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Lecture 22:

Lossy Compression & Rate-Distortion

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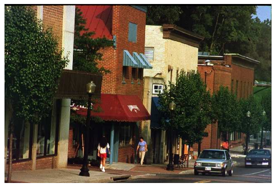
Lossy Compression

- Many kinds of data — such as images and audio signals — contain "noise" and other information that is not really of interest. Preserving such useless information seems wasteful.
- **A common approach:** *Lossy compression*, for which decompressing a compressed file gives you something *close* to the original, but not necessarily exactly the original.
- We should be able to compress to a smaller file size if we don't have to reproduce the original exactly.



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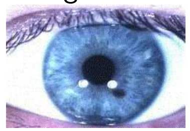
What do We Mean by "Close"?

- Any lossy compression scheme is based (at least implicitly) on some idea of what counts as "close to the original".
- This is a question that can only be answered by considering the *users* of the compression program, and what they want.
- For images and audio signals, two fundamental issues are:
  - What differences can humans perceive?
    For example, to a first approximation, humans perceive only *relative energies* of different frequency bands in audio but not the associated *phases* of sine waves.

  - What differences do humans find annoying or distracting?
    Slight changes in colour might be regarded as less important than making a straight line be jagged.



Formalizing Distortion

- Suppose the input to the compression program is the sequence $a_1, a_2, \ldots, a_N$, and the decompression program outputs the sequence $b_1, b_2, \ldots, b_N$. (The a_i and the b_i might come from the same or different alphabets, e.g. before/after quantization.)
- We can measure how close the decompressed output is to the original by its average "distortion":

$$\bar{d} = \frac{1}{N}\sum_{i=1}^{N} d(a_i, b_i)$$

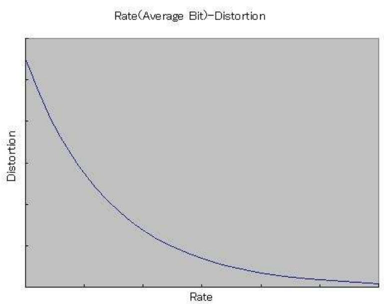
  $d(a, b)$ is a non-negative *distortion function* measuring how bad it is for a decompressed symbol to be b if the original was a.
- **Note:** In practice, the overall distortion might not be a sum of distortions for individual symbols, but we'll ignore that complication.

Simple Distortion Functions 4

- Distortion functions that measure what we're really interested in are likely to be complicated. But we can consider some simple examples that are easier to handle.
- **Hamming distance:** For a bilevel image (such as a FAX), we might use a distortion function for which $d(0,0) = d(1,1) = 0$ and $d(0,1) = d(1,0) = 1$.
- **Squared error:** For a gray-scale image, with pixels values in $\{0,\ldots,255\}$, or for an audio signal with sample quantized to 8 or 16 bits, we might use $d(a,b) = (a-b)^2$.
- **Absolute error:** If we want to penalize big errors less severely, we might consider the distortion $d(a,b) = \|a-b\|$.

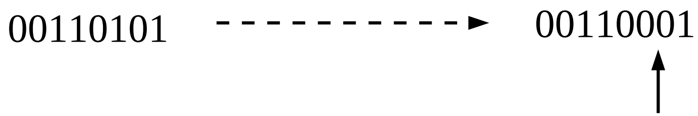
Rate for a Given Distortion 5

- If the entropy of our source is H, we expect to be able to losslessly compress N symbols into NH bits — ie, at rate H.
- But what if decompression is allowed to produce any output that has average distortion less than some limit, D?
- The *rate distortion function*, $R(D)$, tells us how well we can do then. It is the *smallest* rate (average bits per input symbol) for *any* compression scheme that has average distortion no greater than D.
- Note that $R(D)$ depends on both the source probabilities and on the distortion function chosen.



Example: Binary Data 6

- Suppose our source alphabet is binary, with equal probabilities for 0 and 1 (independently from symbol to symbol).
- Suppose we will decompress to the same alphabet, and that we measure distortion by Hamming distance.
- If we insist on lossless compression, we can't compress at all, since the entropy is one.
- How well can we compress if we allow an average distortion of up to $1/8$ — ie, if we allow up to one in eight bits to be wrong?



Lossy Compression Using Hamming Codes 7

- Here's a scheme that compresses a binary source to $4/7$ of the original file size while altering only $1/8$ of the bits, on average:
  1. Grab the next 7 input bits from the source.
  2. Pretend these bits are received data from a $[7,4]$ Hamming code in systematic form.
  3. "Decode" these 7 bits by the usual Hamming code procedure.
  4. Output the 4 message bits from this "decoded" codeword.
- To decompress, we take blocks of 4 bits and "encode" them using 7 bits in the usual way.
- **Result:** Perfect reconstruction of the 7 bits 1/8 of the time; one wrong bit 7/8 of the time.

The Rate Distortion Theorem 8

- Consider all channels, $\mathcal{C}$, with input alphabet $\{a_i\}$ and output alphabet $\{b_j\}$. Given the input probabilities that our source has, we can find for each such channel:
  - Its mutual information, $I(\mathcal{A}, \mathcal{B})$.
  - The average distortion between the channel input and the resulting output.
- Shannon proved that the rate distortion function, $R(D)$, is equal to the minimum value for $I(\mathcal{A}, \mathcal{B})$ over all channels whose average distortion is no more than D.
- For a binary source where 0 has probability $p_0 \le 1/2$, and where distortion is measured by Hamming distance, it turns out that

$$R(D) = \begin{cases} H(p_0) - H(D) & \text{for } 0 \le D \le p_0 \\ 0 & \text{for } D > p_0 \end{cases}$$

How Can We Achieve This? 9

- As for his noisy coding theorem, Shannon's rate distortion theorem can be proved using codes chosen at random.
- Consider a channel $\mathcal{C}$ that minimizes $I(\mathcal{A}, \mathcal{B})$ subject to the distortion between input and output being less than D.
  We find the output probabilities for such channel, and then pick codewords at random with symbol probabilities equal to these output probabilities.
- **Encoding procedure:** Find the codeword closest (as measured by distortion) to the actual message; then send an index of that codeword. If we chose 2^K codewords, sending this index will take K bits, for a rate of K/N.
- **Decoding procedure:** Output the codeword corresponding to the received index. This is called *vector quantization*.

Lossy Data Compression in Practice 10

- Shannon's elegant theory currently plays little role in practical lossy data compression (or the similar task of "vector quantization").
- Instead, various *ad hoc* methods are used.
- Two reasons for this:
  1. Formalizing a suitable distortion function taking account of human perceptual abilities and tolerances is difficult.
  2. The step from the impractical random codes used to prove the rate distortion theorem to a practical method of optimal compression hasn't been achieved.
- Overcoming these issues is a current challenge for research.