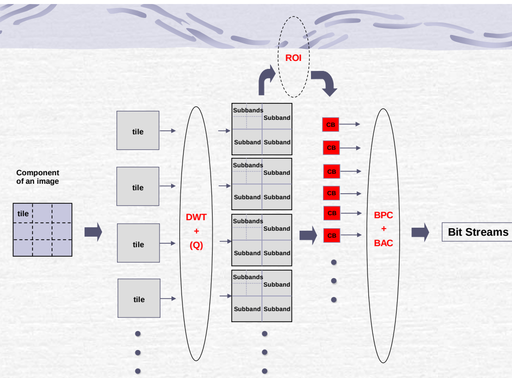
JPEG 2000 - Part I

- **Multi-Component Transform**
- **Discrete Wavelet Transform**
  - **Convolution (9-7 filter)**
  - **Lifting (5-3 filter)**
- **Quantization**
- **Tier-1 coding**
  - **Bit-Plane Coding**
  - **Binary Arithmetic coding**
- **Tier-2 coding**
  - **Tag-Tree coding**
  - **packet header**
- **Region of Interest (ROI)**
- **Bit-Rate control (open issue)**

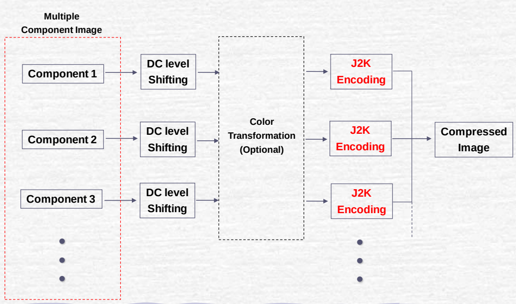


JPEG2000 Encoder Data Flow





Thinking Parallel ?



Parallelism Opportunities

- Processing component(s) in an image
- Processing tile(s) in a component
- Processing subband(s) in a tile
- Processing code block(s) in a subband

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Multi-Component Transform

- **Part I allows color transformation on first three components**
  - Reversible Color Transform (RCT)
  - Irreversible Color Transform (ICT)

Reversible Color Transform

$$Yr = \left\lfloor \frac{R+2G+B}{4} \right\rfloor$$
$$Ur = R - G$$
$$Vr = B - G$$

$$R = Ur + G$$
$$G = Yr - \left\lfloor \frac{Ur+Vr}{4} \right\rfloor$$
$$B = Vr + G$$

Irreversible Color Transform

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.16875 & -0.33126 & 0.5 \\ 0.5 & -0.41869 & -0.08131 \end{bmatrix} * \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1.0 & 0 & 1.402 \\ 1.0 & -0.34413 & -0.71414 \\ 1.0 & 1.772 & 0 \end{bmatrix} * \begin{bmatrix} Y \\ U \\ V \end{bmatrix}$$

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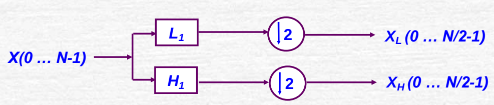
Discrete Wavelet Transform

- **Two procedures**
  - **Convolution based (9-7 filter)**
  - **Lifting based (5-3 filter)**
- **DWT is generally more intensive computationally compared to DCT**
- **Memory requirement is high**
- **Different filters exist**

Forward 1-D DWT

- **Analysis Filter Bank**
  - **The 1-D signal is separately filtered using one** *low-pass* **filter and one** *high-pass* **filter**
  - **Both the filtered output signals are decimated by a factor of two to produce** *low-pass* **and** *high-pass* **subbands.**

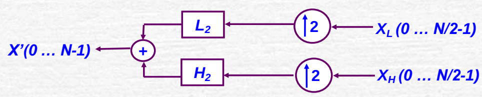


Example - Forward DWT

- **Analysis filters (5, 3):**
  - **Low pass filter L_1 : (-1 2 6 2 -1)/8**
  - **High pass filter H_1: (-1 2 -1)/2**
- **1-D Signal: … 10 10 10 10 20 20 20 20 …**
- **Filtered output before downsampling**
  - **… 10 10 8.75 11.25 18.75 21.25 20 20 …**
  - **… 0 0 0 -5 5 0 0 0 …**
- **Subbands after downsampling**
  - **X_L: … 10 11.25 21.25 20 …**
  - **X_H: … 0 0 5 0 …**

Inverse 1-D DWT

- Synthesis Filter Bank
  - Both the subbands are interpolated by inserting 0's in between two samples.
  - The interpolated low-pass subband is *low-pass* filtered and the interpolated high-pass subband is *high-pass* filtered.
  - Two filtered outputs are added



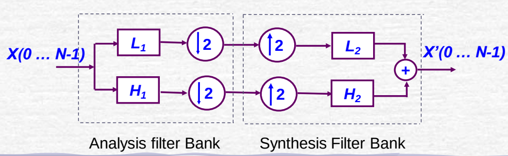
Example - inverse DWT

- Synthesis filters (5, 3):
  - Low pass filter L_2 : (1 2 1)/2
  - High pass filter H_2: (-1 -2 6 -2 -1)/8
- Interpolated subbands
  - … 0 10 0 11.25 0 21.25 0 20 …
  - … 0 0 0 0 5 0 0 0 …
- Filtered outputs
  - L_2: …10 10 10.625 11.25 16.25 21.25 20.625 20 …
  - H_2: … 0 0 -0.625 -1.25 3.75 -1.25 -0.625 0 …
- Reconstructed Signal:
  - … 10 10 10 10 20 20 20 20 …

Perfect Reconstruction Property

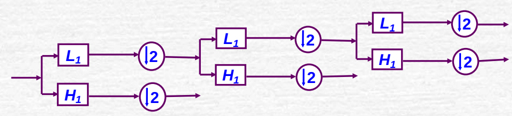
Ideally, the analysis filter pair (L_1, H_1) and the synthesis filter pair (L_2, H_2) are chosen to yield zero overall distortion, i.e.,

$$X(0 \ldots N-1) = X'(0 \ldots N-1).$$

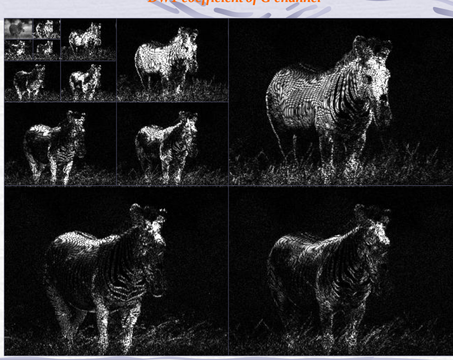


Dyadic DWT Decomposition

In multi-level dyadic decomposition, the analysis filter banks are successively applied to the low-pass subband to further decompose it into two subbands.



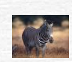
DWT coefficient of G channel



Decoded at different resolutions from the same bit-stream

3 Level DWT

2 Level DWT



1 Level DWT

Lifting scheme for DWT

- usually requires less computation and less memory
- can be adapted to integer-to-integer transform for lossless compression
- forward and backward transforms complexity are same
- does not require explicit signal extension at boundaries
- in-place computation

Lifting Algorithm

- **Split**: The input signal, x_k, is split into even and odd samples (*lazy DWT*)

$$s_k^0 \leftarrow x_{2k} \qquad d_k^0 \leftarrow x_{2k+1}$$

- **Lifting**: This is executed in *N* sub-steps as poly-phase filters

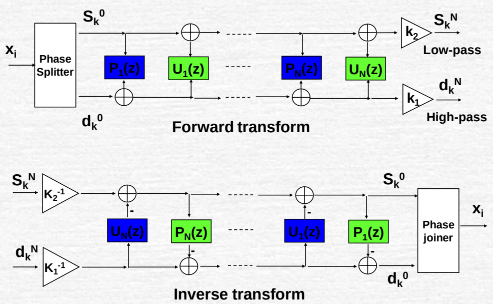
$$d_k^n \leftarrow d_k^{n-1} + \sum P_n(m).s_m^{n-1}, \quad n \in [1, 2, \ldots, N]$$

$$s_k^n \leftarrow s_k^{n-1} + \sum U_n(m).d_m^n, \quad n \in [1, 2, \ldots, N]$$

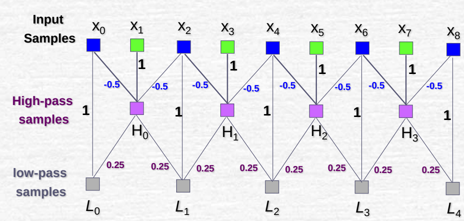
- **Normalization**: Final output is normalized as

$$s_k^N \leftarrow K_1\, s_k^N \qquad d_k^N \leftarrow K_2\, d_k^N$$

Lifting Block Diagram

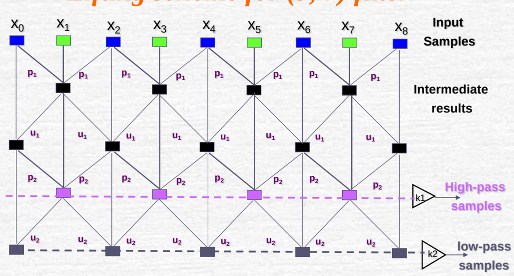


Lifting scheme for (5, 3) filter



$H_k = x_{2k+1} - [x_{2k} + x_{2k+2}]/2$ $\qquad L_k = x_{2k} + [H_{k-1} + H_k]/4$

Lifting scheme for (9, 7) filter



$p_1 = -1.586134342$, $u_1 = -0.052980118$, $k_1 = 1.230174104$

$p_2 = +0.882911075$, $u_2 = +0.443506852$, $k_2 = 1/k_1$

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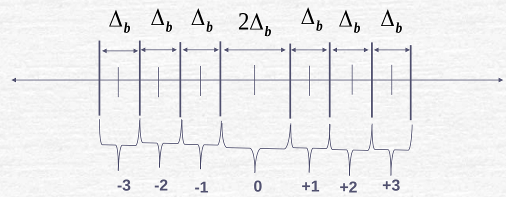
Quantization

- Uniform scalar quantization with deadzone
- No quantization in lossless mode
- Quantization rule:

$$q = sign(y)\left\lfloor \frac{|y|}{\Delta_b} \right\rfloor$$

Dead-Zone Quantization



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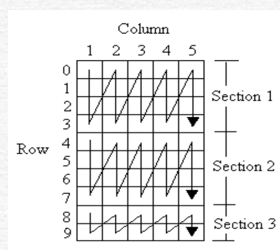
Tier-1 coding

- **Fractional Bit Plane Coding (BPC)**
- **Binary Arithmetic Coding (BAC)**

Bit Plane Coding (BPC)

- **'*Embedded Block Coding with Optimized Truncation*' (EBCOT) algorithm**
- **3 coding passes for each bit plane**
  - **Significance Propagation Pass (SPP)**
  - **Magnitude Refinement Pass (MRP)**
  - **Clean Up Pass (CUP)**
- **4 Coding operations**
  - **Zero Coding (ZC), Sign Coding (SC), Magnitude Refinement Coding (MRC), Run Length Coding (RLC)**
- **Output one or more (CX, D) where CX is a context and 'D' is a binary data.**

BPC – Fixed Scan Pattern



Example of scan pattern for a 5x10 code block

Sign-Magnitude Representation

Quantized DWT coefficients

4	-1	13	15
10	4	0	9
2	-5	14	7
11	8	-15	3

Sign $\chi[m,n]$

0	1	0	0
0	0	0	0
0	1	0	0
0	0	1	0

Magnitude $v^p[m,n]$

4	1	13	15
10	4	0	9
2	5	14	7
11	8	15	3

Significance

- **Each coefficient in a code-block has an associated *binary state variable* called its *significance state* $(\sigma[m,n])$.**
- **'*Significance states*' are initialized to 0 and may become 1 during the course of the coding of the code-block.**
- **Once the significance state for a bit position becomes 1, it stays 1 throughout the encoding of the codeblock.**

Significance Propagation Pass

- **Apply ZC to the samples if**
  - **the bit is in '*insignificant*' state *and***
  - **at least one of its eight neighbors is *significant*.**
- **Apply SC after above ZC if**
  - **the bit value is 1 *and***
  - **this is the most significant bit of the pixel**

Magnitude Refinement Pass

- **Apply MRC to the samples if**
  - **the sample has a bit value of 1 in any of the previous bit planes *and***
  - **the sample has not been encoded by SPP in the current bit plane**

Cleanup Pass

- **The samples that have not been coded in either SPP or MRP, in current bit plane, are coded in this pass.**
- **Apply RLC or ZC (w/ or w/o SC)**

Zero Coding Operation

- **'CX' is determined depending upon the significance state variables of the eight surrounding neighbors.**
- **'D' is equal to the bit value of the sample coefficient at the current location [*m*,*n*] at bit plane *p*.**

$$D = v^p[m,n]$$

Zero Coding Context Table

d	v	d
h	X	h
d	v	d

LL & LH subbands			
$\sum h$	$\sum v$	$\sum d$	CX
2	x	x	8
1	>=1	x	7
1	0	>=1	6
1	0	0	5
0	2	x	4
0	1	x	3
0	0	>=2	2
0	0	1	1
0	0	0	0

Note: HL & HH use different ZC context tables

Sign Coding Operation

- **'CX' is determined by a horizontal contribution value *H* and vertical contribution value *V*.**
- **Possible values of *H* & *V* are -1, 0, +1**
  - **0 implies both neighbors are insignificant or both are significant but has opposite signs**
  - **1 implies that one or both neighbors are significant and positive**
  - **-1implies that one or both neighbors are significant and negative**

Sign Coding (cont.)

H	V	$\hat{\chi}$	CX
1	1	0	13
1	0	0	12
1	-1	0	11
0	1	0	10
0	0	0	9
0	-1	1	10
-1	1	1	11
-1	0	1	12
-1	-1	1	13

$$D = \hat{\chi} \otimes \chi[m,n]$$

Magnitude Refinement Coding Operation

$\sum h + \sum v + \sum d$	First refinement for this coefficient	CX
x	false	16
>=1	true	15
0	true	14

$$D = v^p[m,n]$$

Run Length Coding Operation

The 'RLC' is invoked in place of 'ZC' iff the following conditions hold:

- **Four consecutive samples must have a zero significance state variable.**
- **All four samples must have identically zero neighborhood.**
- **The group of four samples must be aligned on the four-sample boundary within the scan.**

Run Length Coding (cont.)

- **Case 1 – all four bit values are zero**

  (CX, D) = (17, 0)
- **Case 2 – else send (17, 1) and two pairs**

  (CX, D) = (18, *x*)

  (CX, D) = (18, *y*)

where '*xy*' is the distance (in binary) of the first 1 bit in the 4 bit strip

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Binary Arithmetic Coding

- JPEG 2000 uses MQ coder with 19 different contexts generated by EBCOT.
- The data bit ‘D’ in a (CX, D) pair is coded by BAC, ‘CX’ is used to select the necessary Q value from the Q-table.
- A predetermined fixed probability estimation state machine is provided by the standard.

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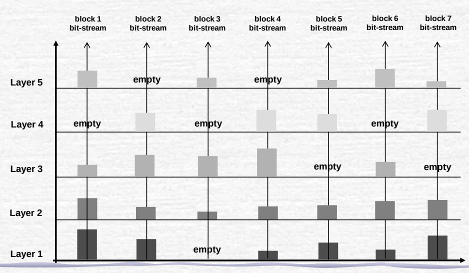
Tier-2 coding

- Bit Stream Formation
- Tag Tree Coding

Code-block contribution to bit-stream layers



Layer

- The coded data (bit-stream) of each “codeblock” is distributed across one or more layers in the code stream
- Each layer consists of some number of consecutive bit-plane coding passes from each codeblock in the tile, including all subbands of all components for that tile.

Resolution

- **Partition of subbands in one tile.**
- **(N_L +1) resolutions for N_L levels DWT decomposition.**

r = 0 : (N_L)LL subband only

r = 1 : (N_L)LH, (N_L)HL, (N_L)HH

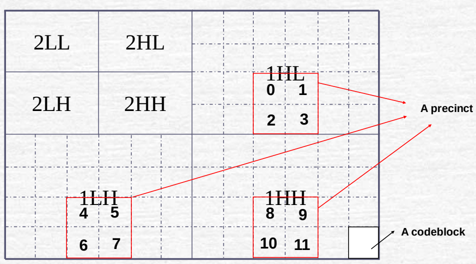
r : (N_L- r+1)LH, (N_L- r+1)HL, (N_L- r+1)HH

r = N_L: 1LH, 1HL, 1HH

Precinct

- **Partition in each resolution (formed in DWT domain).**
- **Power of 2 in size (line up with codeblock size boundary).**
- **Don’t cause block (tile) artifacts.**

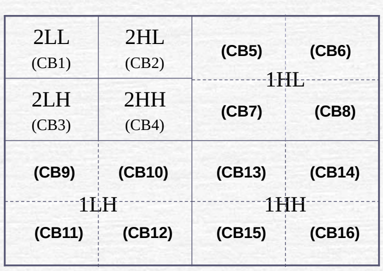
Precinct (cont’)



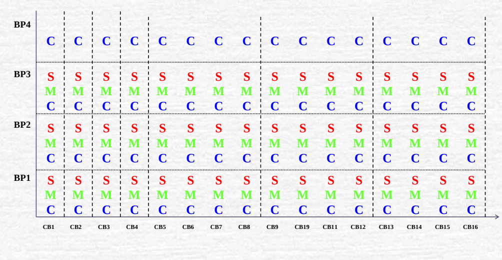
Progression Order

- **Layer-Resolution-Component-Precinct**
- **Resolution-Layer-Component-Precinct**
- **Resolution-Precinct-Component-Layer**
- **Precinct-Component-Resolution-Layer**
- **Component-Precinct-Resolution-Layer**

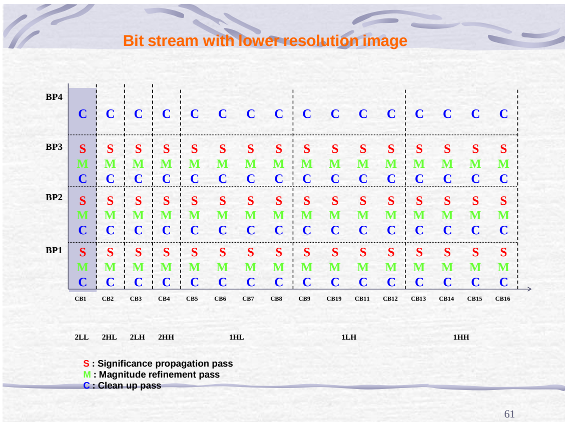
2 level DWT with 16 Code Blocks

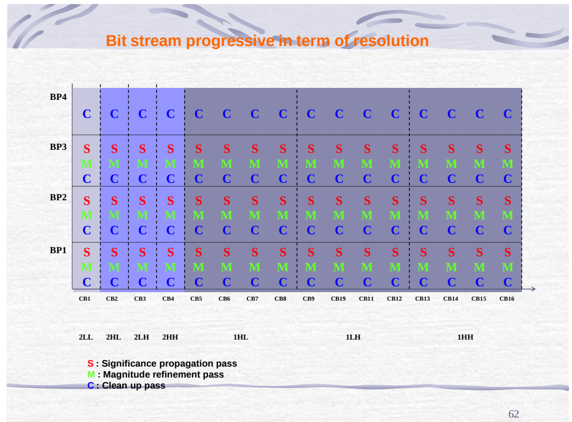


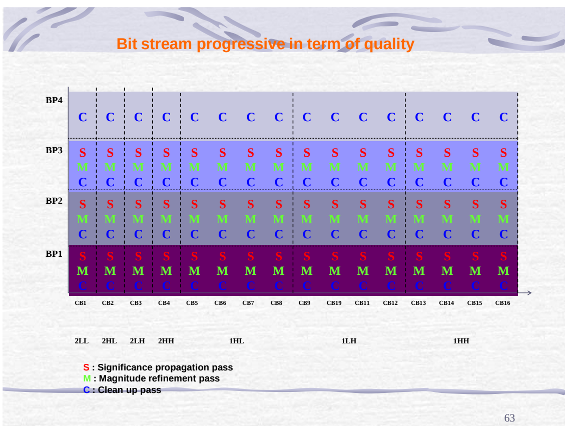
Assume maximum 4 Bit Planes for each Code Block



S : Significance propagation pass
M : Magnitude refinement pass
C : Clean up pass


Bit stream with lower resolution image
BP4
BP3
BP2
BP1
CB1 CB2 CB3 CB4 CB5 CB6 CB7 CB8 CB9 CB19 CB11 CB12 CB13 CB14 CB15 CB16
2LL 2HL 2LH 2HH 1HL 1LH 1HH
S : Significance propagation pass
M : Magnitude refinement pass
C : Clean up pass
61


Bit stream progressive in term of resolution
BP4
BP3
BP2
BP1
CB1 CB2 CB3 CB4 CB5 CB6 CB7 CB8 CB9 CB19 CB11 CB12 CB13 CB14 CB15 CB16
2LL 2HL 2LH 2HH 1HL 1LH 1HH
S : Significance propagation pass
M : Magnitude refinement pass
C : Clean up pass
62


Bit stream progressive in term of quality
BP4
BP3
BP2
BP1
CB1 CB2 CB3 CB4 CB5 CB6 CB7 CB8 CB9 CB19 CB11 CB12 CB13 CB14 CB15 CB16
2LL 2HL 2LH 2HH 1HL 1LH 1HH
S : Significance propagation pass
M : Magnitude refinement pass
C : Clean up pass
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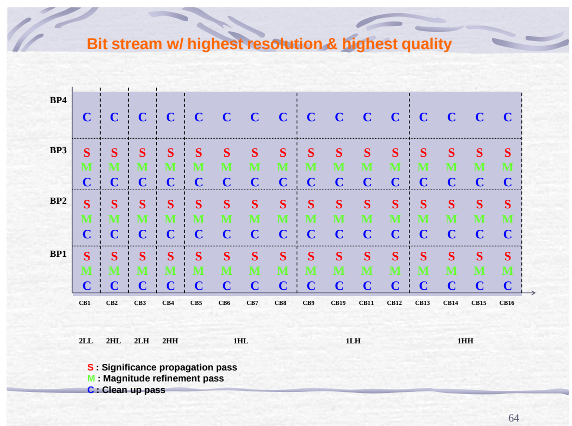
Bit stream w/ highest resolution & highest quality
BP4
BP3
BP2
BP1
CB1 CB2 CB3 CB4 CB5 CB6 CB7 CB8 CB9 CB19 CB11 CB12 CB13 CB14 CB15 CB16
2LL 2HL 2LH 2HH 1HL 1LH 1HH
S : Significance propagation pass
M : Magnitude refinement pass
C : Clean up pass
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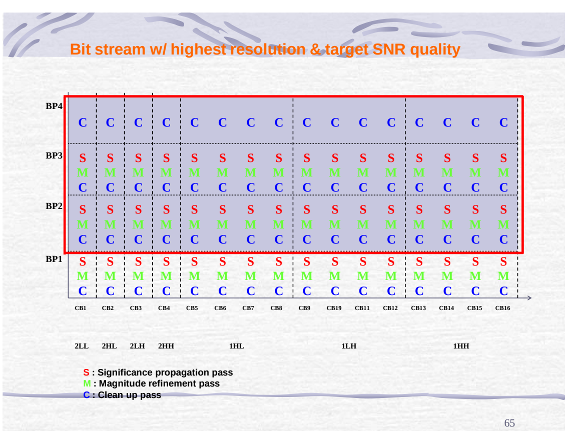
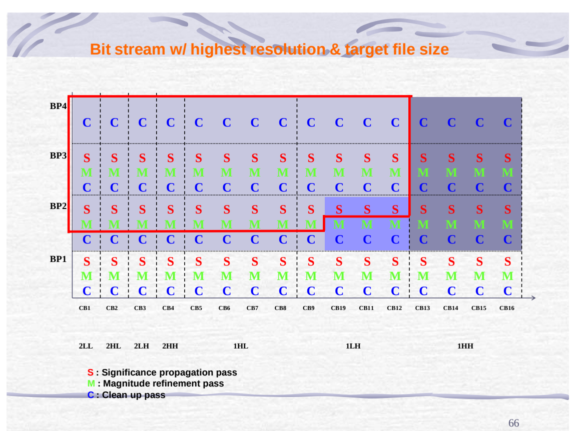

Bit stream w/ highest resolution & target SNR quality
BP4
BP3
BP2
BP1
CB1 CB2 CB3 CB4 CB5 CB6 CB7 CB8 CB9 CB19 CB11 CB12 CB13 CB14 CB15 CB16
2LL 2HL 2LH 2HH 1HL 1LH 1HH
S : Significance propagation pass
M : Magnitude refinement pass
C : Clean up pass
65


Bit stream w/ highest resolution & target file size
BP4
BP3
BP2
BP1
CB1 CB2 CB3 CB4 CB5 CB6 CB7 CB8 CB9 CB19 CB11 CB12 CB13 CB14 CB15 CB16
2LL 2HL 2LH 2HH 1HL 1LH 1HH
S : Significance propagation pass
M : Magnitude refinement pass
C : Clean up pass
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Tag Tree Coding

Tag Tree - Hierarchical representation of a 2D array of non-negative integer values, where successively reduced resolutions form a tree.

Usage in JPEG 2000 (to carry the following information)

- The bit-stream layers to which the code block contributes code words
- The length of these code words
- The most significant magnitude bit-plane at which any sample in the code block is non-zero
- The truncation point between the bit-stream layers

Basic Tag Tree Data Structure

1 $q_3(0,0)$	3 $q_3(1,0)$	2 $q_3(2,0)$	3 $q_3(3,0)$	2 $q_3(4,0)$	3 $q_3(5,0)$
2	2	1	4	3	2
2	2	2	2	1	2

Level 3 – leaf nodes $q_3(x,y)$ (original array of numbers)

1 $q_1(0,0)$	1

Level 1 – internal nodes $q_1(x,y)$

1 $q_2(0,0)$	1 $q_2(1,0)$	2 $q_2(2,0)$
2	2	1

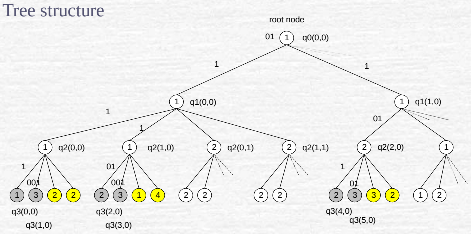
Level 2 – internal nodes $q_2(x,y)$

1 $q_0(0,0)$

Level 0 – root node $q_0(x,y)$

Basic Tag Tree Data Structure

Tree structure



Basic Tag Tree Data Structure

01111	001	101	001	1011	…
$(q_0(0,0),q_1(0,0),q_2(0,0))$ $q_3(0,0)$	$q_3(1,0)$	$(q_2(1,0))$ $q_3(2,0)$	$q_3(3,0)$	$(q_1(1,0),q_2(2,0))$ $q_3(4,0)$	…

Bit Stream generated

Tag Tree Usage in JPEG 2000

Two independent tag trees for each precinct, resolution level, tile and component:

- One for code block first inclusion
- One for number of all zero bit planes

<Outline>

- **JPEG2000 Background & Overview**
- **Part I JPEG2000 Coding**
  - **Multi-Component Transform**
  - **Discrete Wavelet Transform (DWT)**
  - **Dead-Zone Quantization**
  - **Tier one coding**
    - **Bit Plane Coding (BPC)**
    - **Binary Arithmetic Coding (BAC)**
  - **Tier two coding**
  - ***Bit-Rate Control***
  - **Region of Interest (ROI)**

Bit-Rate control

- **To meet a particular target bit-rate**
- **To assure the desired number of bytes is used by the code stream while assuring the highest image quality possible.**
- **Open issue**

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Post Processing Method

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Original image

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2.5 bpp with 4 Level DWT

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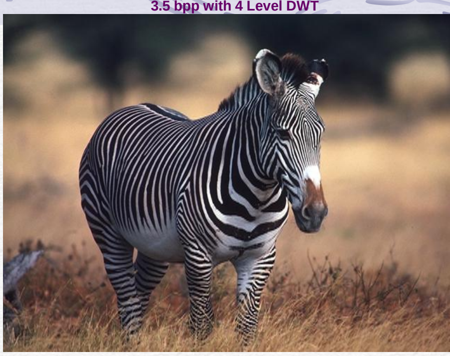
3.5 bpp with 4 Level DWT



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Compressed at 4.9 bpp with 4 level DWT

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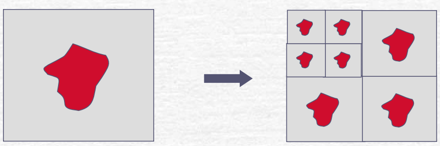
<Outline>

- JPEG2000 Background & Overview
- Part I JPEG2000 Coding
  - Multi-Component Transform
  - Discrete Wavelet Transform (DWT)
  - Dead-Zone Quantization
  - Tier one coding
    - Bit Plane Coding (BPC)
    - Binary Arithmetic Coding (BAC)
  - Tier two coding
  - Bit-Rate Control
  - *Region of Interest (ROI)*

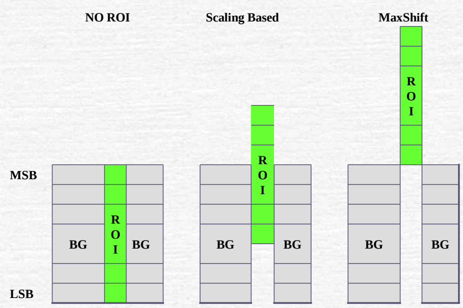
Region of Interest (ROI)

- A binary mask generated in the wavelet domain for distinction of ROI and background
- Max-Shift method (Part I)
- Scaling based (Part II)

ROI mask



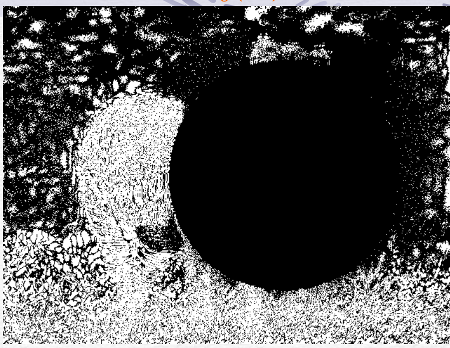
ROI



Original image

ROI Example using Max_Shift (encoded at 5.85 bpp)

Difference image (d > 5)



85

(5.7 bpp)

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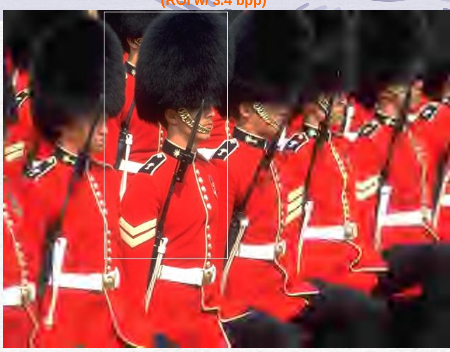
(ROI w/ 3.4 bpp)



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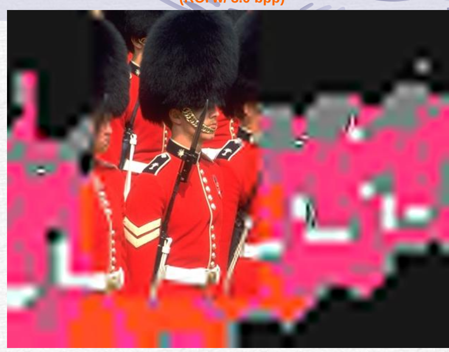
(ROI w/ 3.0 bpp)



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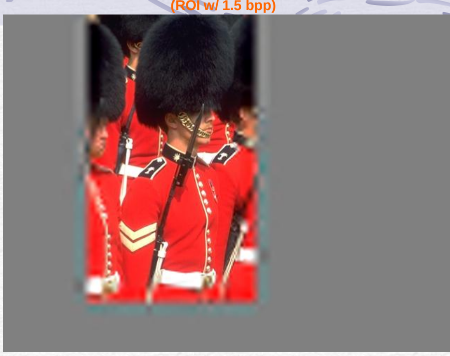
(ROI w/ 1.5 bpp)



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Implementation Challenges

- **Memory management**
- **Data pipeline**
- **Power consumption**
- **Complexity**

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