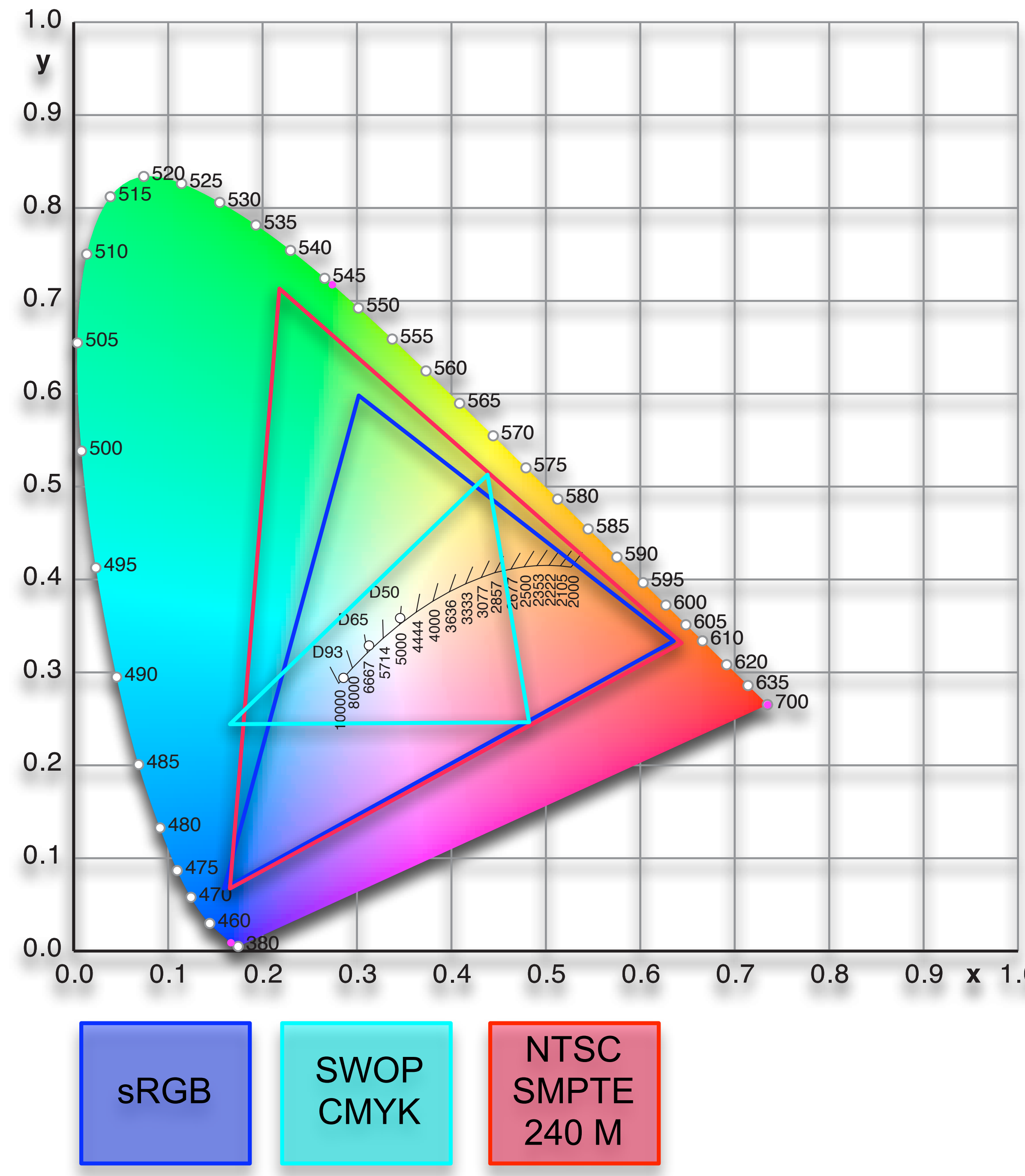
Color Spaces: CIE XYZ 1931

- based on direct measurements of human visual perception
- CIEXYZ color space includes all visible wavelengths of light
- typical visualization: 2D „horseshoe“ plot projection
  - covers chromaticity only
  - brightness not shown
- reference color space for <u>color matching and conversion</u>
- no device has a gamut large enough to display all wavelengths accurately
- natural white point with flat power spectrum at

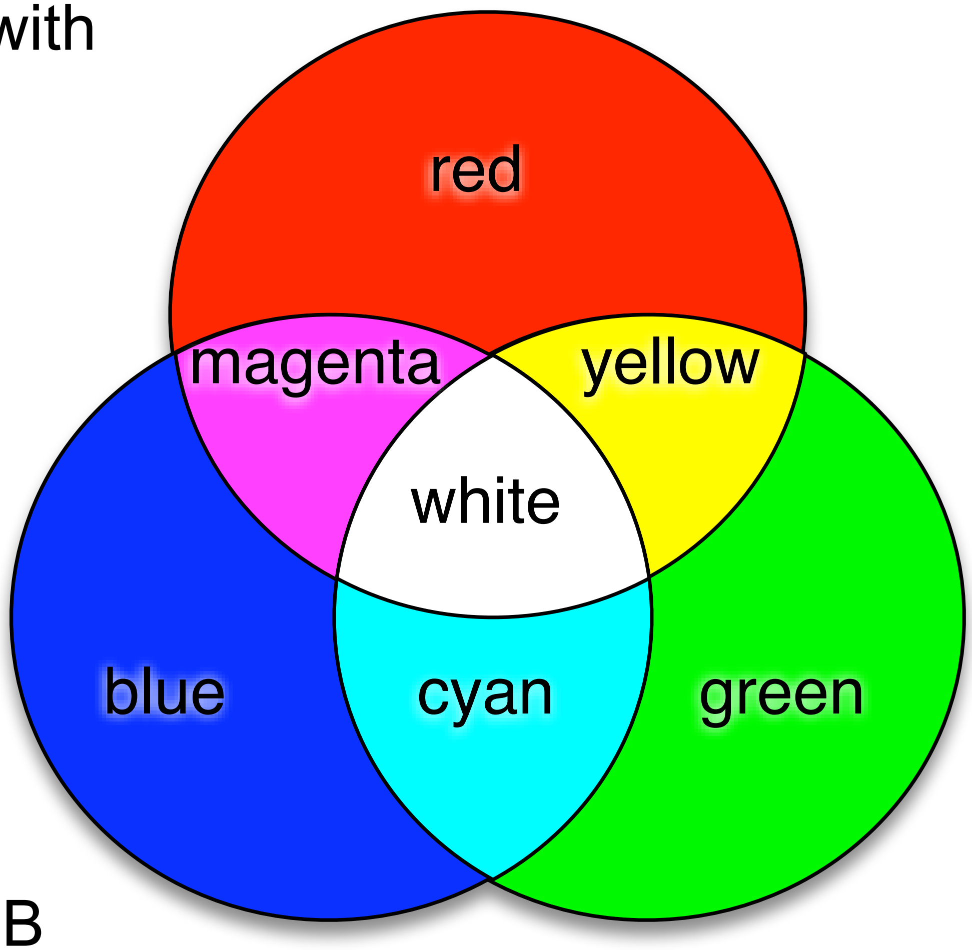


- gamut is visualized by the size of a triangle formed by 3 primaries
- larger gamut equals better contrast in chromaticity

diagram: [G. Hoffmann]

Color Spaces: RGB (1)

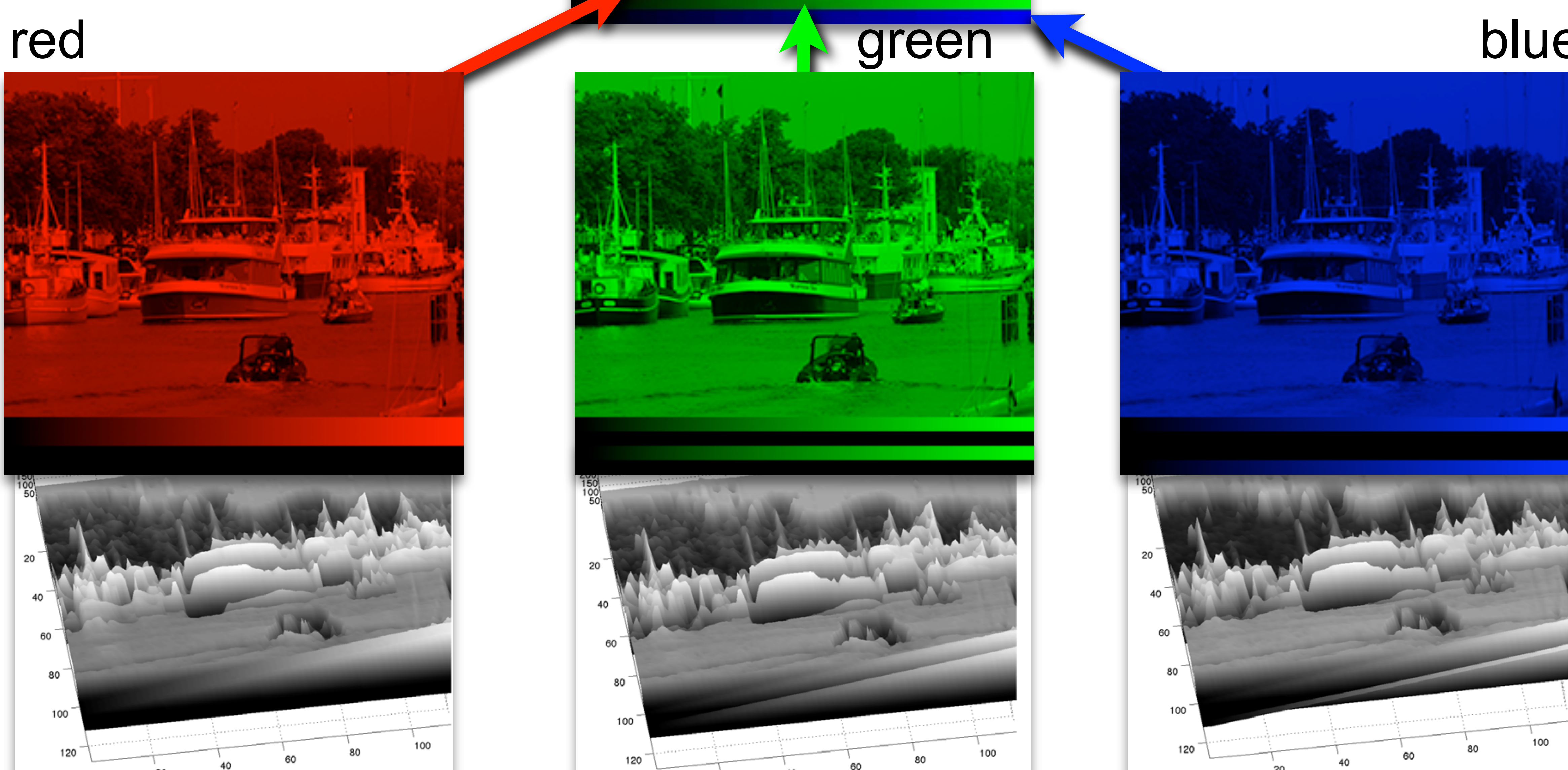
- primaries Red Green Blue
- additive compositing model
- range of components 0,0...1,0
  - typical normalization: 8 bit per component video with integer range of 0...255
  - 256^3 = 16.7 Mio. available colors
- levels
  - zero level of all components equals black
  - full level of all components equals white
- well suited for capture and display
  - television sets
  - computer displays / monitors
  - digital cameras
- most modern devices are able to cover at least sRGB with D65 white point the reference CIE x,y primaries



$$\mathbf{R} = (0.64, 0.33)^T \quad \mathbf{G} = (0.3, 0.6)^T \quad \mathbf{B} = (0.15, 0.06)^T \quad \mathbf{D65} = (0.3127, 0.3290)^T$$

Color Spaces: RGB (2)

compositing between
3 gray planes representing
the color components



YUV / YIQ Color Spaces

- History
  - for the introduction of color television, backwards compatibility to existing black/ white receiver was demanded
  - separation of luma (brightness) from color components (chroma)
  - limited bandwidth for additional color component signals (~1/6 of total video bandwidth)
- Practical advantages
  - luma bandwidth/resolution not tied to chroma resolution
  - controlling brightness, color saturation and contrast easy to perform in comparison to the RGB color model
- Applications
  - NTSC color television (U.S.A., Japan)
    - YIQ color model SMPTE-140M
  - PAL color television (Europe)
    - YUV color model ITU-R Rec. BT.709, SMPTE 170M
  - digital image and video compression formats (e.g. JPEG, MPEG)

YCbCr Color Space (1)

- YCbCr is the quantized and scaled digital correspondence to analog YUV

analog non-linear RGB input (i.e. gamma corrected):

$$E'_R, E'_G, E'_B \in 0, \ldots, 1$$

ITU-R Rec. BT.601, SMPTE 170M:

$$\begin{aligned} E'_Y &= 0.587 \, E'_G + 0.114 \, E'_B + 0.299 \, E'_R \\ E'_{PB} &= -\, 0.331 \, E'_G + 0.500 \, E'_B - 0.169 \, E'_R \\ E'_{PR} &= -\, 0.419 \, E'_G - 0.081 \, E'_B + 0.500 \, E'_R \end{aligned}$$

ITU-R Rec. BT.709 (HDTV):

$$\begin{aligned} E'_Y &= 0.7152 \, E'_G + 0.0722 \, E'_B + 0.2126 \, E'_R \\ E'_{PB} &= -\, 0.386 \, E'_G + 0.500 \, E'_B - 0.115 \, E'_R \\ E'_{PR} &= -\, 0.454 \, E'_G - 0.046 \, E'_B + 0.500 \, E'_R \end{aligned}$$

quantized YCbCr at n bit quantization:

a) limited video dynamic range (BT.601)

$$\begin{aligned} Y &= \left(219 \cdot 2^{n-8} \cdot E'_Y\right) + 2^{n-4} \\ Cb &= \left(224 \cdot 2^{n-8} \cdot E'_{PB}\right) + 2^{n-1} \\ Cr &= \left(224 \cdot 2^{n-8} \cdot E'_{PR}\right) + 2^{n-1} \end{aligned}$$

b) full video dynamic range (JPEG, MPEG-4)

$$\begin{aligned} Y &= \left((2^n - 1) \cdot E'_Y\right) \\ Cb &= \left((2^n - 1) \cdot E'_{PB}\right) + 2^{n-1} \\ Cr &= \left((2^n - 1) \cdot E'_{PR}\right) + 2^{n-1} \end{aligned}$$

Y, Cb, Cr are unsigned integers with grayscale point at $Cb=Cr=2^{n-1}$

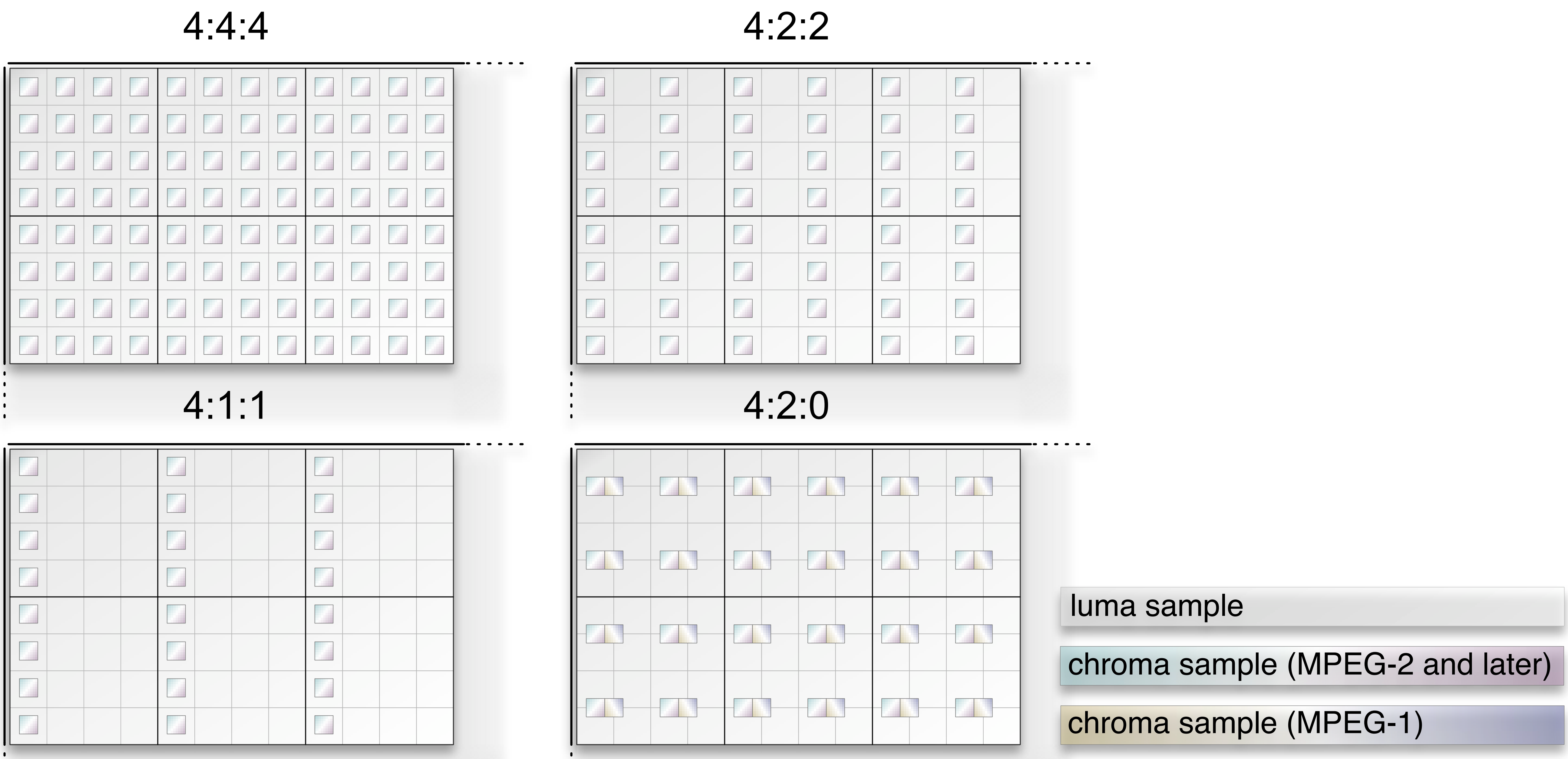
YCbCr Color Space (2)

- Grayscale image if only Y is present
- Cb roughly corresponds to blue/yellow balance
- Cr roughly corresponds to red/green balance

YCbCr chroma subsampling (1)

➠ Specific chroma subsampling variants have standard names

- first digit: number of luma pixels
- second digit: horizontal chroma pixels relative to luma
- third digit: definition dependent



chroma subsampling (2)

YCbCr 4:4:4

YCbCr 4:2:2

YCbCr 4:2:0

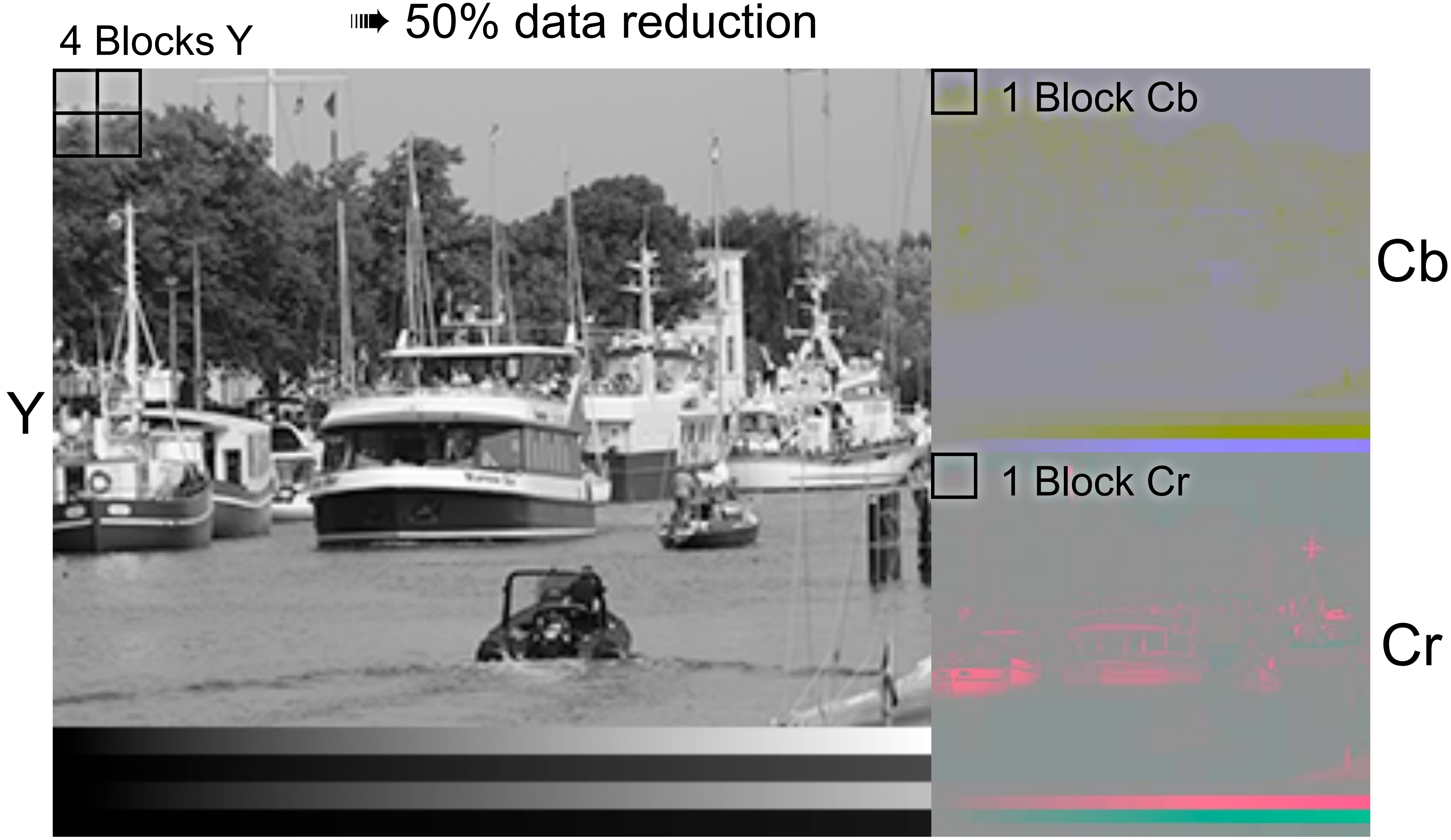
YCbCr 4:1:1

RGB 2:1 horizontal subsampling (same Bits per pixel compared to 4:2:0 and 4:1:1)

➠ <u>human eye less sensitive to color variations than brightness variations (!)</u>

Example

Subsampling of chroma components: YCbCr 4:2:0
➠ 50% data reduction



➠ Subsampling on Sender side
➠ Upsampling on Receiver side

Quantization-1

- Scalar Quantization
  - partitioning of the signal dynamic range into sub-intervals of reduced accuracy
  - algorithm
    - let x be a random signal amplitude, falling into interval q
    - assign a reconstruction amplitude y_q, with $y_q \in$ interval q
      - quantization: $x \rightarrow q$ -- sender
      - reconstruction: $q \rightarrow y_q$, where $y_q = [x]_Q$ -- receiver
    - quantization error: $e_q = x - [x]_Q$

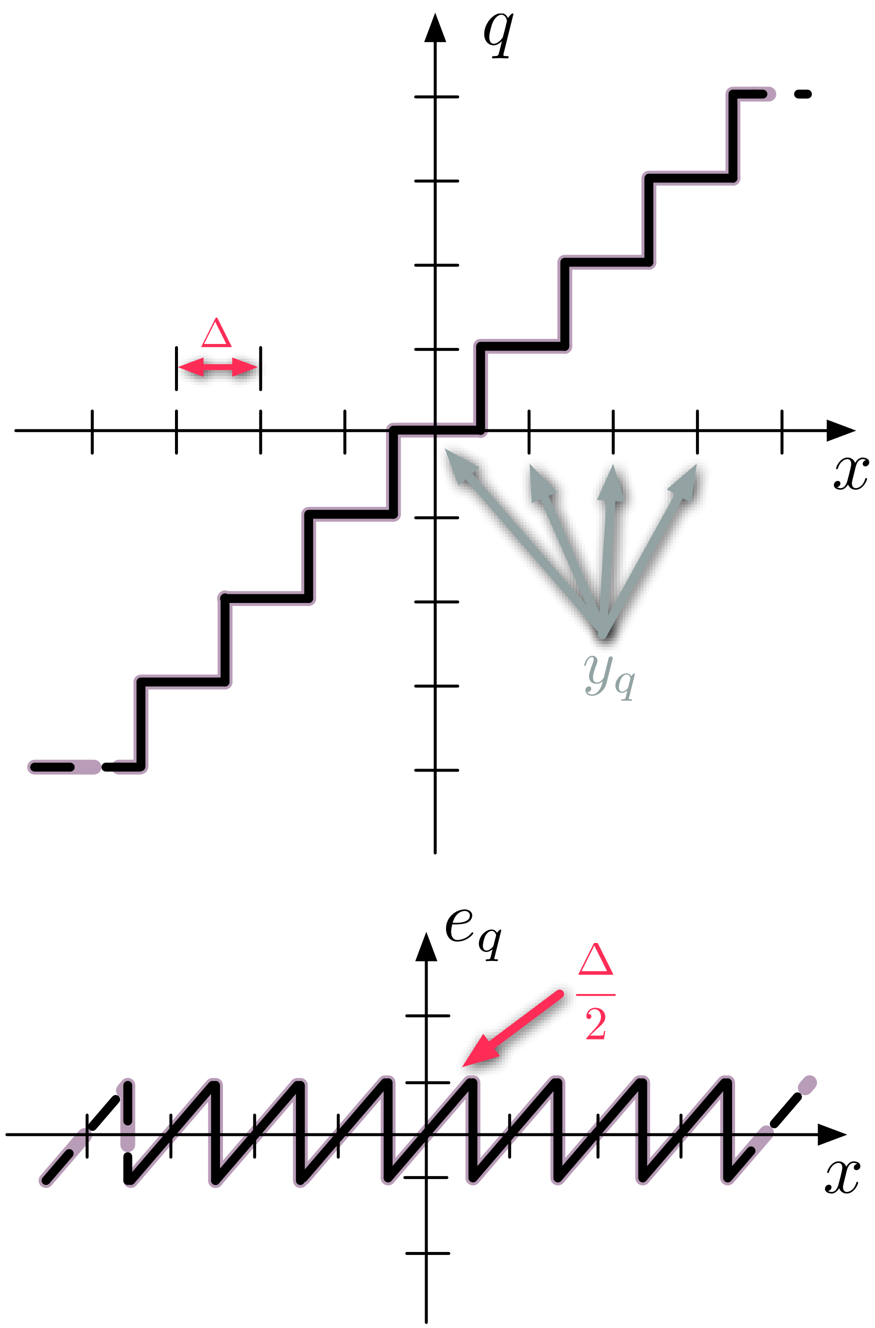
➠ Unrecoverable loss of information

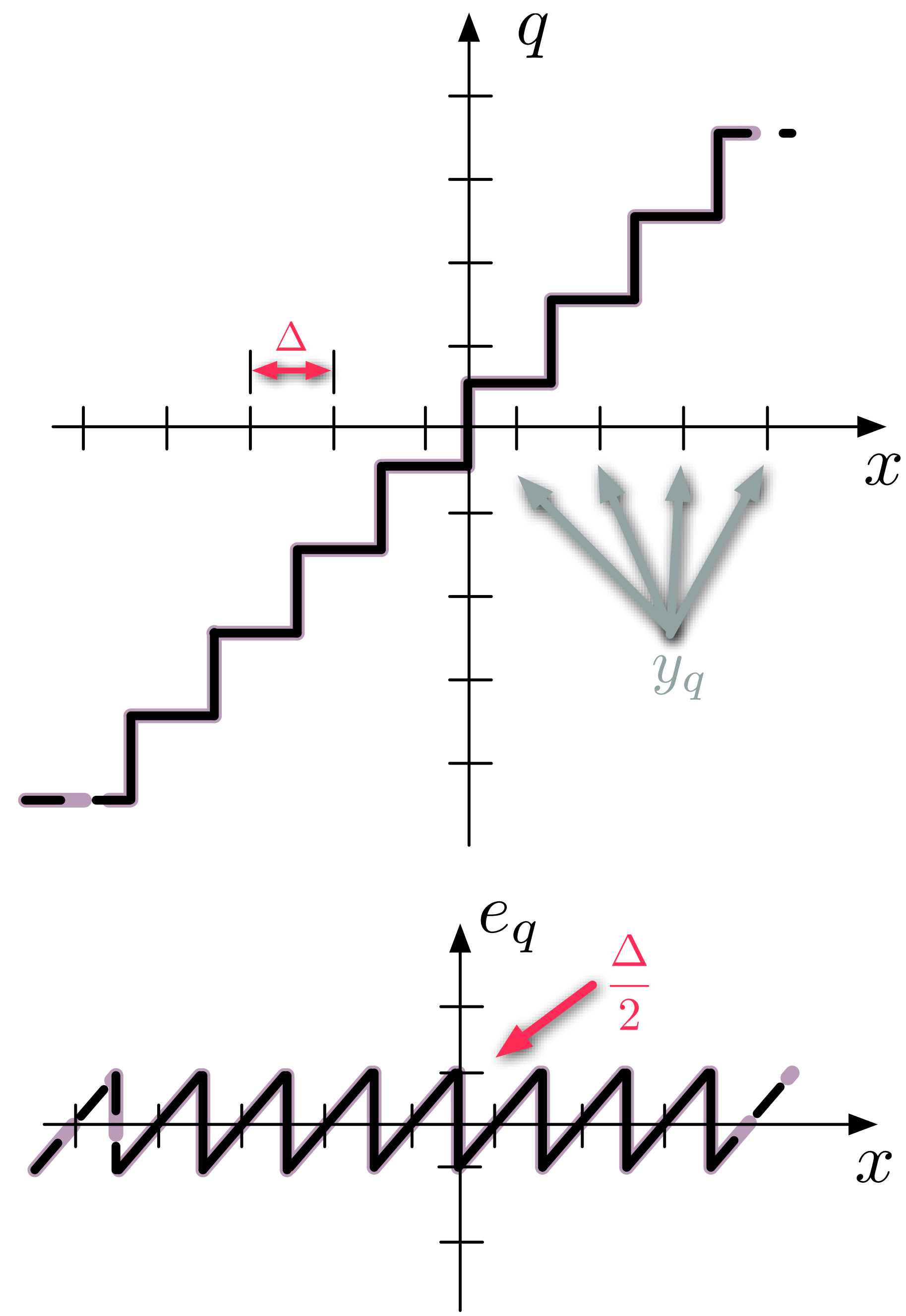
  - choice of intervals application specific, leading to different types of scalar quantizers

Quantization-2

Uniform Quantization

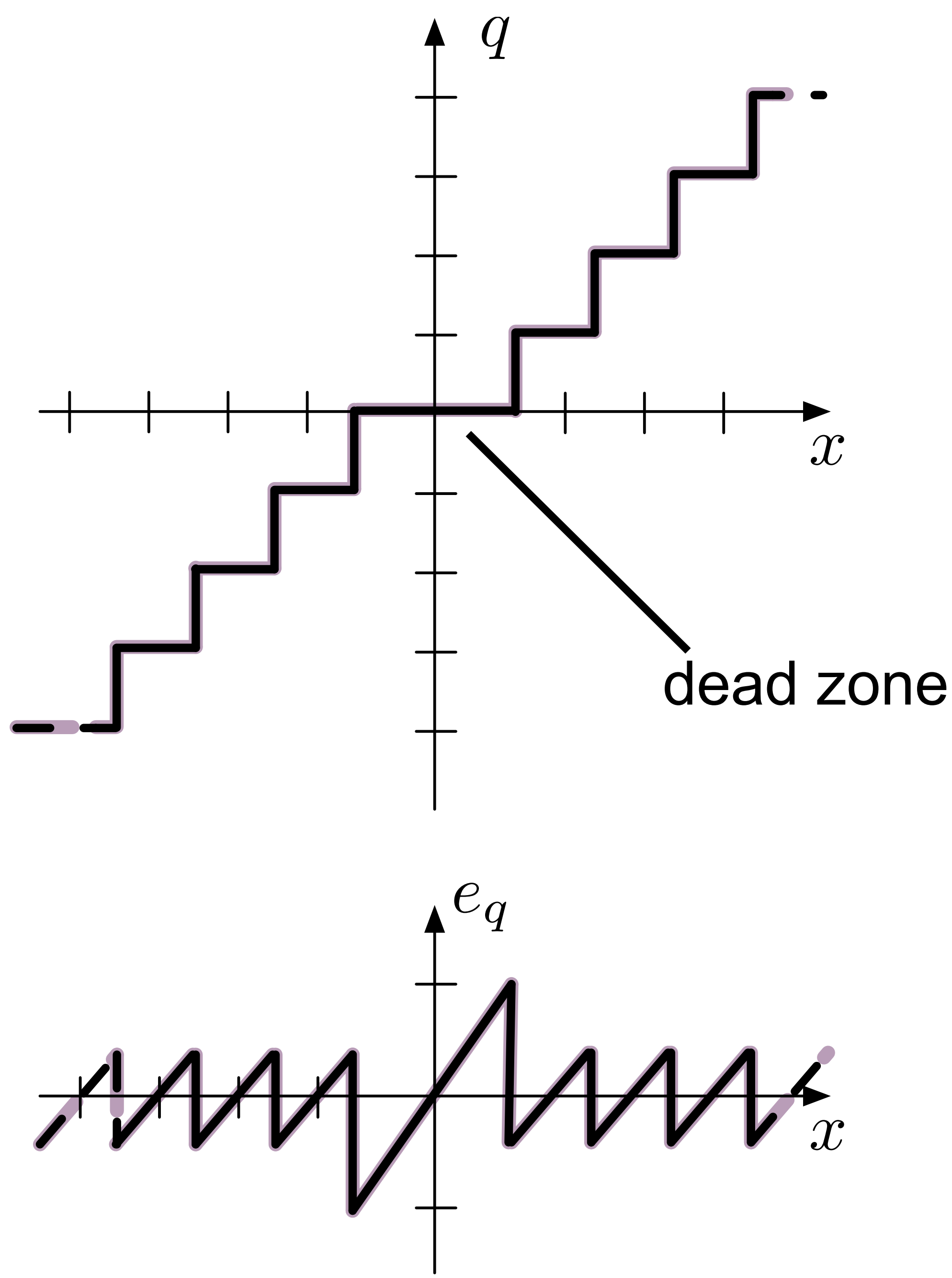
Property: equal width Δ of all sub-intervals

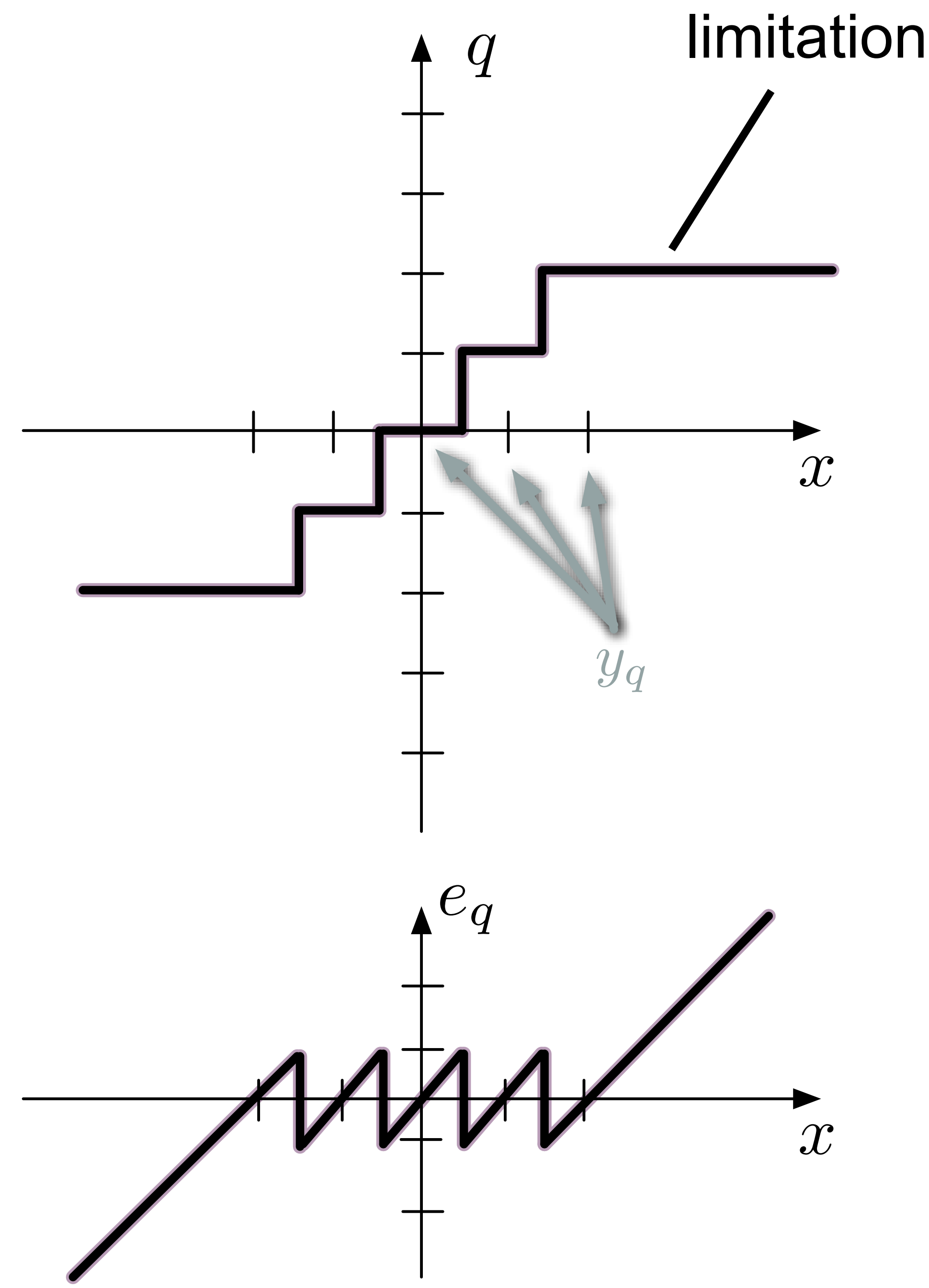




Quantization-3

Uniform Quantization - special variants of uniform quantizers

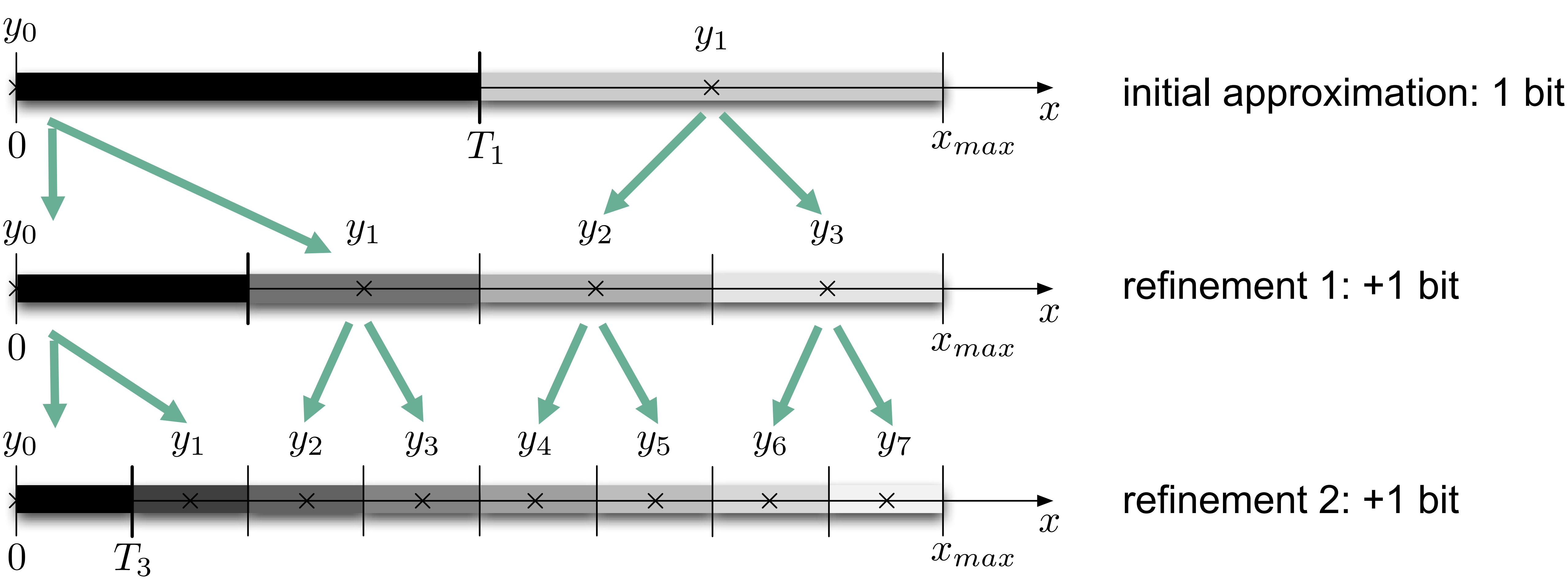




Quantization-4

Successive Approximation

- related to dead zone quantizing (initial dead zone: $(-T1, T1)$ $T_l = \frac{T_{l-1}}{2} \quad l \in \mathbb{N}, l > 0$)
- progressive refinement of initial reconstruction values y_n
- useful for SNR-scalable transmission



Quantization 5

- Example: successive approximation using bit planes $y_q = \left\lfloor \frac{x}{2^n} \right\rfloor \cdot 2^n$ with $n = 7 \ldots 1$

1 bit plane

2 bit planes

3 bit planes

4 bit planes

5 bit planes

6 bit planes

7 bit planes

8 bit planes (ori)

Quantization 6

- Example: reconstruction to half interval Δ

$$y_q = \left\lfloor \frac{x}{2^n} \right\rfloor \cdot 2^n + 2^{n-1} \text{ with } n = 7 \ldots 1$$

1 bit plane

2 bit planes

3 bit planes

4 bit planes

5 bit planes

6 bit planes

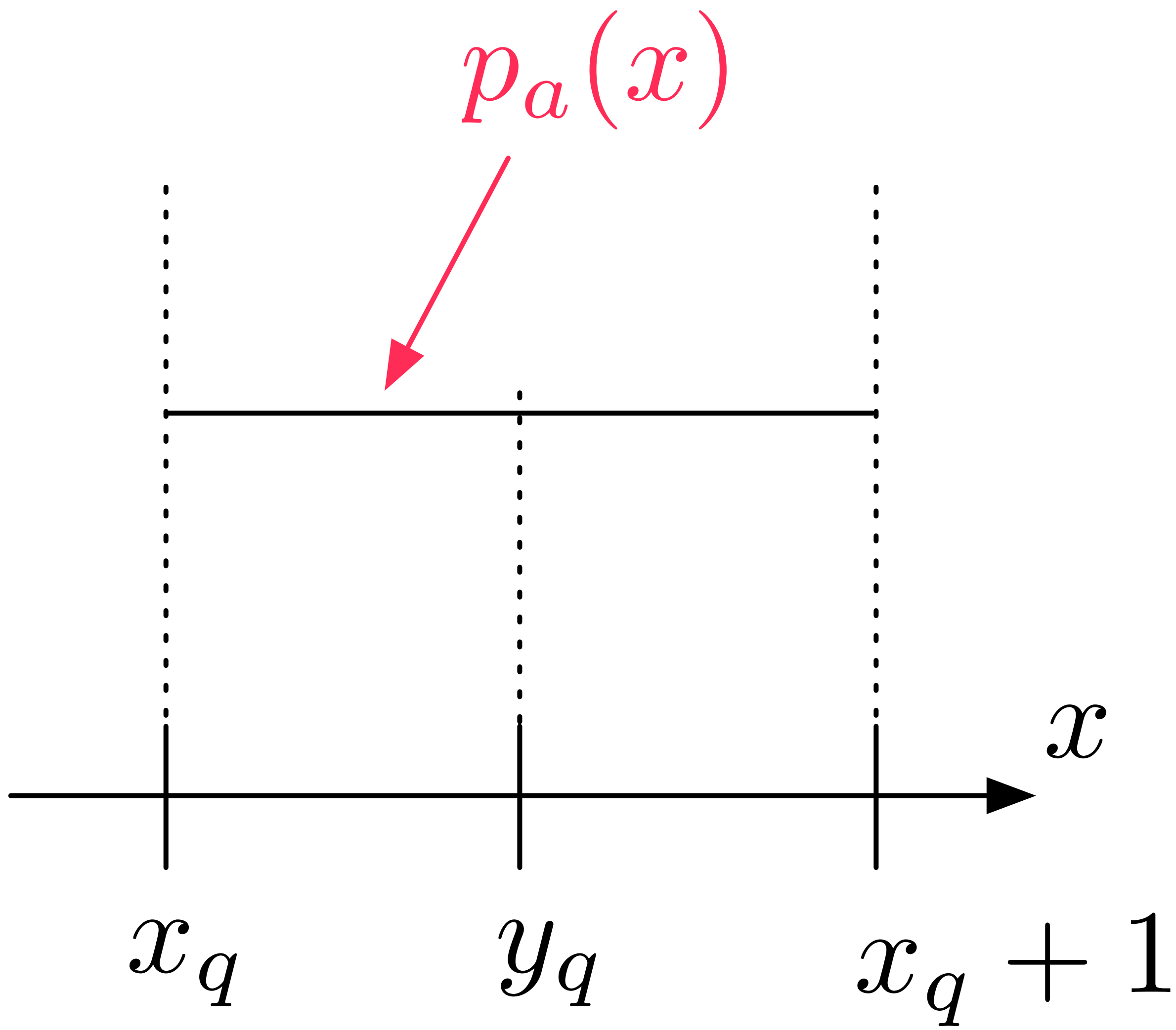
7 bit planes

8 bit planes (ori)

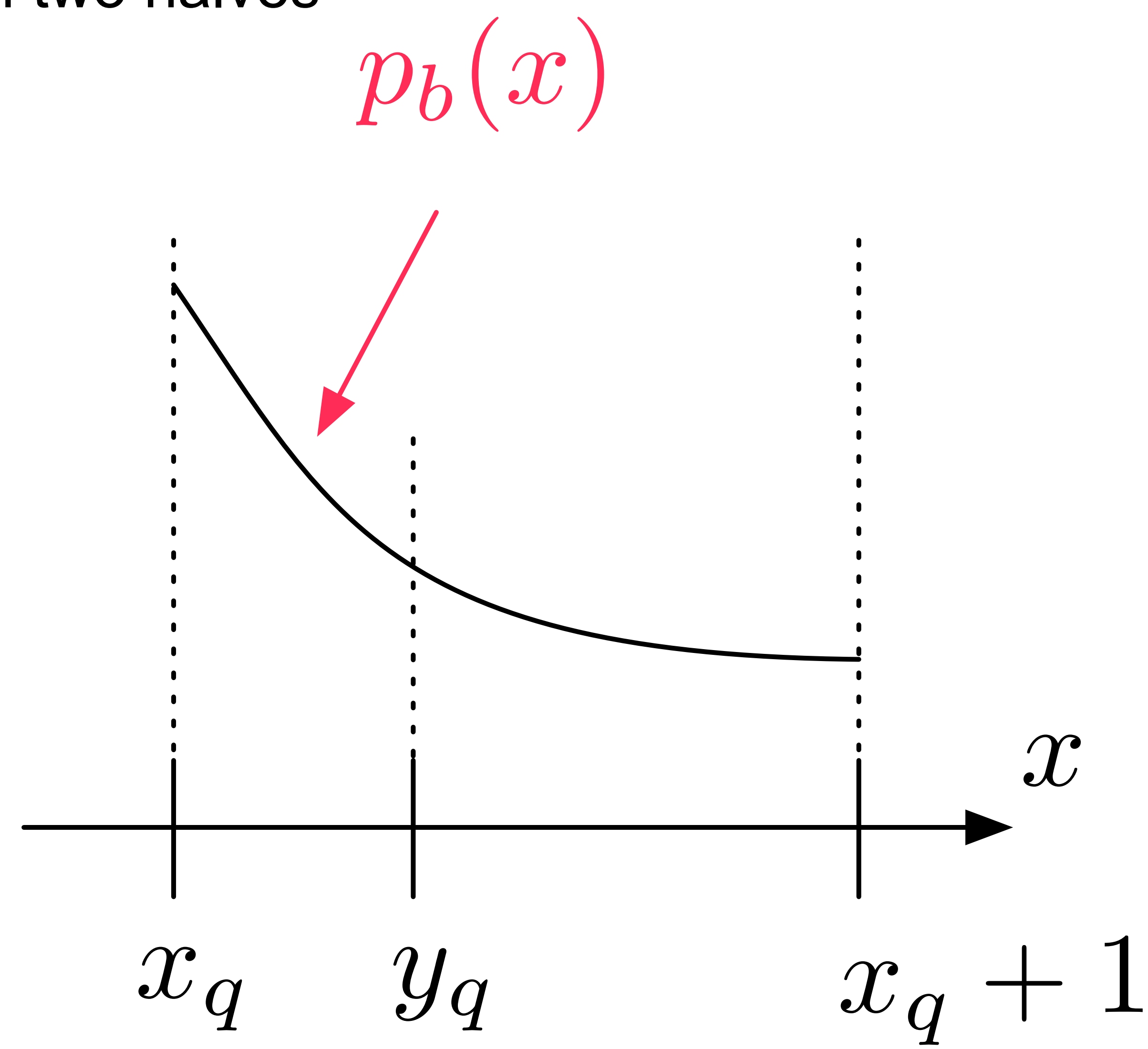
Quantization 7

Determination of proper reconstruction values

- Goal: minimization of mean quantization error
- Solution: y_q should cut area under curve in two halves

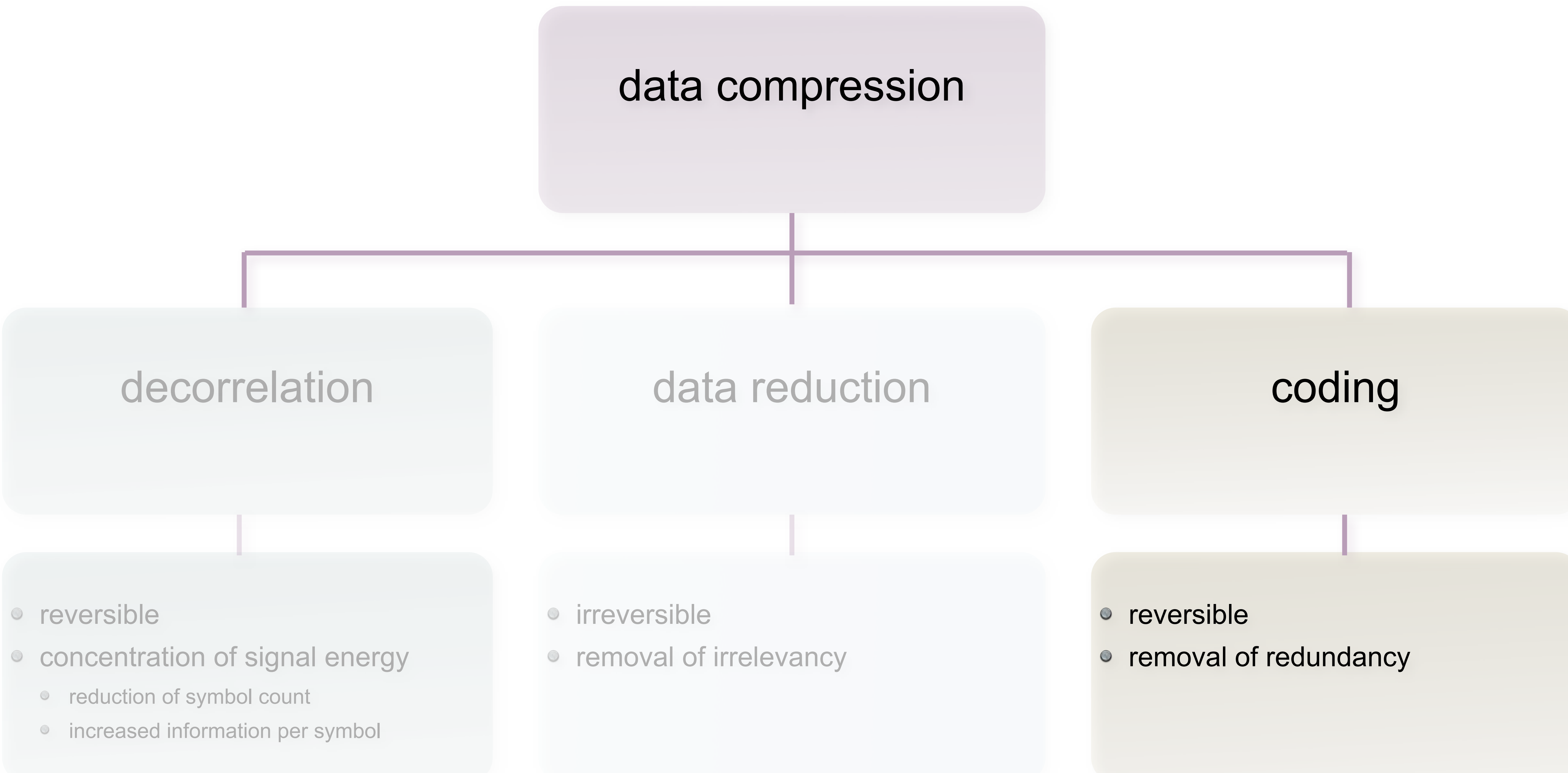


a) uniform probability distribution $p_a(x)$



b) non-uniform probability distribution $p_b(x)$

General data compression tools



General data compression tools

coding

entropy coding

- symbols are assumed to be statistically <u>independent</u>
- mapping of input symbols to output code
- <u>intent:</u> mean code word length in the compressed stream should be as close as possible to the signal entropy

precoding

- symbols are regarded as <u>dependent</u> on each other
- mapping of symbols to new symbols of a different alphabet
- <u>intent:</u> minimization of inter-symbol redundancy