Insight, Analysis, and Advice on Signal Processing Technology

Introduction to Video Compression

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Outline

- **Motivation and scope**
- Still-image compression techniques
- Motion estimation and compensation
- Reducing artifacts
- Color conversion
- Conclusions

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Motivation and Scope

- Consumer video products increasingly rely on video compression
  - DVDs, digital TV, personal video recorders, Internet video, multimedia jukeboxes, video-capable cell phones and PDAs, camcorders…
- Video product developers need to understand the operation of video "codecs"
  - To select codecs, processors, software modules
  - To optimize software
- This presentation covers:
  - Operation of video codecs and post-processing
  - Computational and memory demands of key codec and post-processing components

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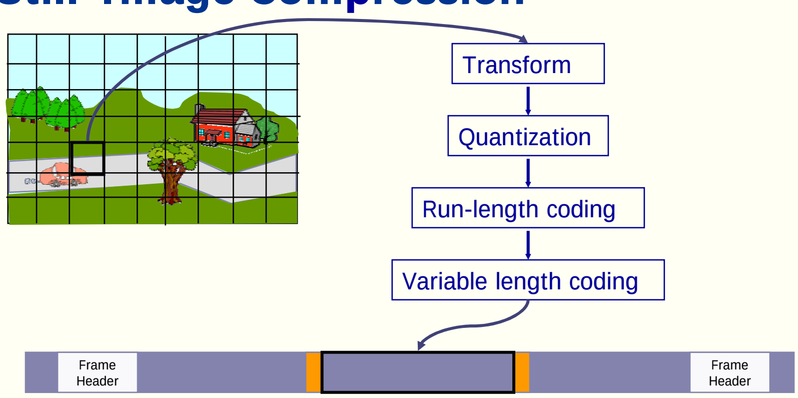
Still-Image Compression

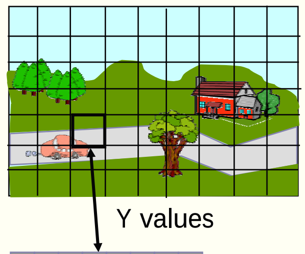
- Still-image compression
  - Still-image techniques provide a basis for video compression
  - Video can be compressed using still-image compression individually on each frame
  - E.g., “Motion JPEG” or MJPEG
- But modern video codecs go well beyond this
  - Start with still-image compression techniques
  - Add motion estimation/compensation
    - Takes advantage of similarities between frames in a video sequence

Still-Image Compression

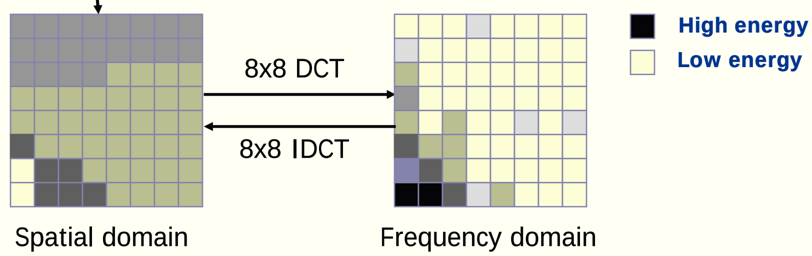


Typical Still-Image Compression Data Flow

Block Transform: 8x8 DCT



- 8x8 DCT blocks applied on Y, U, and V planes individually
- The energy is concentrated in the low frequencies
- Perceptual information also concentrated in low frequencies



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Block Transform: Resource Reqt's

- Compute load:
  - Up to 30% of total video decoder processor cycles
  - MPEG-4 CIF (352x288) @ 30 fps:
    - 71,280 DCTs/s
    - ~40 MHz on a TMS320C55x DSP
    - ~10 MHz if using TMS320C55x DCT accelerator
  - Many implementation and optimization options
    - Can make compute requirements hard to predict
- Memory usage: negligible

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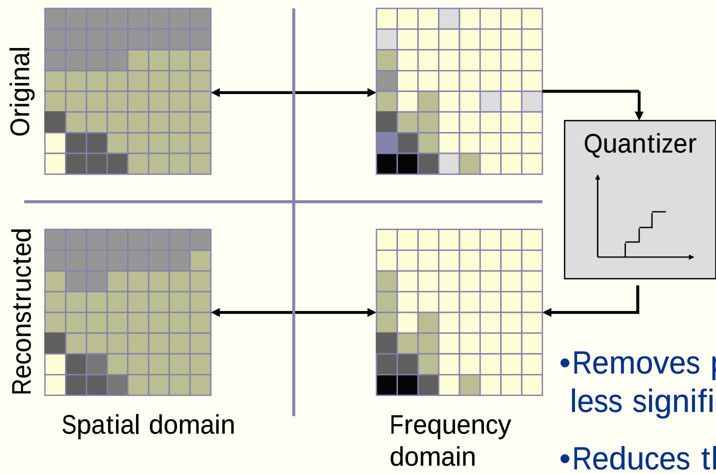
Quantization



- Removes perceptually less significant data
- Reduces the number of bits per DCT coefficient

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Quantization: Resource Reqt's

- Quantization (encoder) and dequantization (decoder and encoder) have similar compute loads
- Compute load:
  - From 3% to about 15% of total decoder processor cycles
    - Typically near the lower end of this range
  - MPEG-4 CIF (352x288) @ 30 fps:
    - ~10 MHz on a TMS320C55x DSP (estimated)
- Memory usage: negligible

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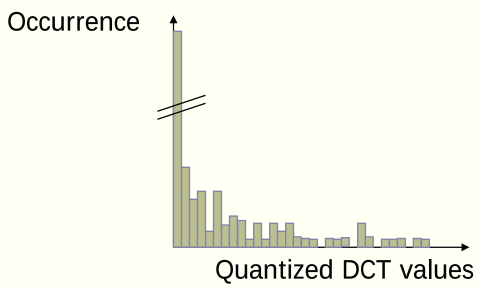
Coding Quantized DCT Coefficients

Goal: Reduce the number of bits required to transmit the quantized coefficients



Observation: Unequal distribution of quantized DCT coefficient values

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Variable Length Coding (VLC/VLD)

- Allocates fewer bits to the most frequent symbols (e.g., using Huffman)
- Integer number of bits per symbol
  - Not the most efficient coding method
  - Arithmetic coding more efficient, but expensive
  - Run-length coding improves efficiency of VLC/VLD for image and video coding

Symbol	Frequency	Code
A	22	1
B	16	011
C	9	0101
D	7	0100
E	4	0011
F	2	0010
…	…	…

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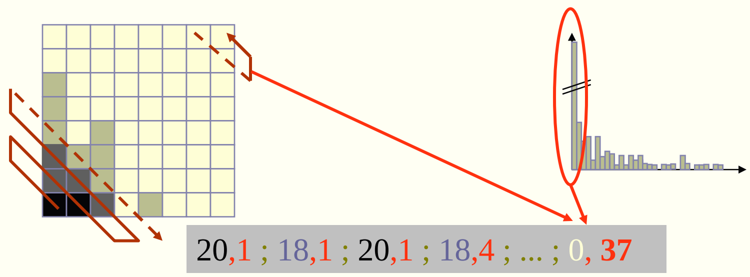
Run-Length Coding

Encodes value and number of successive occurrences

Takes advantage of the high number of recurring zeros

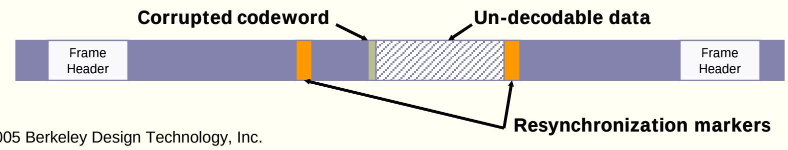


Variable Length Coding: Processing Reqt's

- VL decoding much more computationally demanding than VL encoding
- VLD compute load:
  - Up to 25% of total video decoder processor cycles
  - MPEG-4 CIF (352x288) @ 30 fps, 700 kbps:
    - ~15-25 MHz on a TMS320C55x DSP (estimated)
  - About 11 operations per bit on average
- Memory usage
  - A few KB of memory for lookup tables
  - More for speed optimizations

Resynchronization Markers

- Without markers, a single bit error in the coded bitstream prevents decoding of the rest of the frame
  - Size of a corrupted variable-length code word is unknown
  - Therefore, the start of the next code word (and all following code words) is unknown
- Resynchronization markers help the decoder recover from bitstream errors
  - Provide a known bit pattern interspersed throughout the bitstream
  - In case of an error, decoder searches for next marker, then continues decoding



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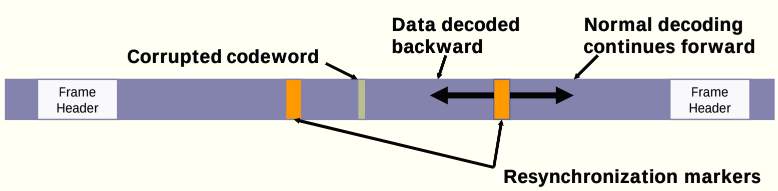
Reversible VLC

- Reversible VLC, in conjunction with resynchronization markers, further assists error recovery
  - Code words can be decoded forward and backward
  - In case of error, data can be decoded backward from the next resynchronization marker
  - More data is recovered compared to resynchronization markers alone



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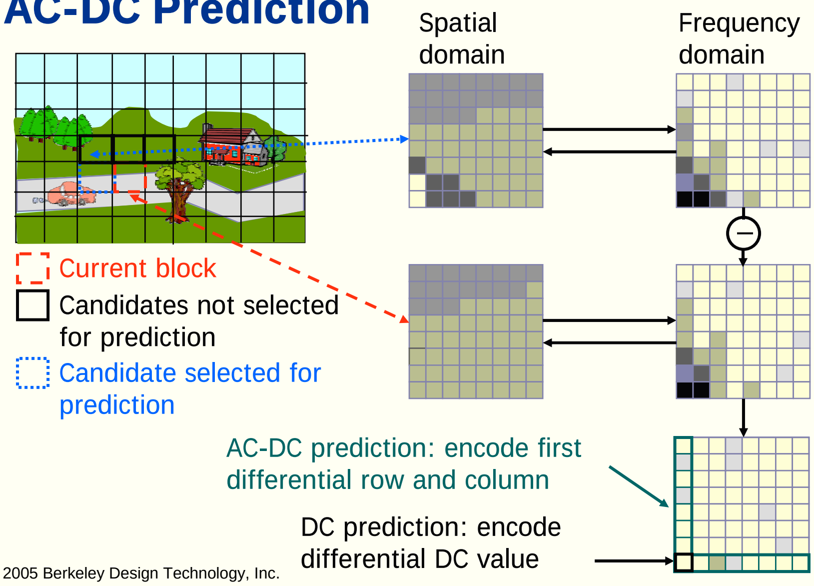
AC-DC Prediction



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AC-DC Prediction

- AC-DC prediction cannot be used in conjunction with motion compensation
  - ⇒ Used mostly for compressing a single image
  - DC prediction used in JPEG
- AC-DC prediction often uses simple filters to predict each coefficient value from one or more adjacent blocks

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AC-DC Prediction: Processing Reqt's

- Compute load:
  - DC prediction has negligible load
  - AC-DC prediction used in about 8% of frames in typical video
    - Negligible average load (~2% of processor cycles in decoder)
    - Substantial per-frame load (~20-30% of cycles required to decode a frame that uses AC-DC prediction)
- Memory usage:
  - Under 2 KB for CIF (352x288) resolution
    - But more memory (up to 10 KB) can result in faster code
  - May be overlapped with other memory structures not in use during prediction

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Motion Estimation and Compensation

- Still image compression ignores the correlation between frames of video
  - JPEG achieves ~10:1 compression ratio
  - Wavelet transform-based image coding reaches compression ratios up to ~30:1
- Adding motion estimation and compensation results in much higher compression ratios
  - Good video quality at compression ratios as high as ~200:1

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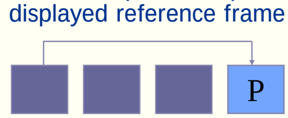
Motion Estimation and Compensation

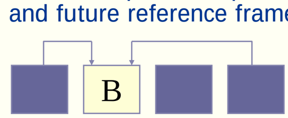
- Requires at least one "reference frame"
  - Reference frame must be encoded before the current frame
  - But, reference frame can be a future frame in the display sequence
- Three kinds of frames: I, P, and B

- I frame is encoded as a still image and doesn't depend on any reference frame

- P frame depends on previously displayed reference frame



- B frame depends on previous and future reference frames



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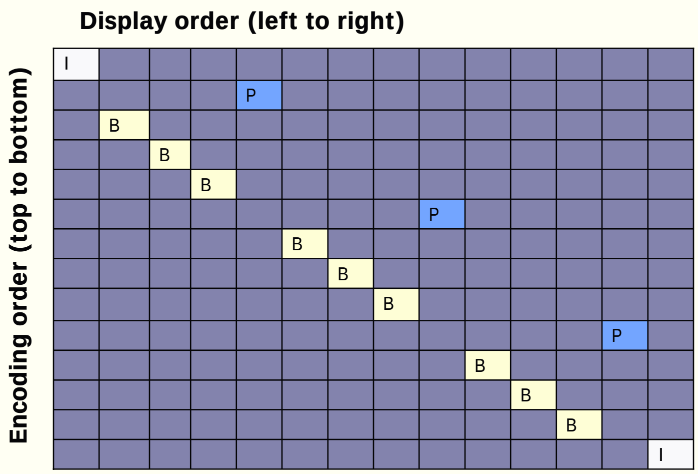
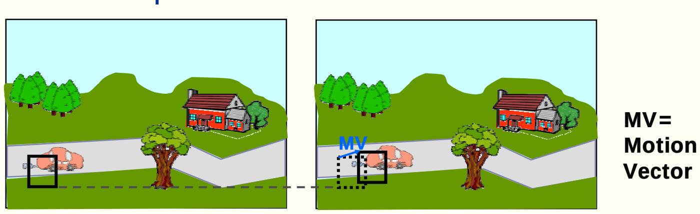
Typical Sequence of I, P, B frames

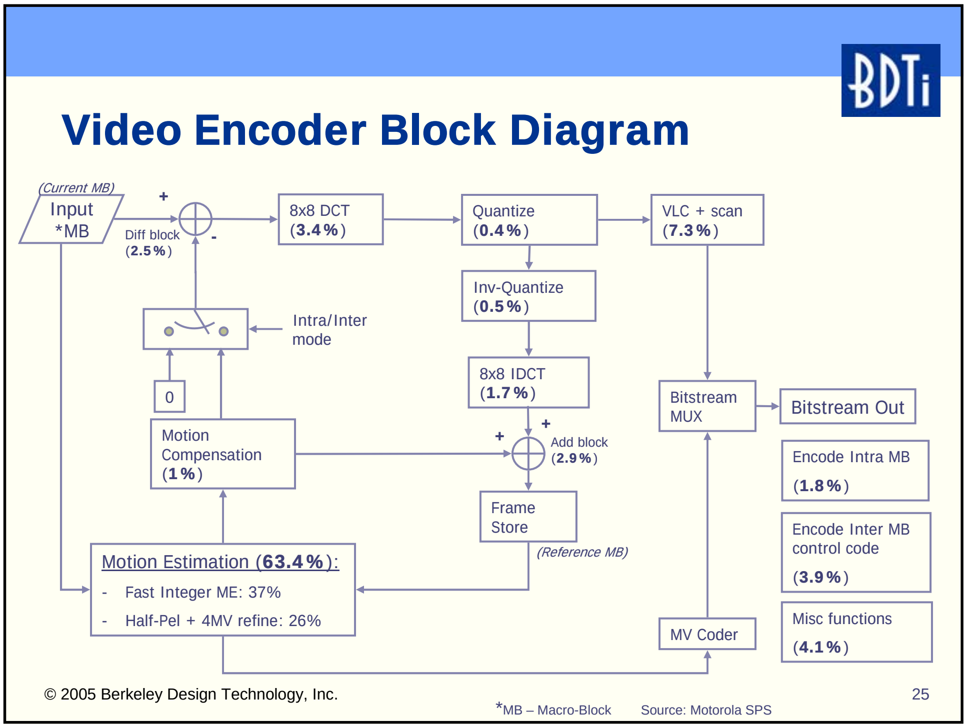


Motion Estimation

- Predict the contents of each macroblock based on motion relative to reference frame
  - Search reference frame for a 16x16 region that matches the macroblock
  - Encode motion vectors
  - Encode difference between predicted and actual macroblock pixels



Reference frame   Current frame


Video Encoder Block Diagram
(Current MB)
Input
*MB
+
Diff block
(2.5%)
-
8x8 DCT
(3.4%)
Quantize
(0.4%)
VLC + scan
(7.3%)
Inv-Quantize
(0.5%)
Intra/Inter
mode
0
8x8 IDCT
(1.7%)
Bitstream
MUX
Bitstream Out
Motion
Compensation
(1%)
+
+
Add block
(2.9%)
Encode Intra MB
(1.8%)
Frame
Store
(Reference MB)
Encode Inter MB
control code
(3.9%)
Motion Estimation (63.4%):
- Fast Integer ME: 37%
- Half-Pel + 4MV refine: 26%
MV Coder
Misc functions
(4.1%)
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*MB – Macro-Block
Source: Motorola SPS
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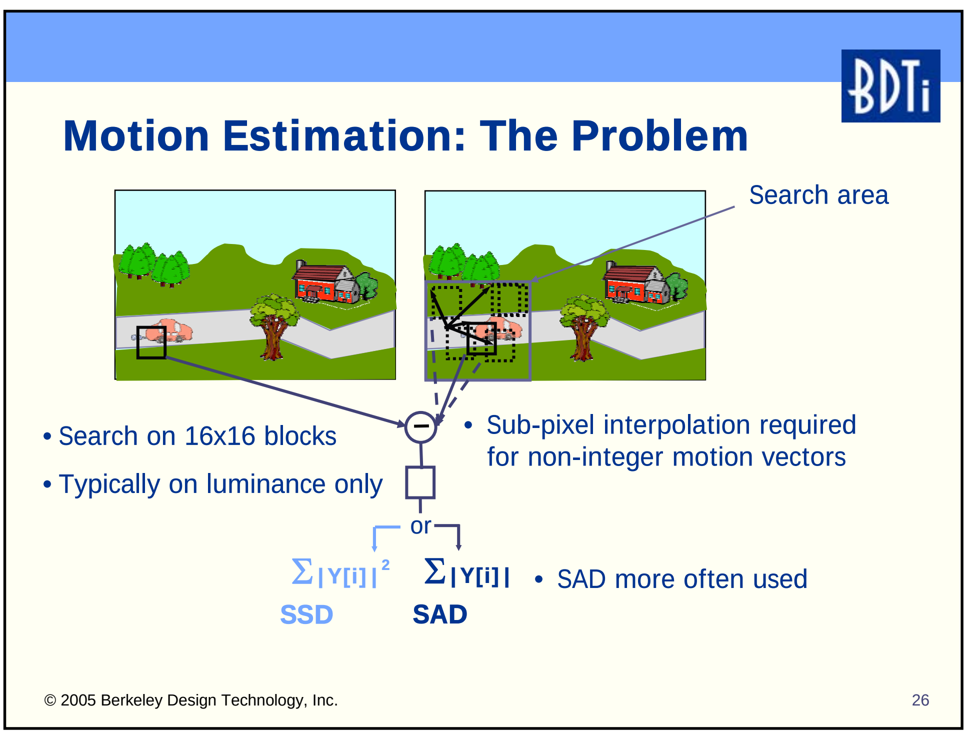
Motion Estimation: The Problem
Search area
• Search on 16x16 blocks
• Typically on luminance only
• Sub-pixel interpolation required
for non-integer motion vectors
or
Σ|Y[i]|²
SSD
Σ|Y[i]|
SAD
• SAD more often used
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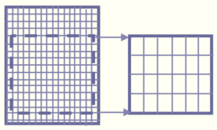
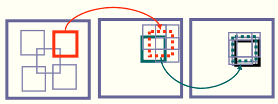
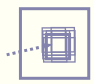
Motion Estimation: Efficient Motion Vector Search







- Exhaustive search is impractical
- Evaluate only promising candidate motion vectors
  - Don’t have to find absolute best match
    - Trade video quality for computational load
  - Many methods in use
    - Often proprietary
    - Refine candidate vector selection in stages
    - Predict candidate vectors from surrounding macroblocks and/or previous frames

Motion vector search approach is a key differentiator between video encoder implementations

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Motion Estimation: Processing Reqt’s

- Compute load
  - Most demanding task in video compression
    - Up to 80% of total encoder processor cycles
    - Many search methods exist; requirements vary by method
    - May vary with video program content
    - Makes encoder computational demand several times greater than that of the decoder
    - Dominated by SAD computation
- Memory usage
  - Motion estimation requires reference frame buffers
    - Frame buffers dominate the memory requirements of the encoder
    - E.g., 152,064 bytes per frame @ CIF (352x288) resolution
  - High memory bandwidth required

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Motion Compensation: Processing Reqt's

- Motion compensation copies pixels from reference frame to predict current macroblock
  - Requires interpolation for non-integer motion vector values
- Compute load
  - Varies with video program content
  - Can require from 5% to 40% of total decoder processor cycles
  - MPEG-4 CIF (352x288) @ 30 fps:
    - Roughly 15-25 MHz on a TMS320C55x DSP (estimated)
- Memory usage
  - Requires reference frame buffers
    - Frame buffers dominate decoder memory requirements
  - Good memory bandwidth is desirable, but less critical compared to motion estimation

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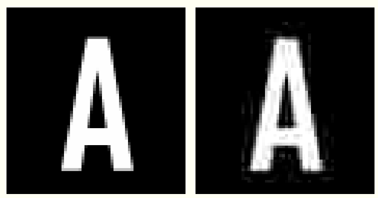
Artifacts: Blocking and Ringing

- **Blocking:** Borders of 8x8 blocks visible in reconstructed frame

- **Ringing:** Distortions near edges of image features

Original image



Reconstructed image (with ringing Artifacts)

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Deblocking and Deringing Filters

Low-pass filters are used to smooth the image where artifacts occur

- **Deblocking:**
  - Low-pass filter the pixels at borders of 8x8 blocks
  - One-dimensional filter applied perpendicular to 8x8 block borders
- **Deringing:**
  - Detect edges of image features
  - Adaptively apply 2D filter to smooth out areas *near* edges
  - Little or no filtering applied to edge pixels in order to avoid blurring

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Artifact Reduction

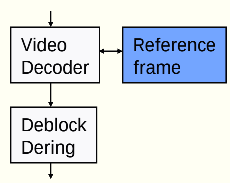
Example: Deblocking

Original MPEG Still Frame

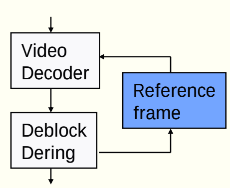
Horizontally & Vertically Deblocked Still Frame

Artifact Reduction: Post-processing vs. In-loop

- Deblocking/deringing often applied after the decoder (post-processing)
  - Reference frames are not filtered
  - Developers free to select best filters for the application or not filter at all



- Deblocking/deringing can be incorporated in the compression algorithm (in-loop filtering)
  - Reference frames are filtered
  - Same filters must be applied in encoder and decoder
  - Better image quality at very low bit-rates



Artifact Reduction: Processing Reqt's

- Deblocking and deringing filters can require more processor cycles than the video decoder
  - Example: MPEG-4 Simple Profile, Level 1 (176x144, 15 fps) decoding requires 14 MIPS on ARM's ARM9E for a relatively complex video sequence
  - With deblocking and deringing added, load increases to 39 MIPS
    - Nearly 3x increase compared to MPEG-4 decoding alone!
- Post-processing may require an additional frame buffer

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Color Space Conversion

- Need for color conversion
  - Capture and display video equipment: RGB...
  - ...while codecs use YUV
- Computational demand
  - 12 operations per pixel ⇒ 36 million operations/second for CIF (352x288) @ 30 fps
    - About 36 MHz on a TMS320C55x DSP
    - Not including interpolation of chrominance planes
  - Roughly 1/3 to 2/3 as many processor cycles as the video decoder

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Conclusions

Understanding the computational and memory requirements of video compression is critical but challenging

- Application design choices are driven by computational and memory requirements
  - Algorithm selection, processor selection, software optimization
  - Video processing often stresses processing resources
- But video applications combine many different signal-processing techniques
  - Transforms, prediction, quantization, entropy coding, image filtering, etc.
- And there is large variation in computational and memory requirements among different applications
  - E.g., digital camcorder has vastly different requirements from a video-enabled cell phone, even when using the same compression standard

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Conclusions, cont.

- Understanding computational load
  - Computational load of encoder is several times greater than that of decoder due to motion estimation
  - Computational load proportional to frame size and rate for most functions
    - Note: VLD computational load is proportional to bit rate
  - Post-processing steps—deblocking, deringing, color space conversion—add considerably to the computational load
- Computational load can be difficult to predict
  - Many different approaches to motion estimation
  - Computational load of some tasks can fluctuate wildly depending on video program content
    - E.g., motion compensation

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Conclusions, cont.

- Understanding memory requirements:
  - Memory requirements dominated by frame buffers
    - A decoder that supports only I and P frames requires two frame buffers (current and reference)
    - A decoder that supports I, P, and B frames requires three buffers (current and two reference)
    - Deblocking/deringing/color conversion may require an additional buffer
  - Program memory, tables, other data comprise a non-negligible portion of memory use
    - But this portion is still several times smaller than frame buffers
- High memory use often necessitates off-chip memory
  - Off-chip memory bandwidth can be a performance bottleneck

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Conclusions, cont.

- Video compression used in many products
  - DVDs, digital TV, personal video recorders, Internet video, multimedia jukeboxes, video-capable cell phones and PDAs, camcorders…
- Different products have different needs
  - Wide range of frame sizes and rates, video quality, bit rates, post-processing options, etc.
  - Result in wide range of computational and memory requirements
- Need to understand the operation of video codecs
  - To understand computational and memory requirements
  - To select codecs, processors, software modules
  - To optimize software

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