A Locally Adaptive Perceptual Masking Threshold Model for Image Coding

by

Trac Duy Tran

Submitted to the Department of Electrical Engineering and Computer Science in partial fulfillment of the requirements for the degrees of

Bachelor of Science

and

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Abstract

This project involved designing, implementing, and testing of a locally adaptive perceptual masking threshold model for image compression. This model computes, based on the contents of the original images, the maximum amount of noise energy that can be injected at each transform coefficient that results in perceptually distortion-free still images or sequences of images.

The adaptive perceptual masking threshold model can be used as a pre-processor to a JPEG compression standard image coder. DCT coefficients less than their corresponding perceptual thresholds can be set to zero before the normal JPEG quantization and Huffman coding steps. The result is an image-dependent gain in the bit rate needed for transparent coding. In an informal subjective test involving 318 still images in the AT&T Bell Laboratory image database, this model provided a gain on the order of 10 to 30%.

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Chapter 1

Introduction

Signal compression has long played a pivotal role in the technologies of long-distance communication, high-quality signal storage and message encryption. In spite of the recent promise of optical transmission media of relatively unlimited bandwidth, signal compression still remains a key technology because of our continued and increasing usage of bandlimited media such as radio, satellite links, and space-limited storage media such as solid-state memory chips and CD-ROM's. Signal compression has various applications, ranging from telephone speech, wideband speech, wideband audio, still images to digital video.

The foundations of signal compression date back to the exceptional work of Shannon in the field of information theory [16]. Shannon defined the information content of a source signal as its entropy, and mathematically showed that the source could be coded with zero error if the encoder used a transmission rate equal to or greater than the entropy, and a long enough processing delay. In particular, in the case of discrete-amplitude sources, the entropy is finite, and therefore the bit rate needed to achieve zero encoding error is also finite. We can take advantage of the statistical redundancy in the uncompressed signal to achieve a rate near or equal to the entropy.

However, there are inadequacies in this classical source coding theory. One of the most important is that the human receiver does not employ a tractable criterion such as the mean-squared error to judge the difference or similarity between the raw signal and the encoded signal. Therefore, a much more practical method of signal coding is
to match the compression algorithm to the human perceptual mechanism; in the case of image coding, the Human Visual System (HVS). This leads to the development of the Perceptual Coding field.

In Perceptual Coding, the ultimate criterion of signal quality from signal compression is that perceived by the human receiver. In other words, we can push the bit rates in the digital representations of the coded signals even lower by designing the compression algorithm to minimize the perceptually meaningful measures of signal distortion rather than the mathematical criteria used in traditional source coding. Although the idea of maximizing perceived image quality rather than minimizing mean-squared error has been known and practiced for a long time, significant progress in the field of Perceptual Coding can still be made thanks to a more thorough understanding of the human visual system, as well as more aggressive, more dynamic, and more sophisticated compression algorithms. Moreover, the capabilities of digital signal processing chips have increased dramatically recently to the point where the computational complexity of such algorithms can be supported in practical hardware.

This project involves designing and testing of a new locally adaptive model for calculating the perceptual masking threshold for the Human Visual System. This model can be applied to both still images or sequences of images. Also, the model will be compatible with different coder types, i.e. general enough to be easily incorporated into any existing DCT-based image coders. A simple linear mapping with the cortex bands can also make the model compatible with other transform coders.
Chapter 2

A Review of Important Human Visual System Properties

A simplified model of the Human Visual System (HVS) is depicted in Figure 2-1 [3].

The lowpass filter in the first box represents the optical properties of the pupil. The nonlinearity helps the eye to be able to perceive a very large range of intensities. This nonlinearity is usually modeled as a logarithmic, or other similar, function. The highpass filter attempts to model the spatial response of the eye due to the interconnection of the numerous receptor regions of the retina.

The Human Visual System possesses two well-known properties that perceptual image coders have exploited. They are frequency response and texture masking.

Figure 2-2 on the following page depicts the frequency sensitivity of the Human Visual System. In general, the HVS acts as a peaky lowpass system. Therefore, features with high spatial frequency content require higher energy than low spatial frequency features to be visible. Special care will be given to the lower frequency region because this is where most of the image information is concentrated. Most of

![Figure 2-1: A Simple Model of the Human Visual System (HVS).](image)

9
the early work has taken advantage of the HVS’s frequency sensitivity as described by the modulation transfer function (MTF) [2]. This function describes the HVS’s response to sine wave gratings at various frequencies.

However, if the thresholds are obtained only from the base sensitivity of the HVS, they are certainly very conservative approximations because the fact that human eyes are far more sensitive to noise in flat fields than in textured regions has not been taken into account. But first, let’s try to answer the simple question: what is texture?

For the purpose of this project, texture can be defined as any deviation from a flat field. An image which contains a lot of texture energy is definitely not smooth. In other words, in an image region with a lot of texture, many pixels have dramatically different values.

A simple example depicted in Figure 2-3 can help clarify the HVS response to texture masking. A flat field as Region B is defined to have no texture at all. Region C has some texture, and Region A has a lot of texture energy. If a fixed amount of uniform white noise is injected into both images, the noise will be easiest to detect
Another question about the HVS that must be answered is: what is masking? Simply, masking is just the change of visibility or detectability of a signal because of the presence of another signal in the same spatial frequency locality. As previously observed from the two images in the texture example (see Figure 2-3), all the white noise can be partially masked by the somewhat moderate texture in Region C, or totally masked by the heavy texture in Region A.

Besides the frequency and texture sensitivity, the HVS is also known to be more sensitive to noise at mid-grey level than at darker or lighter grey levels. Noises at the two ends of the pixel spectrum are more difficult for the eye to detect [8]. This is called the HVS contrast sensitivity. A more detailed and complete description of the Human Visual System's behavior can be found in Cornsweet [4].
Chapter 3

Brief Summary of Previous Related Work

3.1 Common Methodology

There has been considerable work done in the field of Perceptual Coding by engineers and researchers in the past [8]. The most common perceptual coding methodology is described in Figure 3-1 [8]. This methodology not only provides the framework for perceptually lossless coding at the lowest possible bit rate for common coding algorithms, but can also provide a framework for perceptually optimum performance given a certain bit rate constraint (in other words, when the available bit rate is lower than the one needed to provide transparent compression).

In the first stage of this process, a short-term or spatio-temporally local analysis of the input image is performed. In this stage, important properties of the image, such as its frequency, intensity, texture and temporal activities, are measured. These local properties are then used in the second stage of the process where the perceptual distortion thresholds are estimated. These thresholds can be a function of space or frequency, depending on the type of the coder. They are called the just-noticeable distortion profile (JND) or the minimally-noticeable distortion profile (MND). If the distortion or noise introduced by the compression algorithm is at or below these thresholds at all points in the space or frequency domain, the output image is guar-
Anteed to be perceptually distortion-free. After the JND or MND profile calculation, the rest of the process is relatively straightforward. The coding algorithm uses the JND profile to introduce distortion accordingly, and this leads to minimizing the bit rate for a given image quality level or maximizing the quality level given a certain bit rate.

3.2 Image-Independent Approach

This is a very common and popular image coding method. In this approach, the JND or MND profiles are calculated independently of the images. The HVS's sensitivity to texture is not taken into account. The most popular system using this approach is the JPEG standard, which features 8x8 block-size DCT coding.

In the JPEG standard, the image is divided into 8x8-pixel blocks. Each block is then transformed to 64 DCT coefficients $I_{m,n}$. Each coefficient block is then quantized by dividing it element-wise by a quantization matrix $QM$ with each entry labeled as $Q_{m,n}$, and rounding to the nearest integer: $U_{m,n} = \text{Round} \left[ I_{m,n}/Q_{m,n} \right]$. In DCT domain, the resulting quantization error is: $E_{m,n} = I_{m,n} - U_{m,n}$. In this approach, researchers measure threshold $T_{m,n}$, or in other words, the JND profiles psychophysically. Since the maximum possible quantization error is half of the step-size $Q_{m,n}/2$, the image-independent approach can ensure that all the errors are below the thresh-
olds, and hence invisible, by setting: $Q_{m,n} = 2T_{m,n}$. Details of how to design such a quantization matrix are presented in the next chapter. Finally, all the quantized coefficients $U_{m,n}$ from all of the blocks are then passed through an entropy coder to become compressed image data. See Wallace [18] for more details on JPEG.

### 3.3 Image-Dependent Approach

The image-dependent approach exploits the HVS's contrast and texture sensitivity. Some models based on this technique have been developed and employed by Watson [20], Daly [5], and Legge and Foley [9]. In this section, the author chooses to concentrate only on the models developed and used at AT&T Bell Laboratory at Murray Hill, where he practiced his engineering internship.

There are two perceptual masking threshold models already existing at AT&T Bell Labs. The first one is incorporated in Safranek and Johnston's Perceptually Based Sub-Band Image Coder [15]. The second one is developed by Mathews. It is called A Perceptually Masking Threshold Model for Multichannel Image Decompositions [12].

#### 3.3.1 Safranek and Johnston's Model

This perceptual masking threshold model is simple; it only provides an approximate description of the HVS. However, it appears to work very well in practice. This model is composed of three separate components, utilizing the aforementioned well-known properties of the HVS. See [15] for a more complete description of the model.

To obtain the base sensitivity profile, Safranek and Johnston carried out numerous perceptual experiments using three trained subjects. A square of uniformly distributed random noise of known energy was added to the center of a synthetic image with mid-grey level (most sensitive to noise). Then, for each sub-band, the noise was adjusted until the subjects could not reliably determine whether the reconstructed image contained the noise square or not. Since the experiments were carried out under the most severe viewing conditions, i.e. using a stimulus that is most sensitive for the human eyes, this base model provided an overly conservative estimate of the
perceptual threshold.

The base thresholds were then adjusted based on each input image's local properties. Since the HVS is more sensitive to noise at mid-grey than at lighter or darker grey levels, the thresholds were adjusted accordingly with the brightness of each input image's block. Again, subjective perceptual experiments were carried out to obtain a brightness correction curve for each sub-band. Since all these curves were similar, one brightness correction curve was utilized for all sub-bands.

The next components of the model dealt with texture masking adjustments. Texture energy was estimated by the average value of the AC energy over each analysis block in each sub-band. Then, depending on the texture energy present, a correction factor was assigned for the particular analysis block.

Obviously, this model is not locally adaptive enough. It is only adaptive block by block. In other words, all 64 transform coefficients share one common texture correction factor. Also, the masking energy measurement is also crude and inaccurate.

### 3.3.2 Mathews' Perceptual Masking Threshold Model for Multichannel Image Decompositions

Mathews [12] took a similar approach in designing his perceptual masking threshold model. This model consists of two components: (1) A base threshold model that does not take into account the response of the eye to the spatial details of the input image, but only describes the minimum possible threshold value for each channel, and (2) a threshold elevation model that describes how these base threshold values get elevated by the spatial details of the input image.

Mathews' base threshold model was similar to Safranek and Johnston's base sensitivity profile. His major contributions came from the threshold elevation model. Mathews observed that the threshold of detection at radial frequency $f$ can be raised by the presence of another signal component at frequency $f'$ depending on the following factors:

1. The ratio of the frequencies $\frac{f'}{f}$
2. The relative orientation of the two frequencies

3. The contrast (or the intensity) of the masking signal.

Based on these observations, Mathews classified the frequency coefficients into radial bands. For each radial band, he calculated the threshold elevation factor proportionally to the log of the texture energy in that band:

\[
\text{threshold elevation factor} = \log_2(2 + \alpha \text{ masking energy})
\]

where \(\alpha\) was a constant that could be tuned to be just right through subjective testing.

The final threshold was then obtained as a product of the base threshold values calculated from the first component with the threshold elevation factor calculated in the second component.

This model outperformed Safranek and Johnston’s model. It predicted the amount of undetectable distortion that could be injected into the lower frequency radial band reasonably well. With perceptually distortion free output images, Mathews’ model provided much larger threshold values. However, it still leaves a lot of room for improvement. The model does not seem to perform as well at higher frequency bands. Also, the model is still not locally adaptive enough. All the frequency coefficients in the same radial frequency band have the same threshold elevation factor.
Chapter 4

The Peterson-Ahumada-Watson Threshold Model

This threshold model accounts for the HVS's frequency and contrast sensitivity, but not texture sensitivity. It is implemented from the detection model presented in Peterson, Ahumada, and Watson [13]. This detection model is developed to predict visibility thresholds for DCT coefficient quantization error, based on the viewing conditions and the modulation transfer function. This detection model serves as an excellent base model since it is image-independent, and is designed for various display conditions, as well as for compression in different color space. The model takes into account different pixel sizes, different viewing distances, and also different display luminances.

The thresholds are first computed in YOZ color space [13]. A simple transformation can provide the equivalent quantization matrices in other color spaces. In this project, the $YC_6C_b$ color space is of primary interest because this is the color space utilized in digital television systems.
4.1 Quantization Matrix Design in YOZ Color Space

From various visibility threshold contrast ratio measurements, Peterson et al approximates that the luminance threshold of the $m$, $n$th DCT coefficient is given by:

$$\log T_{L,m,n} = \log \frac{s b_L}{r_L + (1 - r_L) \cos^2 \theta_{m,n}} + k_L (\log f_{m,n} - \log f_L)^2$$

(4.1)

with $m, n = 0, \ldots, N - 1$.

The log of the luminance threshold is approximated by a parabola in log spatial frequency. The spatial frequency, $f_{m,n}$, associated with the $m$, $n$th DCT coefficient, is given by:

$$f_{m,n} = \frac{1}{2N} \left( \frac{m}{W_x} \right)^2 + \left( \frac{n}{W_y} \right)^2$$

(4.2)

where $W_x$ and $W_y$ are the horizontal and vertical size of a pixel in degrees of visual angle respectively. $W_x$ and $W_y$ can be calculated by the following relations:

$$W_x = \frac{\alpha_H}{\text{number of horizontal pixels}}, \text{ and } W_y = \frac{\alpha_V}{\text{number of vertical pixels}}$$

(4.3)

where $\alpha_H$, defined as the horizontal visual angle in degrees, and $\alpha_V$, the vertical visual angle, are computed as a function of the viewing distance $VD$ measured as multiple of image heights (see illustration in Figure 4-1):

$$\alpha_H = 2 \cdot \text{Radian-to-Degree} \left( \arctan \frac{\text{image_width/image_height}}{2VD} \right)$$

(4.4)

and

$$\alpha_V = 2 \cdot \text{Radian-to-Degree} \left( \arctan \frac{0.5}{VD} \right)$$

(4.5)

The angular parameter, which accounts for the HVS orientational dependency, is given by:

$$\theta_{m,n} = \begin{cases} 0.0, & m = n = 0 \\ \arcsin \frac{2f_{m,n} f_L}{f_{m,n}^2}, & \text{otherwise} \end{cases}$$

(4.6)
Figure 4-1: Calculation of visual angle $\alpha$. 
Table 4.1: Parameter Values for Peterson et al's Base Model.

The factor $r_{OZ} + (1 - r_{OZ}) \cos^2 \theta_{m,n}$ is to account for the summation-obliqueness effect of the Fourier components. The magnitude of this effect is controlled by the parameter $r_L$. Based on the fourth power summation rule for the two Fourier components [1], $r_L$ is set to 0.6. The minimum luminance threshold $s b_L$, occurring at spatial frequency $f_L$, and the remaining parameter $k_L$ determines the steepness of the luminance parabola. The parameter $0.0 < s < 1.0$ accounts for visual system summation of quantization errors over a spatial neighborhood.

Similar measurements were carried out for the chrominance channels, and the resulting log chromatic thresholds for the $m, n$th DCT basis function are given by:

$$\log T_{O,m,n} = \begin{cases} 
\log \frac{s b_O}{r_{OZ} + (1 - r_{OZ}) \cos^2 \theta_{m,n}}, & \text{if } f_{m,n} \leq f_{OZ} \\
\log \frac{s b_O}{r_{OZ} + (1 - r_{OZ}) \cos^2 \theta_{m,n}} + k_{OZ} (\log f_{m,n} - \log f_{OZ})^2, & \text{if } f_{m,n} > f_{OZ}.
\end{cases}$$

and

$$\log T_{Z,m,n} = \begin{cases} 
\log \frac{s b_Z}{r_{OZ} + (1 - r_{OZ}) \cos^2 \theta_{m,n}}, & \text{if } f_{m,n} \leq f_{OZ} \\
\log \frac{s b_Z}{r_{OZ} + (1 - r_{OZ}) \cos^2 \theta_{m,n}} + k_{OZ} (\log f_{m,n} - \log f_{OZ})^2, & \text{if } f_{m,n} > f_{OZ}.
\end{cases}$$

All of the parameters used to implement this new base threshold model are listed in Table 4.1. $Y_o = 41.19$ and $Z_o = 29.65$ are the CIE values of average white (D65).
4.2 Conversion of Quantization Matrix to $YC_rC_b$ Color Space

As described in the previous section, the thresholds in color space YOZ can be calculated from Equations 4.1, 4.7, and 4.8, the pixel sizes $W_x, W_y$, and the parameters given in Table 4.1. These thresholds can be transformed to the $YC_rC_b$ color space in the following way.

The transformation can be thought of as limiting the errors in each of the channels $Y, C_r, C_b$ such that the resulting errors in the $Y, O, Z$ channels are all below the previously calculated thresholds. The linear transformation matrix $M_{Y', C_r, C_b\rightarrow YOZ}$ relates the errors in the two color spaces. For example, a unit error in a DCT coefficient in channel $C_r$ induces errors of magnitude $|M_{2,1}|, |M_{2,2}|, \text{ and } |M_{2,3}|$ in the $Y, O, Z$ channels respectively:

$$M_{Y', C_r, C_b\rightarrow YOZ} = \begin{bmatrix} M_{1,1} & M_{1,2} & M_{1,3} \\ M_{2,1} & M_{2,2} & M_{2,3} \\ M_{3,1} & M_{3,2} & M_{3,3} \end{bmatrix}$$  \hspace{1cm} (4.9)$$

The transformation matrix from color space $Y', C_r, C_b$ to color space YOZ is given below. $Y'$ is used to help clear up the notational confusion only.

$$M_{Y', C_r, C_b\rightarrow YOZ} = \begin{bmatrix} 66.9 & -1.1 & 48.2 \\ -17.8 & 17.1 & -4.5 \\ -7.0 & 0.6 & 67.9 \end{bmatrix}. \hspace{1cm} (4.10)$$

The YOZ model thresholds are then converted to the $Y'$ threshold. $T_{Y'\rightarrow Y', m,n}$ is the threshold imposed on channel $Y'$ by the threshold of channel $Y$.

$$T_{Y'\rightarrow Y', m,n} = \frac{T_{Y, m,n}}{|M_{1,1}|}, \quad T_{O'\rightarrow Y', m,n} = \frac{T_{O, m,n}}{|M_{1,2}|}, \text{ and } T_{Z'\rightarrow Y', m,n} = \frac{T_{Z, m,n}}{|M_{1,3}|}. \hspace{1cm} (4.11)$$
Similarly,

\[ T_{Y \rightarrow C_r,m,n} = \frac{T_{Y,m,n}}{|M_{2,1}|}, \quad T_{O \rightarrow C_r,m,n} = \frac{T_{O,m,n}}{|M_{2,2}|}, \quad \text{and} \quad T_{Z \rightarrow C_r,m,n} = \frac{T_{Z,m,n}}{|M_{2,3}|}. \] (4.12)

\[ T_{Y \rightarrow C_b,m,n} = \frac{T_{Y,m,n}}{|M_{3,1}|}, \quad T_{O \rightarrow C_b,m,n} = \frac{T_{O,m,n}}{|M_{3,2}|}, \quad \text{and} \quad T_{Z \rightarrow C_b,m,n} = \frac{T_{Z,m,n}}{|M_{3,3}|}. \] (4.13)

Then the minimum rule is used to decide the final thresholds. The minimum rule ensures the most conservative approximations of the visible quantization errors.

\[ T_{Y',m,n} = \min \{ T_{Y \rightarrow Y',m,n}, T_{O \rightarrow Y',m,n}, T_{Z \rightarrow Y',m,n} \}, \] (4.14)

\[ T_{C_r,m,n} = \min \{ T_{Y \rightarrow C_r,m,n}, T_{O \rightarrow C_r,m,n}, T_{Z \rightarrow C_r,m,n} \}, \] (4.15)

\[ T_{C_b,m,n} = \min \{ T_{Y \rightarrow C_b,m,n}, T_{O \rightarrow C_b,m,n}, T_{Z \rightarrow C_b,m,n} \}, \] (4.16)

The final quantization matrix entries in \( Y'C_rC_b \) space are obtained by dividing the new thresholds by the DCT normalization constants \( \alpha \) (given in Equation 5.2):

\[ Q_{Y',m,n} = \frac{T_{Y,m,n}}{\alpha_m \alpha_n}, \quad Q_{C_r,m,n} = \frac{T_{C_r,m,n}}{\alpha_m \alpha_n}, \quad Q_{C_b,m,n} = \frac{T_{C_b,m,n}}{\alpha_m \alpha_n}. \] (4.17)

Actually, in this project, since we are interested in the base threshold value, i.e. the maximum tolerable quantization error, we only have to compute the quantity \( \frac{T_{m,n}}{\alpha_m \alpha_n} \). The factor 2 in Equation 4.17 refers to the obvious fact that the maximum possible quantization error is half the quantizer's step size. See [13] for a more detailed discussion on this base model.

### 4.3 Implementation of Base Thresholds for CIF Images

Since the test images or sequences are available in CIF standard, we have to implement the Peterson-Ahumada-Watson base threshold model accordingly. The implementation is almost exactly the same as described in the previous two sections of the
chapter. There are only a few minor changes.

CIF standard images are in Y'Cr,Cb color space, but the two chrominance channels are down-sampling by a factor of 2. For display, the chrominance channels are then up-sampled, (while the luminance channel stays the same), and the whole image is converted to RGB space. All the CIF standard images have dimension 360x240. Therefore, the chrominance channels have dimension 180x120.

For the luminance channel we have the full number of pixels in both dimensions. For a fixed viewing distance, this translates to a value for $\alpha$ as demonstrated in Figure 4-1. From this value of $\alpha$, we can calculate the corresponding $W_x$ and $W_y$ for the luminance channel. However, for chrominance channels, we have the same viewing conditions, hence the same value of $\alpha$, but the chrominance channels have been down-sampled by a factor of 2 in both dimensions. This means we only have half the number of pixels which results in $W_x$ and $W_y$ for the chrominance channel being double the luminance values. The base weights computed for a viewing distance of 3 image heights for CIF images in color space Y'Cr,Cb are given in Table 4.2 in the following page.

In order to make the base model design more robust, several modifications were added. The first modification accounts for the dependence of the detection thresholds on viewing distance. The aforementioned design procedure is performed for the minimum given viewing distance. The viewing distance is then increased, and the thresholds are recomputed. The output thresholds are now set to the minimum of the two calculated thresholds, and the procedure is repeated until a certain maximum viewing distance is reached. The iteration ensures that there is no visible distortion at any viewing distance greater than the minimum.

The second modification is to account for the dependence of the detection thresholds on viewing condition. It is implemented in a similar fashion. In this case, for each iteration, instead of increasing the viewing distance, a new set of white point is installed (by changing the $Y_0$ and $X_0$ values in Table 4.1). The final output thresholds are set to the minimum of all the thresholds computed from all the white points.
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Table 4.2: Base weights for CIF images in $Y' C_r C_b$ color space (for VD=3).
Chapter 5

Mapping of DCT coefficients on the Cortex Filters

In perceptual image coding, the choice of the filterbank which has the HVS’s structure is very important to the performance of the compression system. The DCT (Discrete Cosine Transform) does not meet this crucial criterion. This leads to difficulty in creating an effective masking model for DCT-based coder since there is a mismatch between the underlying structure of the model and the structure of the DCT. The algorithm presented in this chapter maps the DCT transform coefficients onto the Cortex transform filters, which mimics the the visual system’s structure [19]. The mapping helps to decide which DCT coefficients contribute how much energy to which Cortex transform’s critical bands. This is a pivotal component of the perceptual masking threshold model since it provides the model’s local adaptability, and it solves the aforementioned mismatch problem.

5.1 The Discrete Cosine Transform

The DCT has recently become a standard method of image compression. The JPEG, MPEG, and CCITT H.261 image compression standards all employ the DCT as a basic mechanism. In the Forward DCT, the image pixels are divided into 8x8 blocks; each block is then transformed into 64 DCT coefficients. The DCT transform
coefficients $I_{m,n}$ of an $N \times N$ block and its image pixels $i_{j,k}$ are related by the following equations:

$$I_{m,n} = \sum_{j=0}^{N-1} \sum_{k=0}^{N-1} i_{j,k} c_{j,m} c_{k,n}, \quad \text{with } m, n = 0, \ldots, N - 1,$$

(5.1)

where

$$c_{j,m} = \alpha_m \cos \left( \frac{\pi m}{2N} [2j + 1] \right), \quad \text{and } \alpha_m = \begin{cases} \sqrt{1/N}, & m = 0 \\ \sqrt{2/N}, & m > 0 \end{cases}$$

(5.2)

and

$$i_{j,k} = \sum_{m=0}^{N-1} \sum_{n=0}^{N-1} I_{m,n} c_{j,m} c_{k,n}, \quad \text{with } j, k = 0, \ldots, N - 1,$$

(5.3)

The coefficient with zero frequency in both dimensions $m, n$ is called the DC coefficient; the remaining 63 coefficients are called the AC coefficients.

The DCT is closely related to the Discrete Fourier Transform (DFT). If the 8x8-pixel block is flipped and replicated in such a way that the new 16x16-pixel block is symmetric as demonstrated in Figure 5-1, the 16x16-point DFT of the new image block are very closely related to the 8x8-point DCT [10]. The general framework is
shown below:

\[
N \times N i_{j,k} \leftrightarrow 2N \times 2N y_{j,k} \xrightarrow{DFT} 2N \times 2N Y_{m,n} \leftrightarrow N \times N I_{m,n},
\]

where the relation between \( Y_{m,n} \) and \( I_{m,n} \) is given by:

\[
I_{m,n} = e^{-j\frac{\pi}{N}\frac{m}{2}} e^{-j\frac{\pi}{N}\frac{n}{2}} Y_{m,n}.
\] (5.4)

The above relation ensures the mapping's validity since the cortex transform is also performed in DFT domain with symmetrically replicated data.

### 5.2 The Cortex Transform

The Cortex transform was first introduced by Watson as a rapid computation of simulated neural images [19]. It was later modified and used by Daly in his visible differences predictor (VDP) [5]. The Cortex transform originates from researches in neurophysiology [7] [6] and psychophysical studies in masking [2] [17]. These studies have found a radial frequency selectivity that is essentially symmetric on a log frequency axis with bandwidths nearly constant at one octave. Furthermore, these studies also discovered that the HVS's orientation selectivity is symmetric about a center peak angle with tuning bandwidths varying as a function of radial frequency, ranging from 30 degrees for high frequencies to 60 degrees for low frequencies [14]. These familiar properties of the HVS were also noted and exploited by Mathews [12] in his previously mentioned masking model design.

The frequency selectivity of the HVS was modeled by Watson, and then modified by Daly, as a hierarchy of filters called the *Cortex filters*. The radial selectivity and orientational selectivity in the Cortex transform are modeled with separate classes of filters that are cascaded to give the combined radial and orientational selectivity of the HVS. Note that this is only an attempt to approximate the human visual system. By splitting the original image spectrum into many spatial images with the Cortex filters, we can model the space-frequency localization aspects of the HVS.
The Cortex transform, named after the striate cortex where neurons demonstrating the radial and orientational effects are found, is picked because it proves to model the HVS very accurately as demonstrated in Daly’s Visible Differences Predictor. Moreover, the cortex transform is reversible, flexible, and also easy to implement. Its disadvantages, such as non-orthogonality and computational complexity, do not concern us since we do not have the perfect-reconstruction constraint, and we only have to run the mapping algorithm once. Once the mapping has been found out, the result can be used for all DCT blocks.

The cortex filters are formed as a separable product of the radial frequency and the orientational frequency filters. In order to ensure the reversibility of the cortex filters’ set, i.e. the sum of the filters is 1, the radial frequency bands are formed as differences of a series of 2D low-pass mesa filters which have a flat pass-band, a flat stop-band, and a Hanning-window transition-band. The mesa filter can be completely characterized by its half-amplitude frequency, \( \rho_{\frac{1}{2}} \), and its transition width, \( tw \):

\[
mesa(\rho) = \begin{cases} 
1.0 & \text{for } \rho < \rho_{\frac{1}{2}} - \frac{tw}{2} \\
\frac{1}{2} \left( 1 + \cos \left( \frac{\pi(\rho - \rho_{\frac{1}{2}} + \frac{tw}{2})}{tw} \right) \right) & \text{for } \rho_{\frac{1}{2}} - \frac{tw}{2} < \rho < \rho_{\frac{1}{2}} + \frac{tw}{2} \\
0.0 & \text{for } \rho > \rho_{\frac{1}{2}} + \frac{tw}{2} 
\end{cases} \quad (5.5)
\]

The \( k \)th \( dom \) (differences of mesas) filter is simply the difference of two mesa filters evaluated at two different half-amplitude frequencies:

\[
dom_k(\rho) = mesa(\rho)|_{\rho_{\frac{1}{2}} = 2^{-(k-1)}} - mesa(\rho)|_{\rho_{\frac{1}{2}} = 2^{-k}} \quad (5.6)
\]

The lowest frequency filter, called the \( base \), is designed differently. A truncated Gaussian function is used instead of the mesas to get rid of the unacceptable ringing in the base-band:

\[
base(\rho) = \begin{cases} 
e^{-\left(\frac{\rho^2}{2tw^2}\right)} & \text{for } \rho < \rho_{\frac{1}{2}} + \frac{tw}{2} \\
0.0 & \text{for } \rho \geq \rho_{\frac{1}{2}} + \frac{tw}{2} 
\end{cases} \quad (5.7)
\]
where
\[
\sigma = \frac{1}{3} \left( \rho_{\frac{1}{2}} + \frac{t_w}{2} \right) ; \quad \rho_{\frac{1}{2}} = 2^{-K}, \tag{5.8}
\]
with \( K \) being the total number of radial filters. The transition width \( t_w \) of each filter is defined to be a function of its half-amplitude frequency, as given by
\[
tw = \frac{2}{3} \rho_{\frac{1}{2}} . \tag{5.9}
\]
This choice of transition width gives the Cortex bands constant behavior on a log frequency axis with a bandwidth of 1.0 octave and symmetric response.

The HVS's orientational frequency selectivity is modeled by a set of fan filters. A Hanning window is also used for these filters. The orientation transitions are functions of angular degrees \( \theta \) in Fourier domain. The \( \ell \)th fan filter is given by,
\[
f_{\text{fan}}(\theta) = \begin{cases} 
\frac{1}{2} \left(1 + \cos \left( \frac{\pi \theta - \theta_c(l)}{\theta_{tw}} \right) \right) & \text{for } |\theta - \theta_c(l)| \leq \theta_{tw} \\
0.0 & \text{for } |\theta - \theta_c(l)| > \theta_{tw} ,
\end{cases} \tag{5.10}
\]
where \( \theta_{tw} \) is the angular transition width, and \( \theta_c(l) \) is the orientation of the center angular frequency of fan filter \( l \), given by,
\[
\theta_c(l) = (l - 1) \theta_{tw} - 90^\circ ; \quad \theta_{tw} = \frac{180^\circ}{L} , \tag{5.11}
\]
with \( L \) being the total number of fan filters.

The cortex filters are then formed by a simple polar multiplication of the corresponding dom and fan filter:
\[
cortex_{k,l}(\rho, \theta) = \begin{cases} 
\text{dom}_k(\rho).f_{\text{fan}}(\theta) & \text{for } k = 1, \ldots, K - 1; \ l = 1, \ldots, L \\
\text{base}(\rho) & \text{for } k = K .
\end{cases} \tag{5.12}
\]

The total number of cortex filters is \( L(K-1)+1 \). For the mapping, we use \( K=6 \) and \( L=6 \), combining for a total of 31 critical cortex bands. Notice that there is no orientation selectivity in the baseband, and the choice of \( L \) yields an orientation
Figure 5-2: Complete set of cortex filters for $K=6$ and $L=6$.

bandwidth of 30 degrees, which is consistent with studies in [14]. Also, the set of cortex filters is invertible, i.e.

$$\sum_{k=1}^{K} \sum_{l=1}^{L} \text{cortex}_{k,l}(\rho, \theta) = 1 \quad \text{for all } \rho, \theta . \quad (5.13)$$

Details of the radial and orientational dissections of the frequency space are shown in Figure 5-2. See [5] and [19] for more detailed description and implementation of the cortex filters.
5.3 The DCT-Cortex Transform Mapping

This DCT-Cortex transform masking serves as the heart of our locally adaptive texture masking model. As previously mentioned, texture masking, or contrast masking in some other literatures, refers to the reduction of visibility or detectability of one image signal by the presence of another. The texture masking characteristic of the HVS is known to be dependent on three major factors. The masking is strongest (and, therefore, the thresholds can be elevated highest) when both signals are of the same location, orientation, and spatial frequency [12] [20]. The cortex filters divide up the image spectrum in a similar fashion. They are nothing more than a set of windows that cover the whole frequency spectrum. Signal components at the same location, orientation, and spatial frequency are grouped together in the same Cortex band. Moreover, in this project, we only consider texture masking within a DCT block. Therefore, a simple mapping of the two can help us decide which DCT coefficients contribute how much energy to which cortex band, and from that information, elevate these coefficients’ base thresholds accordingly with the intensity of the texture energy present in that cortex band. Notice that this idea can also be applied to masking across the DCT blocks. The performance of the model would definitely be enhanced by such algorithm thanks to an increase in masking accuracy. However, the computation for such a model would also be more costly because of the increase in complexity.

The mapping algorithm’s complexity lies heavily on the implementation of the cortex filters. Once this task is done, the mapping reduces to 64 numerical integrations of 64 DCT bins over each cortex band.

The algorithm takes in a resolution number, a threshold, $K$, and $L$ as its inputs, and produces one 8x8 overlap-area matrix for each cortex band. $K$, chosen to be 6 in this project, is the number of dom filters; $L = 6$, is the number of fan filters. The threshold is used to produce a binary overlap area matrix for convenience. If an overlap area is greater than the threshold, then it is set to 1. Otherwise, it is set to 0. These binary matrices are used in the early stages when we were setting
Figure 5.3: DCT - Cortex Filters mapping.
up the overall framework for the project. In later stages, when the elevation model’s accuracy becomes an important issue, the actual overlap area values are always used. The resolution \( \text{resnum} \) provides the finer scale for the numerical integrations. Notice that more accuracy can be achieved by higher resolution. However, computational complexity is the trade off. A commonly used value for \( \text{resnum} \) is 32.

Each DCT bin is further divided into \( \text{resnum} \times \text{resnum} \) subbins. The cortex transform of length \( 8 \times \text{resnum} \) is then performed to give us 31 sets of 31 cortex filters’ coefficients. For the \( k \)th, \( l \)h cortex band, the \( m \)th, \( n \)th entry of the overlap area matrix, \( \text{Overlap-area}_{k,l,m,n} \) – the overlap area between the DCT coefficient \( I_{m,n} \) and the aforementioned cortex band is computed by the summation:

\[
\text{Overlap-area}_{k,l,m,n} = \sum_{kk=m\cdot\text{resnum}}^{(m+1)\cdot\text{resnum}} \sum_{ll=n\cdot\text{resnum}}^{(n+1)\cdot\text{resnum}} \text{cortex}_{k,l}(kk, ll). \tag{5.14}
\]

The final output of the DCT-Cortex mapping algorithm is a set of 31 8x8 matrices. Each matrix contains 64 overlap-area values of 64 DCT bins and the corresponding cortex band. Since we are only mapping the primary quadrant of the cortex space to the DCT space (with the DC value line up in the middle of the base band), only 21 out of 31 cortex bands participate in the mapping. The remaining 10 bands have all-zero overlap-area matrices. These overlap-area matrices serve as the basis for the elevation model described in the next chapter. The matrices computed at a resolution of 32 are included in Appendix A.
Chapter 6

The Threshold Elevation Model

This image-dependent threshold elevation model estimates the texture energy, i.e. the amount of spatial details, in each DCT block, and computes a threshold elevation factor for each DCT coefficient.

6.1 Basic Strategy

The threshold elevation model uses a mapping of the DCT coefficients on the Cortex filter bands as described in the previous chapter. For each Cortex band, the model decides which coefficients contribute how much energy to that band, and then increases the elevation factor of those coefficients linearly with the intensity of the Cortex band’s masking energy. For the shaded Cortex band in Figure 5-3, the DCT transform coefficients $I_{1,2}, I_{1,3}, I_{1,4}$, and $I_{2,4}$ contribute most of the texture energy in the band, whereas coefficient $I_{7,6}$ (marked X) has zero contribution. Therefore, the elevation factor of $I_{7,6}$ should not be dependent on the amount of texture present in the shaded Cortex band. This idea comes from the HVS’s tendency to be strongly dependent on locality. Notice also that all the coefficients in the same cortex band share very close spatial frequencies, orientations, and locations. This ensures that the noise introduced by the threshold elevation will be appropriately masked by the texture energy of the corresponding cortex band.

If a certain DCT coefficient gets involved in more than one Cortex band, and thus
correspondingly has more than one elevation factor, we apply the **minimum-of rule**, i.e. the smallest value will be used to prevent overly aggressive estimation.

If there is zero or very little texture energy in the analysis block, there should be no elevation at all, that is, the elevation factor is 1. In this case, the model uses only the conservative base threshold value. There should also be a maximum cut-off value for the elevation factors because noise masking can achieve transparency only up to a certain level. Through observation in the subjective visual tests in this project, if the noise energy exceeds roughly 25 percent of the masking signal energy, distortion will be most likely visible in the reconstructed image. For the cortex band which contains energy between the minimum and the maximum cut-off point, the elevation factors of the contributing DCT coefficients are increased accordingly with the elevation curve. The maximum cut-off value parameter, as well as the characteristics of the elevation curve, can be determined and fine-tuned through subjective testing.

In an image block, the final perceptual masking threshold of any DCT coefficient is then obtained as the product of its base threshold value and its elevation factor. If an image-dependent quantization matrix is desired, each entry of the matrix is simply twice the corresponding final masking threshold.

### 6.2 Implementation

Each image pixel block of size 8x8 is transformed to its equivalent 64 DCT coefficients $I_{m,n}$. For a fixed viewing condition and a fixed viewing distance, an 8x8 base threshold matrix $T_{\text{base,}m,n}$ for each channel is computed according to the method described in Chapter 4. These thresholds can be elevated in accordance with the block's texture energy intensity. A simple threshold elevation model for texture masking in the luminance channel can be implemented in the following ways. (Note that the design and implementation of the chrominance channels' elevation model are exactly the same.)

The algorithm reads in as input the overlap-area matrices generated as described in Chapter 5. For each cortex band (matrix), a set of elevation factors are calculated,
based on the 3-segment piecewise linear texture elevation model shown in Figure 6-1.

The texture energy of the $k$, $l$ th cortex band is computed by summing up the energy of all the 63 AC coefficients that overlap with that cortex filter's passband, and then taking the square root of the summation:

$$\text{total energy}_{k,l} = \sqrt{\sum_{m=0}^{7} \sum_{n=0}^{7} (I_{m,n} \cdot \text{Overlap-area}_{k,l,m,n} / T_{\text{base},m,n})^2} \text{ for } m \neq 0 \text{ or } n \neq 0.$$  \hspace{1cm} (6.1)

The DC value is the average of the pixel values in the block, so it has substantially more energy than the AC coefficients. Especially in the case of uniform light background, (i.e. no texture energy in the block but the pixel values are high), the DC coefficient is large while the AC coefficients are all in the vicinity of 0, 1, or -1. Therefore, the DC term is excluded from the energy calculation. The elevation model also takes into account the viewing distance and the viewing conditions by normalizing the total energy of the cortex band by the base thresholds $T_{\text{base},m,n}$.

If the total energy just computed is less than the low energy threshold, then the elevation is set to a minimum. Obviously, the minimum value is picked to be 1, meaning...
that there is no threshold elevation. If the total energy is greater than the high energy
threshold, then the elevation factor is set to a maximum value. If the total energy
is in between the two energy thresholds, then the elevation factor increases linearly
with the energy. In short, for the involved DCT coefficients \((\text{overlap-area}_{k,l,m,n} \neq 0)\),
the elevation factors can be calculated by:

\[
elevation_{\text{factor}}_{k,l,m,n} = \begin{cases} 
\min, & \text{total}_{\text{energy}}_{k,l,m,n} < energy_{\text{low}} \\
\max, & \text{total}_{\text{energy}}_{k,l,m,n} > energy_{\text{high}} \\
\min + \frac{\max - \min}{energy_{\text{high}} - energy_{\text{low}}} (\text{total}_{\text{energy}}_{k,l,m,n} - energy_{\text{low}}). & \text{else}
\end{cases}
\]

(6.2)

This elevation curve does not have to be linear. In fact, a cubic curve (the dotted line
in Figure 6-1), is probably a more logical choice because a smoothing function makes a
more accurate approximation of the HVS’s sensitivity to texture than segmented lines
with discrete decision regions. However, the linear elevation model is the easiest and
most straightforward to implement. It is also the most computationally inexpensive
choice. It serves as a good cornerstone for the elevation model. Moreover, it appears
to work quite well in practice.

As previously mentioned, if a coefficient contributes energy to more than one
cortex band, its final elevation factor is the minimum of all the values calculated. A
variable called \(etemp\) keeps the current value computed for the current iteration. It is
then compared with the minimum elevation factor calculated so far from the previous
iterations. If this minimum-so-far value is greater than \(etemp\), then it is updated.
Otherwise, it stays the same. Notice that among 64 DCT coefficients, every one of
them belongs to at least one cortex band. So, none of them gets left out from the
iterations. Second, for a particular iteration for a particular cortex band, all the
coefficients belonging to that band have the same temporary elevation factor \(etemp\).
The “minimum of” rule can make two coefficients that contribute about the same
amount of energy to the same cortex band have different elevation factors.

There is one exception for this “minimum of” rule. As shown in the overlap-
area matrices in Appendix A, there are several coefficients that have major energy
collection in certain cortex band, say more than 80 percent. They are also involved
in some other cortex bands; however, the contribution level is much lower, say 10
percent or less. For a particular coefficient of this type, we would like to use the
elevation factor calculated from the cortex band that it is most influential, not the
aforementioned minimum value. We call this high energy contribution reconsideration.

Another little adjustment for the elevation model is the low frequency post-
processing. Not only is the DC coefficient $I_{0,0}$ sensitive to noise, but it is also known
from the HVS's low-pass nature that the DC's low frequency neighbors $I_{0,1}, I_{0,2},$
$I_{1,0}, I_{1,1}, I_{1,2}, I_{2,0},$ and $I_{2,1}$ are very important to be coded right. Therefore, we set
all elevation factors of these low frequency coefficients to $min = 1$.

The final perceptual masking threshold of a coefficient is obtained as a product of
its base threshold and its elevation factor. This final threshold is most likely different
for the 64 coefficients in the same block. Also, the threshold for coefficient $I_{m,n}$ at
frequency bin $m, n$ in the $i$th block is most likely different from the threshold of the
coefficient at the same spatial frequency in block $j$. For the JPEG standard, these two
thresholds are exactly the same. These two facts show the locally adaptive nature of
the new perceptual masking threshold model.

It should be noted that such a model designed in this fashion does not guaran-
tee a performance at perceptually distortion-free level. However, through subjective
testing, we can fine-tune the parameters enough to achieve this goal. The parameters
do not have to be the same for all of the cortex bands. In fact, they should be dif-
ferent. For example, for the cortex bands that cover the lower frequency spectrum,
the elevation model has to be more conservative. The model can be more aggressive
with the cortex bands in the high frequency regions.
Chapter 7

Block Classification

The need for block type classification arose when we conducted early subjective tests of the threshold elevation model. Noises resulting from high elevation factors of coefficients in high textured region within an image block spread out to the remaining uniform background region of the block. This noise spreading is similar to the familiar pre-echoing problem in perceptual audio coding.

7.1 Problem Description and Early Results

Let us take a close look at what we label an edge-block in Figure 7-1, and the threshold elevation model's performance on the corresponding image data.

The definition of an edge in this case is not the same as the one used in numerous edge-detection techniques. An edge-block in our definition is an image block that contains two obvious regions: one contains very high texture energy (the left shaded region in Figure 7-1), and the other is a "clean" uniform background, i.e. has almost zero texture energy (the region on the right). Such an image block has pixel values given in Table 7.1; its equivalent 64 DCT coefficients are shown in Table 7.2, with the DC coefficient $I_{0,0} = 937$ at the upper left corner and the highest frequency coefficient $I_{7,7} = -87$ at the lower right corner. Since the textured region of the block has quickly varying pixel values, the DCT coefficients are quite large, even at high frequencies.

The coefficients in Table 7.2 are then coded using the perceptual masking threshold
Figure 7-1: Example of an edge-block.

Table 7.1: Edge-block pixel values

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Table 7.2: Edge-block’s DCT coefficients

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elevation model. Specifically, the base thresholds obtained in Chapter 4 are elevated by the texture elevation model described in Chapter 6. The locally adaptive quantization matrix $Q_{m,n}$ is obtained as twice the product of the two. The coded coefficients $I_{\text{coded} m,n}$ shown in Table 7.3 are simply: $I_{\text{coded} m,n} = \text{round} \left( I_{m,n} / Q_{m,n} \right)$. In this example, the elevation model used is extremely aggressive with a maximum elevation factor of 5. In this example, where even the original coefficients are high, we still manage to zero-out 11 coefficients. A quick comparison between the DCT coefficients in Table 7.2 and the luminance base weights in Table 4.2 shows that, if we use the base thresholds and no elevation, we can zero-out only 3 coefficients.

From the coded coefficients in Table 7.3, the reconstructed image block can be obtained through normalization and the inverse DCT transform (Equation 5.3). The reconstructed pixels are shown in Table 7.4, and the absolute values of the pixels' differences are in Table 7.5. The elevation model demonstrates well its accuracy and local adaptibility. The left section of the block is overcoded since that is where all of the texture energy located in space domain. In the right, there are not much

| 13 | 86 | 33 | 212 | 219 | 0 | 131 | 130 |
| 191 | 30 | 68 | 113 | 217 | 135 | 138 | 128 |
| 198 | 241 | 46 | 14 | 25 | 146 | 108 | 134 |
| 39 | 220 | 30 | 82 | 122 | 115 | 145 | 126 |
| 106 | 114 | 19 | 226 | 145 | 135 | 123 | 133 |
| 72 | 37 | 5 | 129 | 135 | 108 | 142 | 127 |
| 173 | 175 | 26 | 136 | 116 | 148 | 121 | 129 |
| 206 | 85 | 125 | 132 | 132 | 128 | 131 | 131 |

Table 7.4: Equivalent Reconstructed Image Block Pixels for Max Elevation = 5
noise introduced to the pixels far away from the edge. However, near the edge, we can notice that there is serious error spreading from the left heavily textured region. Differences of 22, 18, or 15 of pixel values in the sensitive mid-grey level of the HVS can cause serious degradation in the reconstructed image quality.

A question arises for the curious: what would have happened if there was no threshold elevation? With the quantization matrix entries set to be twice the base weights, the resulting coded DCT coefficients are shown in Table 7.6.

The reconstructed pixels, with no threshold elevation, are shown in Table 7.7, and the absolute value of the pixels' differences in the space domain are shown in Table 7.8.

Since the base thresholds are obtained image-independently, the base threshold model does not take advantage of the heavy texture in the left region of the edge-block. In this case the model codes both regions the same way which results in the same amount of error in both (see Table 7.8). With threshold elevation, much more error is injected into the textured region as expected.
Table 7.7: Reconstructed Pixels with No Threshold Elevation

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Table 7.8: Error in Space Domain with No Threshold Elevation

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7.2 Classification Methods

The methods presented next are for detecting edge-blocks. They are designed to discriminate textured blocks based on whether the texture is either structured (edge-blocks), or unstructured. The problem is more complicated than the one-dimensional switching from short block to long block to prevent pre-echoing in perceptual audio coding. The difficulty comes from a very basic question: what exactly is texture? (see Chapter 2). However, we can follow a similar approach — breaking the analysis block into sub-blocks.

7.2.1 Over-Under Method

The 8x8 pixel block is broken up into 16 2x2 sub-blocks. In each sub-block, the variance of the pixels is calculated:

\[
\text{variance} = \sum_{j=0}^{1} \sum_{k=0}^{1} (i_{j,k} - \text{average})^2
\]
where

$$\text{average} = \frac{1}{4} \sum_{j=0}^{1} \sum_{k=0}^{1} i_{j,k}. \quad (7.2)$$

If a sub-block's variance is over some high texture energy threshold, that sub-block is labeled as an \textit{over}. Similarly, if its variance is lower than the no texture energy threshold, it is labeled an \textit{under}. Otherwise, the sub-block is labeled a \textit{between}. A block is labeled edgy when the number of \textit{over} sub-blocks and the number of \textit{under} sub-blocks are close, and there are not many \textit{betweens}. The two energy thresholds, as well as the other parameters of the decision rules, are set through numerous experiments. A simple test of the detection model's effectiveness is to zero-out the pixels of the suspected edgy blocks. On display, all of these blocks will be black. We can then subjectively estimate the detection rate, as well as the false alarm rate of the model. Various parameter values can then be tested to increase the model's effectiveness.

The over-under approach does not seem to perform well. If the detection rate is high, then the false alarm rate is also high. If the parameters are reset such that the false alarm rate is low, the detection rate is also low. There are just too many parameters, and it is almost impossible to find a good combination to keep the false alarm rate low and the detection rate high.

### 7.2.2 Variance Ratio Method

In this approach, the pixel block is also divided into 2x2 sub-blocks. The variance of each sub-block is calculated using Equations 7.1 and 7.2.

Among the computed variances, the ratio of the maximum value and the minimum non-zero one, $\frac{\text{max\_variance}}{\text{min\_variance}}$, is used to decide whether or not the block is edgy. If the ratio is large, it means that certain parts of the image block have significantly more texture energy than others. Also, since we are only worrying about noise spreading in the very "clean" region of a pixel block, the minimum variance has to be under a certain low energy threshold for the block to be labeled an edge-block. An empirical value for the ratio threshold is 25. A typical value used for the low variance threshold is 15. The model seems to perform well with these parameter choices.
This method for edge-block detection still has flaws. One of the most obvious is its sensitivity in extreme cases. In the case of an image block with 15 textured sub-blocks and 1 clean sub-block, or 1 textured and 15 clean sub-blocks, the model will label the block edgy. We can prevent this false alarm by assigning two more parameters: over and under, as in the over-under method. However, we choose not to further increase the complexity of the model since this situation rarely occurs in practice.

7.3 Coding of Edge-blocks

The coding of edge-blocks is still a puzzling question. In the time (or space) domain, it is obvious that which parts of an image are smooth, and which are textured. However, when the pixels are transformed to its frequency domain, the summations of the pixel values projected onto the cosine basis totally destroy the pixels' correlation. As observed from the example in Section 7.1, while it is clear in the space domain that the left part of the block contains very high texture energy, it is unclear in the DCT domain which coefficients contribute to that texture. The threshold elevation model does a good job of injecting most of the noise into the textured region. For this high threshold elevation case, the problem of noise spreading into the uniform region is unavoidable. For now, the only solution is to detect the edge-blocks, and use lower elevation factors on them. One can even be more conservative by just using the base thresholds for these edge-blocks.

Another solution to the noise spreading problem is to process the image with a finer space resolution. The frequency resolution, however, will suffer. Furthermore, we would like to preserve the standard 8x8 DCT decomposition. In this case, a finer resolution, meaning using a smaller size for analysis blocks, can still be achieved by using a DCT with overlapped analysis blocks — the Extended Lapped Transform (ELT) [11]. The elevation factor of a particular coefficient is the minimum of the factors computed from the analysis blocks to which the coefficient belongs. This will significantly improve the accuracy of the elevation model. However, the computational complexity
of the coding process also increases accordingly. With an overlapping factor of 2, the cost of coding an image increases approximately four times. This idea needs a more in-depth investigation.
Chapter 8

Subjective Tests and Results

Subjective tests are an essential part of the project. Still images and sequences of different, but known, levels of coding difficulty were tested using the new model, as well as the old ones for performance comparison purposes. Another important contribution of subjective testing experiments was to fine-tune the new masking threshold model's parameters as previously mentioned.

8.1 Set-up

The experiments were carried out on an 8x8 DCT decomposition of images. The test images at AT&T Bell Laboratory are digital images in CIF format with size 360x240 for the luminance channel, and 180x120 for the chrominance channels. All of the pixels have an 8 bit resolution (pixel values ranging from 0 to 255). When displayed, the images are interpolated to be twice the storage dimensions.

Each test image channel was divided into 8x8-pixel blocks. Each pixel block was then transformed to its equivalent DCT. The pre-computed base threshold values were multiplied by the elevation factors computed from the locally adaptive texture elevation model to obtain the final threshold values. Next, each input image was corrupted with the maximum amount of noise allowed by the model, i.e. specifically, each DCT coefficient in each analysis block was randomly either subtracted or added.
by its computed threshold value:

\[ I_{\text{coded}k,l,m,n} = I_{k,l,m,n} \pm \text{threshold}_{k,l,m,n} \quad (8.1) \]

where

\[ \text{threshold}_{k,l,m,n} = \text{base\_threshold}_{k,m,n} \cdot \text{elevation\_factor}_{k,l,m,n}. \quad (8.2) \]

For the above formulae and also for rest of the chapter, \( k \) refers to the channel index, \( l \) refers the block index, and \( m \) and \( n \) are the indices of the spatial DCT frequencies. Notice that the base thresholds are not block-dependent; they do not have index \( l \). To obtain the reconstructed image pixels, an inverse DCT (Equation 5.3) was performed on the "coded" coefficients \( I_{\text{coded}m,n} \).

This noise-adding scheme was used in the early stages of the project. It resulted in huge levels of noise injected to the high frequency DCT coefficients, and it was certainly an overly conservative approximation of the masking threshold model's performance. A more realistic approximation was the zero-out coefficients scheme, in which all coefficients below their corresponding thresholds were set to zero. For coefficients that were larger than the thresholds, the noise-adding scheme was applied. Specifically, the "coded" coefficient was obtained as follows:

\[ I_{\text{coded}k,l,m,n} = \begin{cases} 0, & \text{for } |I_{k,l,m,n}| \leq \text{threshold}_{k,l,m,n} \\ I_{k,l,m,n} \pm \text{threshold}_{k,l,m,n}, & \text{otherwise} \end{cases} \quad (8.3) \]

with the thresholds calculated from Equation 8.2

### 8.2 Subjective Evaluation Tests

Test subjects were invited to subjectively determine if any distortion was perceivable in the resulting reconstructed images. For a standard subjective test, the original image or sequence was always shown first. The original and the coded image or sequence were then loaded onto two high-resolution TV monitors side by side. The subjects were asked to point out which one was the original and which was the coded.
Subjects invited to the numerous subjective tests were mostly members of the Image Group who were experienced and well-trained. They are more sensitive to noise than normal people. The model was fine-tuned until all the subjects could not reliably detect any visual difference between the coded and the original image or sequence.

### 8.3 Objective Statistics

In perceptual coding, we have two measures of evaluating the performance of our model: one is the subjective measure presented in the previous section, and the other is the objective statistics. The goal is to keep the subjective performance at the perceptually lossless level and then use the objective measures to evaluate alternative models.

For each channel of the input image, an 8x8 matrix of average mean-square error for each DCT frequency bin was obtained. For each analysis block, using the zero-out scheme, the block’s mean-square error matrix was computed in DCT domain as the square of the difference between the original coefficient and the coded one:

$$mse_{k,l,m,n} = \begin{cases} \frac{I_{k,l,m,n}^2}{n}, & \text{for } |I_{k,l,m,n}| \leq \text{threshold}_{k,l,m,n} \\ \text{threshold}_{k,l,m,n}^2 & \text{otherwise.} \end{cases}$$  \hspace{1cm} (8.4)

The average mean-square error matrix for channel $k$ is the summation of all the blocks’ mean-square error in that channel normalized by the total number of blocks $num\_block$:

$$\text{average}_mse_{k,m,n} = \frac{1}{num\_block} \sum_{l=1}^{num\_block} mse_{k,l,m,n}$$  \hspace{1cm} (8.5)

The average mean-square error matrix provides the traditional objective evaluation measure of source coding — the Signal-to-Noise Ratio (SNR). Not only does the SNR show how effective the masking model is, but it also can be used for various demonstration purposes. One popular demonstration had three images displayed side-by-side: the original sequence, the perceptually distortion-free coded sequence,
and the original sequence corrupted by uniformly distributed white noise with the same SNR as the perceptually coded sequence.

Besides the mean-square error, the drop percentage is another useful objective statistic. The drop percentage gives an approximation of the compression ratio needed to achieve coding at the perceptually lossless level. For each channel of the coded image or sequence, an 8x8 matrix of dropped coefficients percentage \( drop\_percentage_{m,n} \) was kept. Each element of the matrix shows the percentage of how many DCT coefficients in that frequency bin are smaller than the threshold computed at the same frequency (and hence, the coefficient is set to zero):

\[
drop\_percentage_{k,m,n} = 100\% \cdot \frac{1}{\text{num\_block}} \sum_{l=1}^{\text{num\_block}} \text{drop}_{k,l,m,n}
\]  

(8.6)

where

\[
drop_{k,l,m,n} = \begin{cases} 1, & \text{for } |I_{k,l,m,n}| \leq \text{threshold}_{k,l,m,n} \\ 0, & \text{otherwise} \end{cases}
\]  

(8.7)

with \( k \) is the channel index, and \( l \) is the block index.

In a similar fashion, an 8x8 average threshold matrix was also obtained:

\[
\text{average\_threshold}_{k,m,n} = \frac{1}{\text{num\_block}} \sum_{l=1}^{\text{num\_block}} \text{threshold}_{k,l,m,n}
\]  

(8.8)

The average threshold values provide a good measure of how the threshold elevation model works in a particular image or sequence. They are also excellent tools for debugging the model’s source code.

### 8.4 Results

The new adaptive perceptual threshold model (APxJPEG) was tested with two other popular image compression models already in use: the JPEG compression standard and the perceptual Johnston-Safranek model (PxJPEG), both described in Chapter 3. 318 still images in the AT&T image database were used to compile this performance comparison statistics. As expected, the adaptive perceptual masking model outper-
formed JPEG by a large margin. The gain in the bit rate needed for transparent coding was on the order of 10 to 30%. The race was closer for the two picture-dependent models. In general, the new model had the same or better performance than the Johnston-Safranek model. For images with a lot of directed texture, we got much better performance from the new model thanks to its locally adaptibility. The bit rate savings comparison between APxJPEG and JPEG is depicted in Figure 8-1. The same comparison between APxJPEG’s and PxJPEG’s performance is shown in Figure 8-2. The complete bit rate saving percentage for each particular image can be found in Appendices B and C. Also included are three lenna images: the original image (Figure 8-3), the reconstructed image using JPEG (Figure 8-4), and the reconstructed image using the new adaptive perceptual threshold model as a pre-processor for JPEG (Figure 8-5). The original 512x512 gray-scale image has a bit rate of 8 bits per pixel. The resulting bit rate for the reconstructed JPEG image is 1.026 bits per pixel. The resulting bit rate for the reconstructed APxJPEG image is 0.813 bits per pixel (a 15% bit rate saving). One can easily verify that both of the reconstructed images were coded at perceptually lossless level.
Figure 8-1: Performance Comparison between APxJPEG and JPEG
Figure 8-2: Performance Comparison between APxJPEG and PxJPEG
Figure 8-3: Original Image for Reference
Figure 8-4: Reconstructed JPEG Image coded at 1.026 bits/pixel
Figure 8-5: Reconstructed APxJPEG Image coded at 0.813 bits/pixel
Chapter 9

Conclusion

In this project, a new locally adaptive perceptual masking threshold model for the human visual system was designed and implemented. The model's development was based on many evident characteristics of the HVS available from numerous psychophysical experiments. The model not only performs much better than the JPEG's standard image-independent perceptually lossless model, but it also out-performs, as expected because of its local adaptibility, AT&T's currently used threshold elevation model developed by Johnston and Safranek [15]. The mapping of the cortex transform's critical bands onto the DCT bins proves to approximate accurately the locality as well as the intensity of the mask. The DCT-cortex mapping is the pivotal basis of the image-dependent texture elevation model.

Despite the success of the project, much more work remains to be done in this area. As we can see from Chapter 7, aggressive elevation in the DCT domain due to the presence of a heavy texture region in an analysis block can cause serious noise spreading to the flat-field region of the same block in space domain. In this case, the noise spread is most vulnerable to detectability. A more robust threshold elevation model that can effectively deal with these edge-blocks needs to be developed. One of the solutions to this problem is to increase the accuracy of our threshold elevation model by extending the masking ideas across DCT blocks. However, this masking-across-DCT-block extension, as discussed in Chapter 7, can be very computationally expensive.
Another important piece totally missing from this perceptual masking threshold model is temporal masking. Although the model was tested with image sequences, this study did not consider temporal masking effects at all. However, we recognize that the human visual system’s perception of dynamic noise in image sequences is, in general, very different from its perception of static noise in still images. A full masking model which includes temporal noise masking needs to be studied and applied to coding of image sequences.

Besides the problem of noise spreading and the lack of temporal masking, the threshold elevation model developed in this project is also not robust enough. It was primarily designed and geared to be compatible with DCT-based coders. Its effectiveness when used with other different coder types is doubtful and has not yet been tested.

In short, this project raises more new questions than it resolves. Many aspects of the project need more in-depth investigation. However, it serves as a good building block for the understanding, as well as the advancing of the perceptual image coding field.
# Appendix A

## DCT-Cortex Overlap Area Matrices

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binary matrix for cortex band k=0 l=3

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binary matrix for cortex band k=0 l=4

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binary matrix for cortex band k=0 l=5

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binary matrix for cortex band k=1 l=0

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binary matrix for cortex band k=1 l=1

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binary matrix for cortex band k=1 l=2

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binary matrix for cortex band k=1 l=3

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binary matrix for cortex band k=1 l=4

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binary matrix for cortex band \( k=1 \) \( l=5 \)

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0.151463 & 0.510103 & 0.303556 & 0.039198 & 0.000131 & 0.000000 & 0.000000 & 0.000000 \\
0.029949 & 0.093043 & 0.036653 & 0.000803 & 0.000000 & 0.000000 & 0.000000 & 0.000000 \\
0.000303 & 0.000213 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 \\
0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 \\
0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 \\
\end{bmatrix}
\]

binary matrix for cortex band \( k=2 \) \( l=0 \)

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0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 \\
\end{bmatrix}
\]

binary matrix for cortex band \( k=2 \) \( l=1 \)

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0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 \\
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0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 \\
0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 \\
\end{bmatrix}
\]

binary matrix for cortex band \( k=2 \) \( l=2 \)

\[
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\end{bmatrix}
\]
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binary matrix for cortex band k=2 l=3

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binary matrix for cortex band k=2 l=4

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binary matrix for cortex band k=2 l=5

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binary matrix for cortex band k=3 l=0

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binary matrix for cortex band k=3 l=5

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0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 260
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binary matrix for cortex band k=4 l=0

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0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000
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0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000

binary matrix for cortex band k=4 l=1

0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 280
0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000
0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000
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binary matrix for cortex band k=4 l=2

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65
binary matrix for cortex band k=4 l=3

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binary matrix for cortex band k=4 l=4

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binary matrix for cortex band k=4 l=5

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binary matrix for cortex base band

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Appendix B

Comparison Between Adaptive Perceptual Threshold Model and JPEG

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