ETC2:
Texture Compression using Invalid Combinations

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Ericsson Research

ERICSSON

TAKING YOU FORWARD

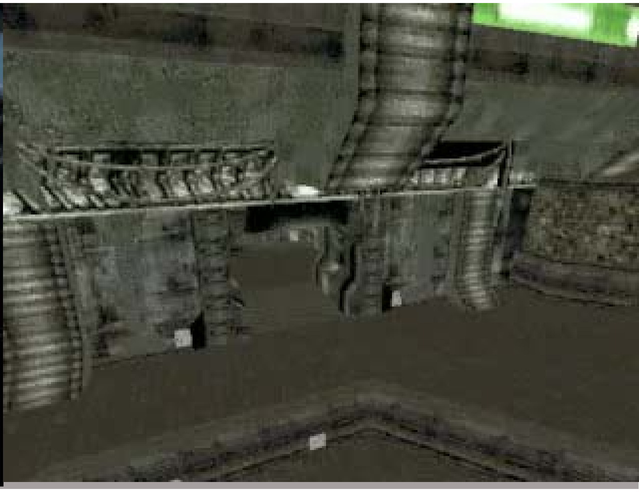
Outline

- Motivation, Previous work
- ETC1, advantages and shortcomings
- Invalid Codes and their use
- ETC 2 = ETC1 + three new modes
- Results compared to ETC 1 and DXTC

Why 3D Graphics...

on a Mobile Phone?

- Man-Machine Interfaces
- Screen Savers
- Games
- Maps, Messaging, Browsing and more...



Why is 3D Graphics Hard

on a Mobile Phone?

Limited resources:

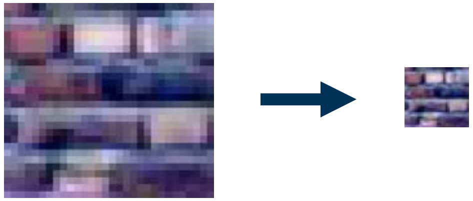
Why is 3D Graphics Hard

on a Mobile Phone?

Limited resources:

- Small amount of memory
- Little memory bandwidth
- Little chip area for special purpose
- Powered by batteries

Texture Compression Helps



- Small amount of memory
  - More texture data can fit in the limited amount of memory
- Little memory bandwidth
  - More texturing possible for same amount of bandwidth
- Little chip area for special purpose
  - A texture cache using compressed data can be made smaller
- Powered by batteries
  - Reduced bandwidth means lower energy consumption

Previous Work

- CCC [Campbell et al. ’86]

col 0 🟫

col 1 🟥

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col 0 ■

col 1 ▨

0	0	1	1
0	1	1	1
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col 0 🟥

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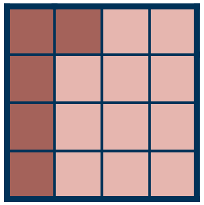

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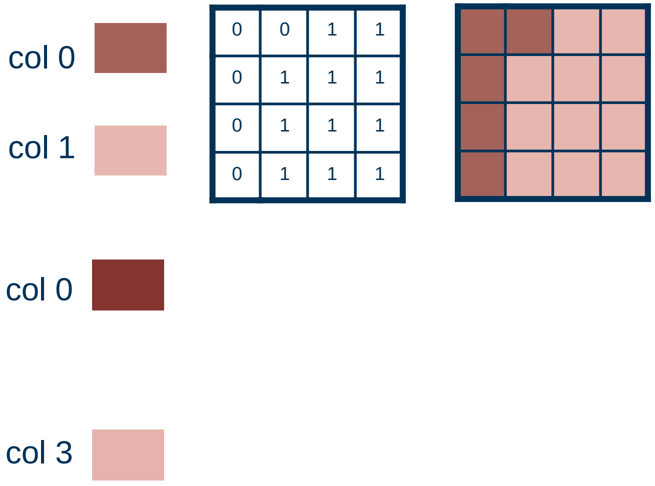

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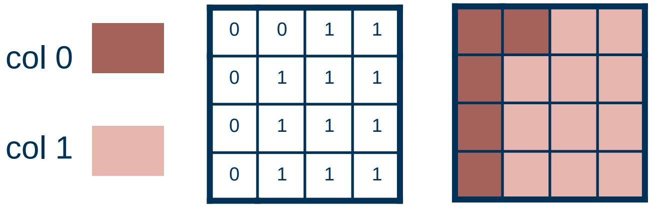

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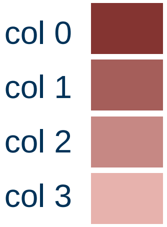

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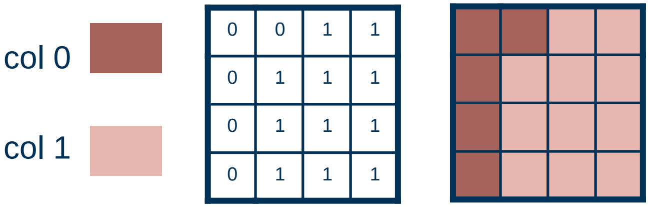

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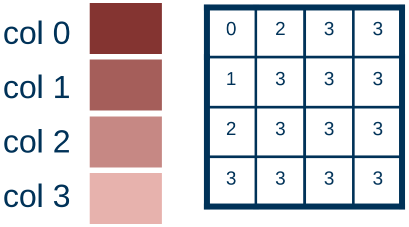

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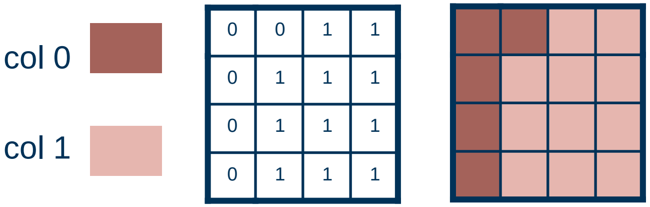

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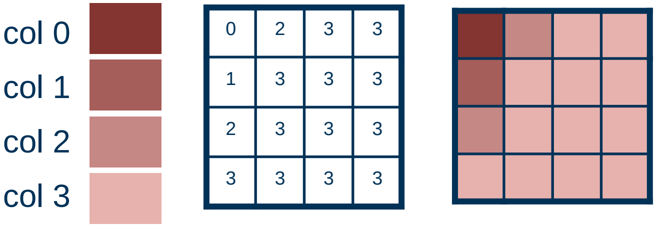

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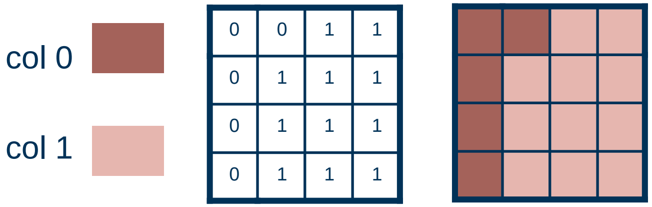

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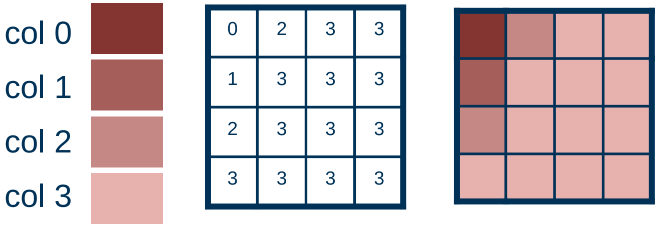

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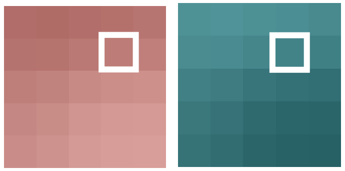
- PVR-TC [Fenney ’03]



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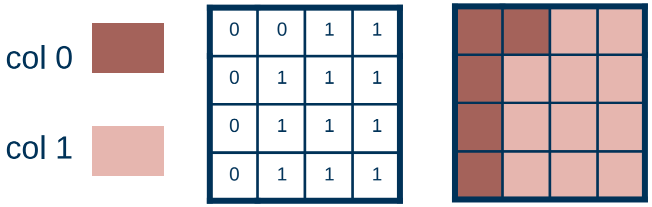

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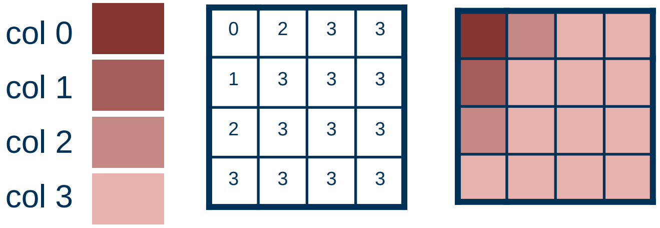

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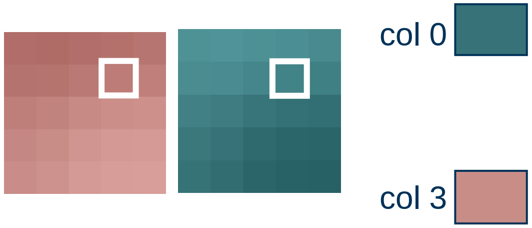

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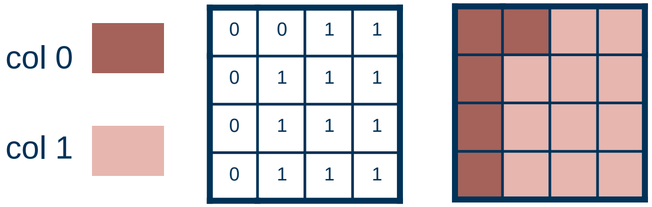

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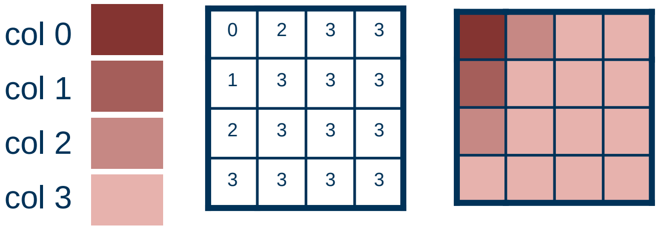

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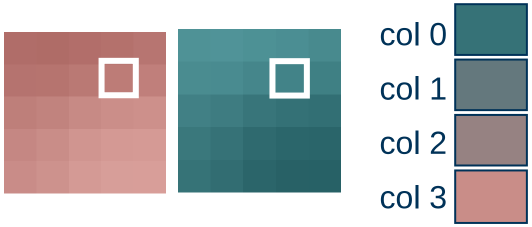

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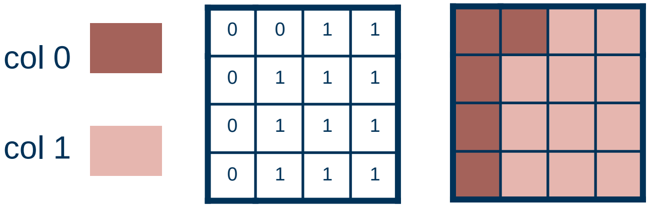

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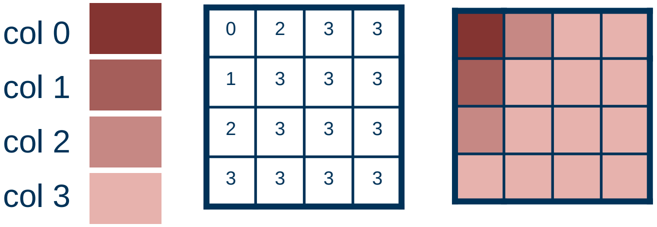

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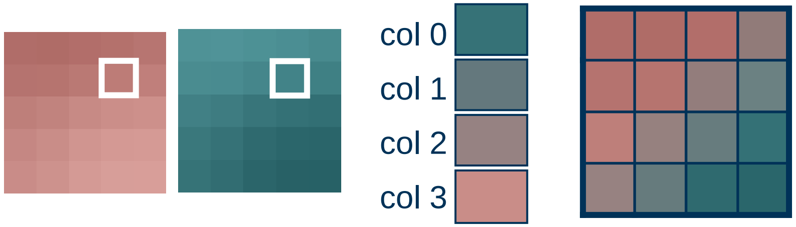

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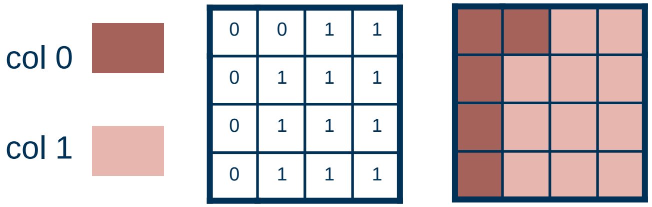

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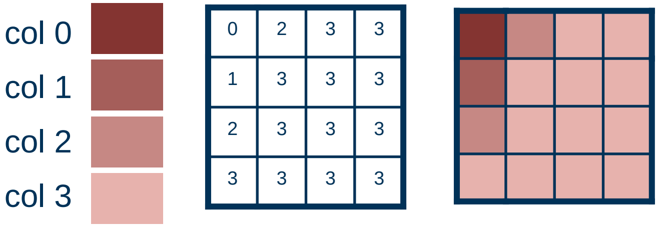

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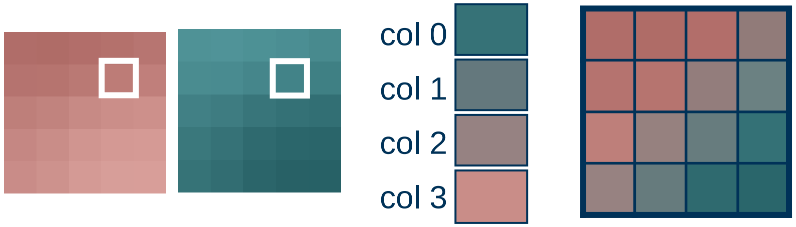


- Compressed Lossless Texture Representation and Caching [Inada and McCool 06']
  - uses special purpose caches to allow for variable bit rate

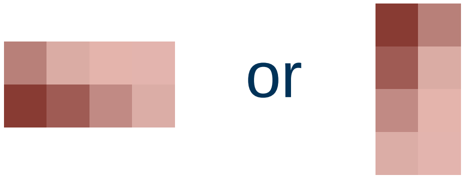
Previous Work

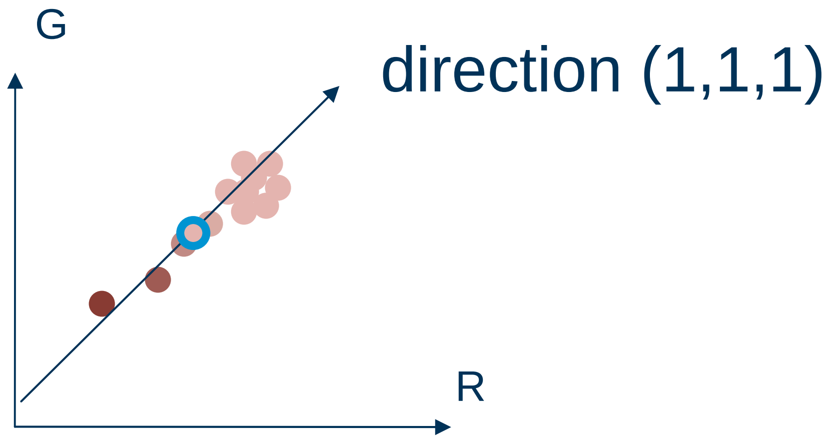
continued

- Of the fixed rate systems, S3TC/DXTC achieved the best quality
- Could a equally good system of lower complexity be built?
- PACKMAN [Strom and Akenine-Moller ’03]
  - very simple but considerably lower quality (around 2.5 dB)
- iPACKMAN/Ericsson Texture Compression (ETC) [Strom and Akenine-Moller ’05]
  - still simple and quality on par with S3TC/DXTC
- Could ETC be enhanced to surpass S3TC/DXTC in quality?

Recap ETC1

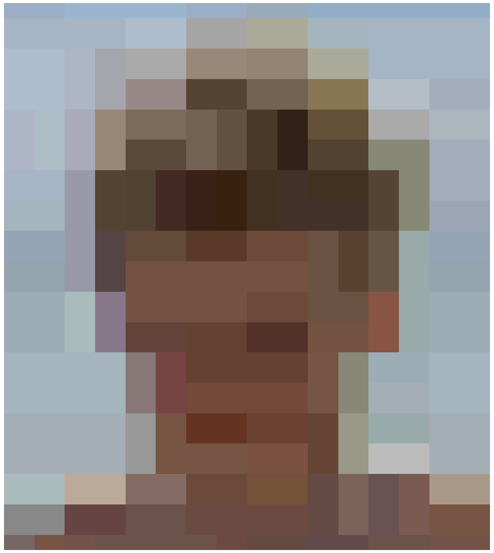
- The human visual system is more sensitive to luminance than to chrominance.
- The idea is to specify the base color for an entire 2x4 block (base color marked with a blue circle)
- The luminance can then be changed per pixel by moving along the intensity direction (1,1,1)





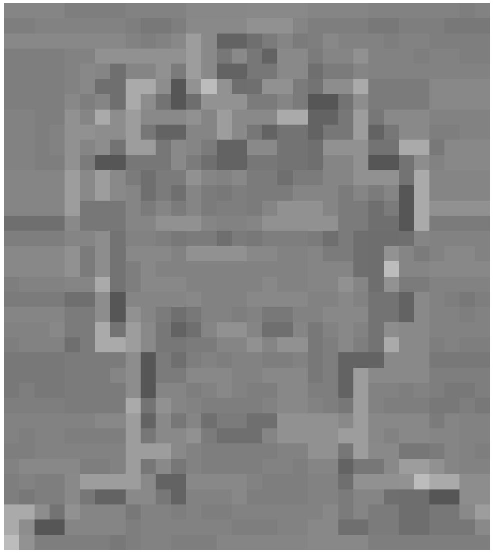
ETC1 Recap

- On a macro level, it can look like this



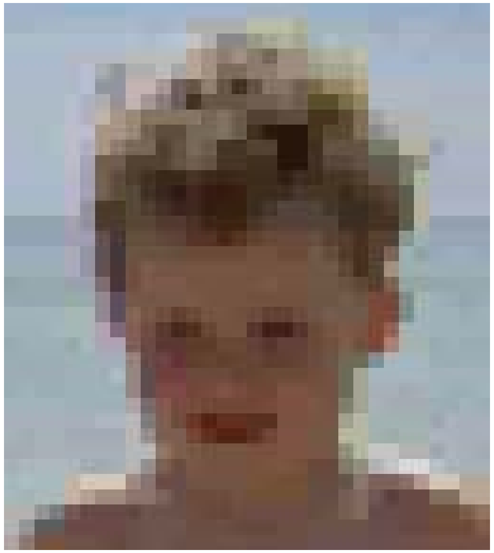
“base color”

+



per-pixel luminance

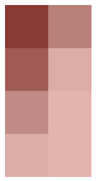
=

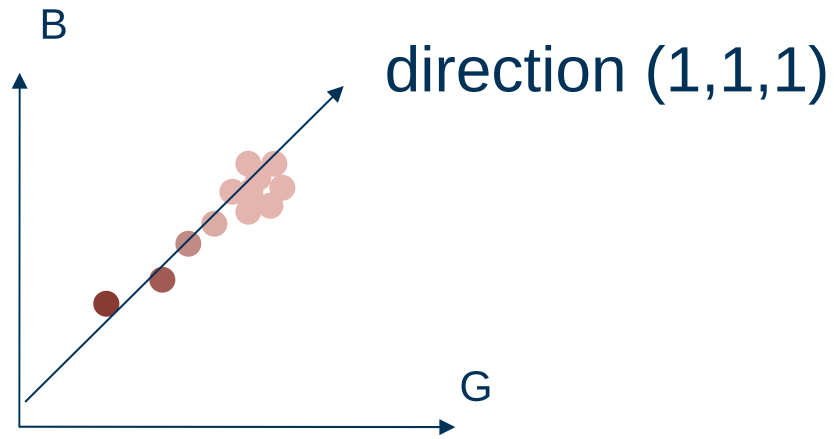


resulting image

ETC1 Recap

- This is all fine, if the variation inside a sub-block is aligned more or less with the intensity direction.

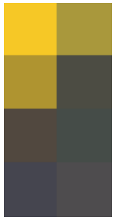




direction (1,1,1)

ETC1 Weaknesses

- However, if the block contains a number of pixels with very different chrominance, the results will be poor.



original block

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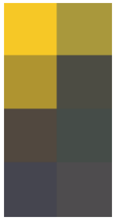

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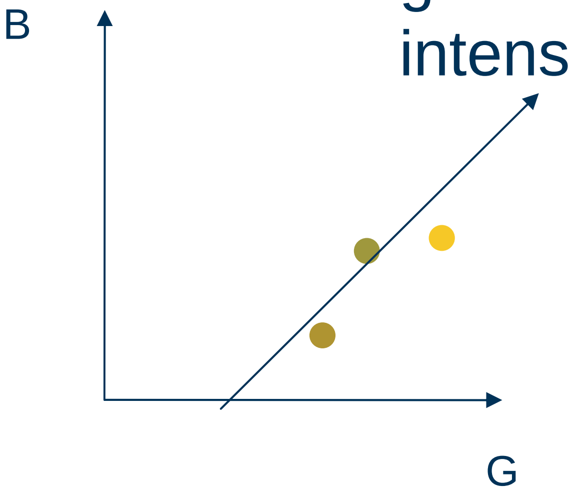

good fit with intensity dir.

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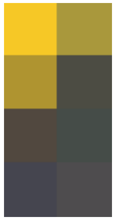

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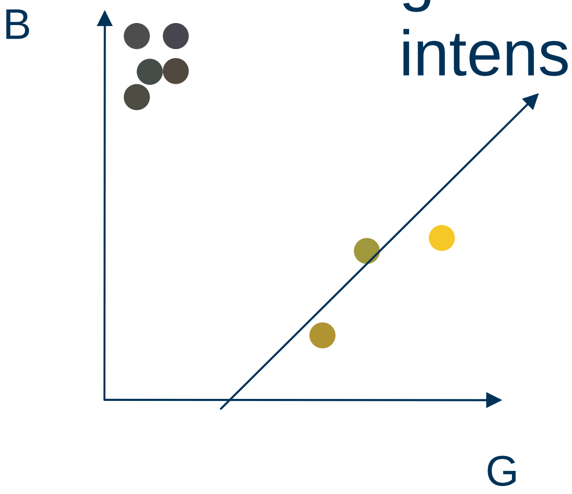

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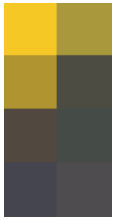

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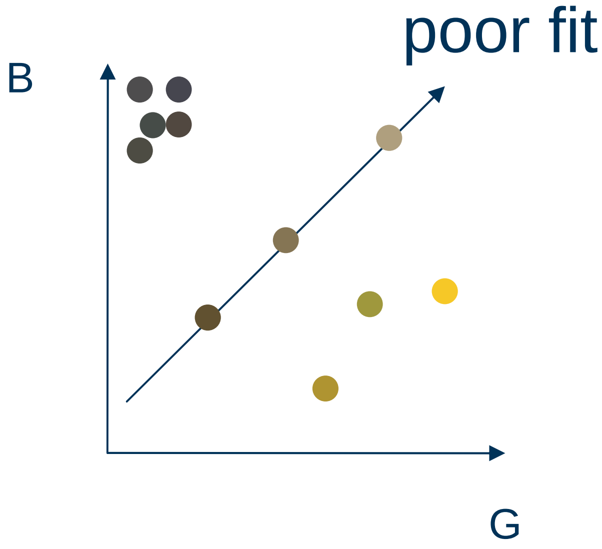

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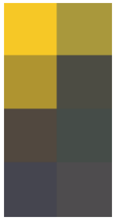

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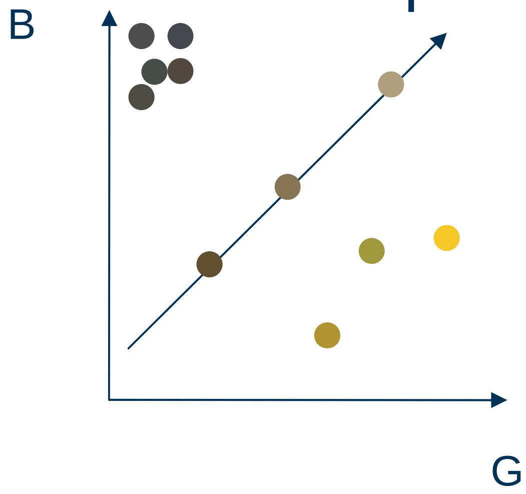
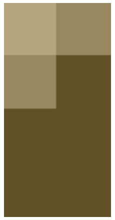


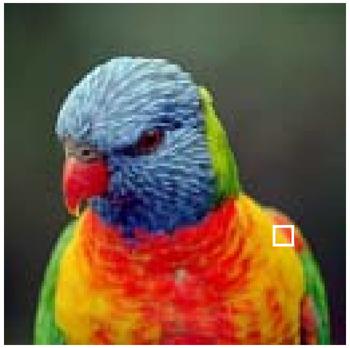
poor fit

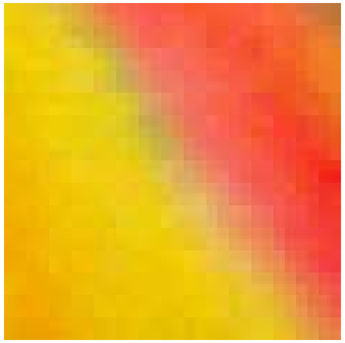


Weaknesses

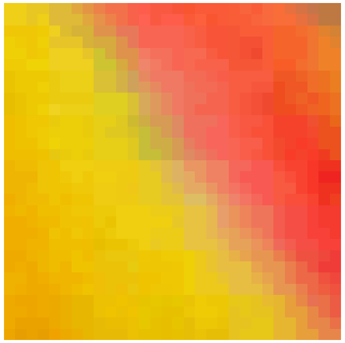
ETC 1.0

- Another weakness is smooth transitions between two colors of equal luminance.

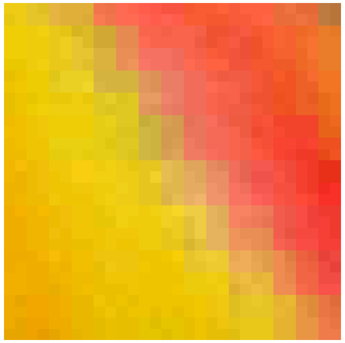




original



S3TC/DXTC

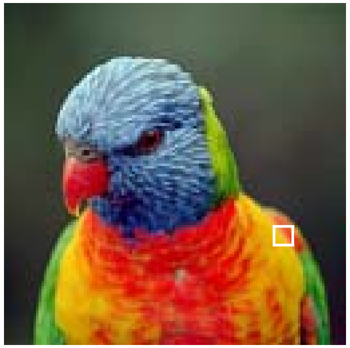


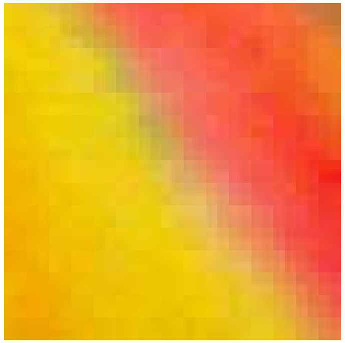
ETC 1.0

Weaknesses

ETC 1.0

- Another weakness is smooth transitions between two colors of equal luminance.
- Since only one color per sub-block is possible, block artifacts are more pronounced than for S3TC/DXTC for such blocks.





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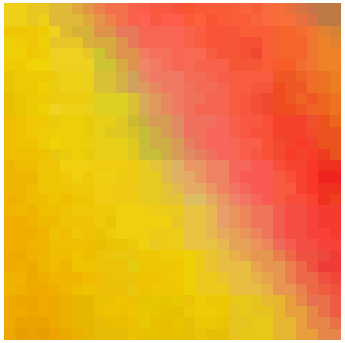

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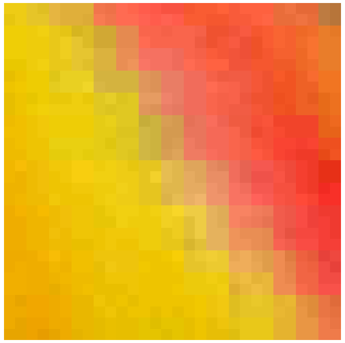

ETC1

How to Improve ETC1

- We have realized the need to improve ETC1 for certain blocks, but how do we do it?
- Each 4x4 blocks takes 64 bits in ETC1. One way would be to add another bit to signal new modes for problematic blocks.
- But 65 bits per block is less than ideal...

Redundant Bit Sequences

- In S3TC, there are coded bit sequences that produce exactly the same output block.

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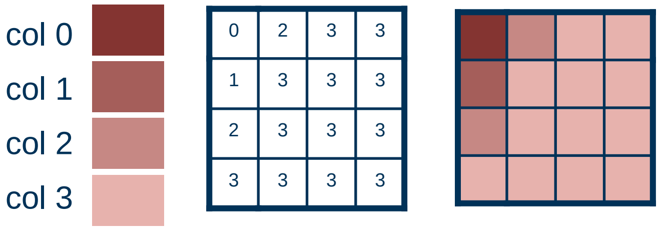

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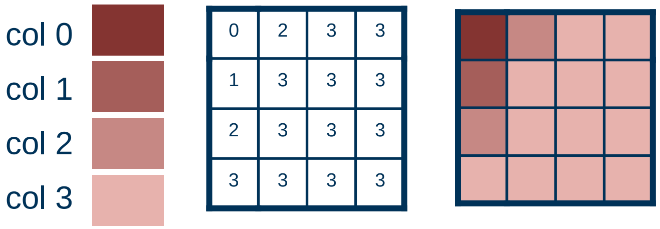

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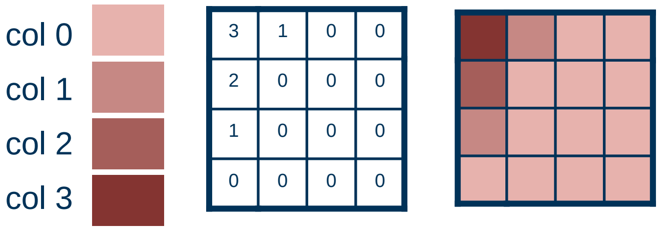

3	1	0	0
2	0	0	0
1	0	0	0
0	0	0	0

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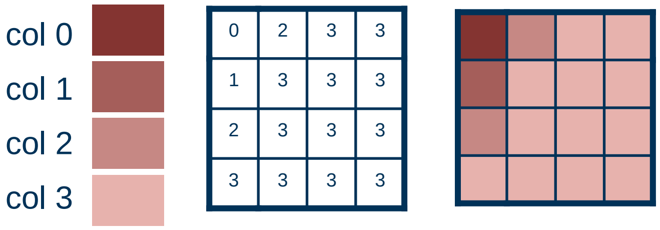

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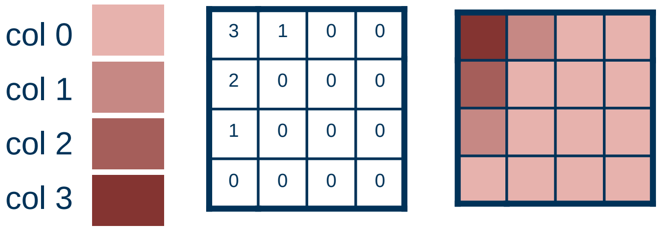
3	3	3	3

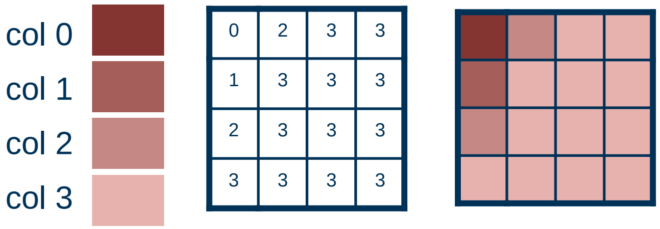


3	1	0	0
2	0	0	0
1	0	0	0
0	0	0	0

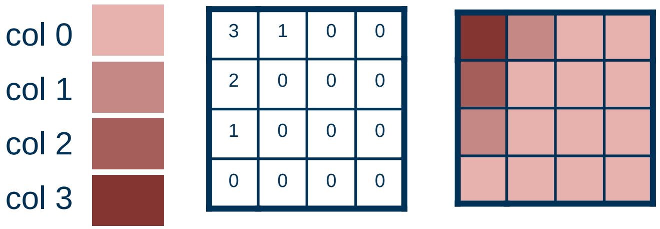
- This is of course wasteful, so instead the ”darkest” colour is forced to be the first one. If not, the block is decoded with one color being black:

Redundant Bit Sequences

- In S3TC, there are coded bit sequences that produce exactly the same output block.

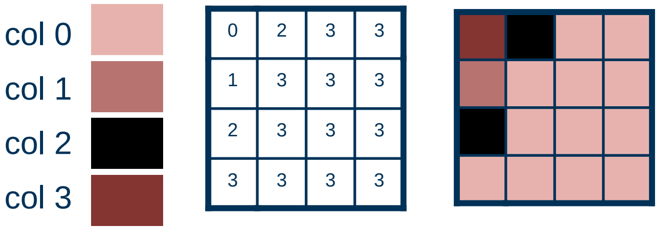


0	2	3	3
1	3	3	3
2	3	3	3
3	3	3	3



3	1	0	0
2	0	0	0
1	0	0	0
0	0	0	0

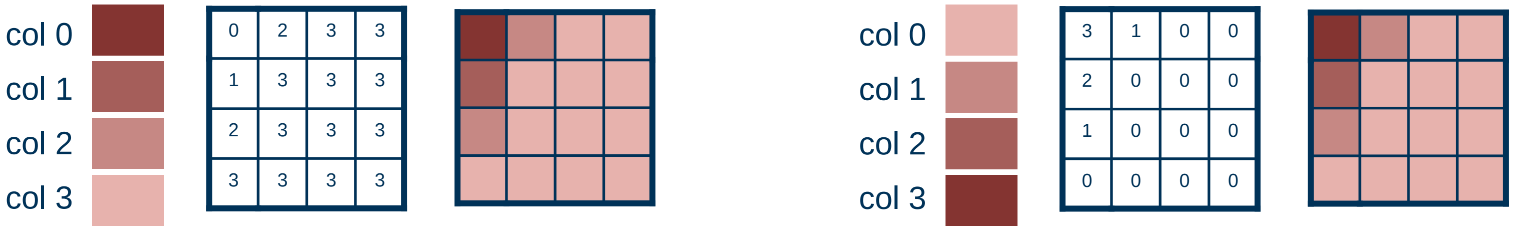
- This is of course wasteful, so instead the ”darkest” colour is forced to be the first one. If not, the block is decoded with one color being black:



0	2	3	3
1	3	3	3
2	3	3	3
3	3	3	3

Redundant Bit Sequences

- In S3TC, there are coded bit sequences that produce exactly the same output block.



0	2	3	3
1	3	3	3
2	3	3	3
3	3	3	3

3	1	0	0
2	0	0	0
1	0	0	0
0	0	0	0

- This is of course wasteful, so instead the ”darkest” colour is forced to be the first one. If not, the block is decoded with one color being black:
- This technique was also used by Munkberg et al. under the name the ”ordering trick”.

Redundant Bit Sequences

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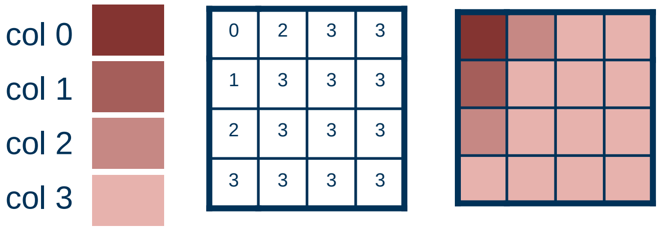
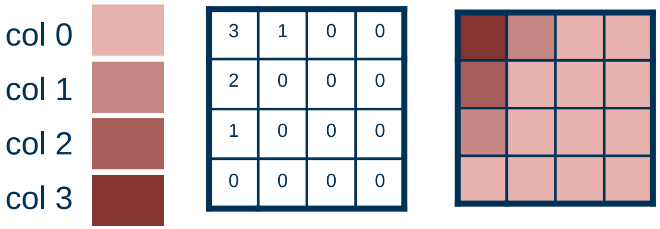


0	2	3	3
1	3	3	3
2	3	3	3
3	3	3	3



3	1	0	0
2	0	0	0
1	0	0	0
0	0	0	0

- This is of course wasteful, so instead the ”darkest” colour is forced to be the first one. If not, the block is decoded with one color being black:
- This technique was also used by Munkberg et al. under the name the ”ordering trick”.
- We looked for redundant bit combinations in ETC1...

Invalid Bit Sequences

and their use

- ... and found nothing exploitable.

Invalid Bit Sequences

and their use

- ... and found nothing exploitable.
- But what if some 64-bit sequences do not produce valuable blocks? They can then be used for new modes.

Invalid Bit Sequences

and their use

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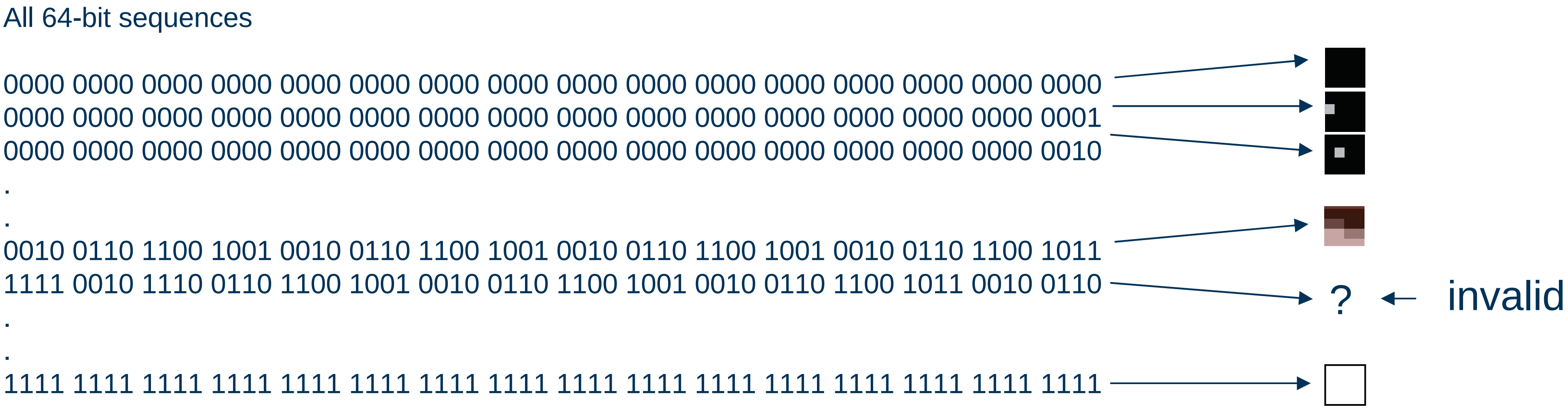
- But what if some 64-bit sequences do not produce valuable blocks? They can then be used for new modes.



All 64-bit sequences

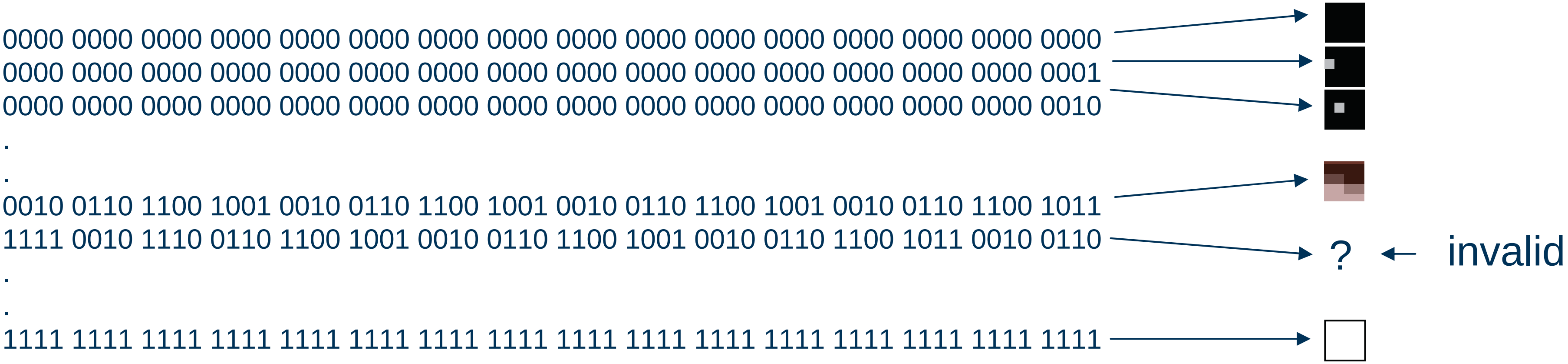
```
0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000
0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0001
0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0010
.
.
0010 0110 1100 1001 0010 0110 1100 1001 0010 0110 1100 1001 0010 0110 1100 1011
1111 0010 1110 0110 1100 1001 0010 0110 1100 1001 0010 0110 1100 1011 0010 0110
.
.
1111 1111 1111 1111 1111 1111 1111 1111 1111 1111 1111 1111 1111 1111 1111 1111
```

Invalid Bit Sequences

and their use

- ... and found nothing exploitable.
- But what if some 64-bit sequences do not produce valuable blocks? They can then be used for new modes.
- So we started to look for invalid bit sequences instead

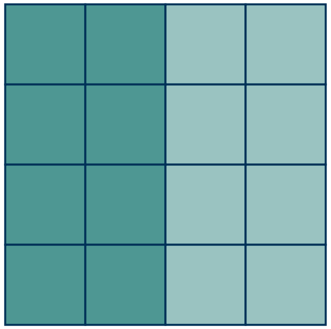
All 64-bit sequences



0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000
0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0001
0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000 0010
.
.
0010 0110 1100 1001 0010 0110 1100 1001 0010 0110 1100 1001 0010 0110 1100 1011
1111 0010 1110 0110 1100 1001 0010 0110 1100 1001 0010 0110 1100 1011 0010 0110
.
.
1111 1111 1111 1111 1111 1111 1111 1111 1111 1111 1111 1111 1111 1111 1111 1111

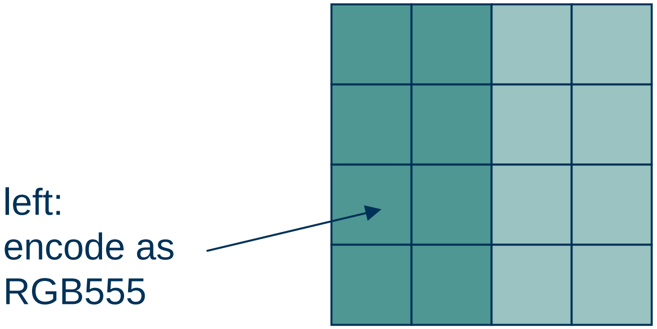
Invalid Bit Sequences in ETC1

- In some blocks in ETC1, the base color of the right sub-block is coded differentially w.r.t. the left sub-block.



Invalid Bit Sequences in ETC1

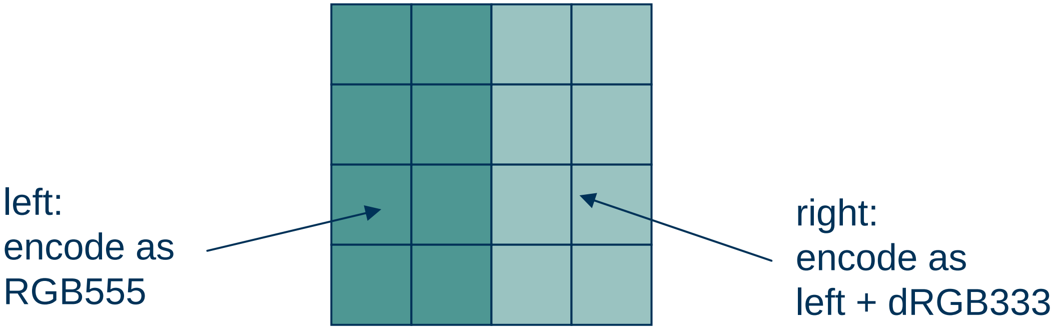
- In some blocks in ETC1, the base color of the right sub-block is coded differentially w.r.t. the left sub-block.



left:
encode as
RGB555

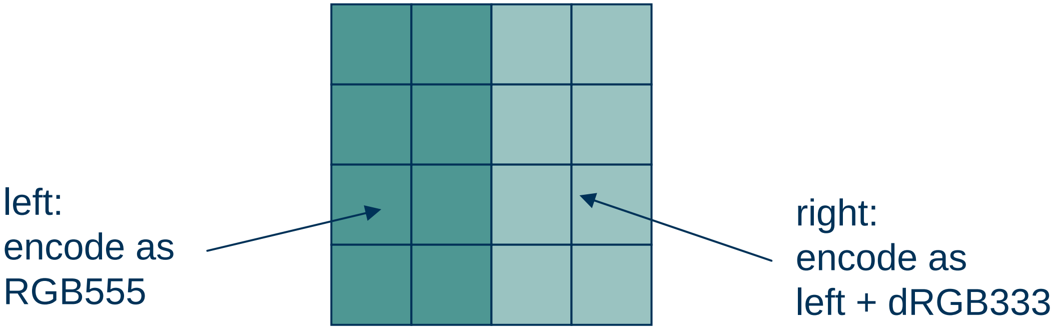
Invalid Bit Sequences in ETC1

- In some blocks in ETC1, the base color of the right sub-block is coded differentially w.r.t. the left sub-block.



Invalid Bit Sequences in ETC1

- In some blocks in ETC1, the base color of the right sub-block is coded differentially w.r.t. the left sub-block.
- Right_RED = Left_RED + dR

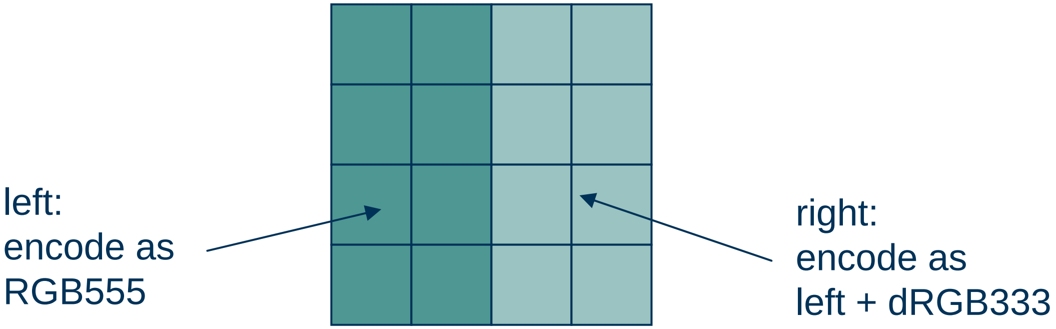


left:
encode as
RGB555

right:
encode as
left + dRGB333

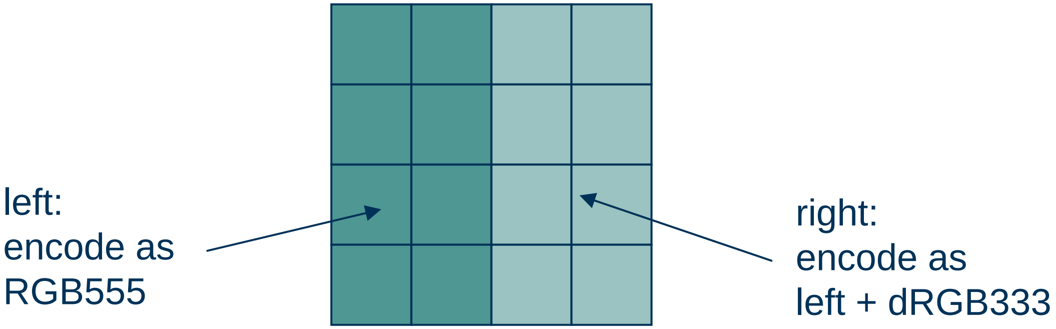
Invalid Bit Sequences in ETC1

- In some blocks in ETC1, the base color of the right sub-block is coded differentially w.r.t. the left sub-block.
- Right_RED = Left_RED + dR
- But if Left_RED is 0, a negative dR would mean a negative color (physically impossible). Such a bit sequence is possible but would never be used by the encoder.

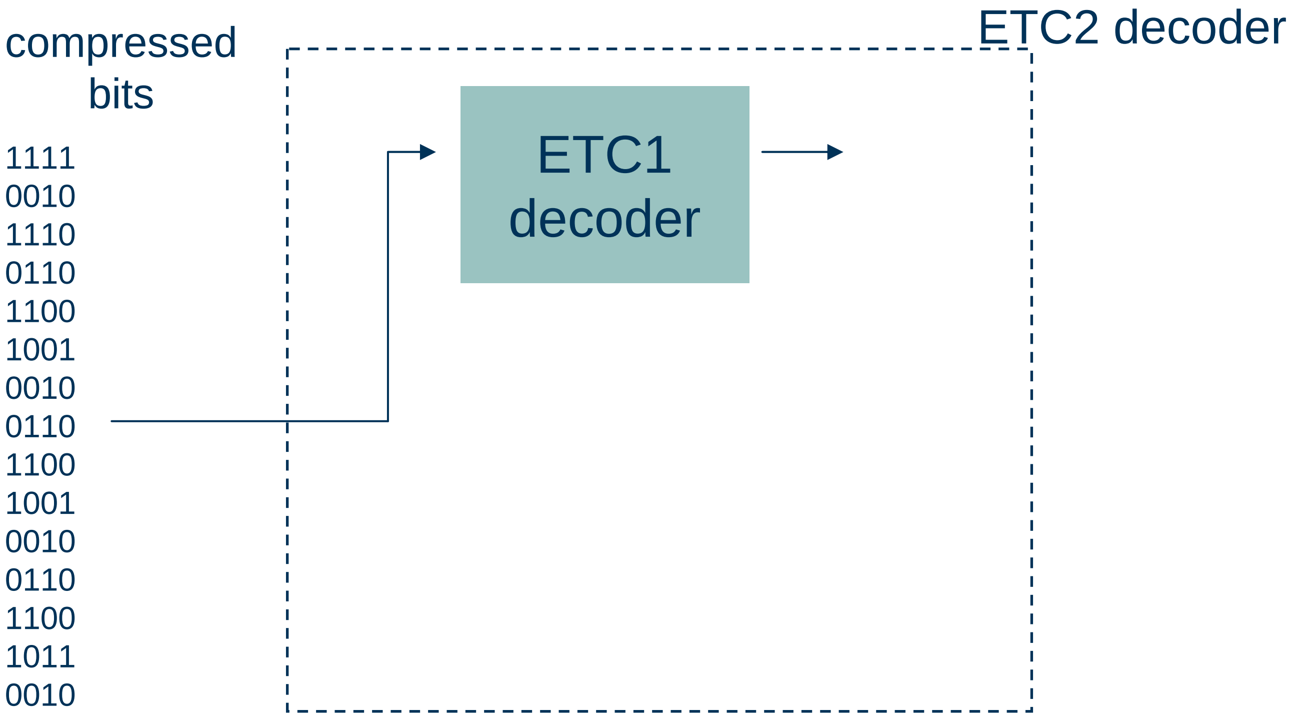


Invalid Bit Sequences in ETC1

- In some blocks in ETC1, the base color of the right sub-block is coded differentially w.r.t. the left sub-block.
- Right_RED = Left_RED + dR
- But if Left_RED is 0, a negative dR would mean a negative color (physically impossible). Such a bit sequence is possible but would never be used by the encoder.
- These bit sequences can be detected and the bits can be decoded a different way.



Schematic of a ETC2 decoder



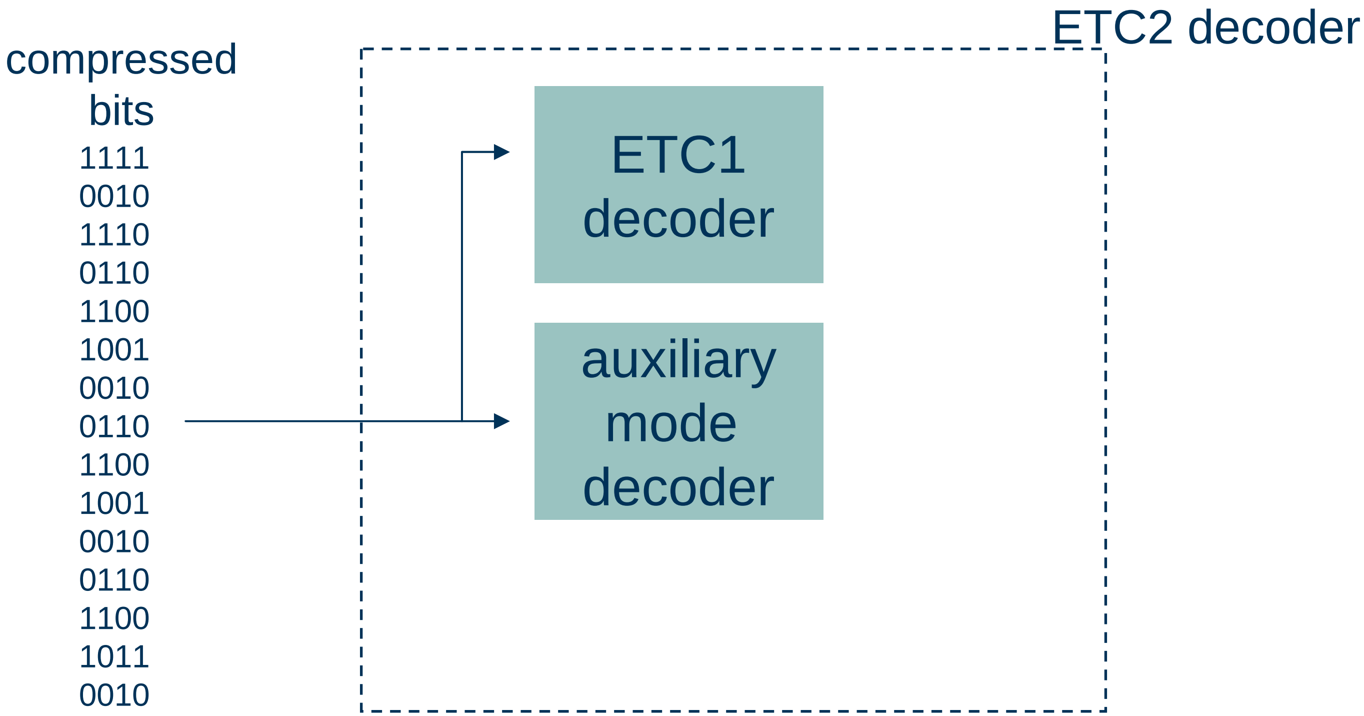
compressed
bits

1111
0010
1110
0110
1100
1001
0010
0110
1100
1001
0010
0110
1100
1011
0010

ETC2 decoder

ETC1
decoder

Schematic of a ETC2 decoder



compressed bits

1111
0010
1110
0110
1100
1001
0010
0110
1100
1001
0010
0110
1100
1011
0010

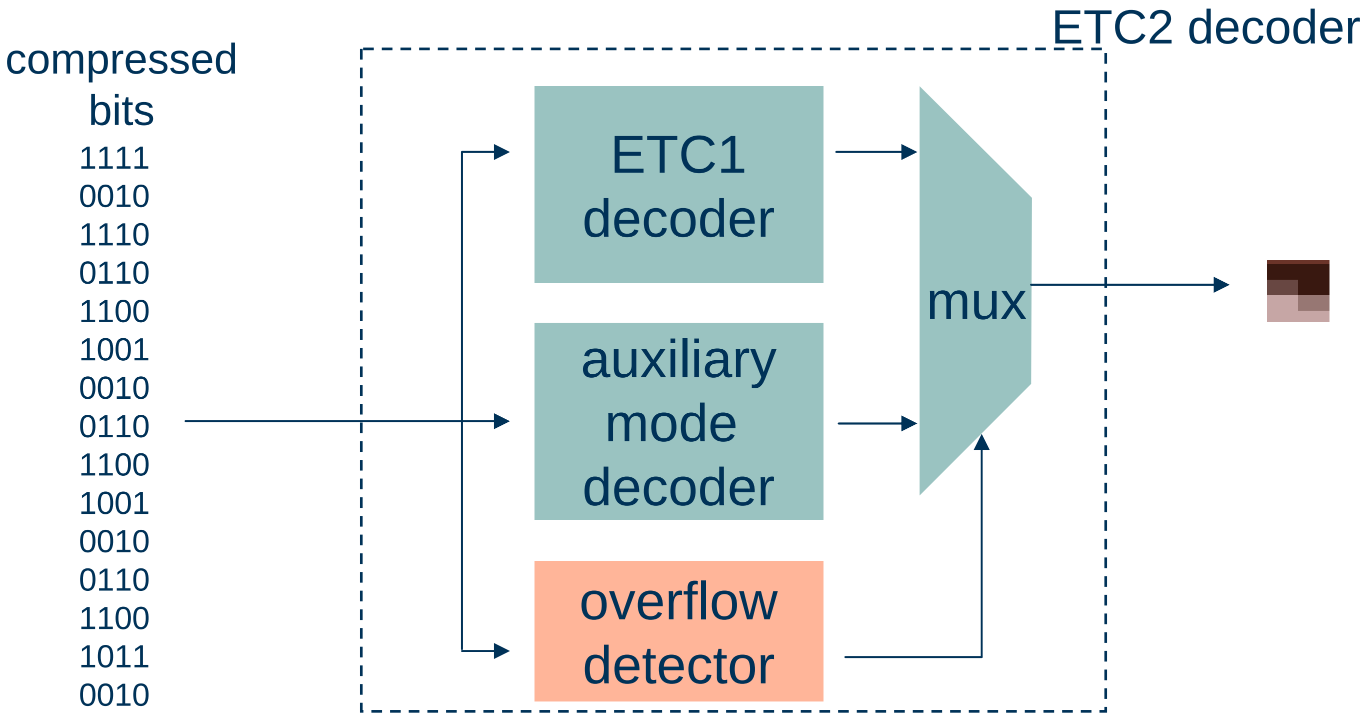
ETC2 decoder

ETC1 decoder

auxiliary mode decoder

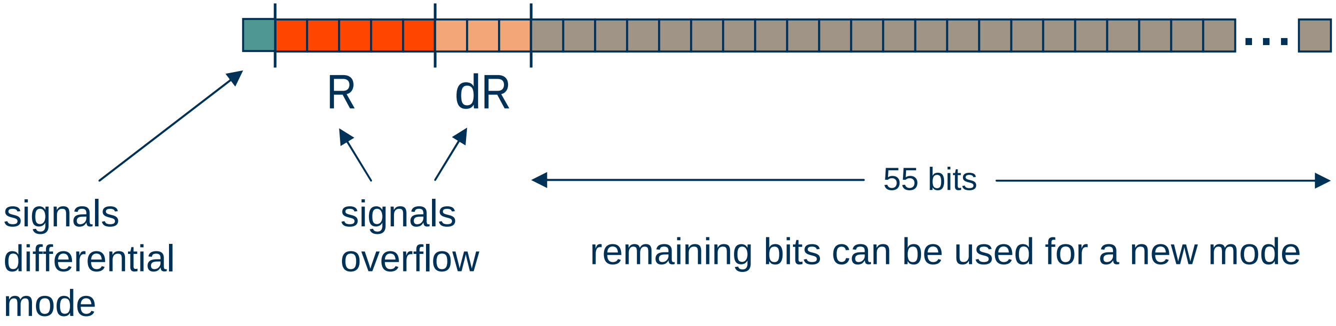
Schematic of a ETC2 decoder

- ETC1 can always be used – ETC2 better or same
- Decoder is backward compatible



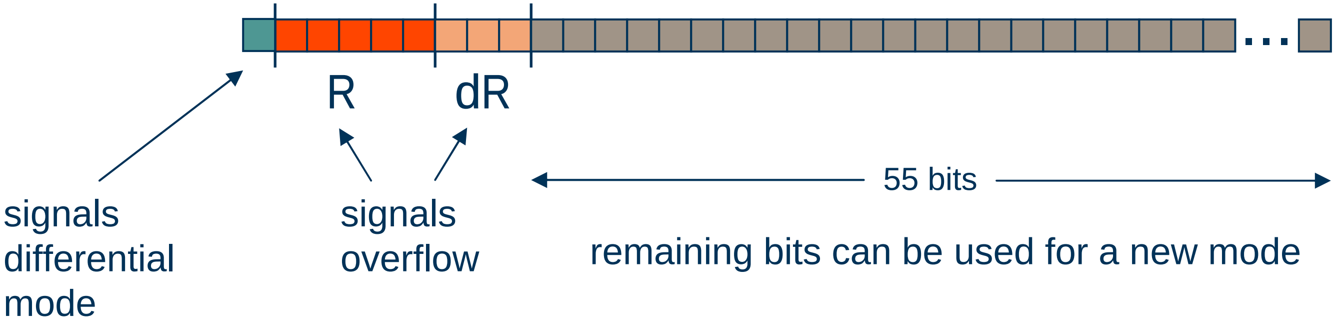
How many bits can we recover?

- How much data can be transmitted using bit sequences that overflow in the red component?


R
dR
signals differential mode
signals overflow
55 bits
remaining bits can be used for a new mode

How many bits can we recover?

- How much data can be transmitted using bit sequences that overflow in the red component?
- But R+dR can overflow (or underflow) in exactly 16 ways, which means we can signal 4 more bits for the new mode.


R
dR
...
55 bits
signals differential mode
signals overflow
remaining bits can be used for a new mode

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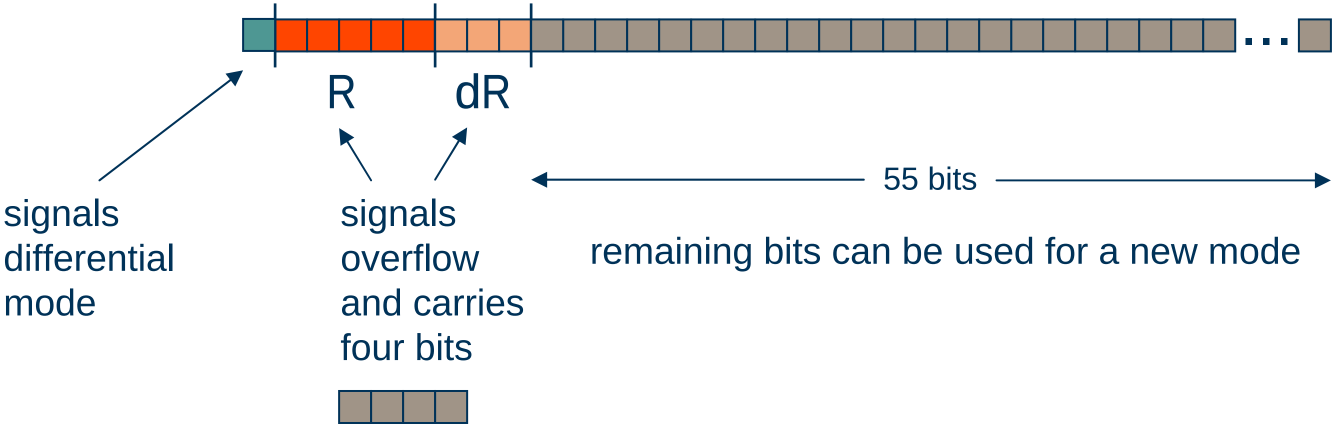
R
dR
…
55 bits
signals differential mode
signals overflow and carries four bits
remaining bits can be used for a new mode

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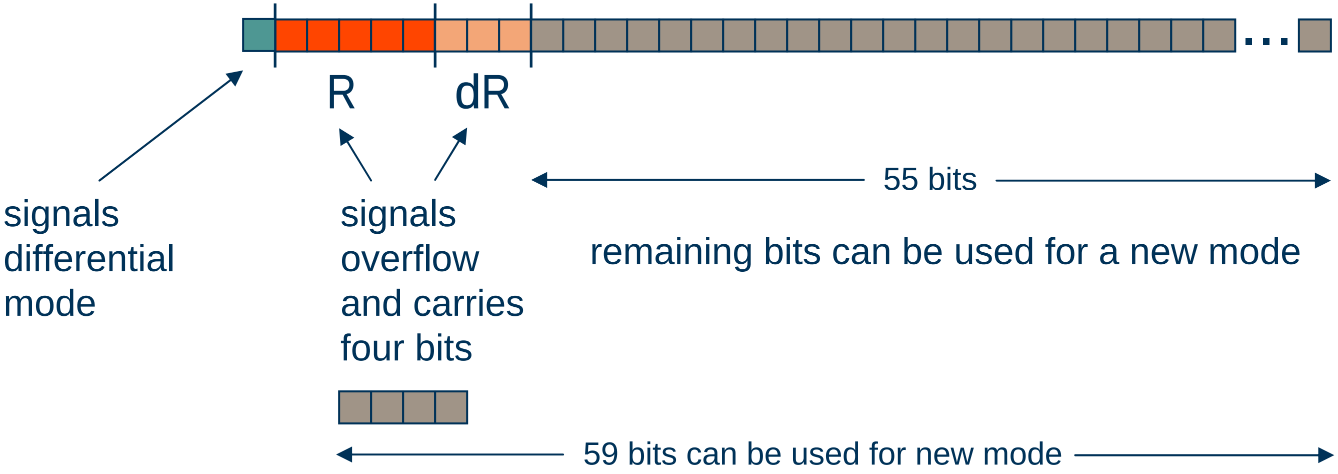
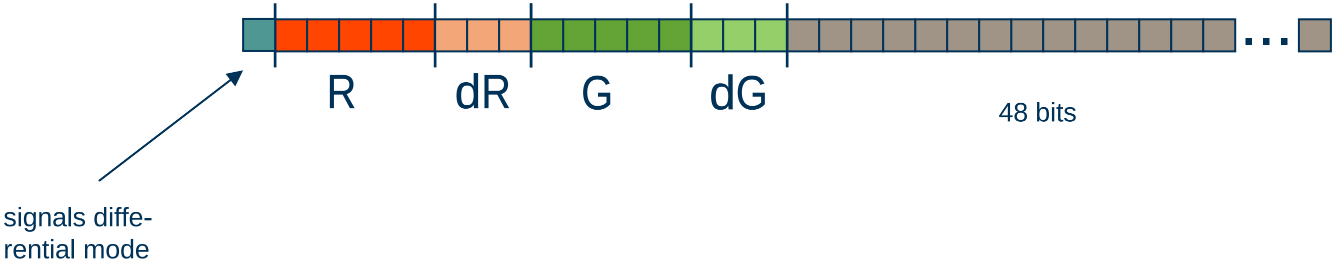


R
dR
55 bits
signals differential mode
signals overflow and carries four bits
remaining bits can be used for a new mode
59 bits can be used for new mode

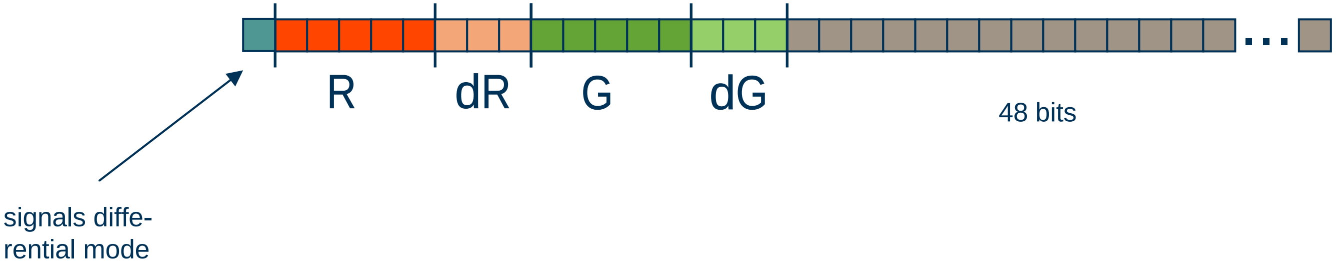
More Modes

- But the Green Component can also overflow, so we can get another mode.



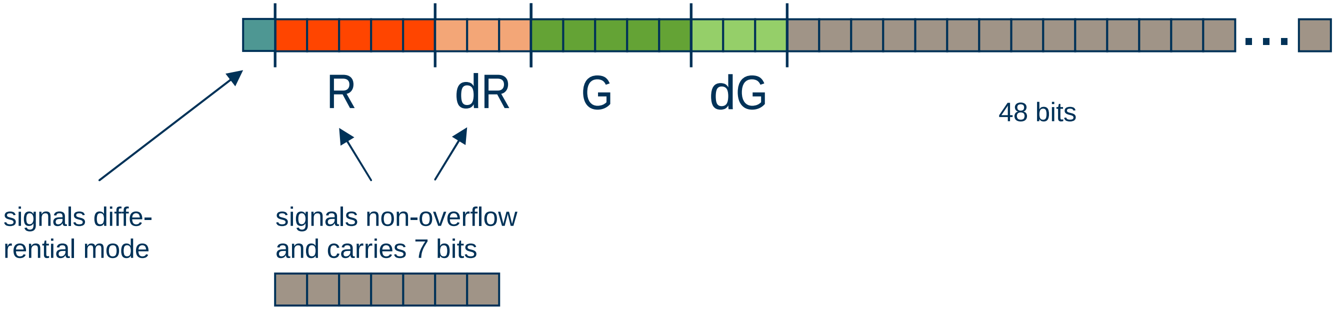
More Modes

- But the Green Component can also overflow, so we can get another mode.
- We must first make sure the red does not overflow, otherwise the decoder will think it is that mode.



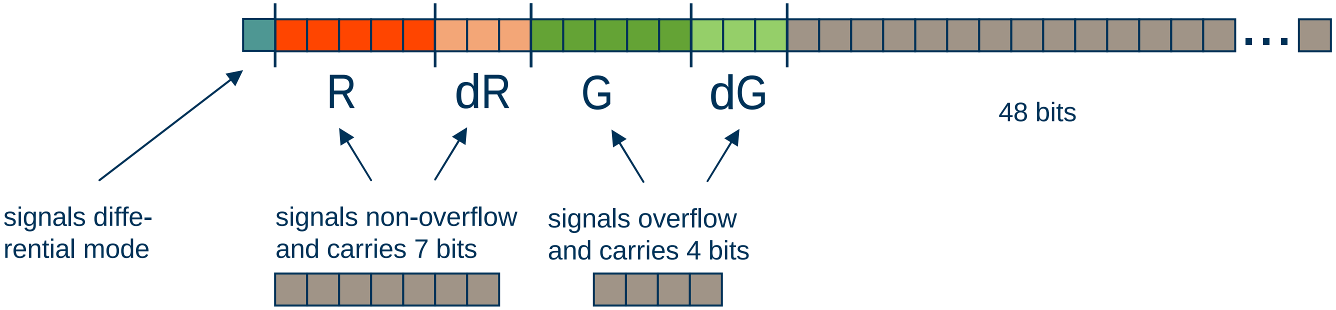
More Modes

- But the Green Component can also overflow, so we can get another mode.
- We must first make sure the red does not overflow, otherwise the decoder will think it is that mode.
- R+dR can avoid to overflow in 256-16 ways, so we can safely store 7 bits in R+dR


R
dR
G
dG
48 bits
signals differential mode
signals non-overflow and carries 7 bits

More Modes

- But the Green Component can also overflow, so we can get another mode.
- We must first make sure the red does not overflow, otherwise the decoder will think it is that mode.
- R+dR can avoid to overflow in 256-16 ways, so we can safely store 7 bits in R+dR
- And 4 bits in G+dG


R
dR
G
dG
48 bits
signals diffe-rential mode
signals non-overflow and carries 7 bits
signals overflow and carries 4 bits

More Modes

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- R+dR can avoid to overflow in 256-16 ways, so we can safely store 7 bits in R+dR
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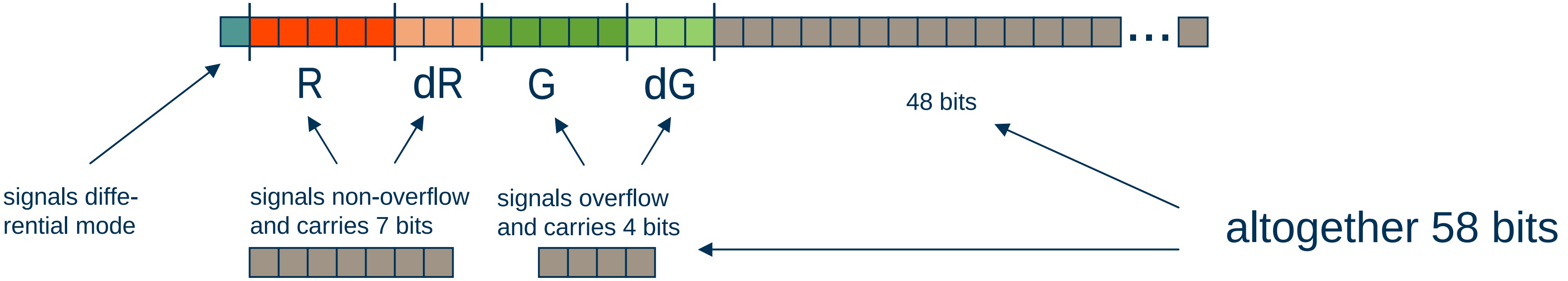


R
dR
G
dG
48 bits
signals diffe-rential mode
signals non-overflow and carries 7 bits
signals overflow and carries 4 bits

altogether 58 bits

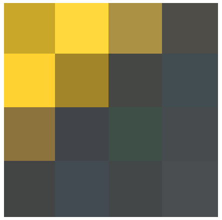
More Modes...

continued

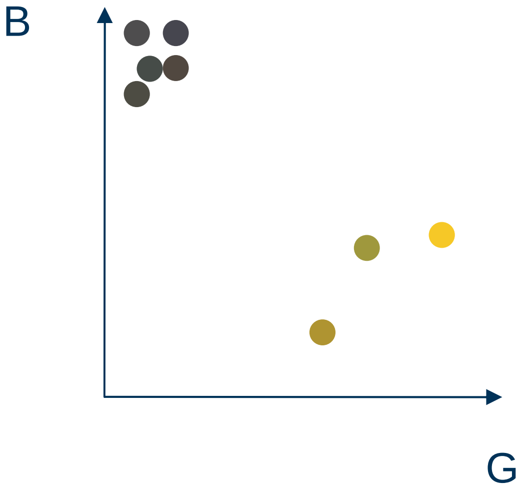
- The same can be done for the blue component and we have three new modes:
  - Mode 1: 59 bits payload
  - Mode 2: 58 bits payload
  - Mode 3: 57 bits payload
- We want three new modes that targets blocks that ETC1 has most problems with:
  - Colors in block have very different chrominances
  - Smooth transitions between several colors in the block
- The first problem was addressed by us in a previous paper published at a small national conference.

Mode 1: The ”T-Mode”

- The first mode targets blocks where some pixels are of a very different chrominance.

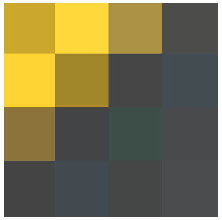


original block

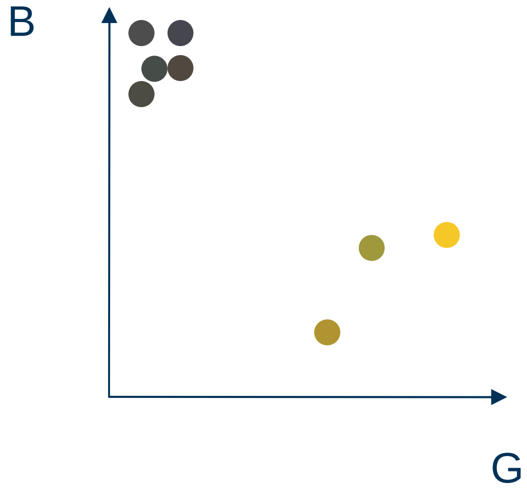


Mode 1: The ”T-Mode”

- The first mode targets blocks where some pixels are of a very different chrominance.
- Two colors are stored in the block.



original block



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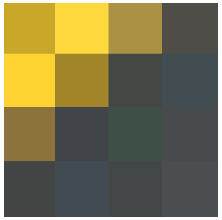
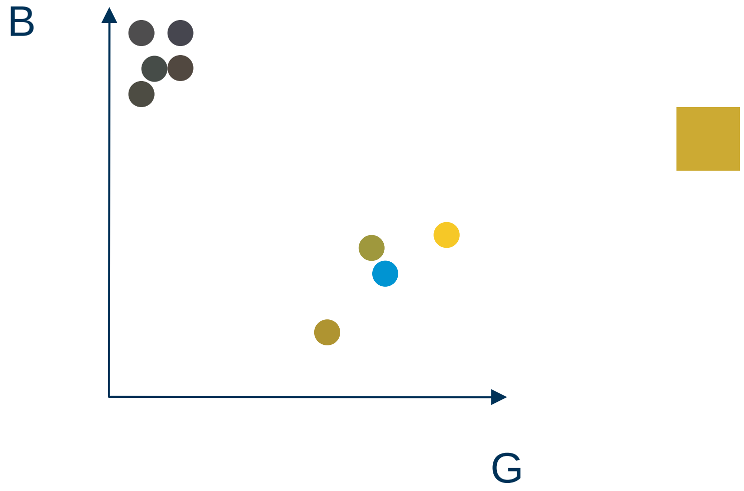


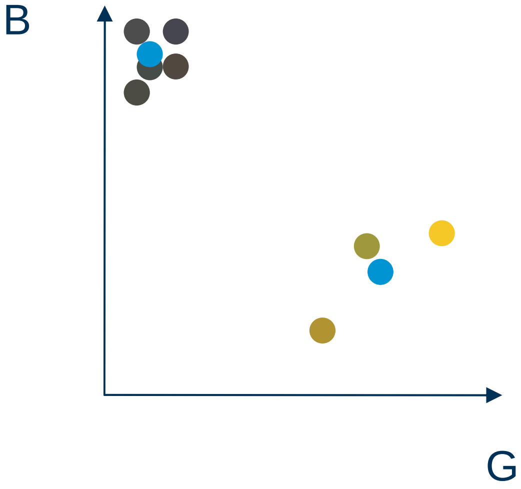
original block



Mode 1: The ”T-Mode”

- The first mode targets blocks where some pixels are of a very different chrominance.
- Two colors are stored in the block.

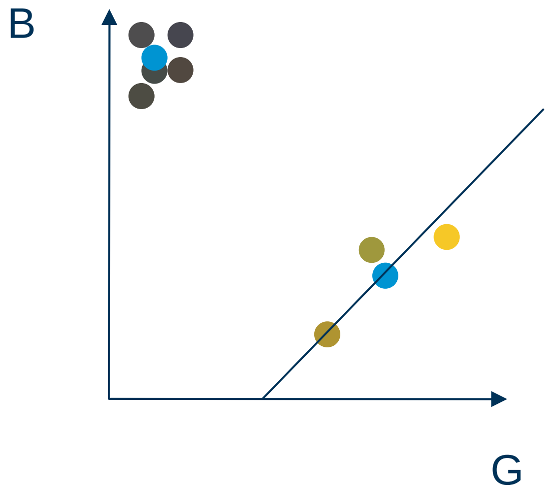
original block



Mode 1: The ”T-Mode”

- The first mode targets blocks where some pixels are of a very different chrominance.
- Two colors are stored in the block.
- Two more colors are obtained by modulating the first color along the intensity direction.

original block



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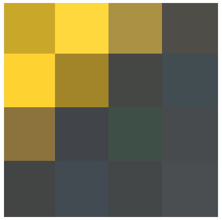
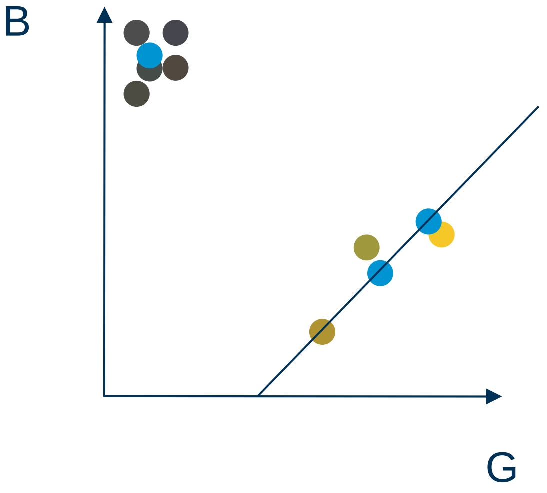


original block



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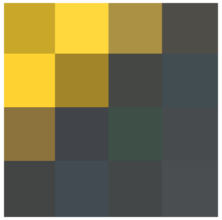
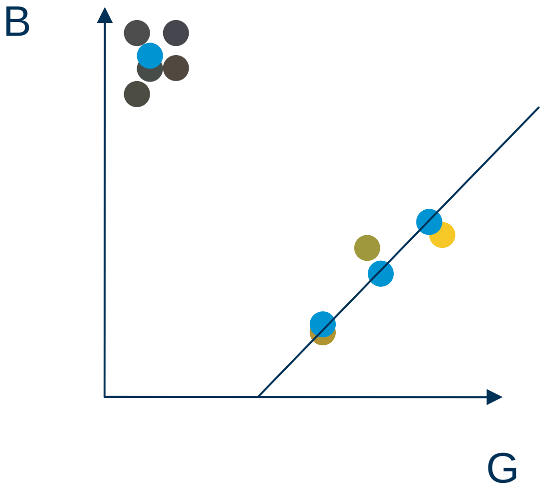
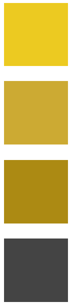


original block





Mode 1: The ”T-Mode”

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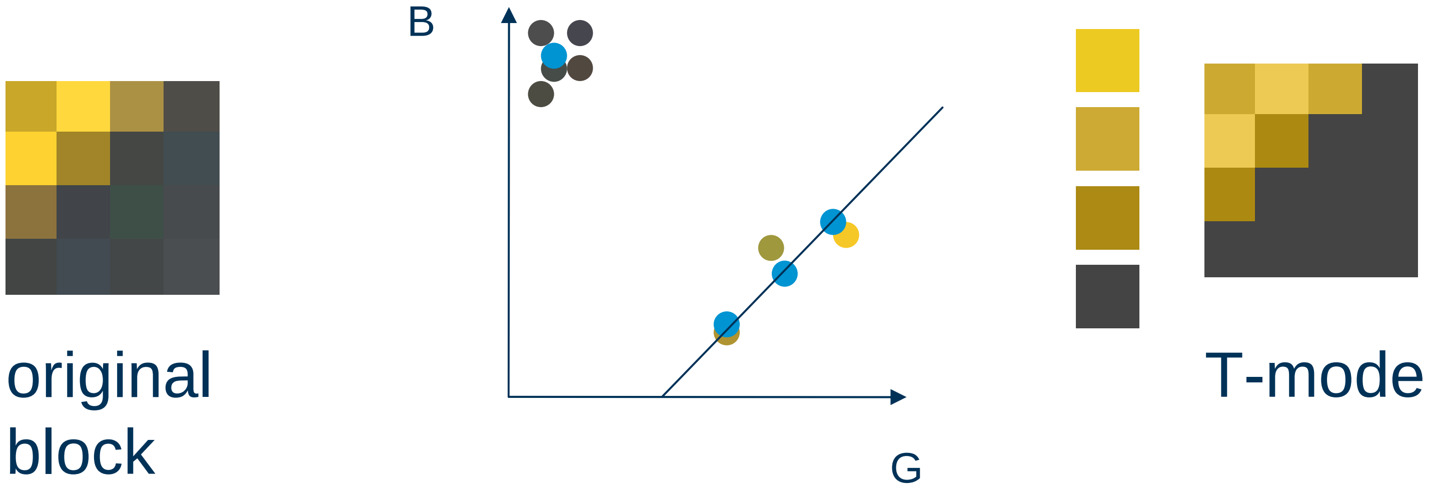

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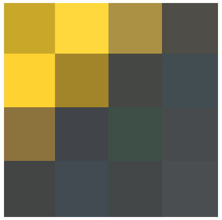
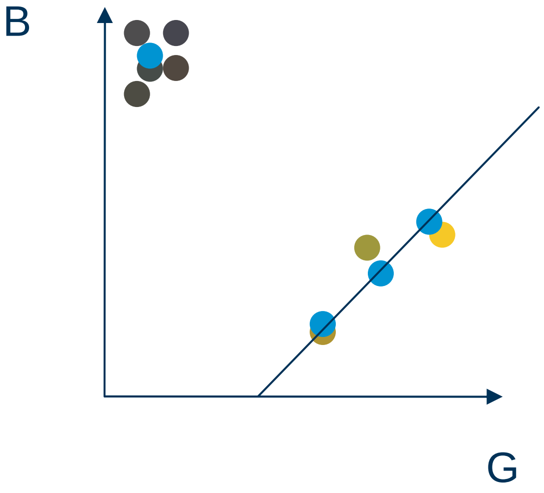
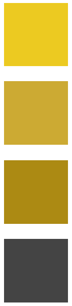
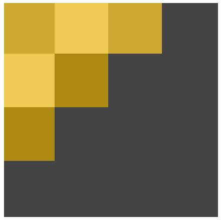


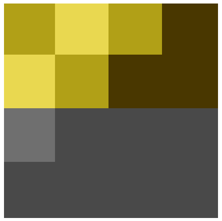
original block







T-mode



ETC1

Mode 1: The ”T-Mode”

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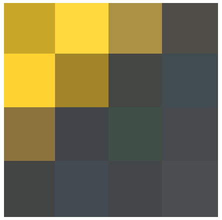
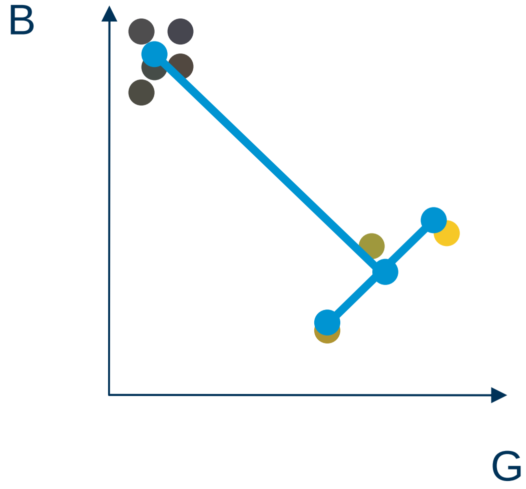
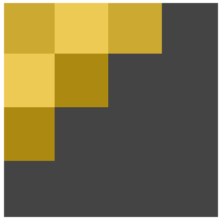
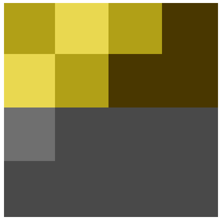


original block





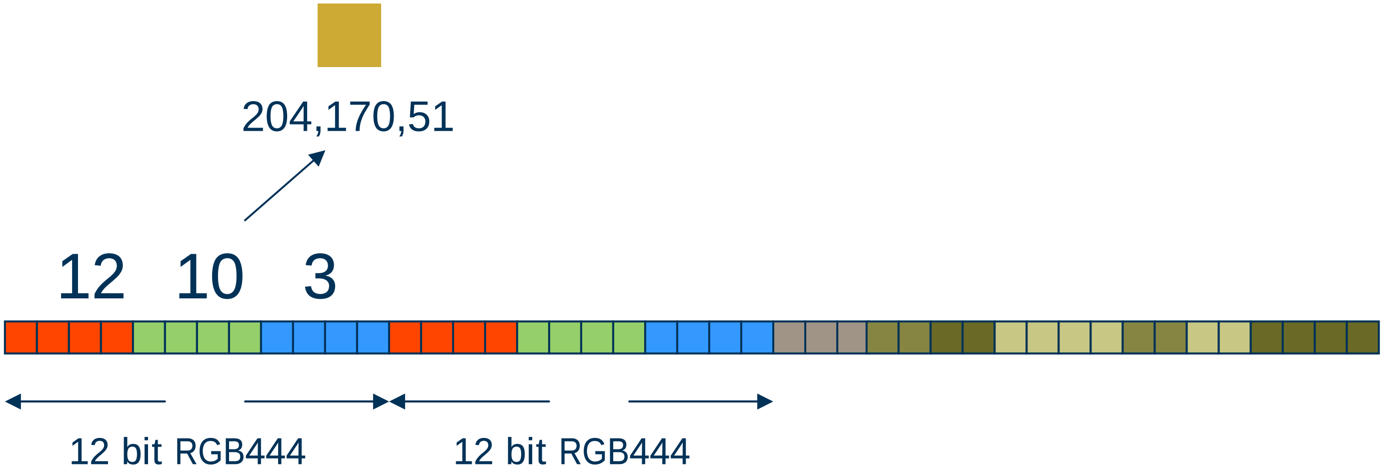
T-mode



ETC1

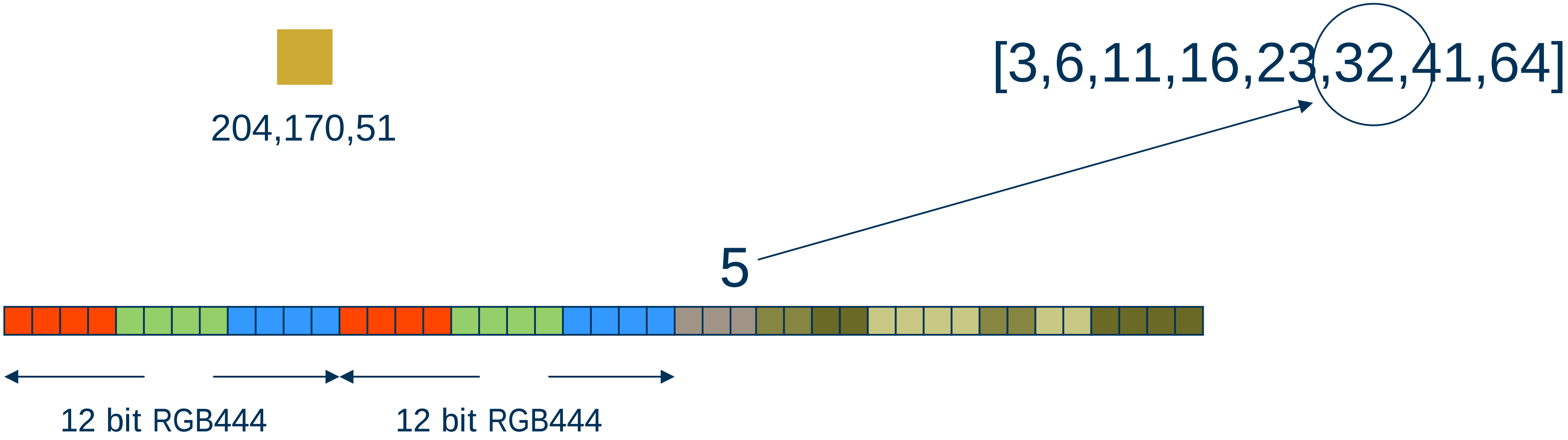
T-Mode Decompression

- The first color is expanded from RGB444 to RGB888.



T-Mode Decompression

- The first color is expanded from RGB444 to RGB888.
- Three bits are then used to select one of eight intensity modifiers.



204,170,51

[3,6,11,16,23,32,41,64]

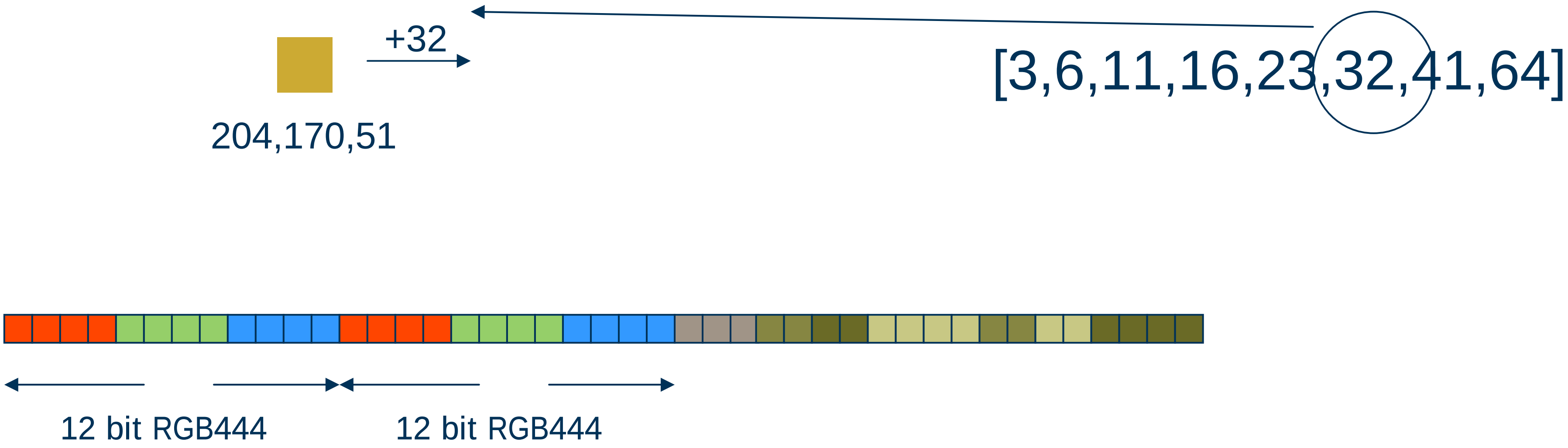
5

12 bit RGB444

12 bit RGB444

T-Mode Decompression

- The first color is expanded from RGB444 to RGB888.
- Three bits are then used to select one of eight intensity modifiers.
- This value is then used additively and subtractively to get two more colors.



+32

204,170,51

[3,6,11,16,23,32,41,64]

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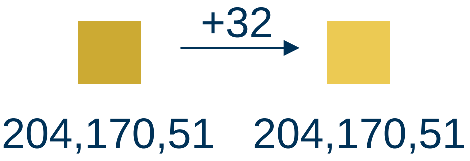

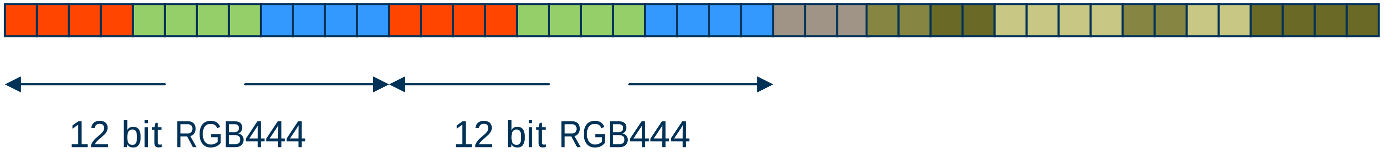

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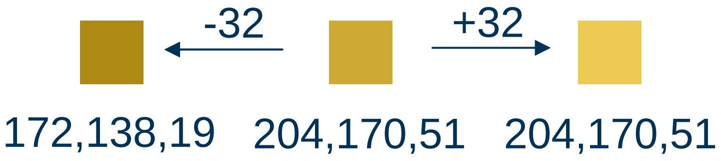
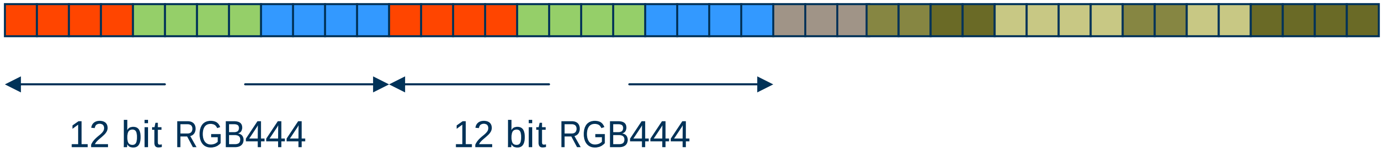

-32

+32

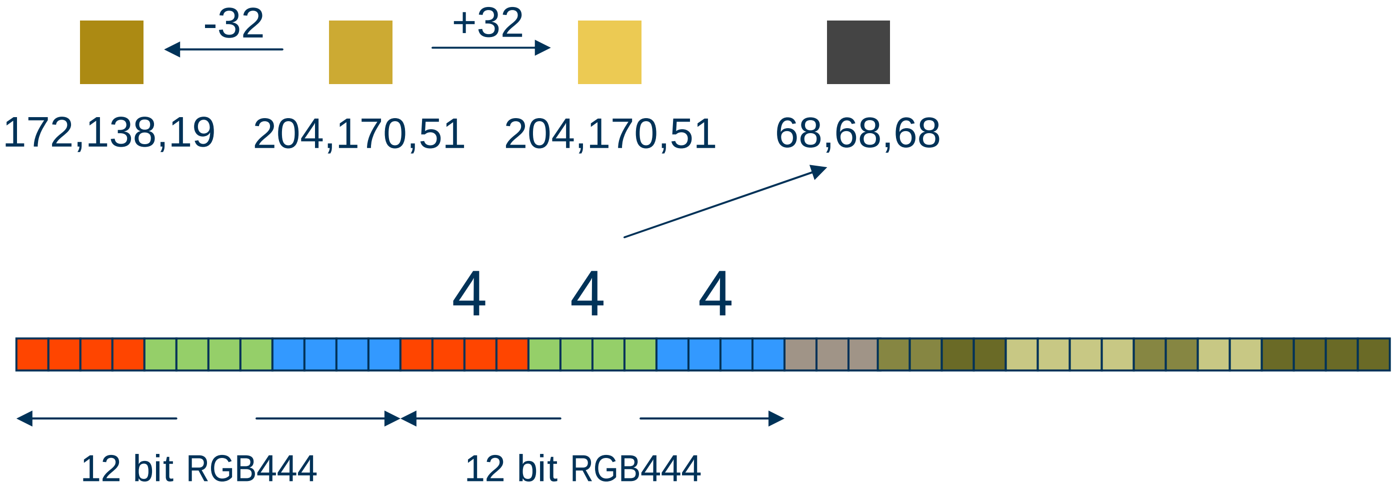
172,138,19 204,170,51 204,170,51


12 bit RGB444

12 bit RGB444

T-Mode Decompression

- The first color is expanded from RGB444 to RGB888.
- Three bits are then used to select one of eight intensity modifiers.
- This value is then used additively and subtractively to get two more colors.
- The second color is then expanded to RGB888.



-32

+32

172,138,19

204,170,51

204,170,51

68,68,68

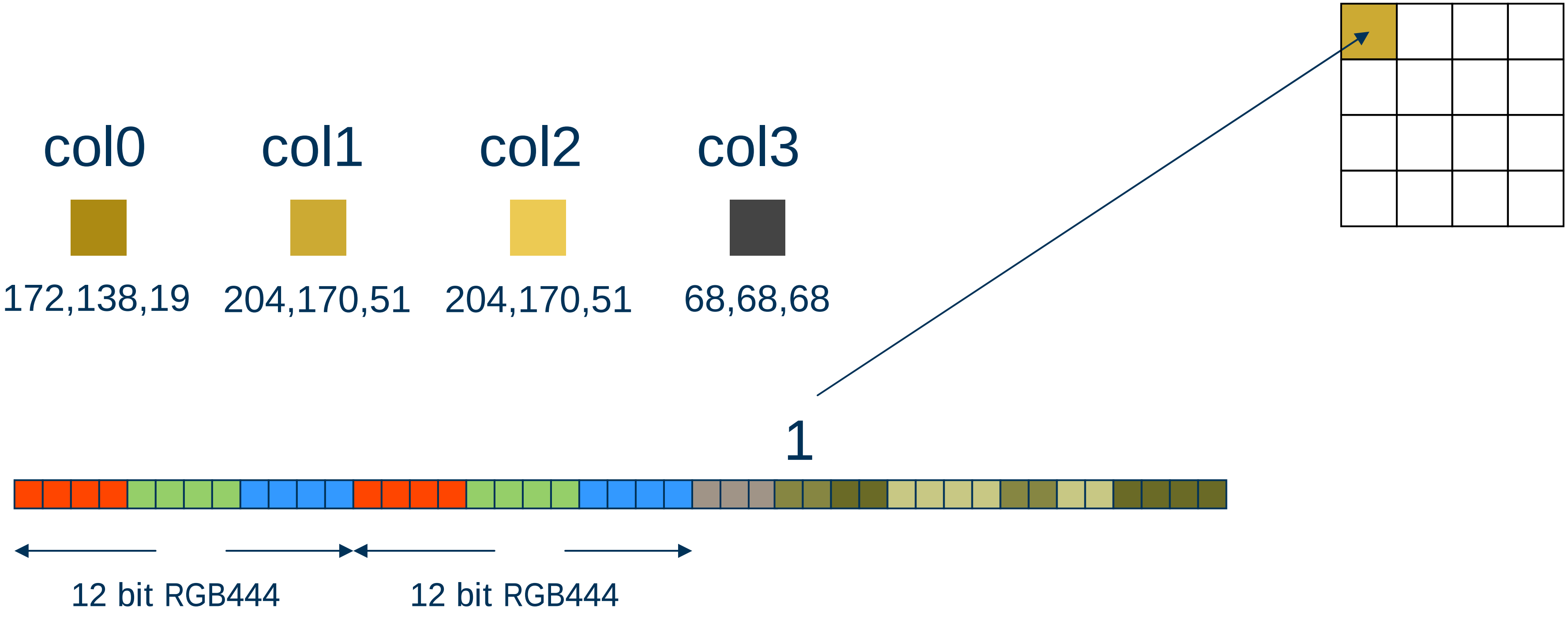
4 4 4

12 bit RGB444

12 bit RGB444

T-Mode Decompression

- Two bits per pixel decides which of the four colors to choose from.



col0 col1 col2 col3

172,138,19 204,170,51 204,170,51 68,68,68

1

12 bit RGB444

12 bit RGB444

T-Mode Decompression

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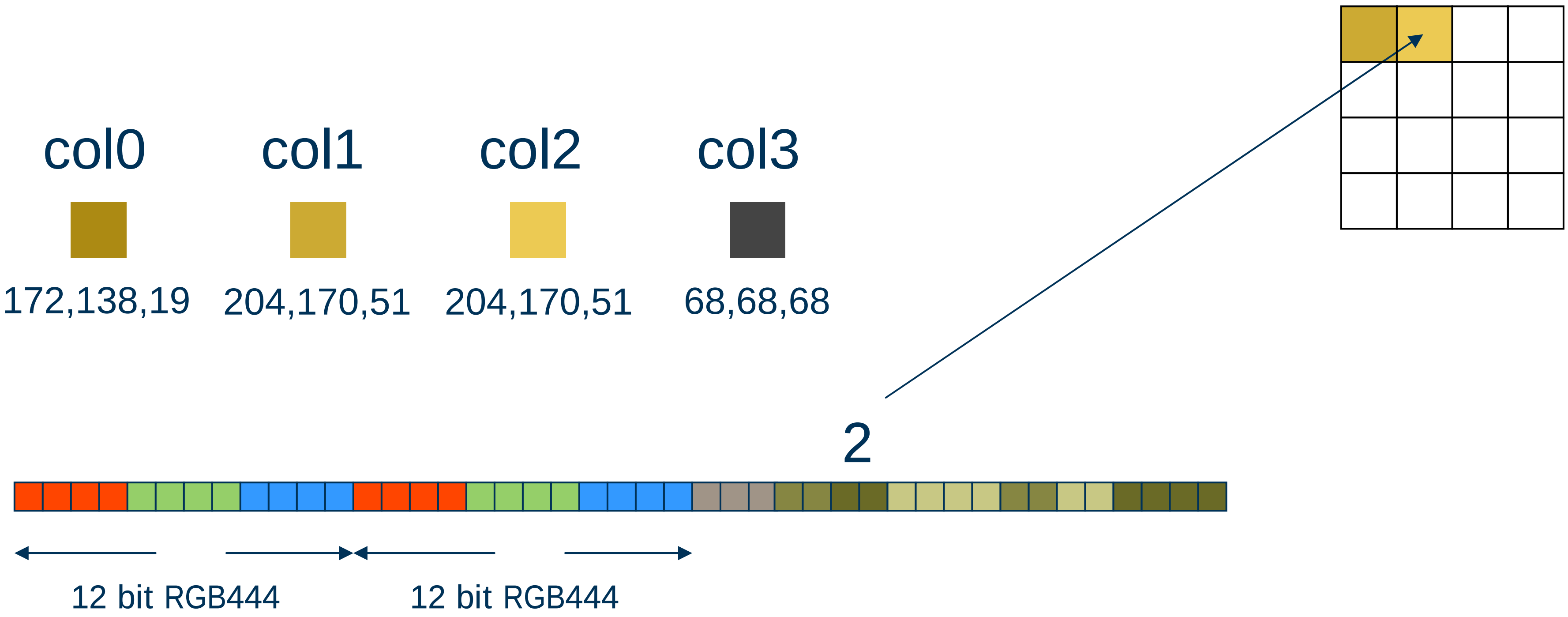


col0 col1 col2 col3

172,138,19 204,170,51 204,170,51 68,68,68

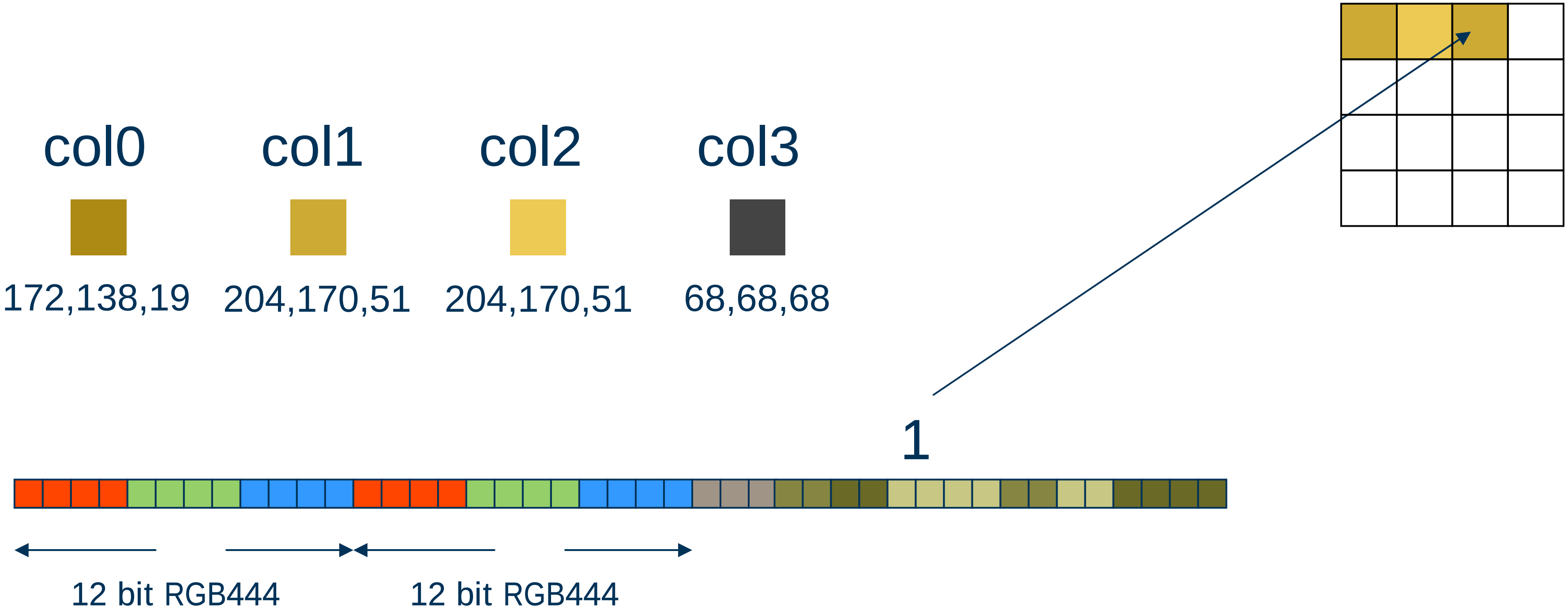
2

12 bit RGB444

12 bit RGB444

T-Mode Decompression

- Two bits per pixel decides which of the four colors to choose from.



col0	col1	col2	col3
172,138,19	204,170,51	204,170,51	68,68,68

1

12 bit RGB444

12 bit RGB444

T-Mode Decompression

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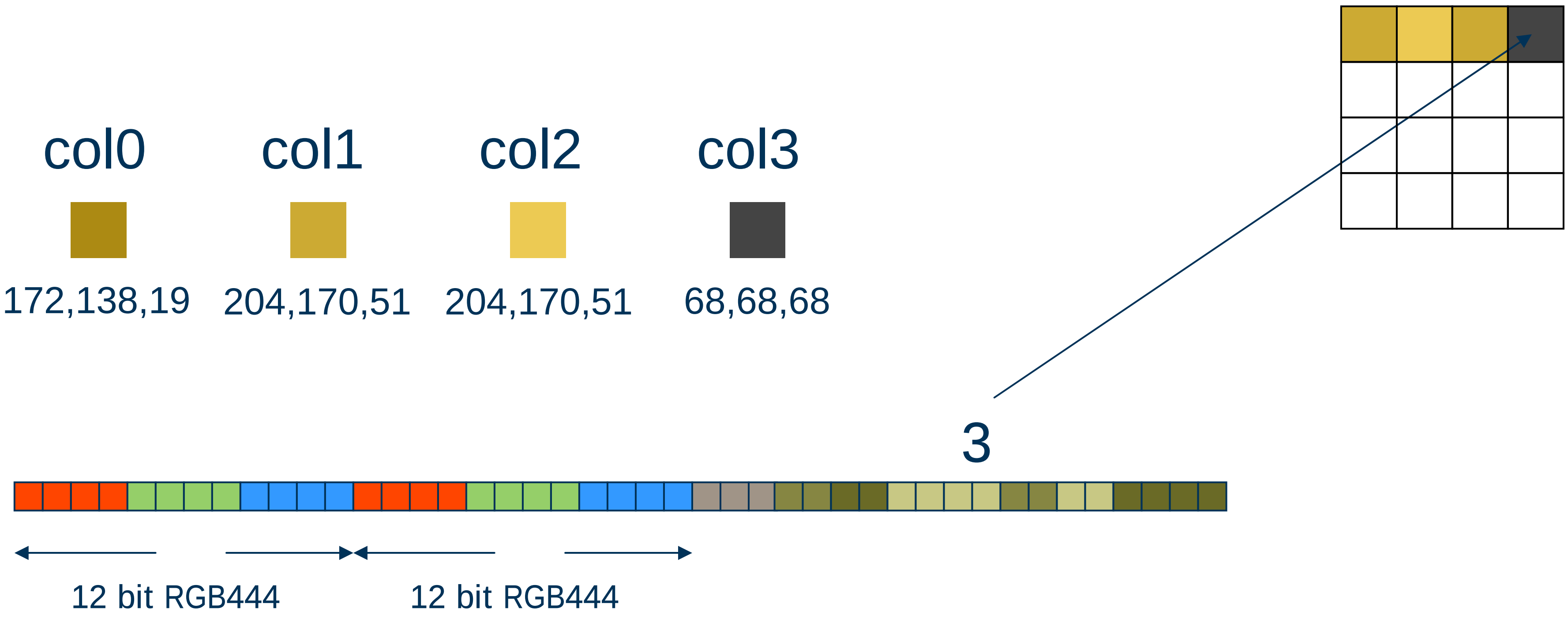

T-Mode Decompression

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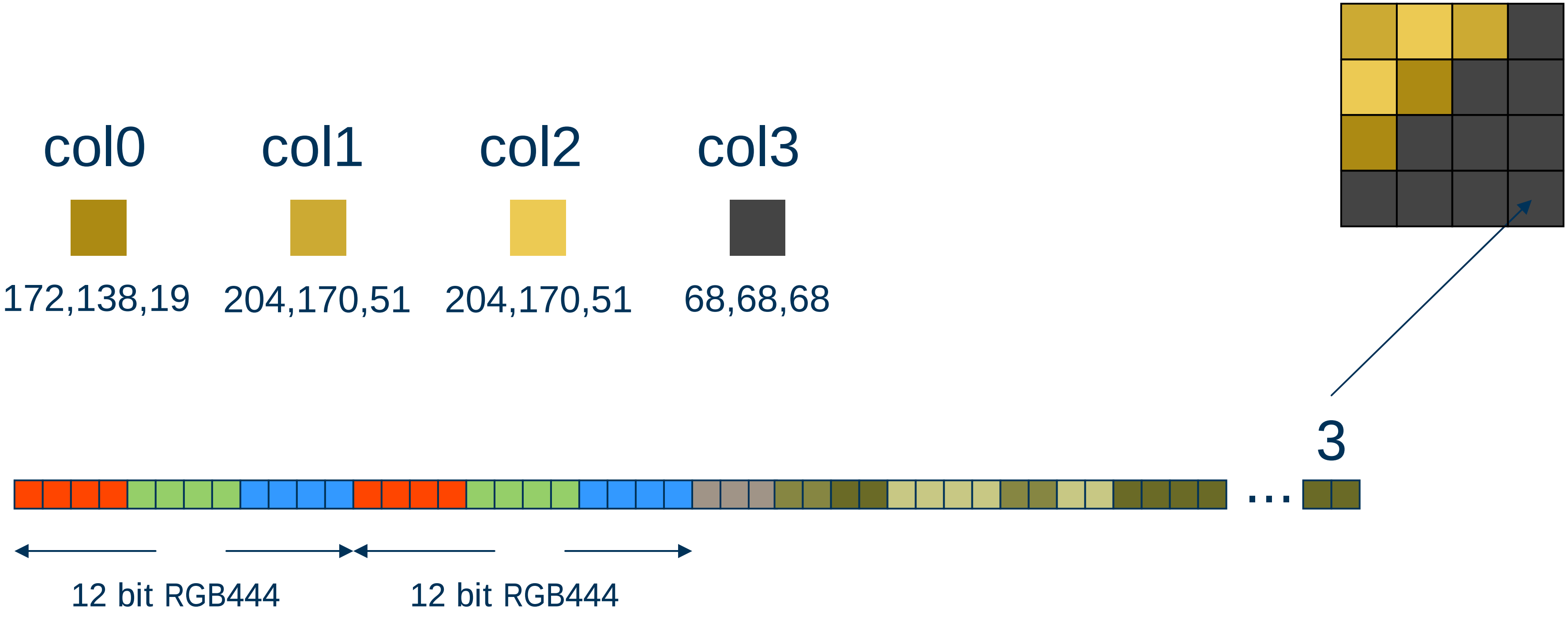
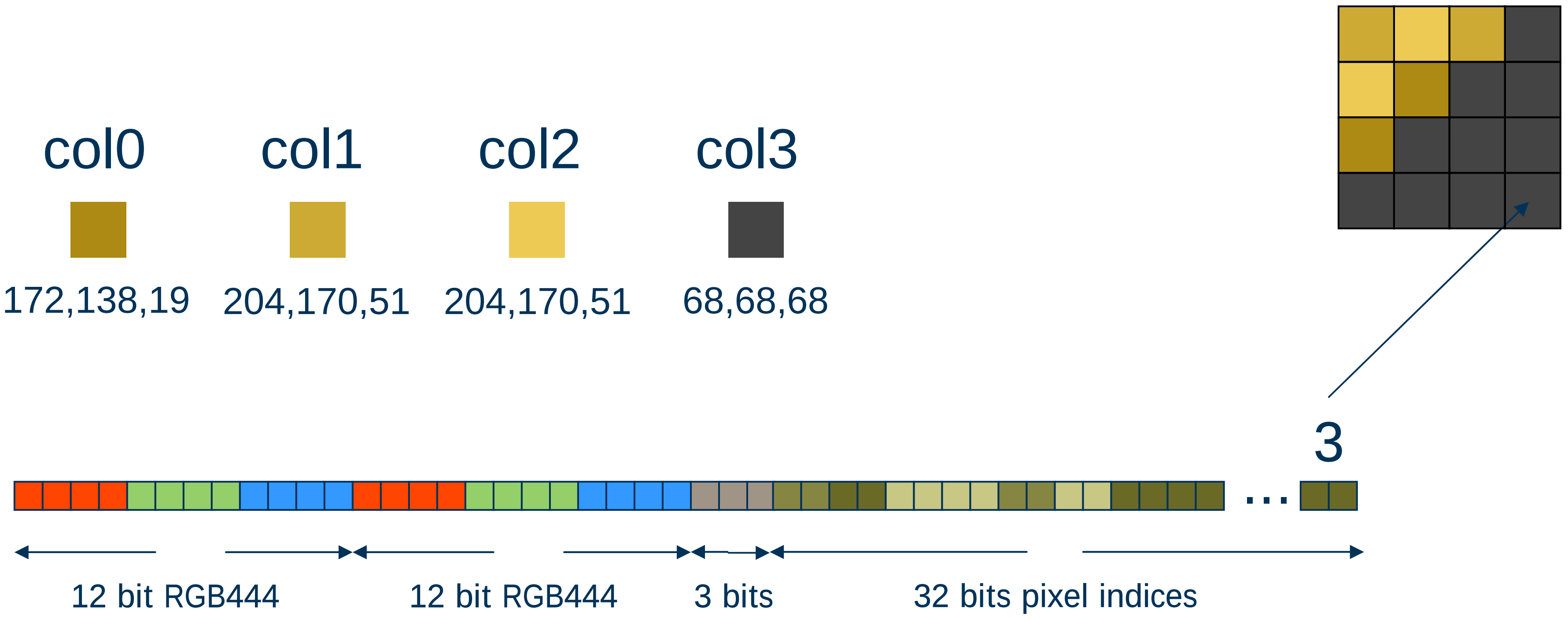


col0 col1 col2 col3

172,138,19 204,170,51 204,170,51 68,68,68

T-Mode Decompression

- Two bits per pixel decides which of the four colors to choose from.
- All in all 59 bits which fits into the first mode.

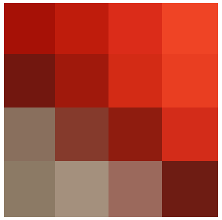


col0 col1 col2 col3

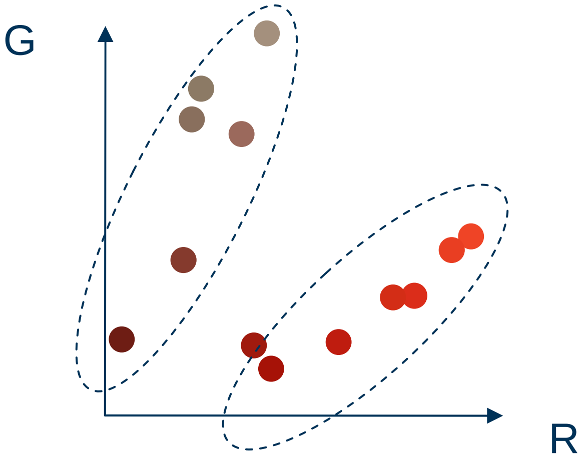
172,138,19 204,170,51 204,170,51 68,68,68

Mode 2: The ”H-Mode”

- The second mode targets blocks where there are two groups of pixels that can be intensity modulated.

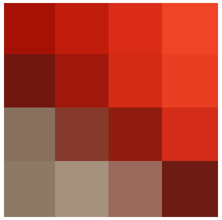


original block

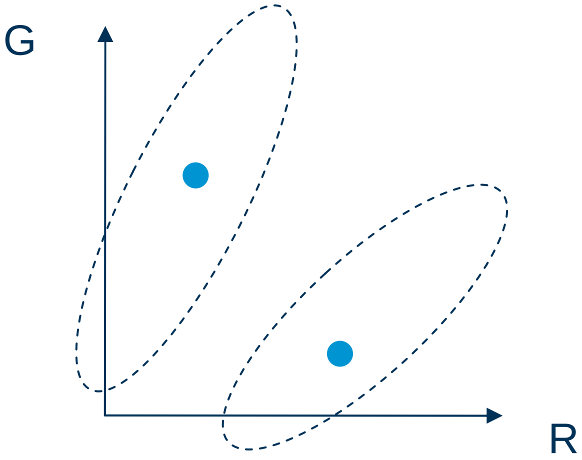


Mode 2: The ”H-Mode”

- The second mode targets blocks where there are two groups of pixels that can be intensity modulated.
- Two colors are stored in the block.

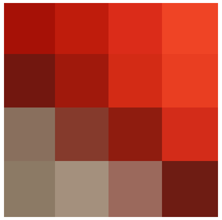


original block

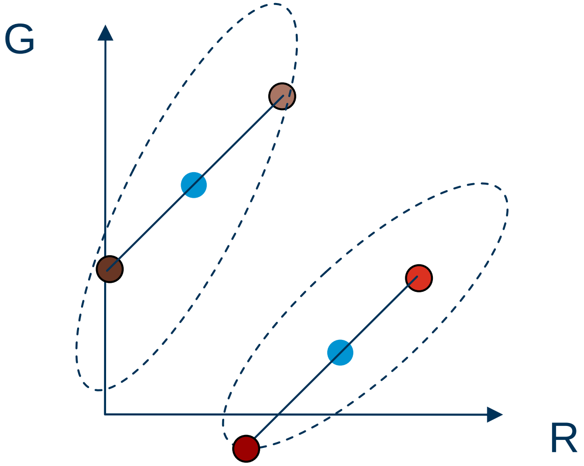


Mode 2: The ”H-Mode”

- The second mode targets blocks where there are two groups of pixels that can be intensity modulated.
- Two colors are stored in the block.
- Both colors are modulated in the intensity direction...

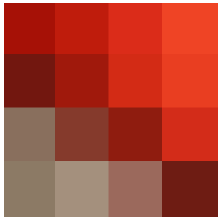


original block

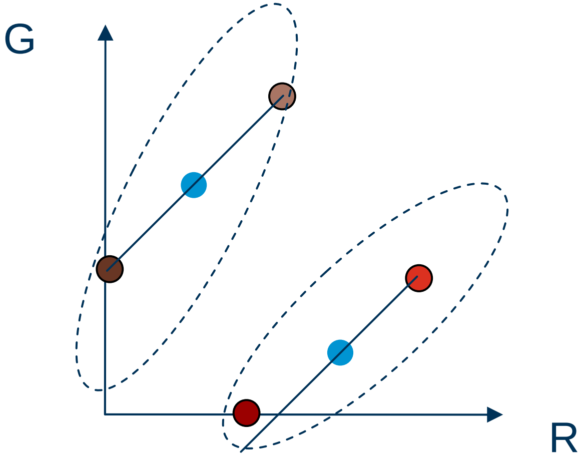


Mode 2: The ”H-Mode”

- The second mode targets blocks where there are two groups of pixels that can be intensity modulated.
- Two colors are stored in the block.
- Both colors are modulated in the intensity direction... and clamped.



original block



Mode 2: The ”H-Mode”

- The second mode targets blocks where there are two groups of pixels that can be intensity modulated.
- Two colors are stored in the block.
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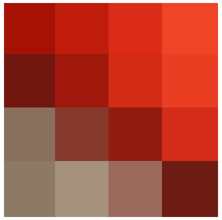
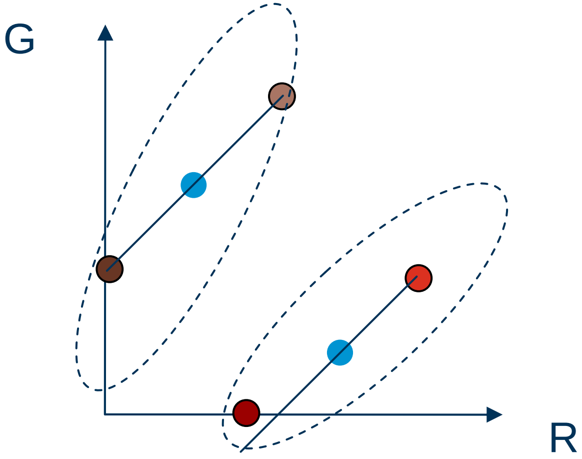
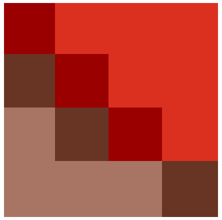
- These four colors are used to build up the block



original block





H-mode

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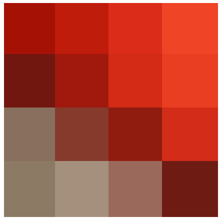
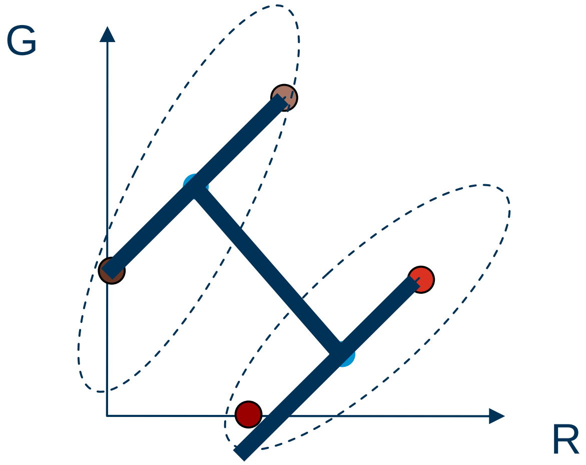
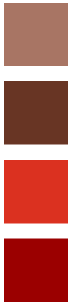
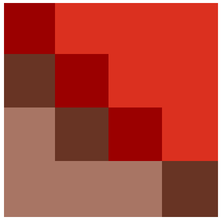


original block

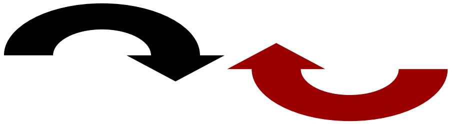






H-mode

H-mode: Ordering Trick



- The H mode needs 59 bits just as the T-mode.
- However, only 58 bits are available.
- But since the two colors are interchangeable, we can use the “ordering trick” to signal an extra bit:
  - “Darkest” color first signals a 0
  - “Brightest” color first signals a 1
- This way we can fit the H-mode into the 58 bit slot.

Last Mode: The Planar mode

- Some blocks have very slowly varying colors. These are not always well approximated with ETC or S3TC/DXTC.

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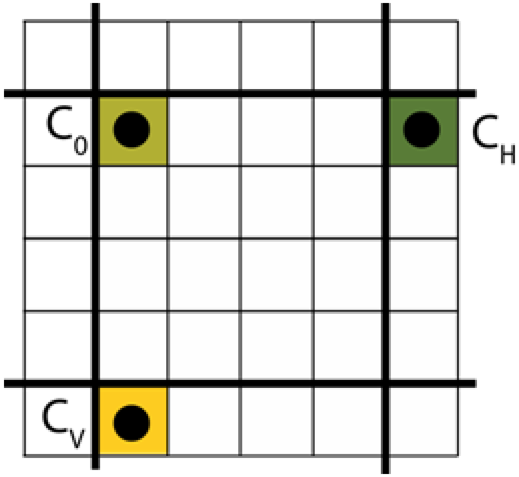
- Such blocks contain very little information – can be handled well with a special mode.
- Three colors are stored per block: C_0, C_H and C_V in RGB676. The color is interpolated colinearly (using a planar model) in between.



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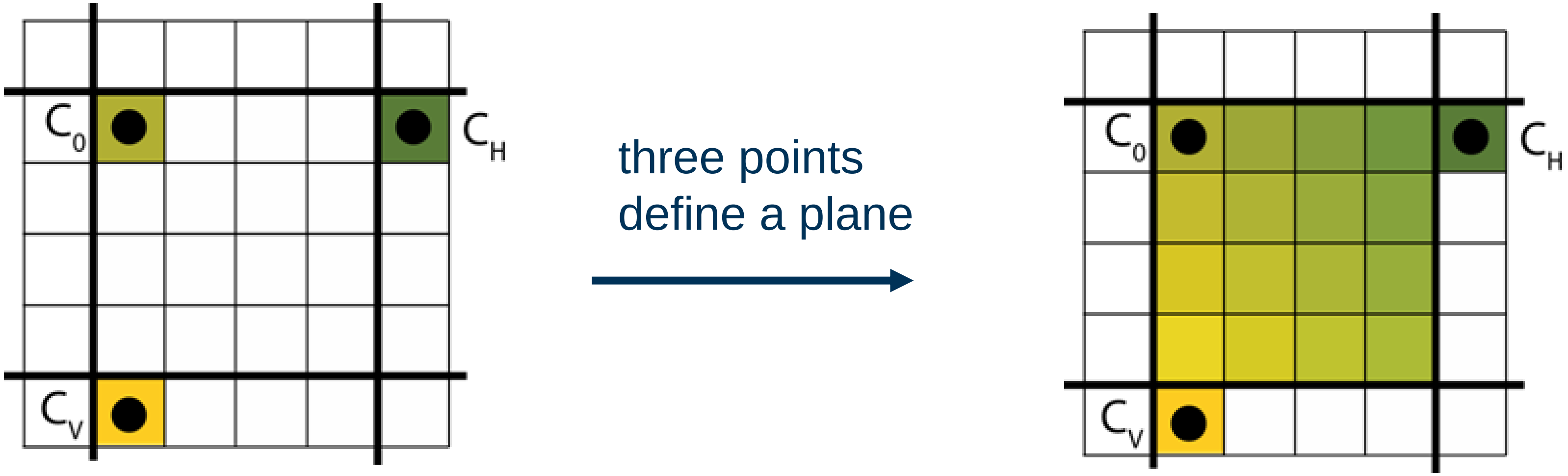


three points define a plane

Results

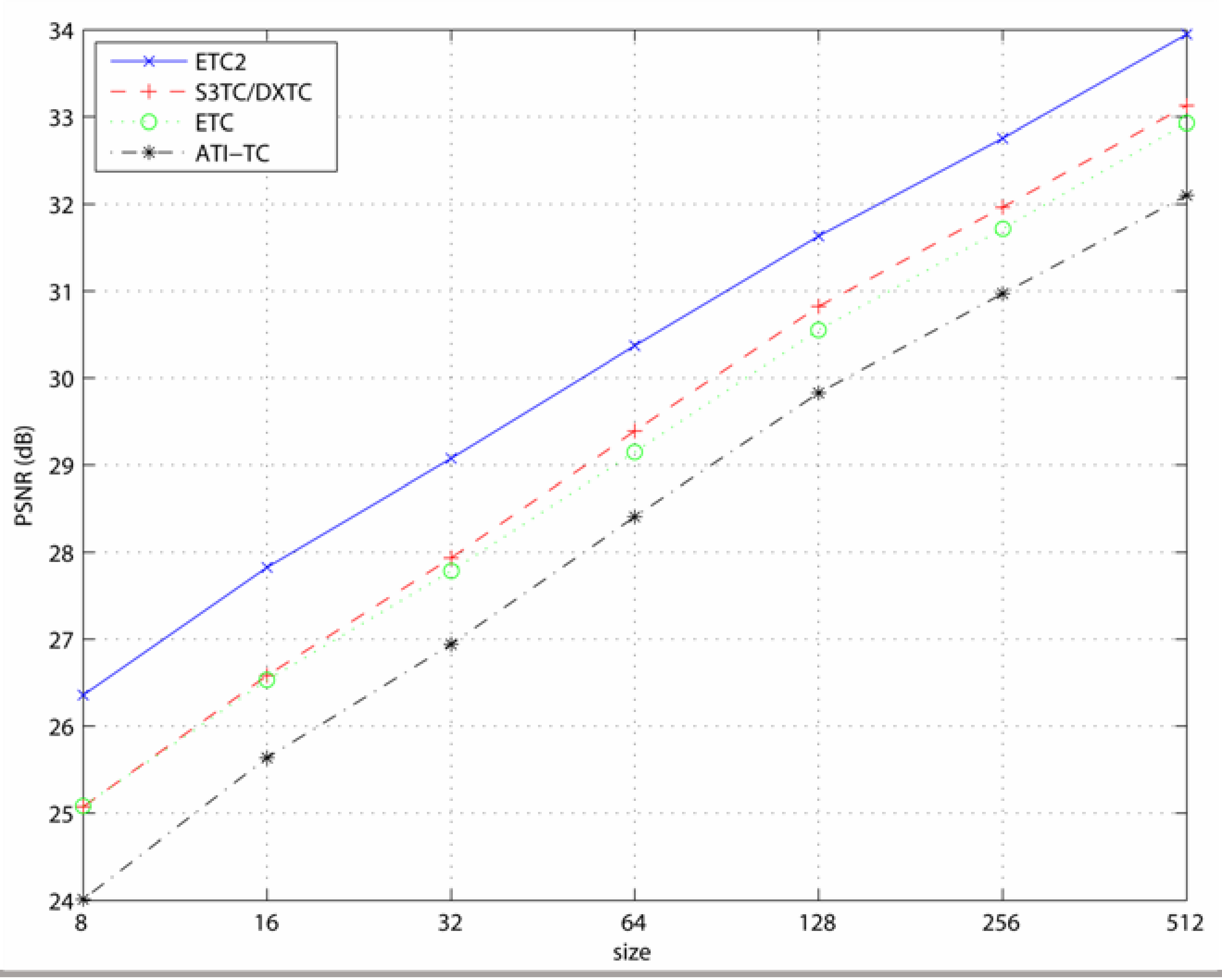
- ETC2 was tested on 64 textures, each texture on all mipmap sizes between 512x512 and 8x8 pixels.
- The textures were both photographic images and game textures.
- The system has been compared to
  - ETC1
  - S3TC/DXTC
  - ATI-TC

Results

- For the highest mipmap:
  - 0.8 dB higher quality than S3TC/DXTC (same bitrate)
  - 1.0 dB higher quality than ETC1 (same bitate)
  - 1.8 dB higher quality than ATI-TC (same bitrate)

Results – All Mipmaps

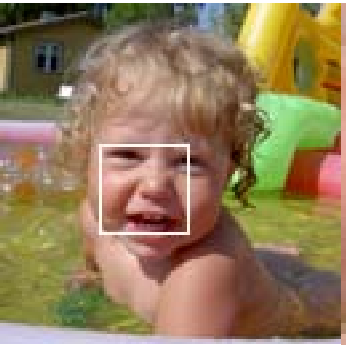
margin to next best varies between 0.8 dB and 1.3 dB

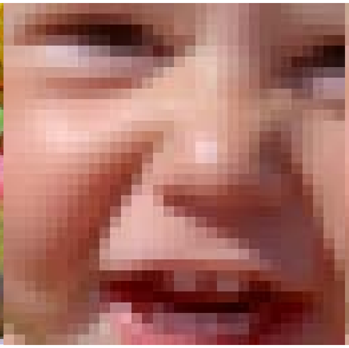


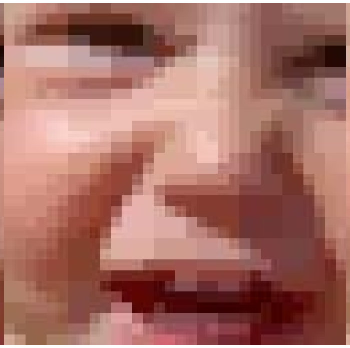
Results

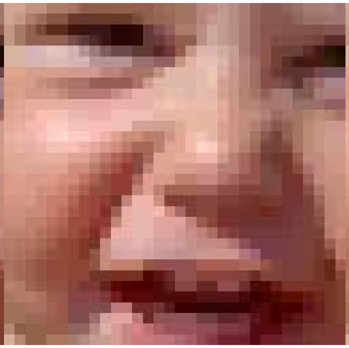
🟦 ETC1
🟨 T-mode
🟪 H-mode
🟩 Planar

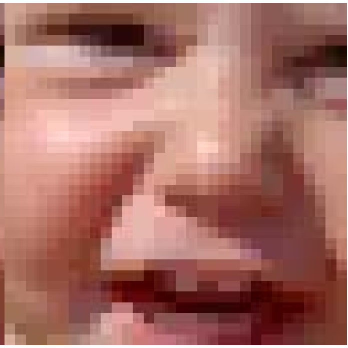
original S3TC/DXTC ETC1 ETC2

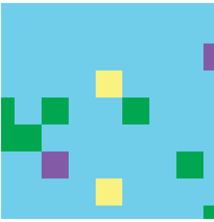








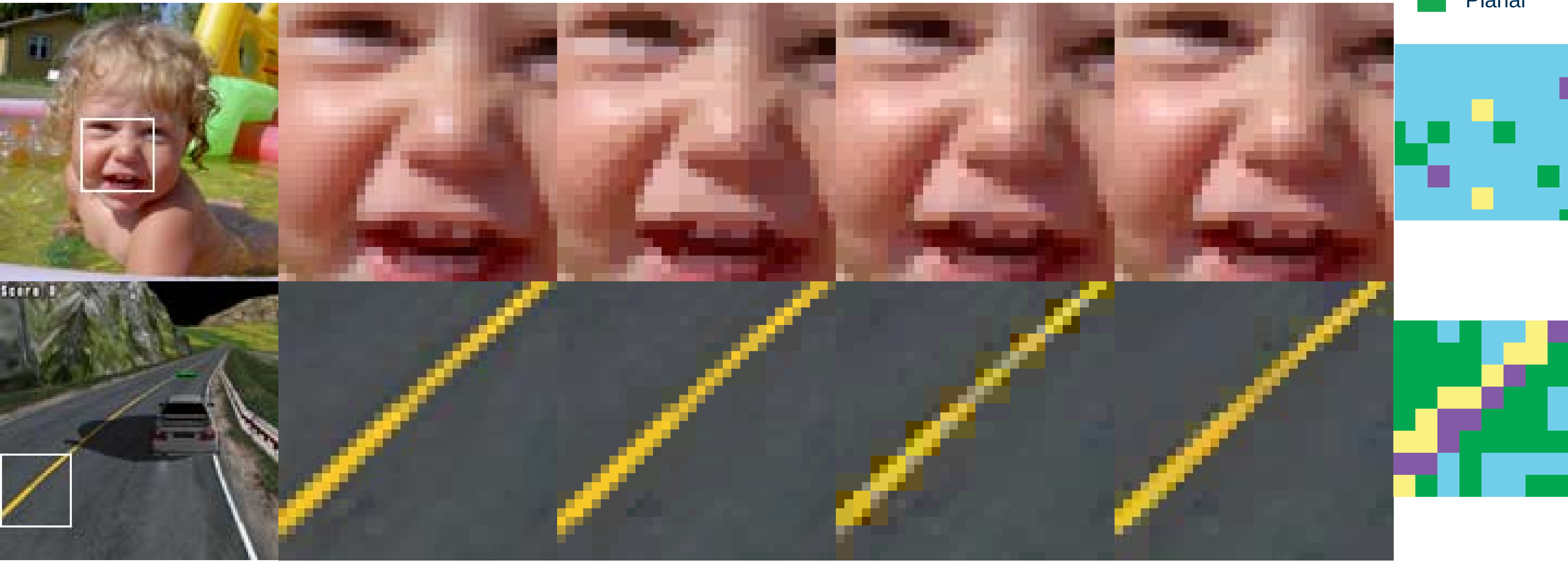




original S3TC/DXTC ETC 1 ETC2

Results

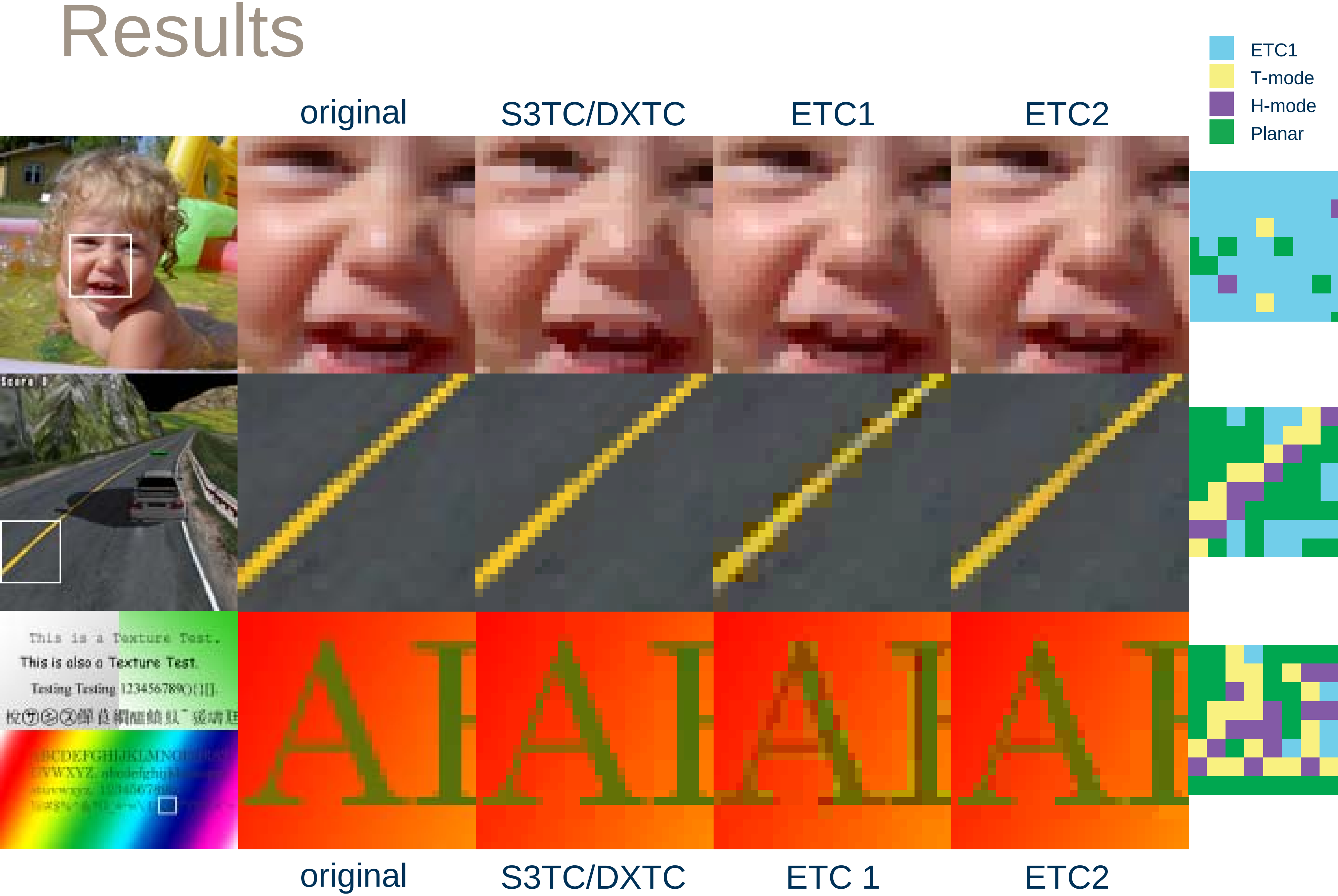
original S3TC/DXTC ETC1 ETC2



- 🟦 ETC1
- 🟨 T-mode
- 🟪 H-mode
- 🟩 Planar

original S3TC/DXTC ETC 1 ETC2

Results



original S3TC/DXTC ETC1 ETC2

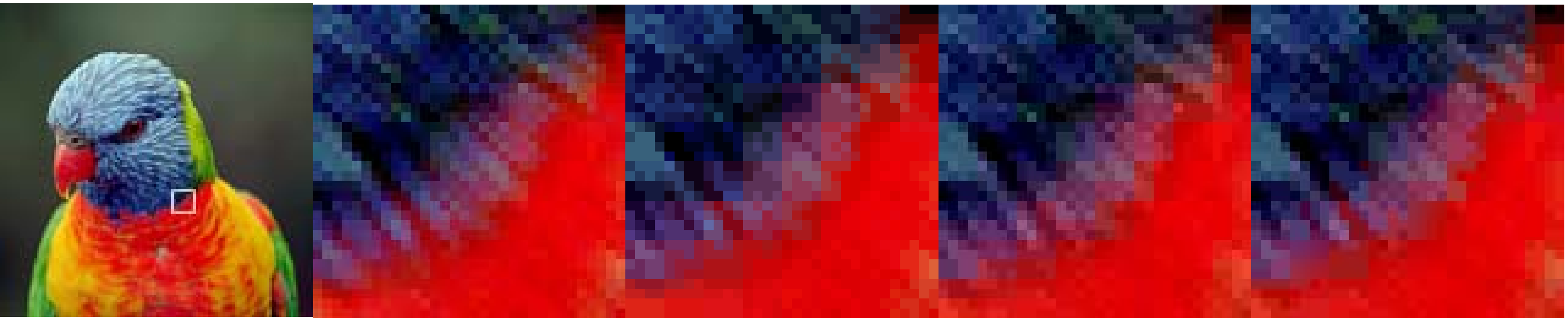
🟦 ETC1
🟨 T-mode
🟪 H-mode
🟩 Planar

original S3TC/DXTC ETC 1 ETC2

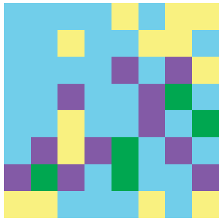
Results

cont.

original S3TC/DXTC ETC1 ETC2



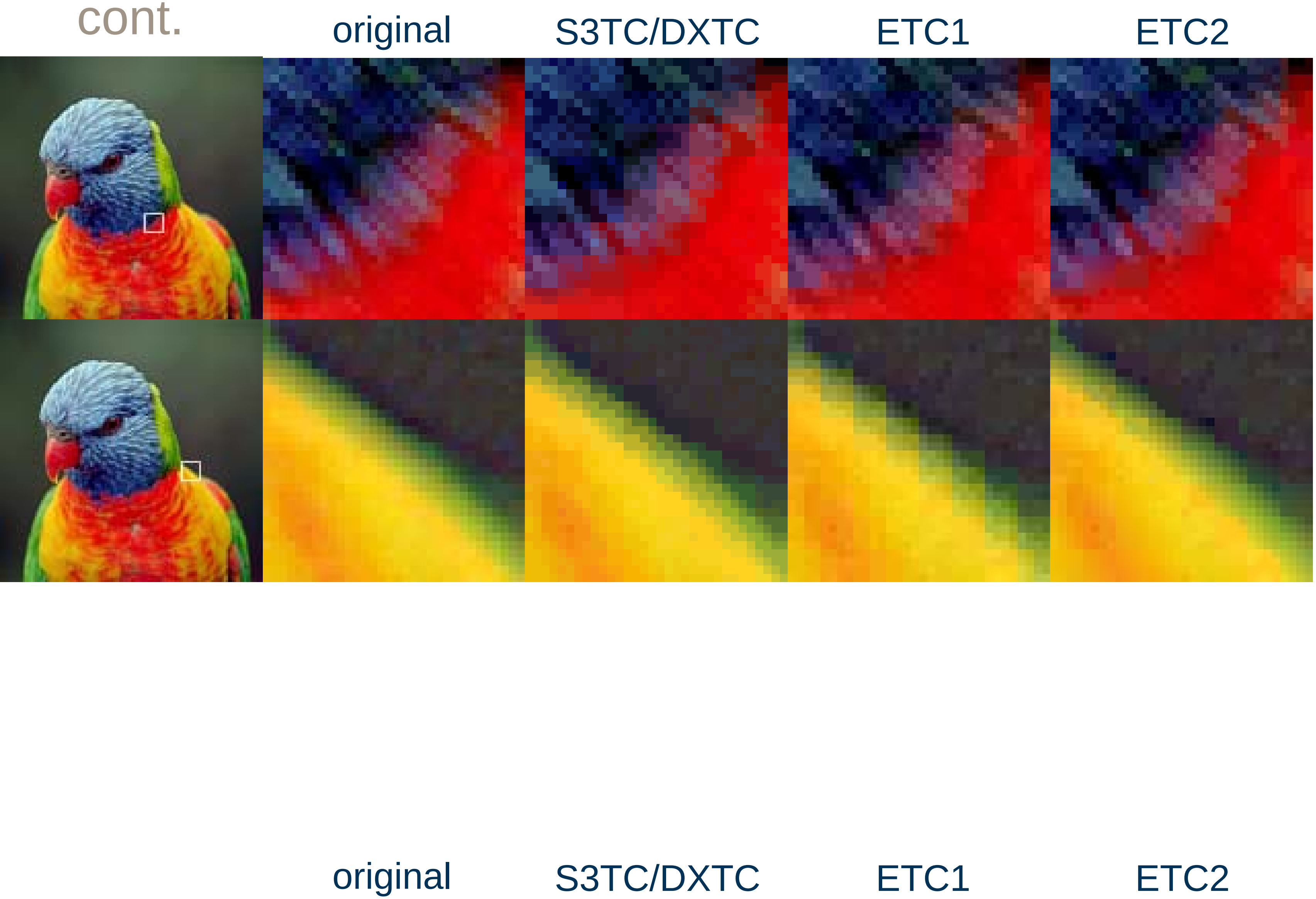
🟦 ETC1
🟨 T-mode
🟪 H-mode
🟩 Planar



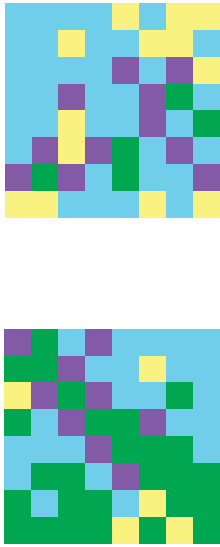
original S3TC/DXTC ETC1 ETC2

Results

cont.

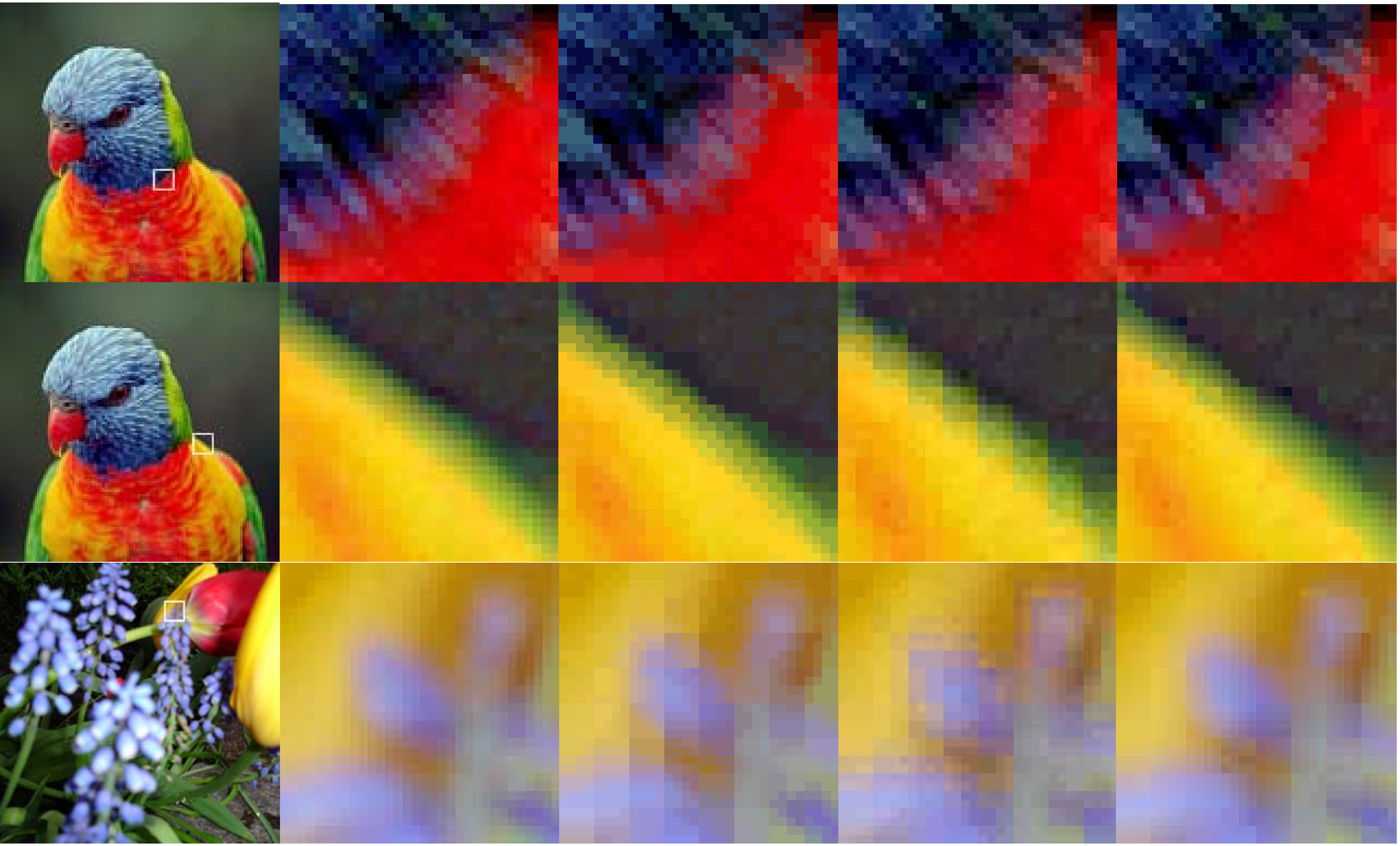


🟦 ETC1
🟨 T-mode
🟪 H-mode
🟩 Planar



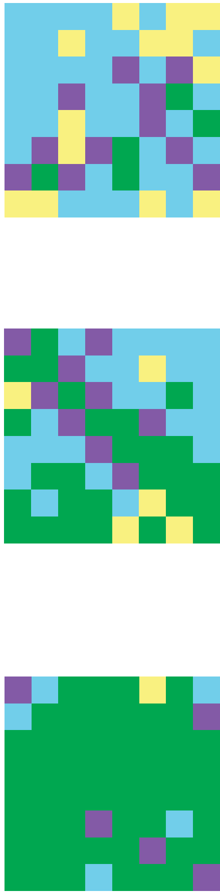
Results
cont.

original S3TC/DXTC ETC1 ETC2



original S3TC/DXTC ETC1 ETC2

- 🟦 ETC1
- 🟨 T-mode
- 🟪 H-mode
- 🟩 Planar



Conclusion

- We have presented ETC2
- It is backward compatible with ETC1 – new hardware will automatically decompress both correctly
- Three new modes are added without changing the old modes – thus it is guaranteed to always be better or equal to ETC1
- Tests show that it is 0.8 dB better than S3TC/DXTC which is a significant improvement
- Visual improvements are especially pronounced for blocks with sharp chrominance changes and for smooth regions.

Thank You

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Decompression Complexity

- Due to the new modes, ETC2 is more complex than ETC1.
- We have not implemented the two algorithms in VHDL in order to compare their complexity.
- The extra cost for the T- and H- mode is mostly control logic (which is simple), seven multiplexors per color channel and one 12-bit comparator.
- The extra cost for the planar mode is five adders per color channel, and multiplexors.

Results

- ETC2 was tested on 64 textures, each texture on all mipmap sizes between 512x512 and 8x8 pixels.
- The images were contained both photographic images and game textures.
- The system has been compared to
  - ETC1 (compressed exhaustively)
  - S3TC/DXTC (compressed using ATI’s The Compressonator with weights set to 1,1,1 to maximize PSNR)
  - ATI-TC (compressed with ATI’s The Compressonator)