Exact and Error-bounded Approximate Color Buffer Compression and Decompression

Jim Rasmusson[1,2]

Jon Hasselgren[1]

Tomas Akenine-Möller[1]

[1] Lund University
[2] Ericsson

Outline

- Rationale
- Prior art
- A new color buffer compression algorithm
  - Exact (lossless) mode
  - Approximate (lossy) mode
- Results
- Conclusions
- Future work

Why color buffer compression?

- Graphics processing speeds: ~ +70% /yr
- Memory bandwidth speeds: ~ +25% /yr

  ➡ increasing need for compression techniques aimed at saving bandwidth

- Texture, depth and color buffer compression

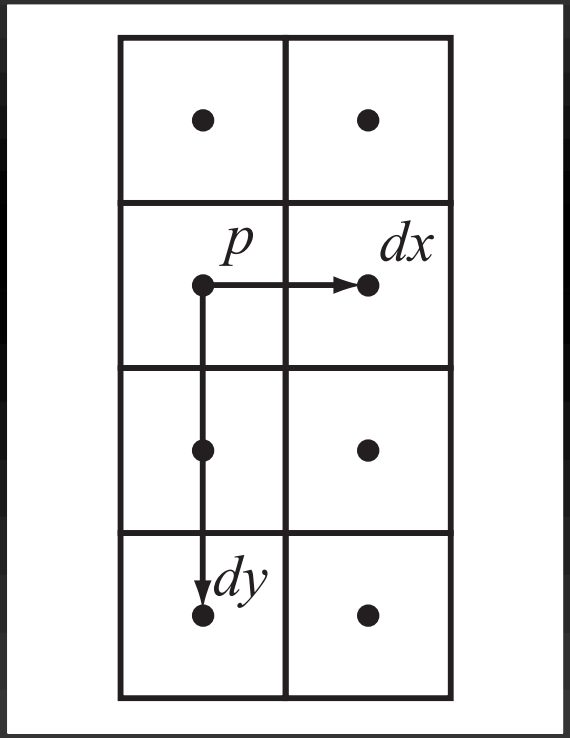
Prior art

1. Color plane compression [Molnar et al 04]
2. Color offset compression [Morein and Natale 03]
3. Entropy coded pixel differences [van Hook 06]

- All are tiles based
- All are lossless
- Implemented and benchmarked

Prior art 1: Color plane compression

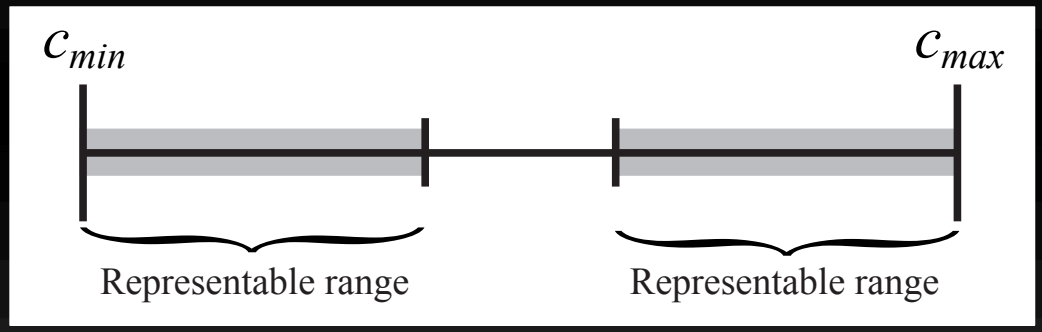
- Calculate predictor plane using 3 fixed reference pixels (p, dx, dy)
- Store differences between plane and actual color
- 2x4 pixel tiles



- Simple and robust
- Low compression ratios

Prior art 2: Color offset compression

- Identify and store reference values (e.g. max and min)

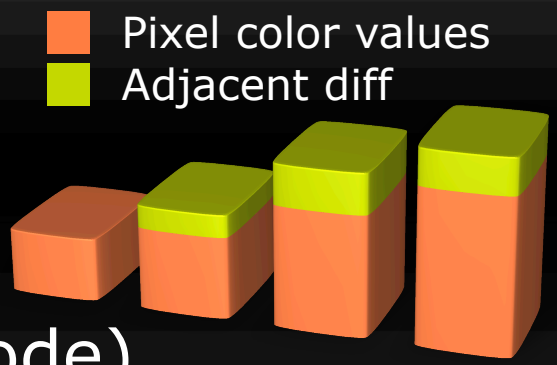


- Store offset values and reference index

- Simple and robust
- Medium compression ratios

Prior art 3: Entropy coded pixel differences

- Calculate adjacent pixel differences
  - Different traversal modes

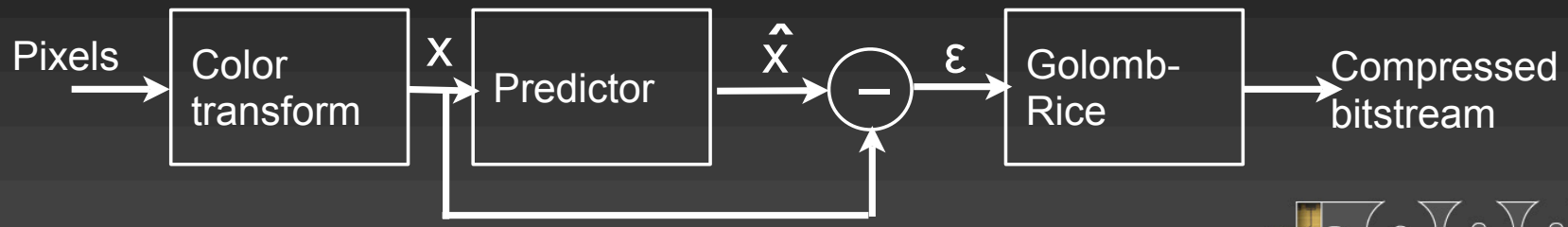


- Entropy coding ("Exponent" encode)
  - Similar to Golomb-Rice

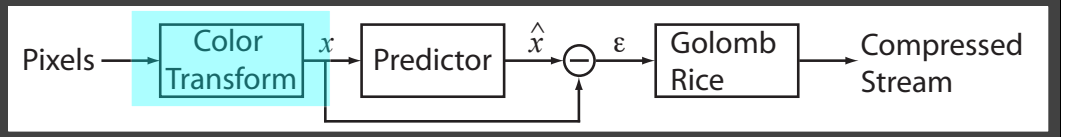
- Medium complexity
- Good compression ratios

Our algorithm, Exact mode

- New combination of known building blocks
  - Exact reversible color transform (RGB to Luminance-Chrominance)
  - Predictor (2x2 pixels)
  - Golomb-Rice encoding (adaptive variable bit rate)
- 8x8 pixel tiles



Exact reversible color transform



- Bit-exact reversible
- Decorrelates RGB components
  - typically improves compression rates
- We use Malvar and Sullivan [03]
- An alternative is RCT (JPEG2000)

- Enables different compression modes for luminance and chrominance

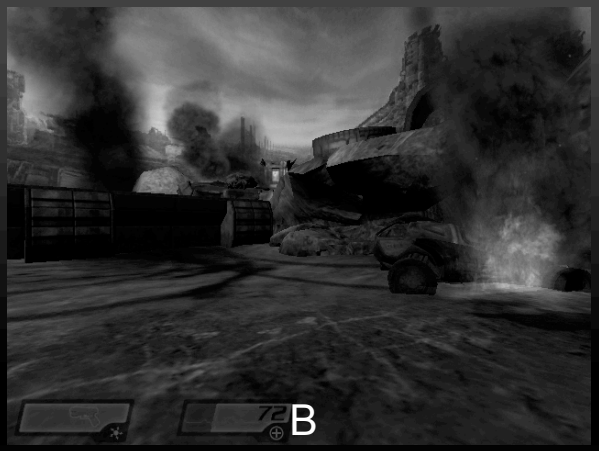
RGB to YCoCg:

Co = R – B
temp = B + (Co >> 1)
Cg = G – temp
Y = temp + (Cg >> 1)

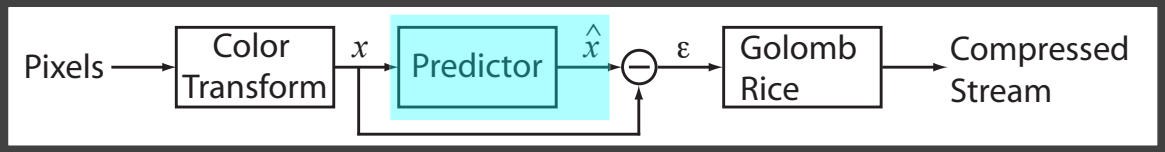
YCoCg to RGB:

temp = Y – (cg >> 1)
G = Cg + temp
B = temp – (Co >> 1)
R = B + Co

RGB vs Luminance-Chrominance

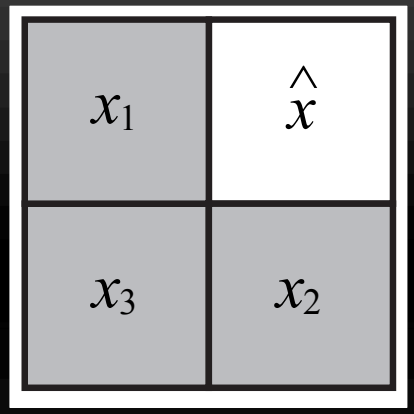


Predictor



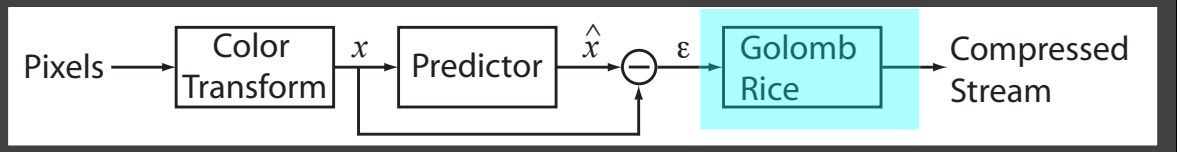
- Weinberger et al [96]

$$\hat{x} = \begin{cases} min(x_1, x_2), & x_3 \geq max(x_1, x_2) \\ max(x_1, x_2), & x_3 \leq min(x_1, x_2) \\ x_1 + x_2 - x_3, & \text{otherwise.} \end{cases}$$



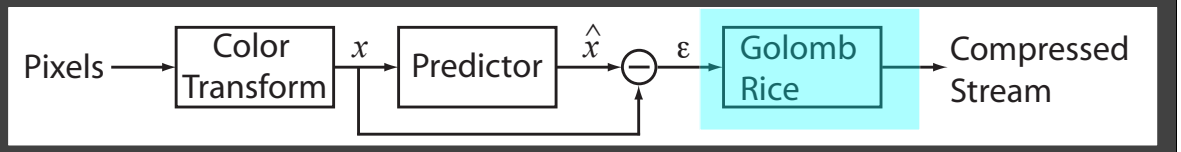
- 2x2 pixel blocks
- Built-in "edge detection"
- Low complexity, decent performance

Golomb-Rice coding



- We then encode the residuals using the Golomb-Rice scheme [Golomb66], [Rice79]
  - Compact coding of small values
  - Adaptive and variable bit rate
  - High compression ratios
  - Medium complexity

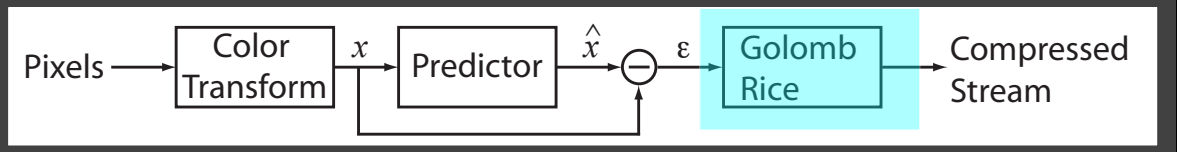
Golomb-Rice coding



- Find divisor, 2^k, (we do exhaustive search)
- Divide values in 2x2 block, v_i, with 2^k
  - Quotient $q_i = \text{int}(v_i/2^k)$
  - Remainder $r_i = v_i \bmod 2^k$
- Store results
  - q with unary coding (see table)
  - r with binary coding
  - Termination zero to separate q and r
  - k as a 3 bit header per 2x2 block

Value	Unary coding
0	0
1	10
2	110
3	1110
4	11110
5	111110
6	1111110

Example



- Example v = (3, 0, 9, 1)
  - We find k=1
  - After division ⇒ (q,r)-pairs: (1,1), (0,0), (4,1), (0,1)
  - q unary and r binary coded ⇒

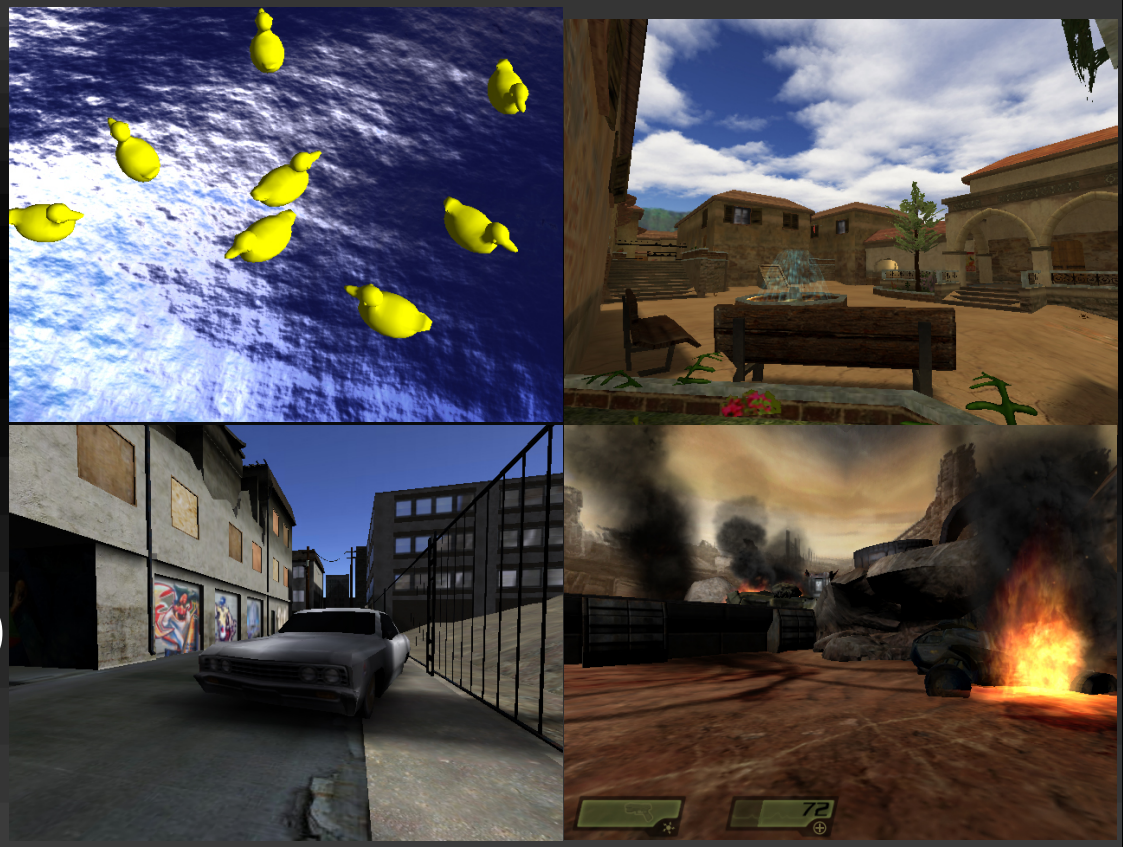
    (10,1), (0,0), (11110,1), (0,1)

Value	Unary coding
0	0
1	10
2	110
3	1110
4	11110
5	111110
6	1111110

- Algo (once again):
  - Find divisor 2^k
  - Divide with 2^k
    - Quotient $q_i = \text{int}(v_i/2^k)$, Remainder $r_i = v_i \% 2^k$
  - q unary and r binary
  - Termination zero to separate

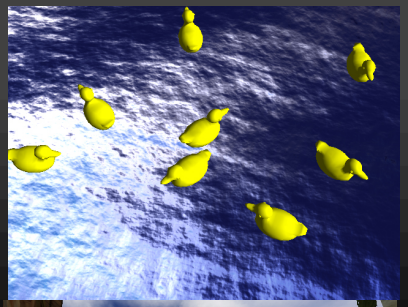
Tested scenes

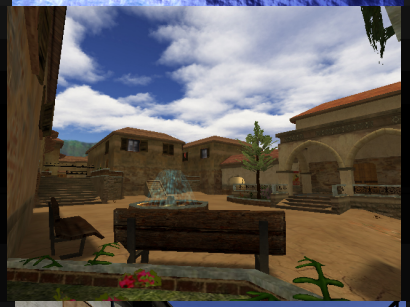
- Logging OpenGL driver
- Full incremental rasterization

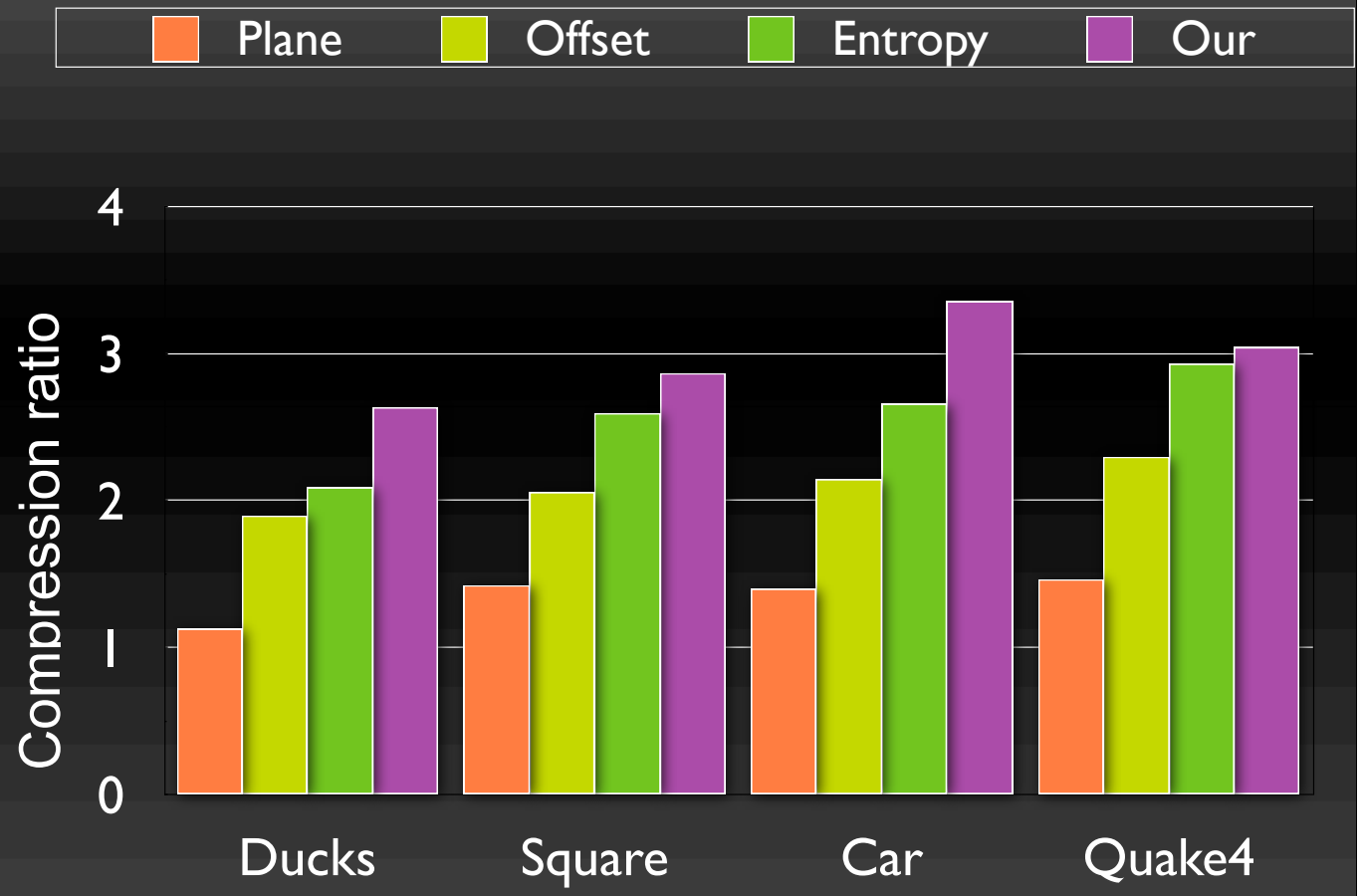


- “Ducks” (homebrew)
- “Square” (Quake 3)
- “Car” (Quake 3)
- “Quake 4”

Results (lossless)

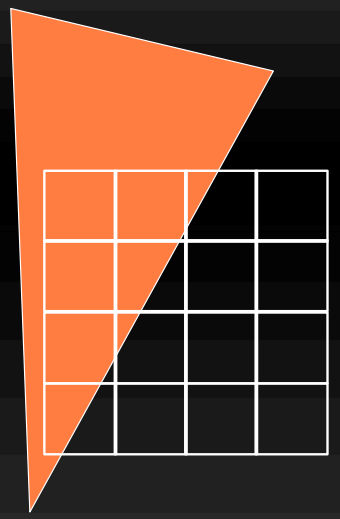






Approximate mode (lossy)

- Why is lossy color buffer compression so "unpopular"?
  - Tandem lossy compression accumulates errors incrementally and can grow very large



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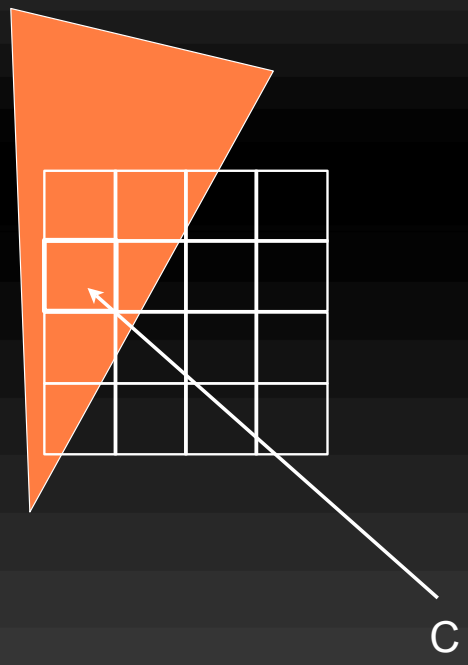

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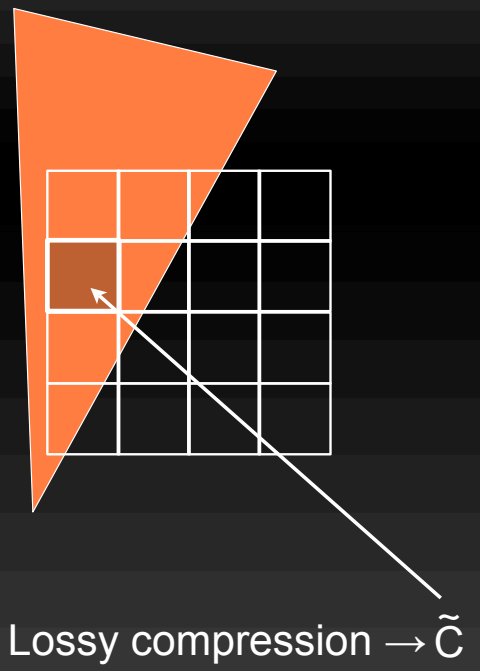

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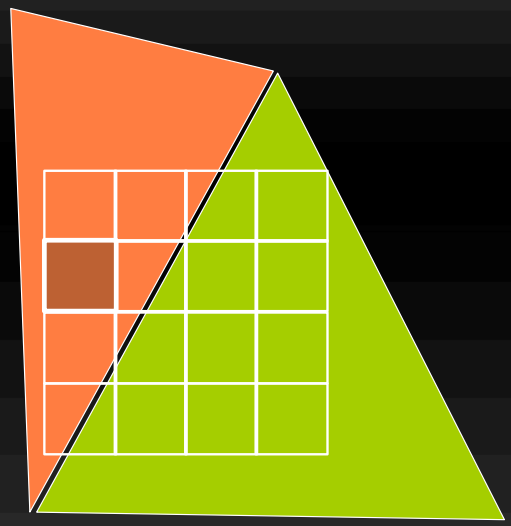

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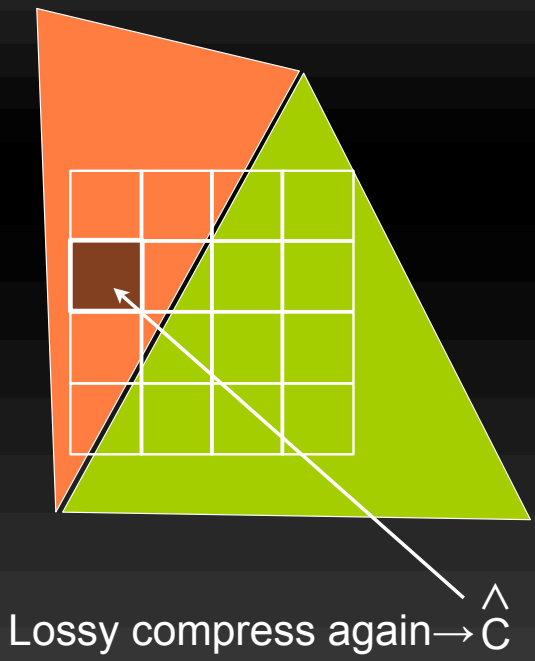

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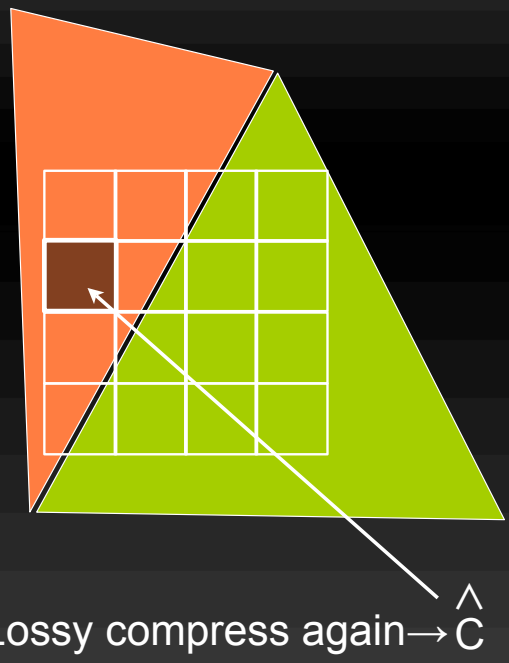
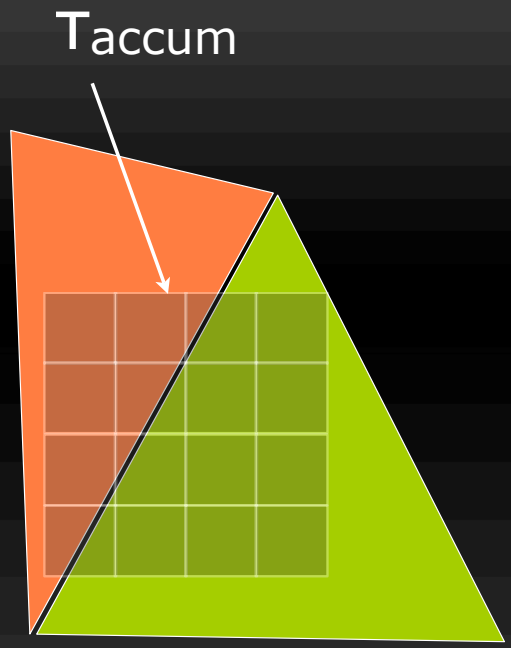


➡ An error control mechanism is needed that bounds the error!

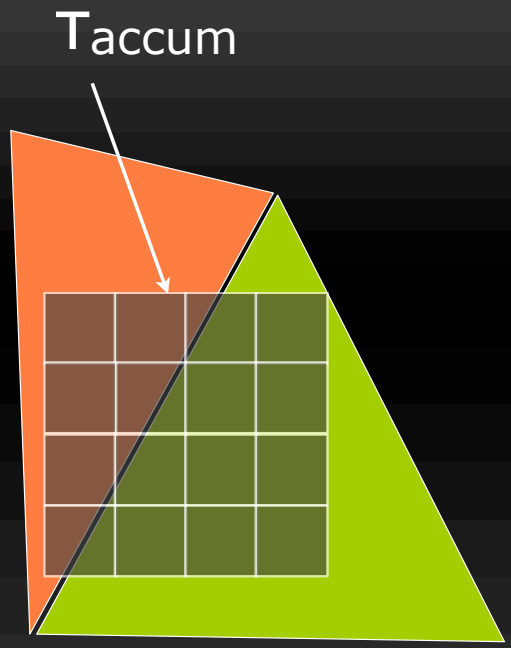
Error control mechanism

- Track and store an accumulated error metric for each tile, T_{accum}



Error control mechanism

- Track and store an accumulated error metric for each tile, T_{accum}



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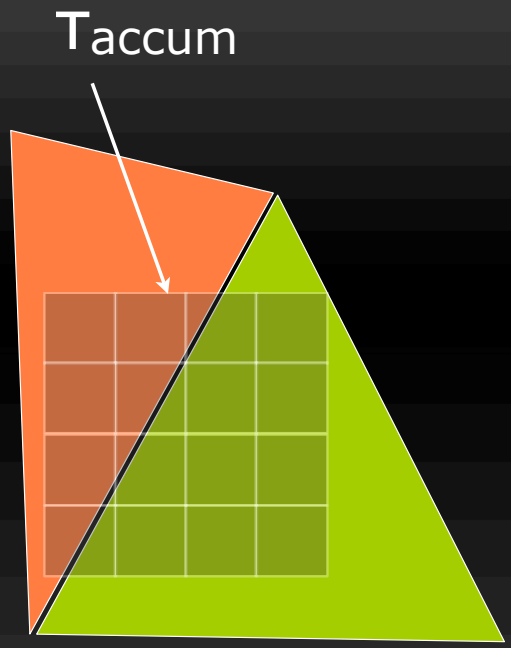
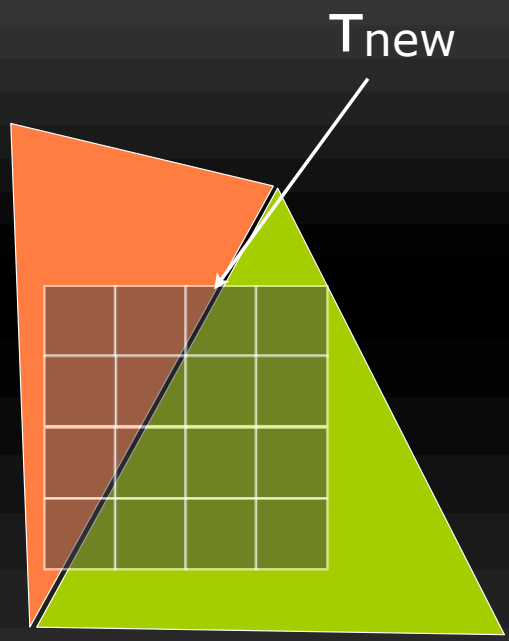


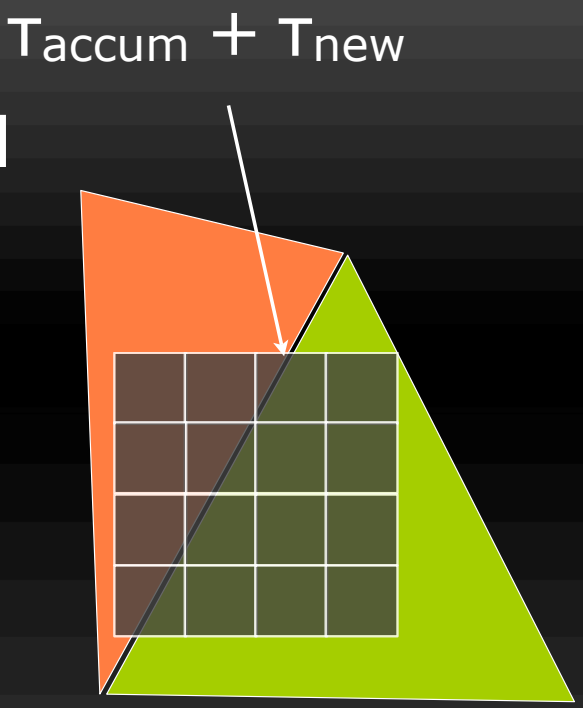
Error control mechanism

- Track and store an accumulated error metric for each tile, T_{accum}
- Before applying more lossy compression:
  - Calculate T_{new} (new error contribution)



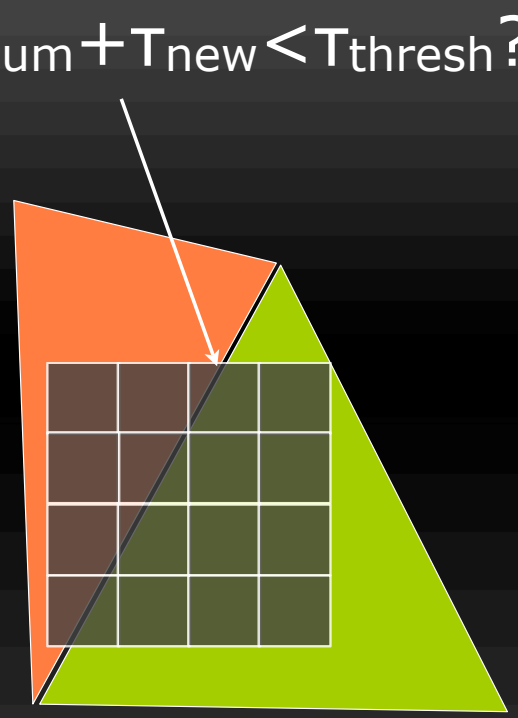
Error control mechanism

- Track and store an accumulated error metric for each tile, T_{accum}
- Before applying more lossy compression:
  - Calculate $T_{accum} + T_{new}$



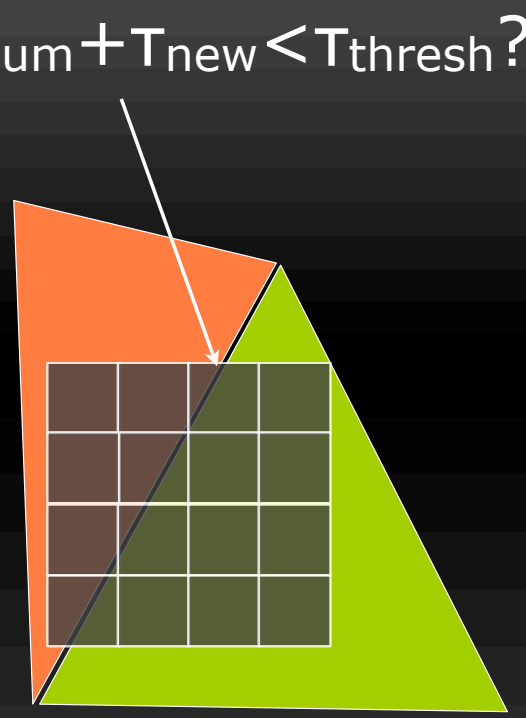
Error control mechanism

- Track and store an accumulated error metric for each tile, T_{accum}
- Before applying more lossy compression:
  - Check if $T_{accum} + T_{new} < T_{thresh}$?



Error control mechanism

- Track and store an accumulated error metric for each tile, T_{accum}
- Before applying more lossy compression:
  - Check if $T_{accum} + T_{new} < T_{thresh}$?
    - Yes ⇒ Lossy compress
    - No ⇒ Lossless compress
- We used RMSE as error metric
  - MSE or SAD also useful



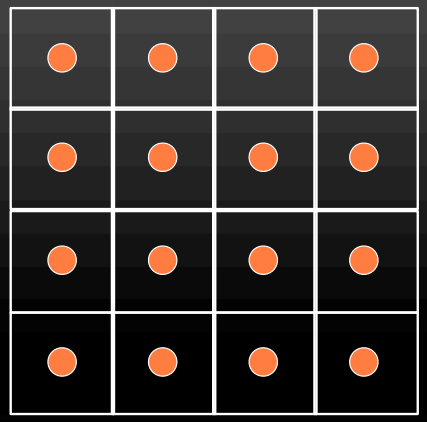
Bounded errors

- The error control mechanism
  - Good control
  - Upper error bound
  - Minimize visual impact

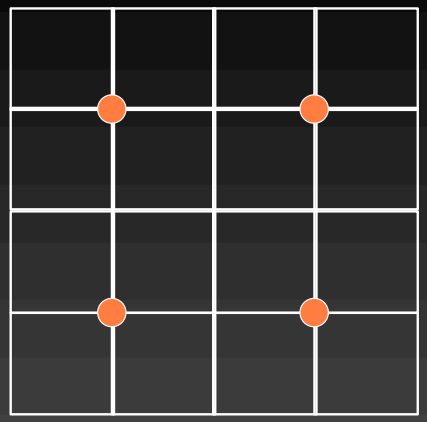
Our compression scheme

- Chrominance 2x2 sub-sampling
- Only sub-sample if errors are below T_{thresh}
- Luminance is always losslessly compressed

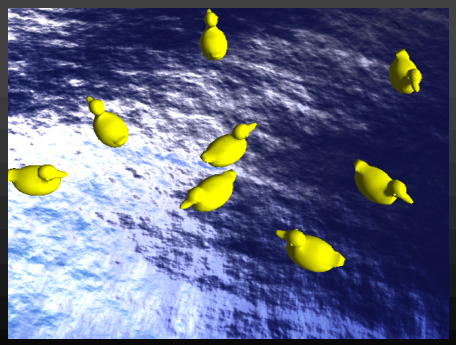
Example:
Chrominance Co

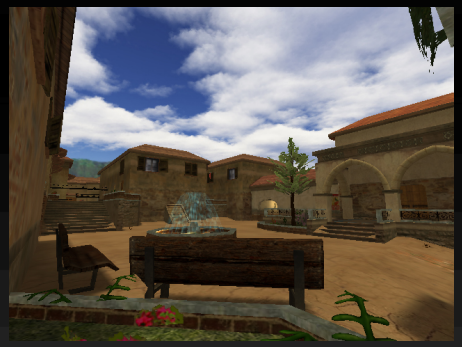


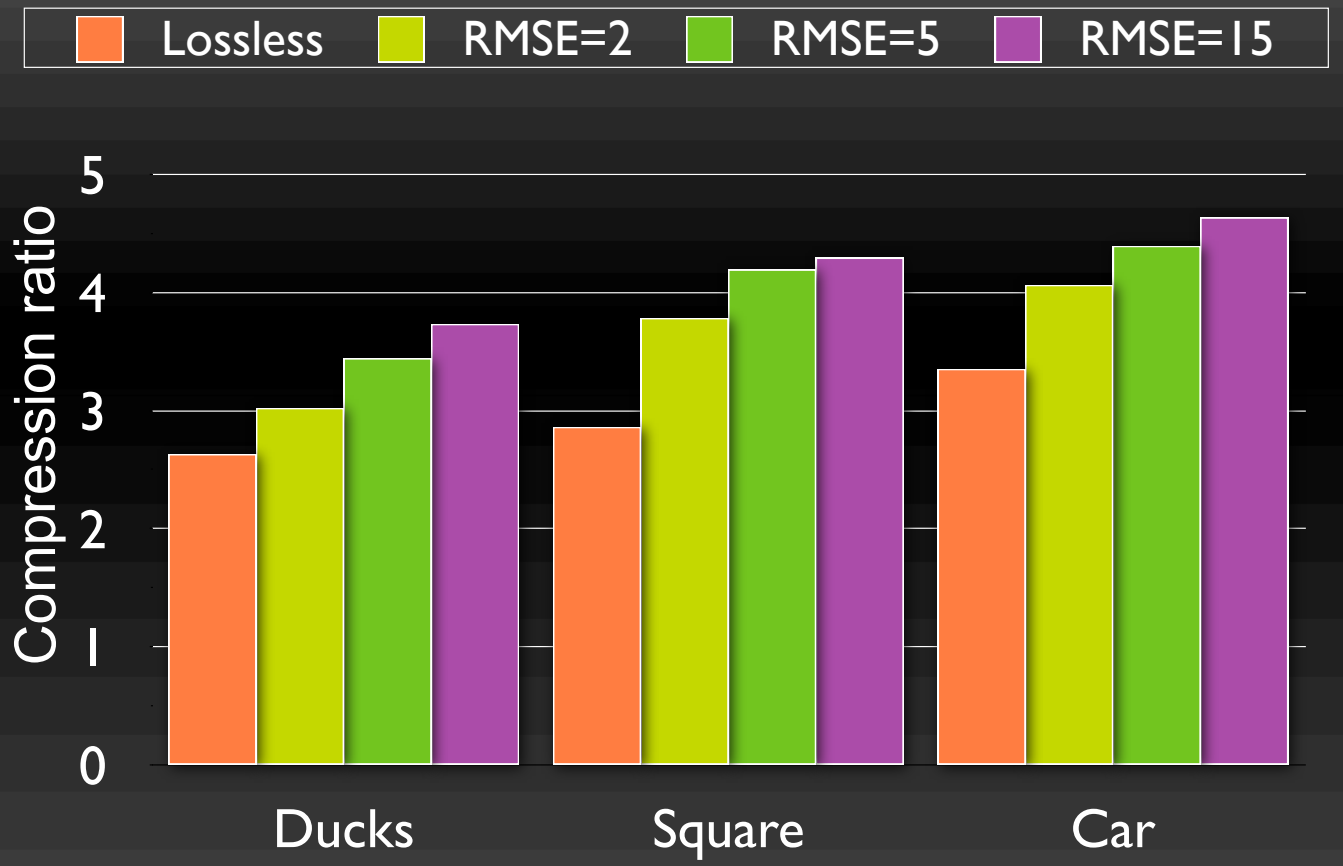
After subsampling



Results (lossless vs lossy)

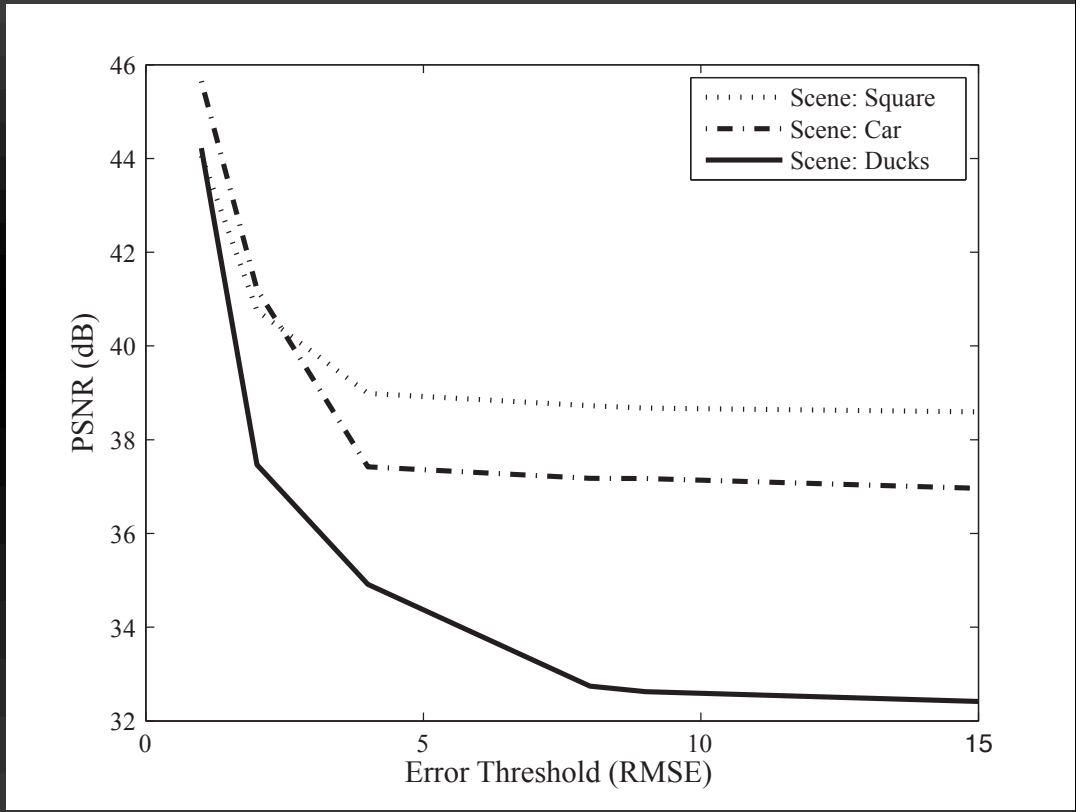






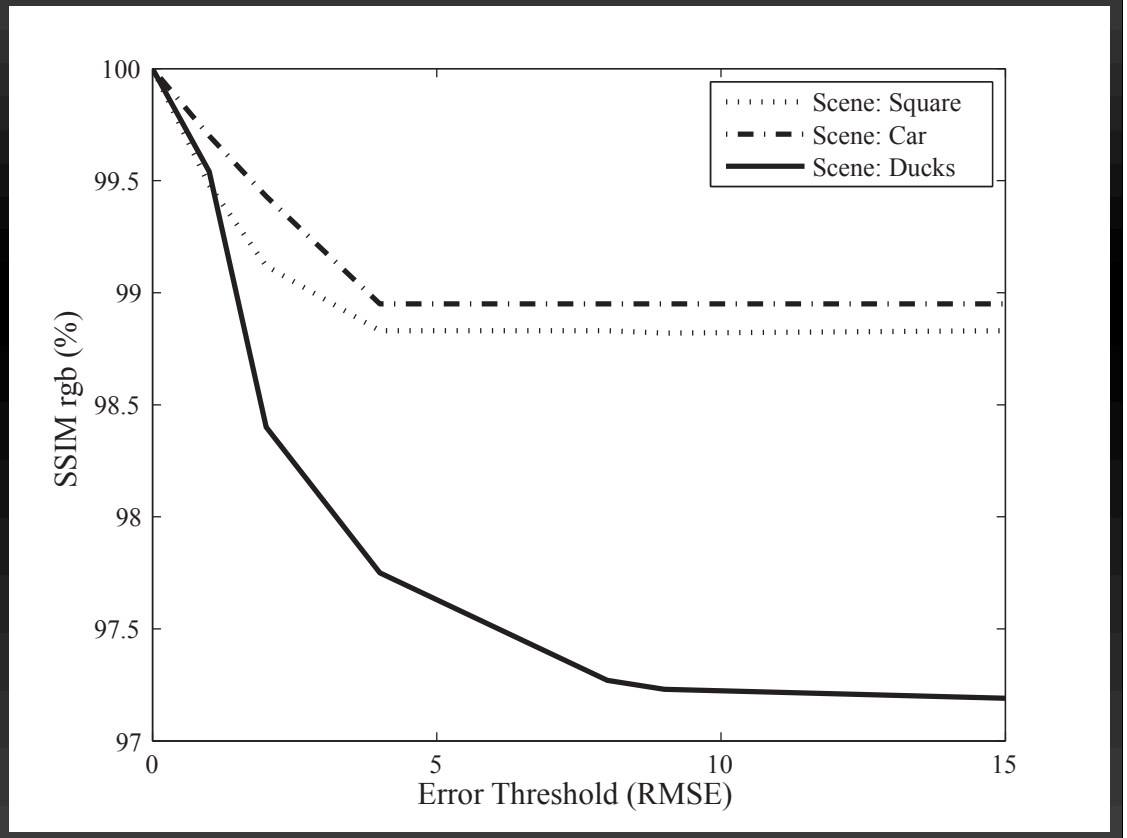
Visual quality - PSNR

- PSNR reasonably good for “square” and “car”
- “Ducks” - quality drops fast!



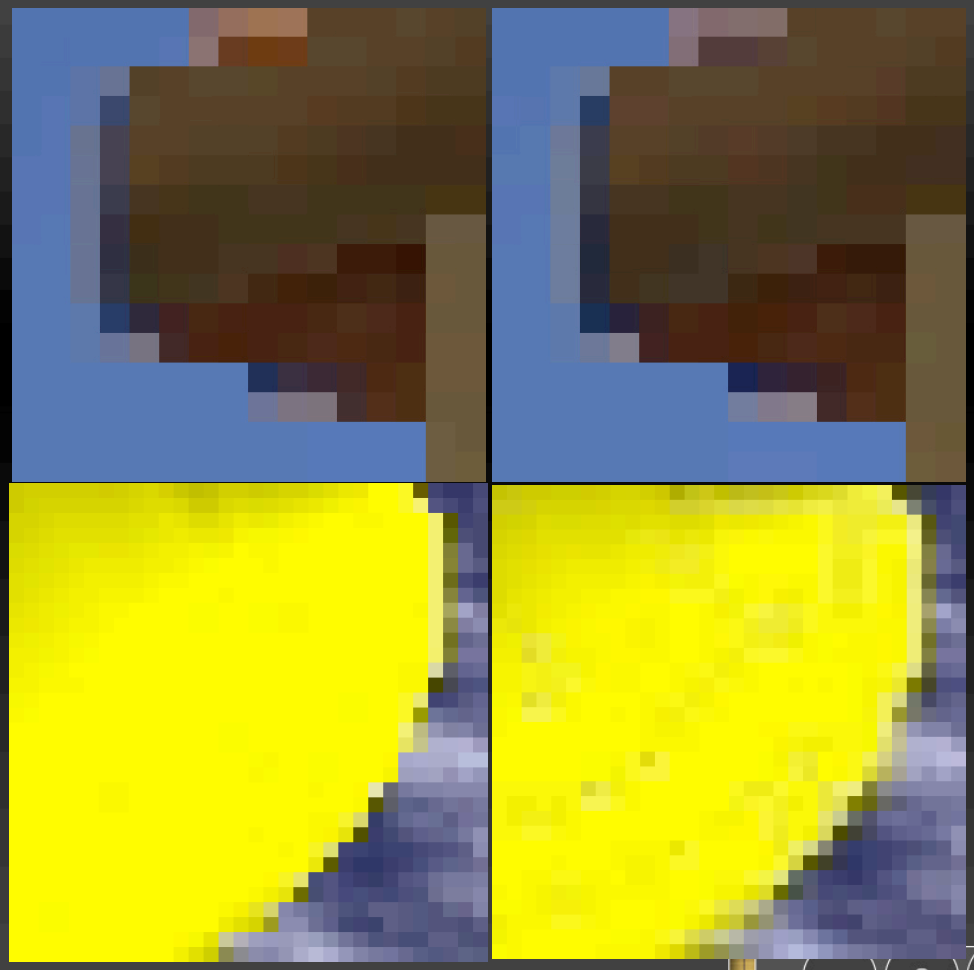
Visual quality -Structural Similarity Index Metric (SSIM)

- SSIM [Wang02]
  - "Square" and "car" - high quality
  - "Ducks" - something is not good



Visual quality - Artifacts

- “Square” and “car” have very small artifacts
- “Ducks” has clearly visible artifacts



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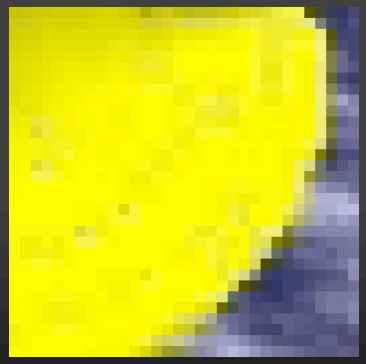

- Ducks artifacts - why?
  - Chrominance errors leak into luminance component due to sub-sampling, color transform and tandem compression
  - On slowly changing color areas (small color gradients) this becomes visible

And animated?

- Lossless vs lossy for animated content
- Next slide shows video for simple animation
- Lossy configuration
  - Max chrominance RMSE error is 15 (the highest error threshold featured in the paper)
- Note the diagonally split screen

And animated?

Conclusions

- Lossless color buffer compression
  - Reversible color transform
  - Simple and effective predictor (2x2 pixels)
  - Golomb-Rice coding of residuals
  - Higher performance than state-of-the-art patents
- Lossy mode
  - Lossless algo with chrominance sub-sampling
  - Improves compression rates even more
  - Error control mechanism bounds the error
  - Very small visual impact
    for most scenes

Future work

- More sophisticated lossy algorithms
- Multi-sampling
- Floating-point and high dynamic range
- Approximate depth buffer compression?

Thank You!

- http://graphics.cs.lth.se