Compression: Video Compression (MPEG and others)

We need to compress video (more so than audio/images) in practice since:

1. Uncompressed video (and audio) data are huge.
   In HDTV, the bit rate easily exceeds 1 Gbps. — big problems for storage and network communications.

   E.g. HDTV: 1920 x 1080 at 30 frames per second, 8 bits per YCbCr (PAL) channel = 1.5 Gbps.

2. Lossy methods have to be employed since the **compression ratio** of lossless methods (e.g., Huffman, Arithmetic, LZW) is not high enough for image and video compression.

Not the complete picture studied here

Much more to MPEG — Plenty of other tricks employed.

We only concentrate on some basic principles of video compression:

- Earlier H.261 and MPEG 1 and 2 standards.

with a brief introduction of ideas used in new standards such as H.264 (MPEG-4 Advanced Video Coding).

Compression Standards Committees

Image, Video and Audio Compression standards have been specified and released by two main groups since 1985:

ISO - International Standards Organisation: JPEG, MPEG.

ITU - International Telecommunications Union: H.261 — 264.

Compression Standards

Whilst in many cases one of the groups have specified separate standards there is some crossover between the groups.

For example:

- JPEG issued by ISO in 1989 (but adopted by ITU as ITU T.81)
- MPEG 1 released by ISO in 1991,
- H.261 released by ITU in 1993 (based on CCITT 1990 draft).
  CCITT stands for **Comité Consultatif International Téléphonique et Télégraphique** (International Telegraph and Telephone Consultative Committee) whose parent organisation is ITU.
- H.262 is alternatively better known as MPEG-2 released in 1994.
- H.263 released in 1996 extended as H.263+, H.263++.
- MPEG 4 release in 1998.
- H.264 releases in 2002 to lower the bit rates with comparable quality video and support wide range of bit rates, and is now part of MPEG 4 (Part 10, or AVC – Advanced Video Coding).

How to compress video?

Basic Idea of Video Compression: Motion Estimation/Compensation

- Spatial Redundancy Removal – Intraframe coding (JPEG)

  NOT ENOUGH BY ITSELF?

- Temporal — Greater compression by noting the temporal coherence/incoherence over frames. Essentially we note the difference between frames.

- Spatial and Temporal Redundancy Removal – Intraframe and Interframe coding (H.261, MPEG)

Simple Motion Estimation/Compensation Example

Things are much more complex in practice of course.

Which Format to represent the compressed data?

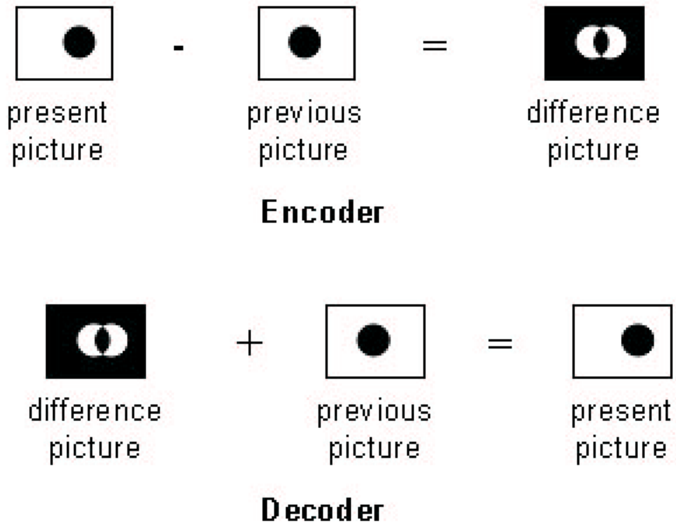
- Simply based on Differential Pulse Code Modulation (DPCM).

Simple Motion Example (Cont.)

Consider a simple image (block) of a moving circle.

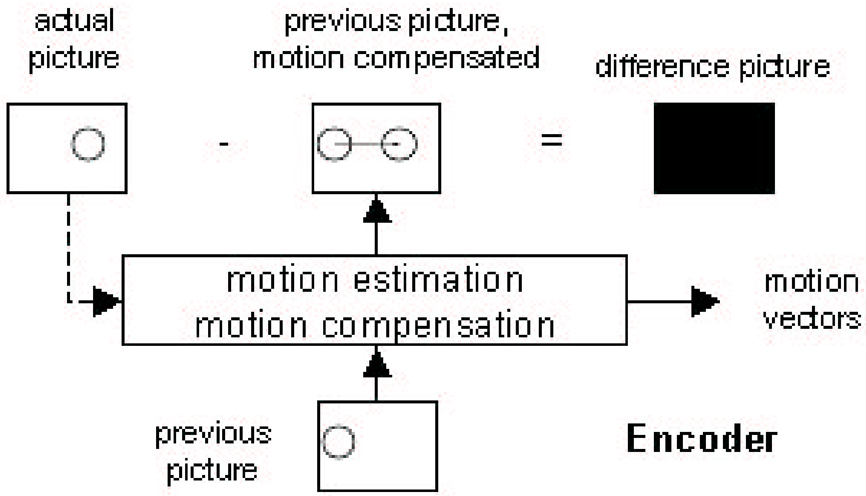
Lets just consider the difference between 2 frames.

It is simple to encode/decode:



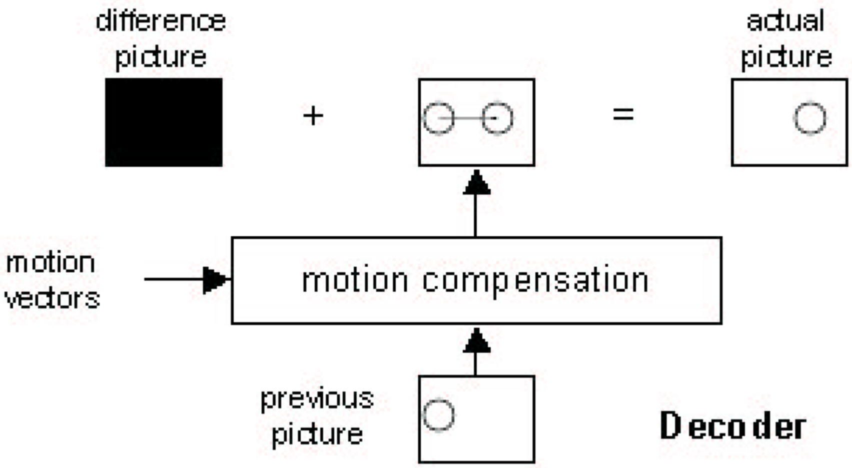
Now lets Estimate Motion of blocks

We will examine methods of estimating motion vectors in due course.



Back
Close

Decoding Motion of blocks



Why is this a better method than just frame differencing?

How is Block Motion used in Compression?

Block Matching:

- MPEG-1/H.261 is done by using block matching techniques,

For a certain area of pixels in a picture:

- find a good estimate of this area in a previous (or in a future) frame, within a specified search area.

Motion compensation:

- Uses the motion vectors to compensate the picture.
- Parts of a previous (or future) picture can be reused in a subsequent picture.
- Individual parts spatially compressed — JPEG type compression

Any Overheads?

- Motion estimation/compensation techniques reduces the video bitrate significantly

  but

- Introduce extras computational complexity and delay (?),
  - Need to buffer reference pictures - backward and forward referencing.
  - Reconstruct from motion parameters

Lets see how such ideas are used in practice.

H.261 Compression

The basic approach to H. 261 Compression is summarised as follows:

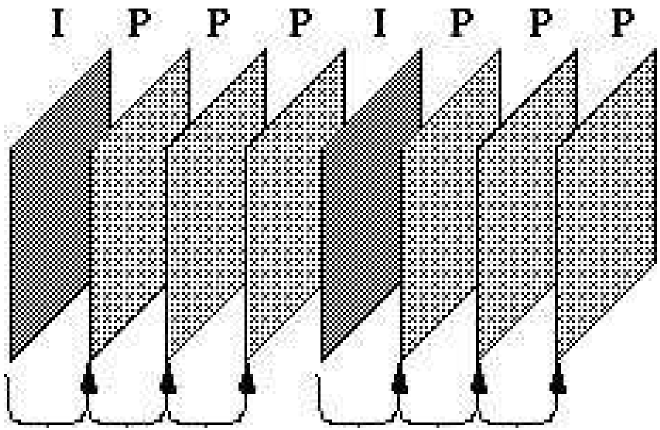
H. 261 Compression has been specifically designed for video telecommunication applications:

- Developed by CCITT in 1988-1990
- Meant for videoconferencing, videotelephone applications over ISDN telephone lines.
- Baseline ISDN is 64 kbits/sec, and integral multiples (px64)

Overview of H.261

- Frame types are CCIR 601 CIF (Common Intermediate Format) (352x288) and QCIF (176x144) images with 4:2:0 subsampling.
- Two frame types:
  Intraframes (*I-frames*) and **Interframes (*P-frames*)**
- I-frames use basically JPEG — **but** YUV (YCrCb) and **larger** DCT windows, **different** quantisation
- I-frames provide us with a refresh accessing point — **Key Frames**
- P-frames use **pseudo-differences** from previous frame (predicted), so frames depend on each other.

H.261 Group of Pictures



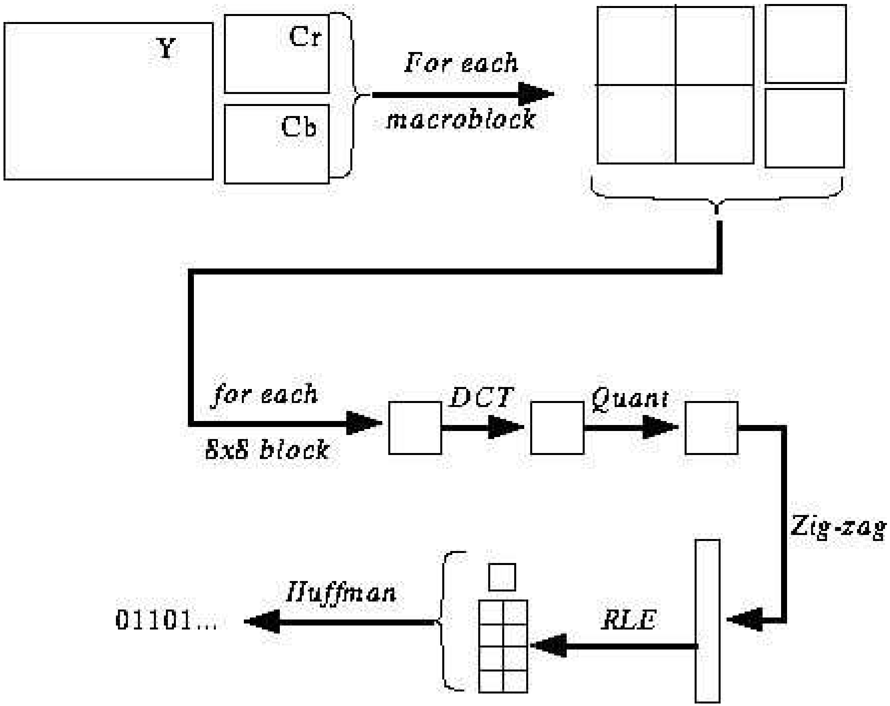
- We typically have a group of pictures — one *I-frame* followed by several *P-frames* — a **group of pictures**
- Number of *P-frames* followed by each *I-frame* determines the size of GOP – can be fixed or dynamic. Why this can't be too large?

Intra Frame Coding

- Various lossless and lossy compression techniques use — like JPEG.
- Compression contained only within the current frame
- Simpler coding – Not enough by itself for high compression.
- Cant rely on intra frame coding alone not enough compression:
  - Motion JPEG (MJPEG) standard does exist — not commonly used.
  - So introduce idea of inter frame difference coding
- However, cant rely on inter frame differences across a large number of frames
  - So when Errors get too large: Start a new I-Frame

Intra Frame Coding (Cont.)

Intraframe coding is very similar to JPEG:



What are the differences between this and JPEG?

Intra Frame Coding (Cont.)

A basic Intra Frame Coding Scheme is as follows:

- Macroblocks are typically 16x16 pixel areas on Y plane of original image.
- A **macroblock** usually consists of 4 Y blocks, 1 Cr block, and 1 Cb block. (4:2:0 chroma subsampling)
  - Eye most sensitive to luminance, less sensitive to chrominance.
    - We operate on a **more effective** color space: YUV (YCbCr) colour which we studied earlier.
  - Typical to use 4:2:0 macroblocks: one quarter of the chrominance information used.
- Quantization is by constant value for all DCT coefficients. **I.e., no quantization table as in JPEG**.

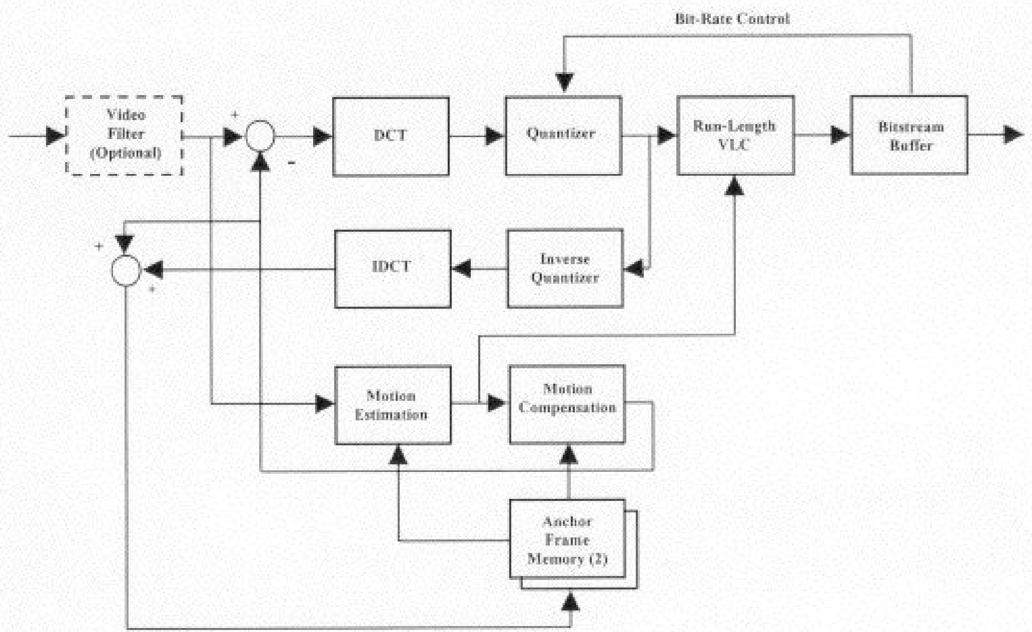
Inter-frame (P-frame) Coding

- Intra frame limited to spatial basis relative to 1 frame
- Considerable more compression if the inherent temporal basis is exploited as well.

BASIC IDEA:

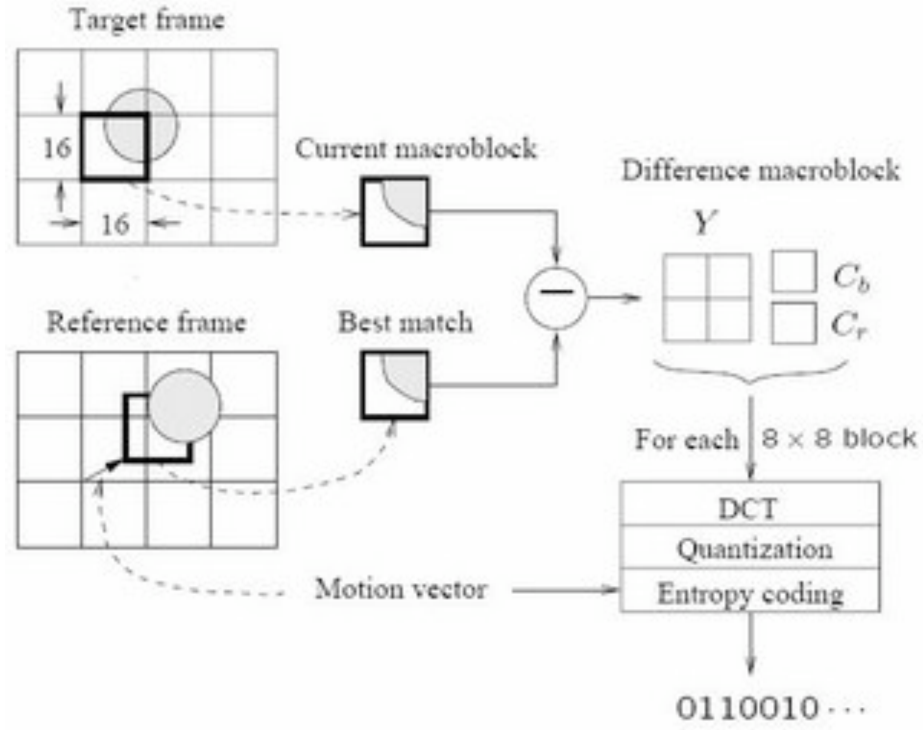
- Most consecutive frames within a sequence are very similar to the frames both before (and after) the frame of interest.
- Aim to exploit this redundancy.
- Use a technique known as **block-based motion compensated prediction**
- Need to use **motion estimation**
- Coding needs extensions for **Inter** but encoder can also supports an **Intra** subset.

Inter-frame (P-frame) Coding (Cont.)



Inter-frame (P-frame) Coding (Cont.)

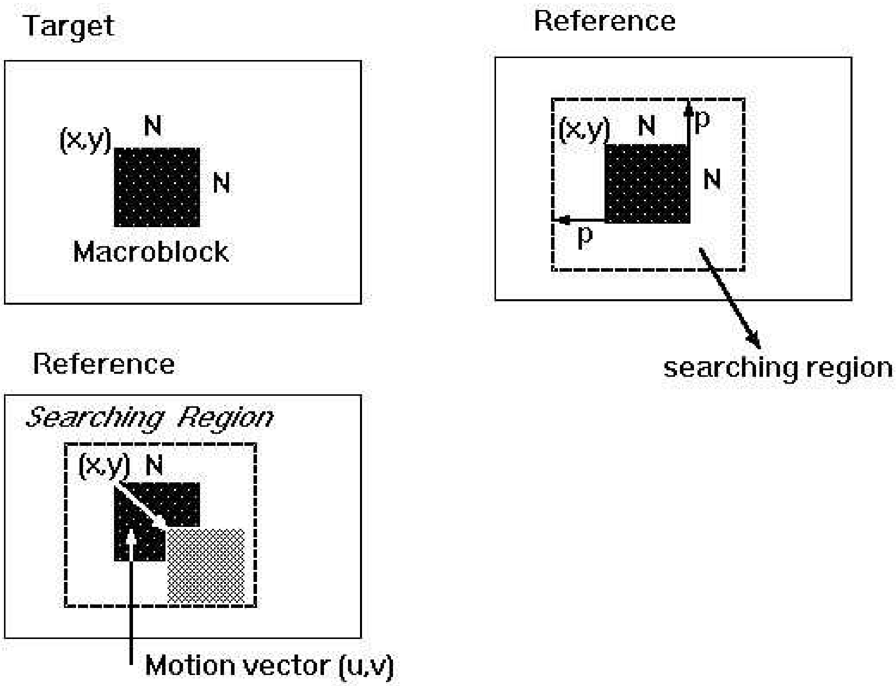
P-coding can be summarised as follows:



Motion Vector Search

So we know how to encode a P-block.

How do we find the motion vector?



Motion Estimation

- The temporal prediction technique used in MPEG video is based on motion estimation.

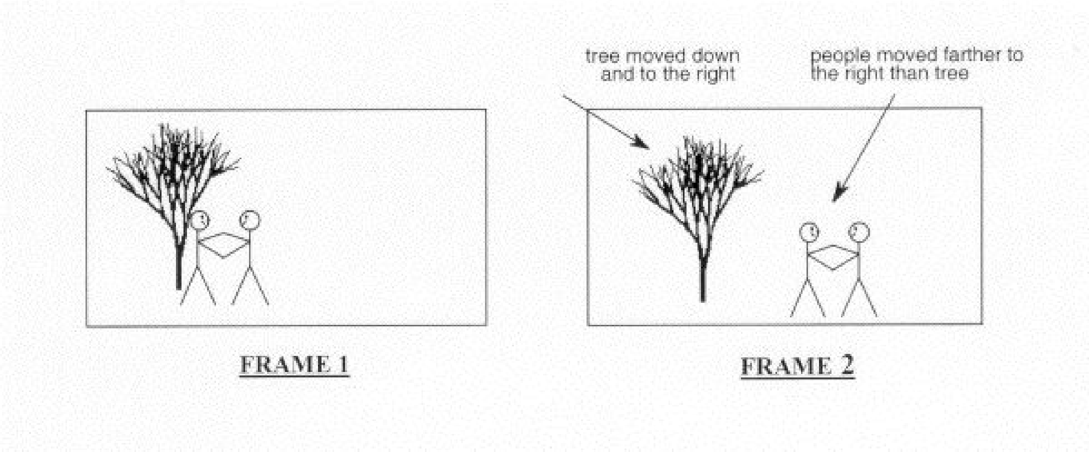
The basic premise:

- Consecutive video frames will be similar except for changes induced by objects moving within the frames.
- Trivial case of zero motion between frames — no other differences except noise, etc.),
- Easy for the encoder to predict the current frame as a duplicate of the prediction frame.
- When there is motion in the images, the situation is not as simple.

Example of a frame with 2 stick figures and a tree

The problem for motion estimation to solve is :

- How to adequately represent the changes, or differences, between these two video frames.

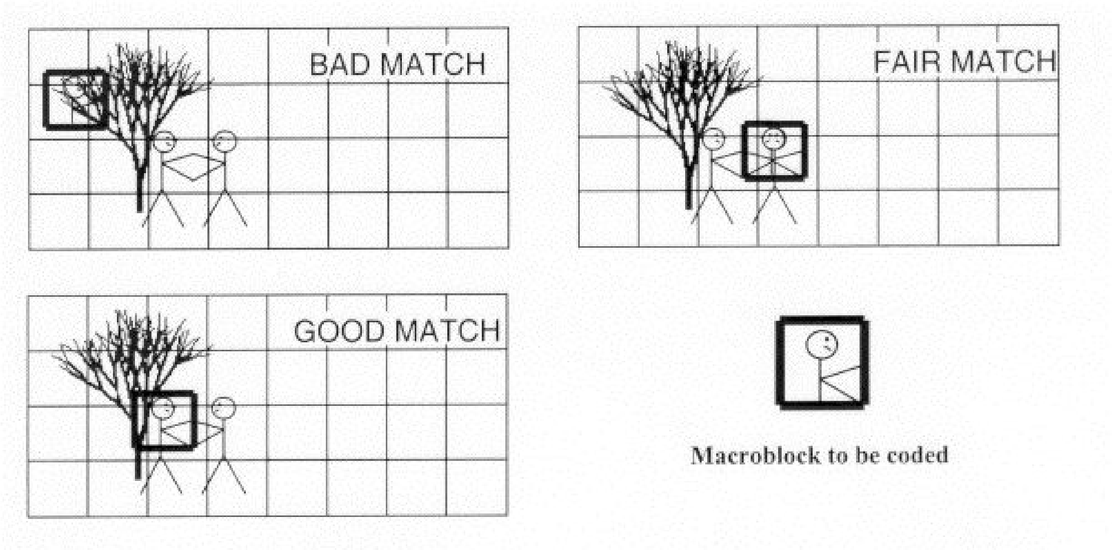


Solution:

A comprehensive 2-dimensional spatial search is performed for each luminance macroblock.

- Motion estimation is not applied directly to chrominance in MPEG
- MPEG does *not* define how this search should be performed.
- A detail that the system designer can choose to implement in one of many possible ways.
- Well known that a full, exhaustive search over a wide 2-D area yields the best matching results in most cases, but at extreme computational cost to the encoder.
- Motion estimation usually is the most computationally expensive portion of the video encoding.

Motion Estimation Example

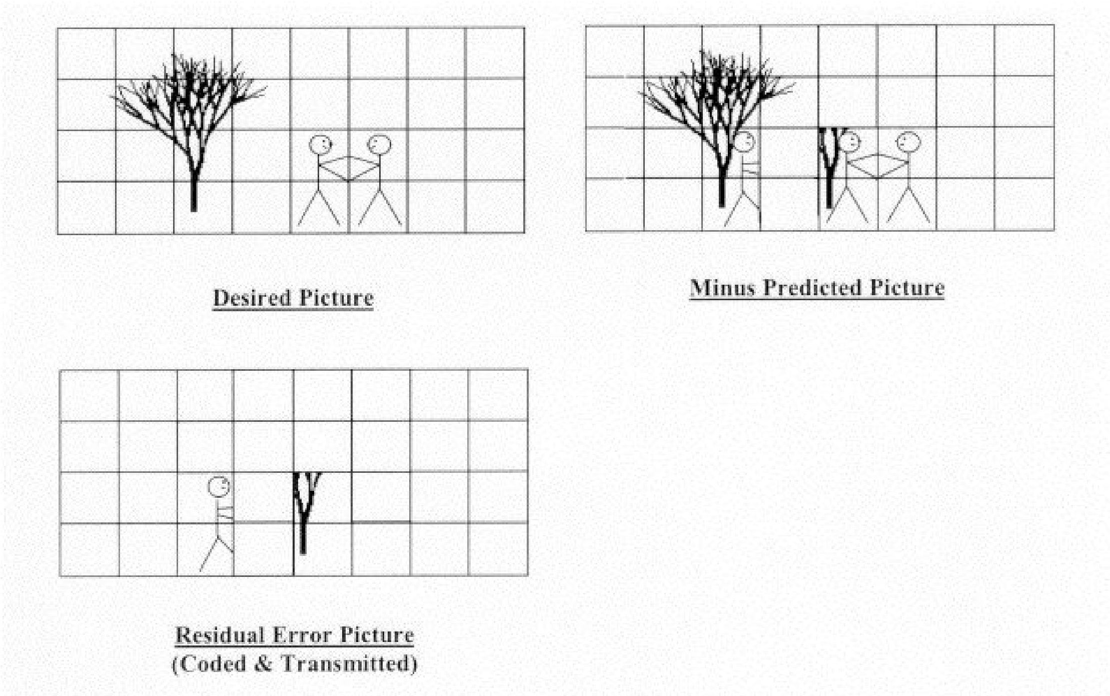


Motion Vectors, Matching Blocks

Previous figure shows an example of a particular macroblock from Frame 2 of earlier example, relative to various macroblocks of Frame 1:

- The top frame has a bad match with the macroblock to be coded.
- The middle frame has a fair match, as there is some commonality between the 2 macroblocks.
- The bottom frame has the best match, with only a slight error between the 2 macroblocks.
- Because a relatively good match has been found, the encoder assigns motion vectors to that macroblock,

Final Motion Estimation Prediction



Final Motion Estimation Prediction (Cont.)

Previous figure shows how a potential predicted Frame 2 can be generated from Frame 1 by using motion estimation.

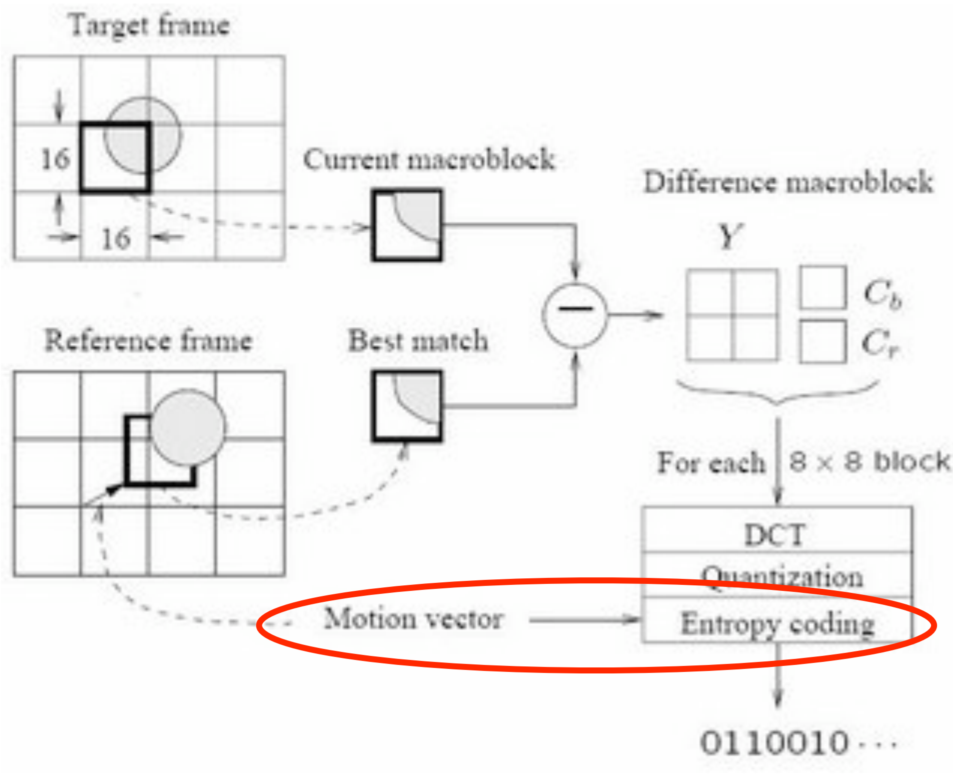
- The predicted frame is subtracted from the desired frame,
- Leaving a (hopefully) less complicated residual error frame which can then be encoded **much more efficiently** than **before** motion estimation.
- The more accurate the motion is estimated and matched, the more likely it will be that the residual error will approach zero — and the coding efficiency will be **highest**.

Further coding efficiency

Differential Coding of Motion Vectors

- Motion vectors tend to be highly correlated between macroblocks:
  - The horizontal component is compared to the previously valid horizontal motion vector and
    - Only the **difference** is coded.
  - Same difference is calculated for the **vertical** component
  - Difference codes are then described with a **variable length code** (*e.g.* Huffman) for **maximum** compression efficiency.

RECAP: P-Frame Coding Summary



What Happens if we can't find acceptable match?

P Blocks may not be what they appear to be?

If the encoder decides that no acceptable match exists then it has the option of

- Coding that particular macroblock as an intra macroblock,
- Even though it may be in a P frame!
- In this manner, high quality video is maintained at a slight cost to coding efficiency.

Estimating the Motion Vectors

So How Do We Find The Motion?

Basic Ideas is to search for Macroblock (MB)

- Within a $\pm n$ x m pixel search window
- Work out **Sum of Absolute Difference (SAD)** (or Mean Absolute Error (MAE) for each window but this is computationally more expensive)
- Choose window where SAD/MAE is a **minimum**.

Sum of Absolute Difference (SAD)

SAD is computed by:

```
For i = -n to +n
  For j = -m to +m
```

$$SAD(i,j) = \Sigma_{k=0}^{N-1}\Sigma_{l=0}^{N-1} \mid C(x+k, y+l) - R(x+i+k, y+j+l) \mid$$

- N = size of Macroblock window typically (16 or 32 pixels),
- (x, y) the position of the original Macroblock, C, and
- R is the **reference** region to compute the SAD.
- $C(x+k, y+l)$ – pixels in the macro block with upper left corner (x, y) in the Target.
- $R(X+i+k, y+j+l)$ – pixels in the macro block with upper left corner $(x+i, y+j)$ in the Reference.

Mean Absolute Error (MAE)

- **Cost function** is:

$$MAE(i,j) = \frac{1}{N^2}\Sigma_{k=0}^{N-1}\Sigma_{l=0}^{N-1} \mid C(x+k, y+l) - R(x+i+k, y+j+l) \mid$$

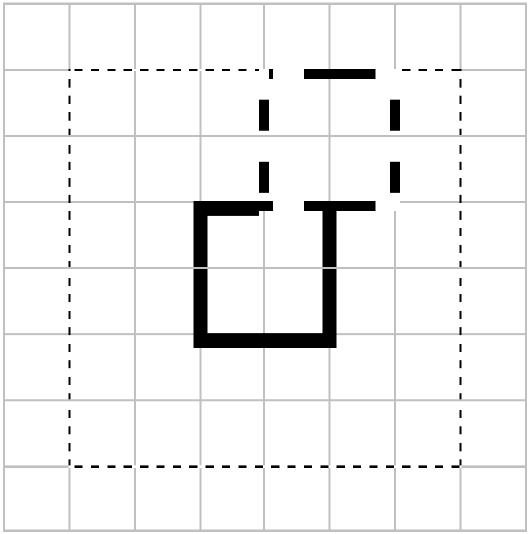
$$\mathrm{MAE}(i, j) = \frac{1}{N^2}\sum_{k=0}^{N-1}\sum_{l=0}^{N-1}\left| C(x+k, y+l) - R(x+i+k, y+j+l)\right|$$

Search For Minimum

- Goal is to find a vector (u, v) such that SAD/MAE (u, v) is minimum
  - Full Search Method
  - Two-Dimensional Logarithmic Search
  - Hierarchical Search

SAD Search Example

So for a $\pm$ 2x2 Search Area given by dashed lines and a 2x2 Macroblock window example, the SAD is given by bold dot dash line (near top right corner):



Full Search

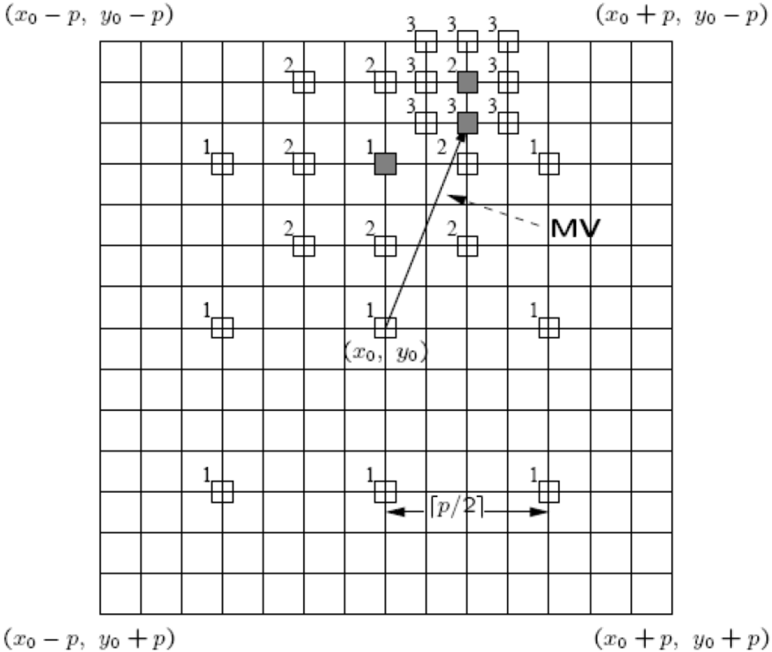
- Search exhaustively the whole $(2n+1) \times (2m+1)$ window in the Reference frame.
- A macroblock centred at each of the positions within the window is compared to the macroblock in the *target* frame pixel by pixel and their respective SAD (or MAE) is computed.
- The vector (i, j) that offers the least SAD (or MAE) is designated as the motion vector (u, v) for the macroblock in the *target* frame.
- Full search is very costly — assuming each pixel comparison involves three operations (subtraction, absolute value, addition), the cost for finding a motion vector for a single macroblock is $(2n+1) \cdot (2m+1) \cdot N^2 \cdot 3 = O(nmN^2)$.

2D Logarithmic Search

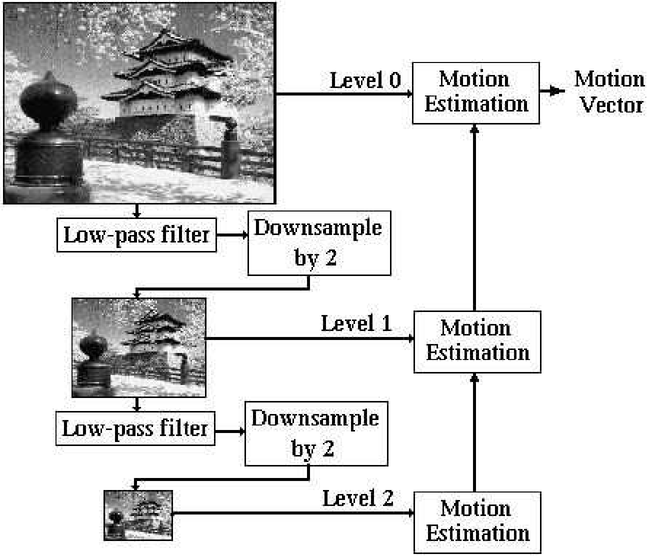
- An approach takes several iterations akin to a binary search.
- Computationally cheaper, suboptimal but usually effective.
- Initially only nine locations in the search window are used as seeds for a SAD(MAE)-based search (marked as '1').
- After locating the one with the minimal SAD(MAE), the centre of the new search region is moved to it and the step-size ("offset") is reduced to half.
- In the next iteration, the nine new locations are marked as '2' and this process repeats.
- If L iterations are applied, for altogether 9^L positions, only $9L$ positions are checked.

2D Logarithmic Search (cont.)

2D Logarithmic Search for Motion Vectors



Hierarchical Motion Estimation:



1. Form several low resolution version of the target and reference pictures
2. Find the best match motion vector in the lowest resolution version.
3. Modify the motion vector level by level when going up

Selecting Intra/Inter Frame coding

Based upon the motion estimation a decision is made on whether INTRA or INTER coding is made.

To determine INTRA/INTER MODE we do the following calculation:

$$MB_{mean} = \frac{\Sigma_{i=0,j=0}^{N-1}|C(i,j)|}{N^2}$$

$$A = \Sigma_{i=0,j=0}^{N-1} \mid C(i,j) - MB_{mean} \mid$$

If $A < (SAD - 2N)$ INTRA Mode is chosen.

MPEG Compression

MPEG stands for:

- **Motion Picture Expert Group** — established circa 1990 to create standard for delivery of audio and video
- MPEG-1 (1991).Target: VHS quality on a CD-ROM (320 x 240 + CD audio @ 1.5 Mbits/sec)
- MPEG-2 (1994): Target Television Broadcast
- MPEG-3: HDTV but subsumed into an extension of MPEG-2
- MPEG 4 (1998): Very Low Bitrate Audio-Visual Coding, later MPEG-4 Part 10(H.264) for wide range of bitrates and better compression quality
- MPEG-7 (2001) "Multimedia Content Description Interface"
- MPEG-21 (2002) "Multimedia Framework"

Three Parts to MPEG

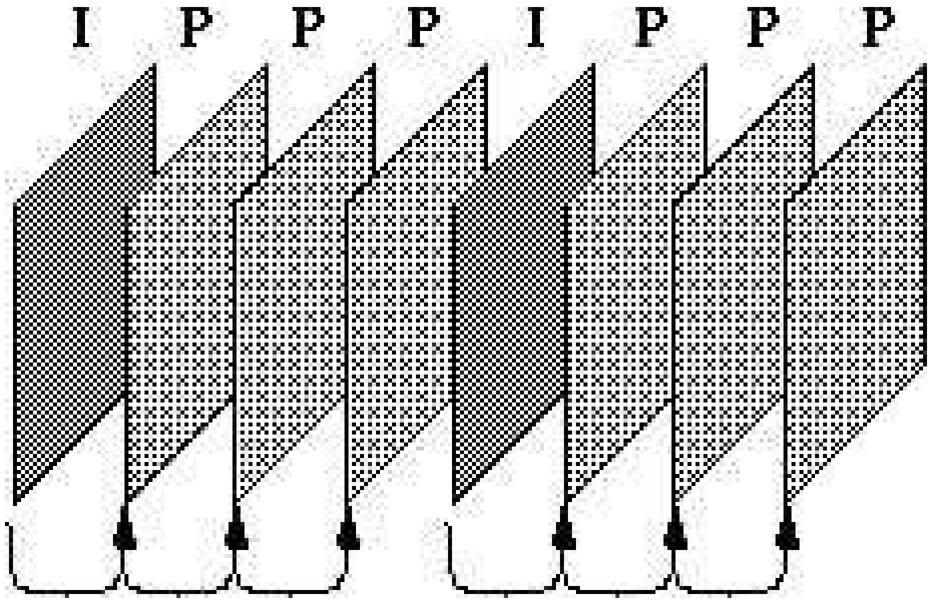
- The MPEG standard had three parts:

  1. Video: based on H.261 and JPEG
  2. Audio: based on MUSICAM (Masking pattern adapted Universal Subband Integrated Coding And Multiplexing) technology
  3. System: control interleaving of streams

MPEG Video

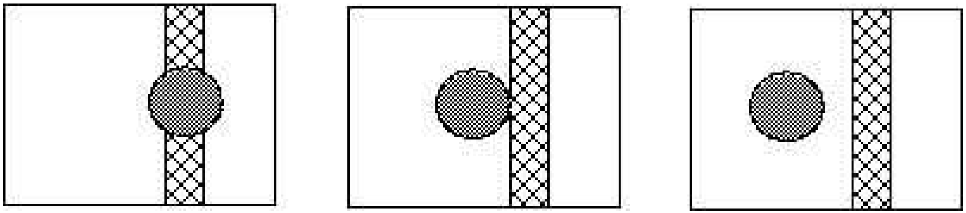
MPEG compression is essentially an attempt to overcome some shortcomings of H.261 and JPEG:

- Recall H.261 dependencies:



The Need for a Bidirectional Search

- The Problem here is that many macroblocks need information that is **not** in the reference frame.
- For example:

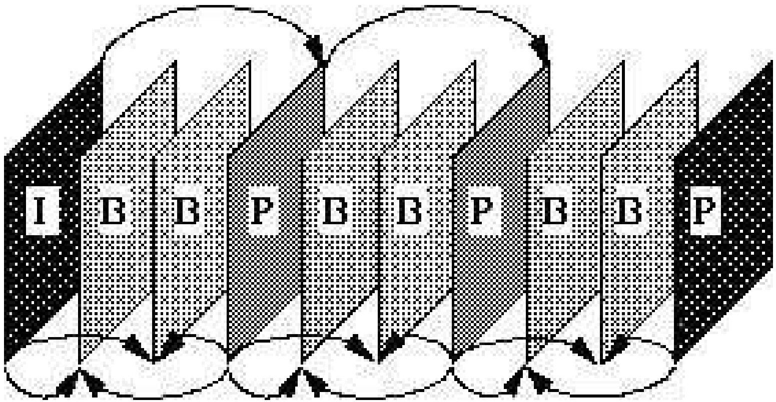


- Occlusion by objects affects differencing
- Difficult to track occluded objects *etc.*
- MPEG uses **forward/backward** interpolated prediction.

MPEG B-Frames

- The **MPEG solution** is to add a third frame type which is a **bidirectional** frame, or *B-frame*
- B-frames search for macroblock in *past* and *future* frames.
- Typical pattern is IBBPBBPBB IBBPBBPBB IBBPBBPBB

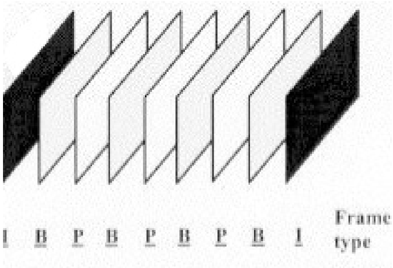
  Actual pattern is up to encoder, and need not be regular.



Example I, P, and B frames

Consider a group of pictures that lasts for 6 frames:

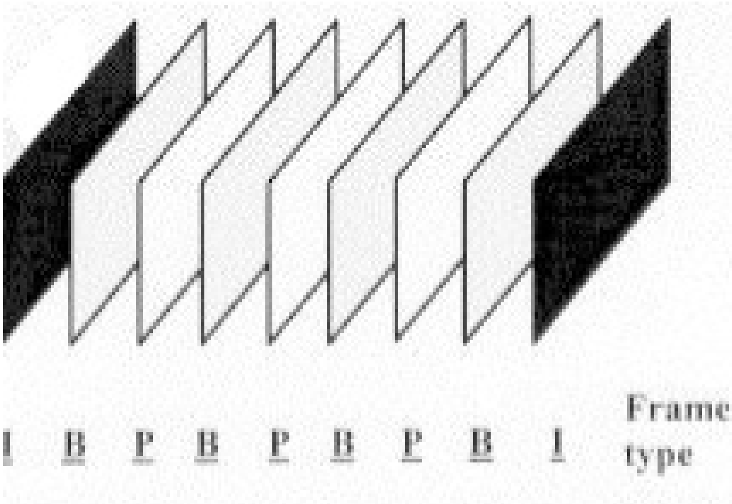
- Given: I,B,P,B,P,B,I,B,P,B,P,B,



- I frames are coded spatially only (as before in H.261).
- P frames are forward predicted based on previous I and P frames (as before in H.261).
- B frames are coded based on a forward prediction from a **previous** I or P frame, **as well** as a **backward prediction** from a **succeeding** I or P frame.

Example I, P, and B frames (Cont.)

- 1st B frame is predicted from the 1st I frame and 1st P frame.
- 2nd B frame is predicted from the 1st and 2nd P frames.
- 3rd B frame is predicted from the 2nd and 3rd P frames.
- 4th B frame is predicted from the 3rd P frame and the 1st I frame of the **next** group of pictures.

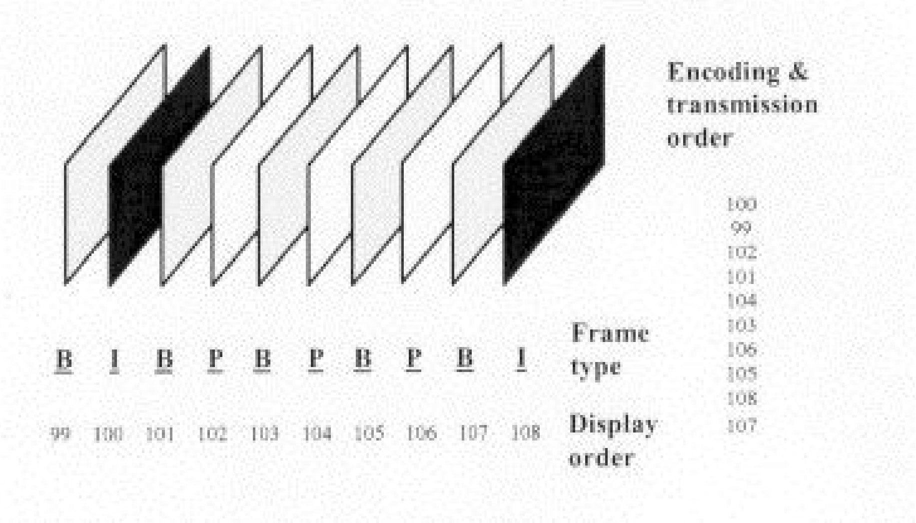


Backward Prediction Implications

Note: Backward prediction requires that the **future frames** that are to be used for **backward prediction** be

- Encoded and Transmitted **first**, *I.e.* **out of order**.

This process is summarised:



Backward Prediction Implications (Cont.)

Also NOTE:

- No defined limit to the number of consecutive B frames that may be used in a group of pictures,
- Optimal number is application dependent.
- Most broadcast quality applications however, have tended to use 2 consecutive B frames (I,B,B,P,B,B,P,) as the ideal trade-off between compression efficiency and video quality.
- MPEG suggests some standard groupings.

Advantage of the usage of B frames

- **Coding efficiency**.
- Most B frames use less bits.
- Quality can also be improved in the case of moving objects that reveal hidden areas within a video sequence.
- Better Error propagation: B frames are not used to predict future frames, errors generated will not be propagated further within the sequence.

Disadvantage:

- Frame reconstruction memory buffers within the encoder and decoder must be doubled in size to accommodate the 2 anchor frames.
- More delays in real-time applications.

MPEG-2, MPEG-3, and MPEG-4

- MPEG-2 target applications

Level	size	Pixels/sec	bit-rate (Mbits)	Application
Low	352 x 240	3 M	4	VHS tape equiv.
Main	720 x 480	10 M	15	studio TV
High 1440	1440 x 1152	47 M	60	consumer HDTV
High	1920 x 1080	63 M	80	film production

- MPEG-2 differences from MPEG-1

1. Search on fields, not just frames.
2. 4:2:2 and 4:4:4 macroblocks
3. Frame sizes as large as 16383 x 16383
4. Scalable modes: Temporal, Progressive,...
5. Non-linear macroblock quantization factor
6. A bunch of minor fixes

MPEG-2, MPEG-3, and MPEG-4 (Cont.)

- MPEG-3: Originally for HDTV (1920 x 1080), got folded into MPEG-2
- MPEG-4: very low bit-rate communication (4.8 to 64 kb/sec). Video processing

MATLAB MPEG Video Coding Code

MPEGVideo (DIRECTORY)
MPEGVideo.zip (All Files Zipped)