Audiovisuelle Dateiformate

Reto Kromer • AV Preservation by reto.ch

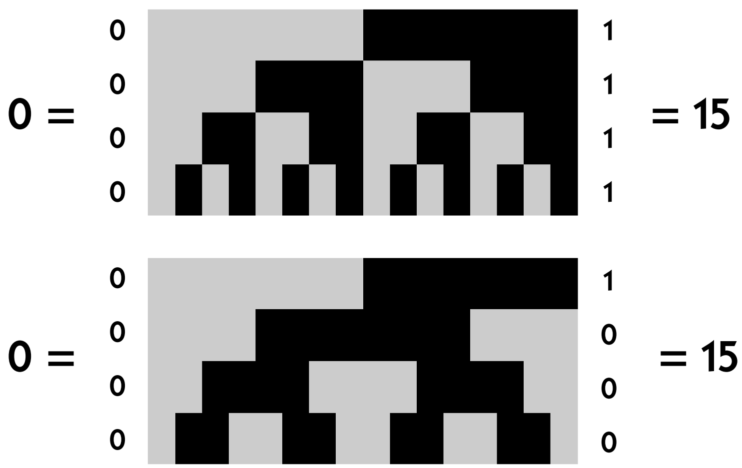
Memoriav-Workshop
FFmpeg-Aufbaukurs
Bern, 16. März 2026

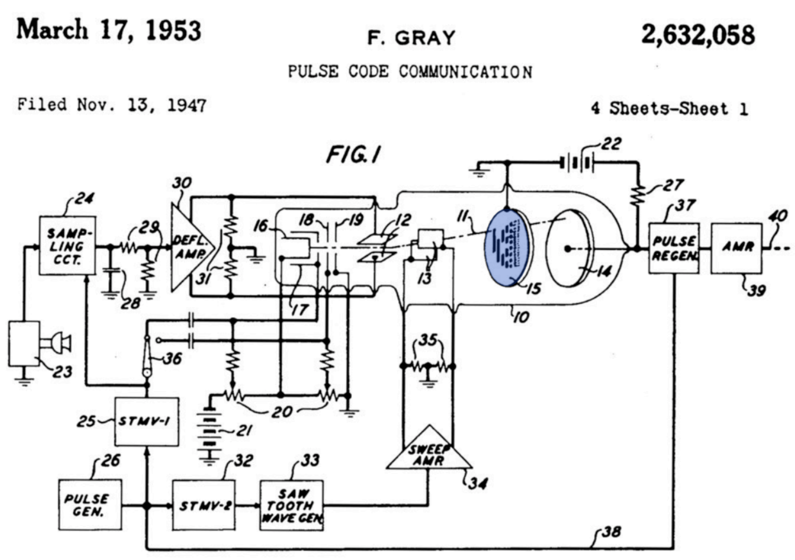
Inhalt

- digitaler Ton und digitales Bild
- Container, Codec, Rohdaten
- verschiedene Formate für unterschiedliche Zwecke
- audiovisuelle Dateiumwandlungen
- Datensicherung und Migration

Digitaler Ton

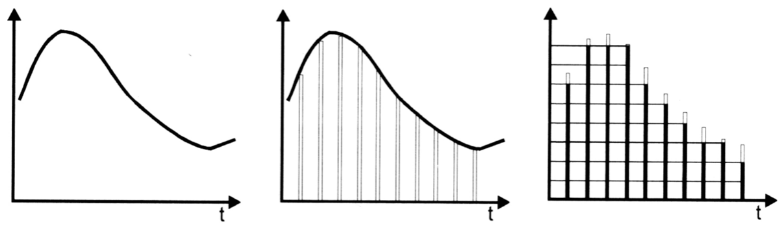
Frank Gray (1887–1969)





Digitaler Ton

- Abtastung
- Quantisierung
- Kompression



Digitalisierung = Abtastung + Quantisierung

source: Agathe Jarczyk

Abtastrate

- 44.1 kHz
- 48 kHz
- 96 kHz
- 192 kHz
- 500 kHz

Quantisierungsauflösung

- 16 bit (2^{16} = 65 536)
- 24 bit (2^{24} = 16 777 216)
- 32 bit (2^{32} = 4 294 967 296)

Digitales Bild

Digitales Bild

- Bildauflösung
- Quantisierungsauflösung
- linear, Potenzfunktion, logarithmisch
- Farbraum
- Kompression und Farbunterabtastung
- Normlicht

Bildauflösung

- SD 480i / SD 576i
- HD 720p / HD 1080i
- 2K / HD 1080p
- 4K / UHD-1
- 8K / UHD-2

Oft wird sie auch kurz «Auflösung» genannt.

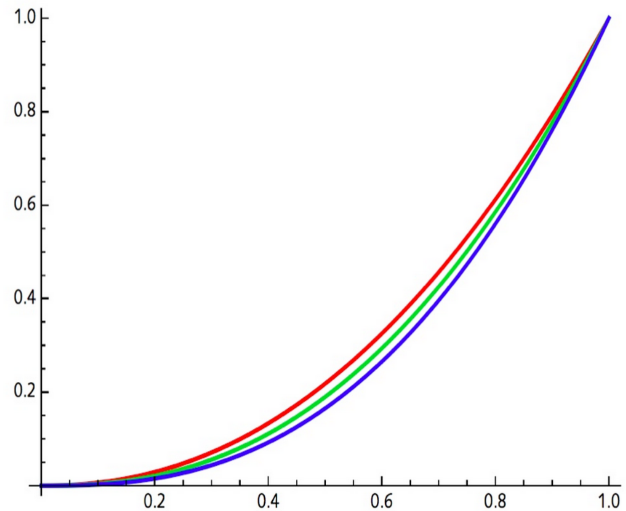
Quantisierungsauflösung

- 8 bit (2^8 = 256)
- 10 bit (2^{10} = 1 024)
- 12 bit (2^{12} = 4 096)
- 16 bit (2^{16} = 65 536)
- 24 bit (2^{24} = 16 777 216)

Linear, Potenz, Logarithmus

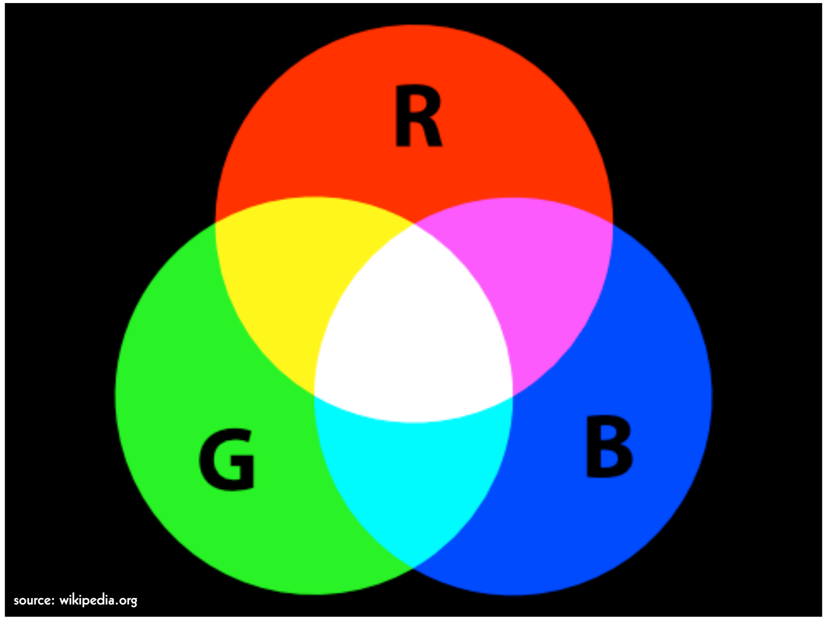
«Mittelgrau»

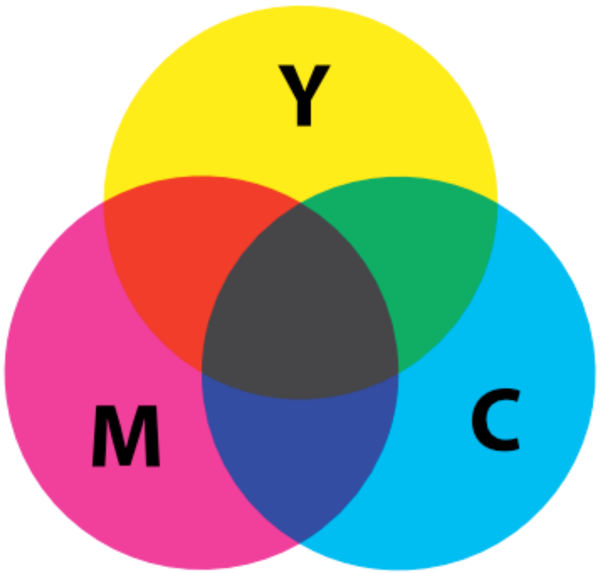
- lineare Funktion: etwa 18 %
- Potenzfunktion: 50 %
- Logarithmusfunktion: 50 %



Farbraum

- XYZ, L*a*b*
- RGB / R′G′B′ / CMY / C′M′Y′
- $Y'IQ$ / $Y'UV$ / $Y'D_BD_R$
- $Y'C_BC_R$ / $Y'C_OC_G$
- $Y'P_BP_R$





source: wikipedia.org

$$\begin{pmatrix} R' \\ G' \\ B' \end{pmatrix} = \begin{pmatrix} 1 & 0 & 1.396523 \\ 1 & -0.342793 & -0.711348 \\ 1 & 1.765078 & 0 \end{pmatrix} \begin{pmatrix} Y' \\ C_B \\ C_R \end{pmatrix}$$

$$\begin{pmatrix} Y' \\ C_B \\ C_R \end{pmatrix} = \begin{pmatrix} 0.299 & 0.587 & 0.114 \\ -0.168074 & -0.329965 & 0.498039 \\ 0.498039 & -0.417947 & -0.080992 \end{pmatrix} \begin{pmatrix} R' \\ G' \\ B' \end{pmatrix}$$

$$\begin{pmatrix} R' \\ G' \\ B' \end{pmatrix} = \begin{pmatrix} 1 & 1 & -1 \\ 1 & 0 & 1 \\ 1 & -1 & -1 \end{pmatrix} \begin{pmatrix} Y' \\ C_O \\ C_G \end{pmatrix}$$

$$\begin{pmatrix} Y' \\ C_O \\ C_G \end{pmatrix} = \begin{pmatrix} \frac{1}{4} & \frac{1}{2} & \frac{1}{4} \\ \frac{1}{2} & 0 & -\frac{1}{2} \\ -\frac{1}{4} & \frac{1}{2} & -\frac{1}{4} \end{pmatrix} \begin{pmatrix} R' \\ G' \\ B' \end{pmatrix}$$

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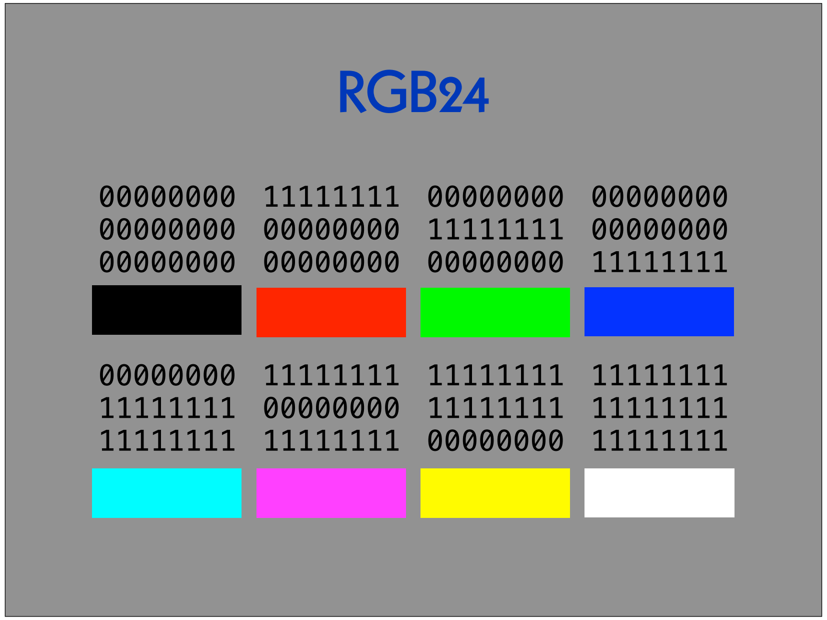

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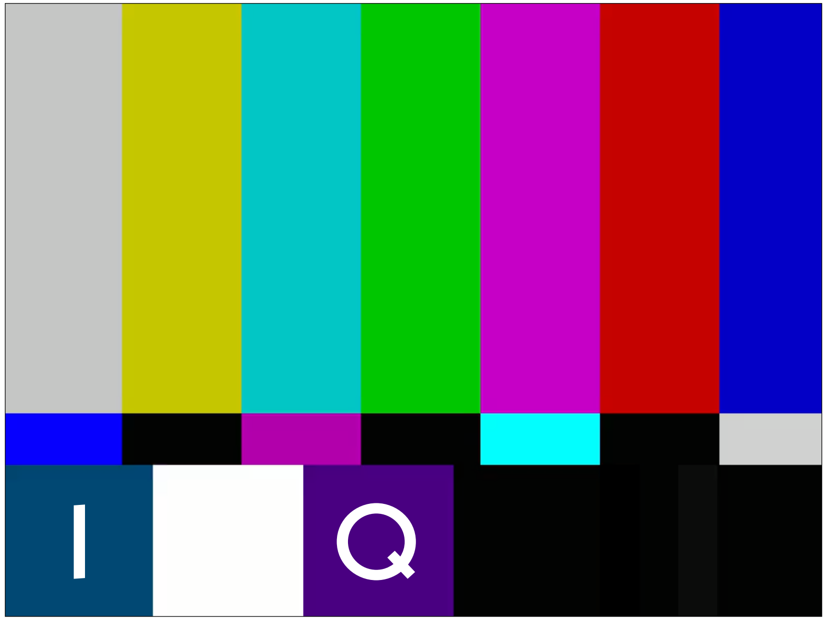
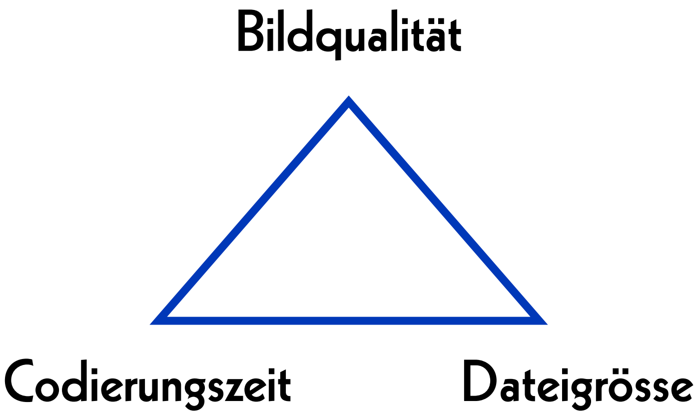


24



Kompression

- nicht komprimiert
- verlustfrei komprimiert
- verlustbehaftet komprimiert
- Farbunterabtastung
- komprimiert generiert

Nicht komprimiert

+ Daten sind leichter zu bearbeiten
+ Software läuft schneller
– grössere Dateien
– langsameres Schreiben, Übermitteln und Lesen der Dateien

Beispiele: TIFF, DPX, DNG, OpenEXR

Verlustfrei komprimiert

+ kleinere Dateien
+ schnelleres Schreiben, Übermitteln und Lesen der Dateien
– Daten sind komplexer zu bearbeiten
– Software läuft langsamer

Beispiele: JPEG 2000, FFV1

Verlustbehaftet komprimiert

- optimiert für Aufnahme und/oder Postproduktion
- optimiert für Zugang und Distribution

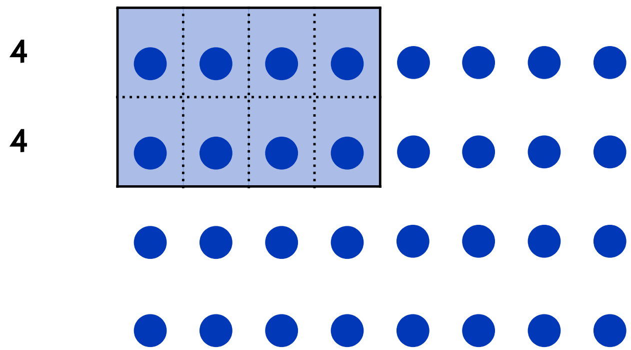
Beispiele (Mezzanine): ProRes 422, ProRes 4444; DNxHD, DNxHR

Beispiele (Zugang): H.264 (AVC), H.265 (HEVC), H.266 (VVC); AV1

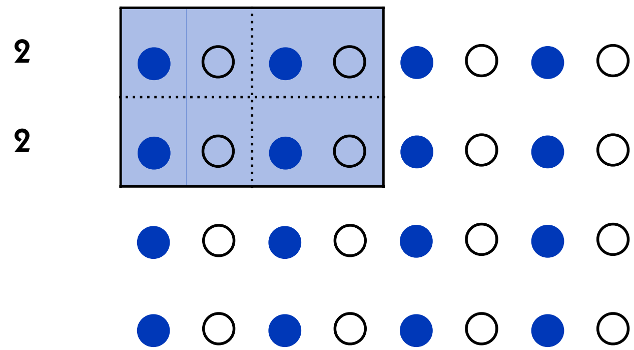
Farbunterabtastung

- 4:4:4
- 4:2:2
- 4:2:0 / 4:1:1

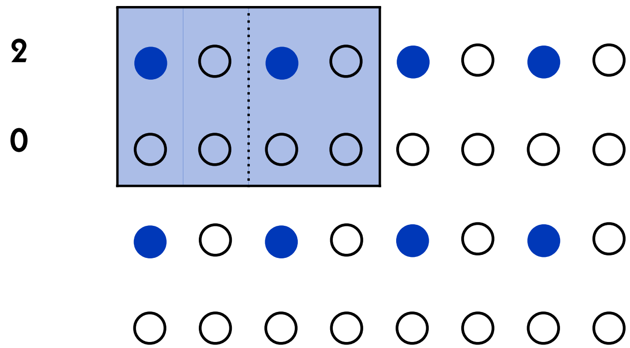
4:4:4



4:2:2



4:2:0



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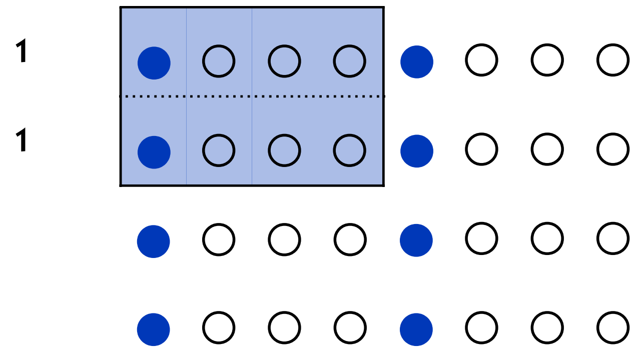
4:1:1



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Komprimiert generiert

- sowohl für Aufnahme als auch für Postproduktion optimiert

Beispiele: CineForm RAW, ProRes RAW, Blackmagic RAW

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Unbequeme Tatsachen

- die meisten Sensoren sind farbenblind
- Bayer-Sensoren erzeugen kein vollständiges RGB-Bild, sondern nur einen Drittel davon

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Bryce E. Bayer
(1929–2012)

United States Patent [19] **Bayer**

[11] **3,971,065**
[45] **July 20, 1976**

[54] **COLOR IMAGING ARRAY**

[75] Inventor: **Bryce E. Bayer,** Rochester, N.Y.

[73] Assignee: **Eastman Kodak Company,** Rochester, N.Y.

[22] Filed: **Mar. 5, 1975**

[21] Appl. No.: **555,477**

[52] **U.S. Cl.** .... **358/41;** 350/162 SF; 350/317; 358/44
[51] **Int. Cl.²** **H04N 9/24**
[58] **Field of Search** .... 358/44, 45, 46, 47, 358/48; 350/317, 162 SF; 315/169 TV

[56] **References Cited**

UNITED STATES PATENTS

2,446,791	8/1948	Schroeder	358/44
2,508,267	5/1950	Kasperowicz	358/44
2,884,483	4/1959	Ehrenhaft et al.	358/44
3,725,572	4/1973	Kurokawa et al.	358/46

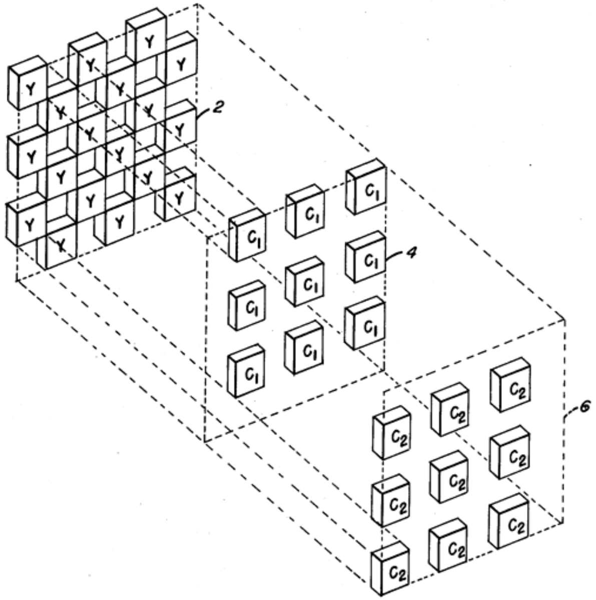
Primary Examiner—George H. Libman
Attorney, Agent, or Firm—George E. Grosser

[57] **ABSTRACT**

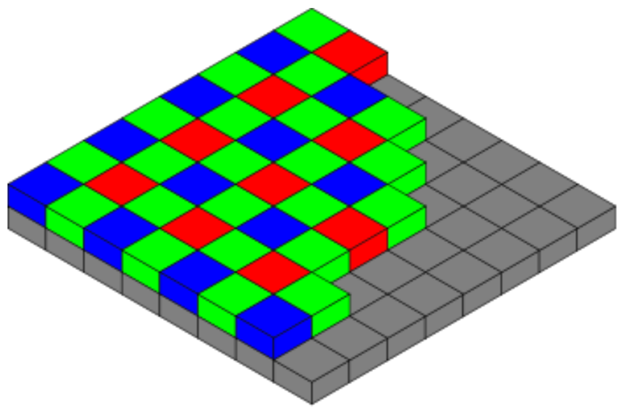
A sensing array for color imaging includes individual luminance- and chrominance-sensitive elements that are so intermixed that each type of element (i.e., according to sensitivity characteristics) occurs in a repeated pattern with luminance elements dominating the array. Preferably, luminance elements occur at every other element position to provide a relatively high frequency sampling pattern which is uniform in two perpendicular directions (e.g., horizontal and vertical). The chrominance patterns are interlaid therewith and fill the remaining element positions to provide relatively lower frequencies of sampling.

In a presently preferred implementation, a mosaic of selectively transmissive filters is superposed in registration with a solid state imaging array having a broad range of light sensitivity, the distribution of filter types in the mosaic being in accordance with the above-described patterns.

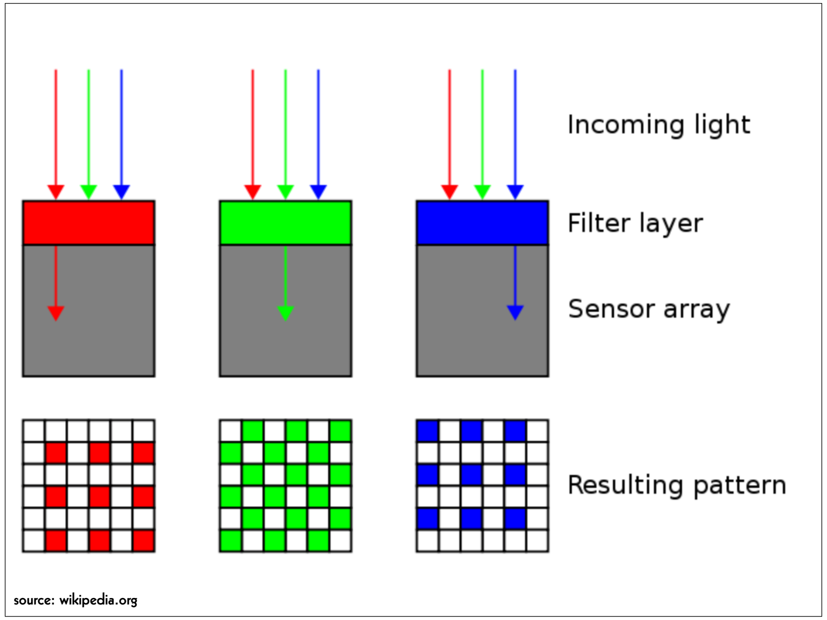
11 Claims, 10 Drawing Figures

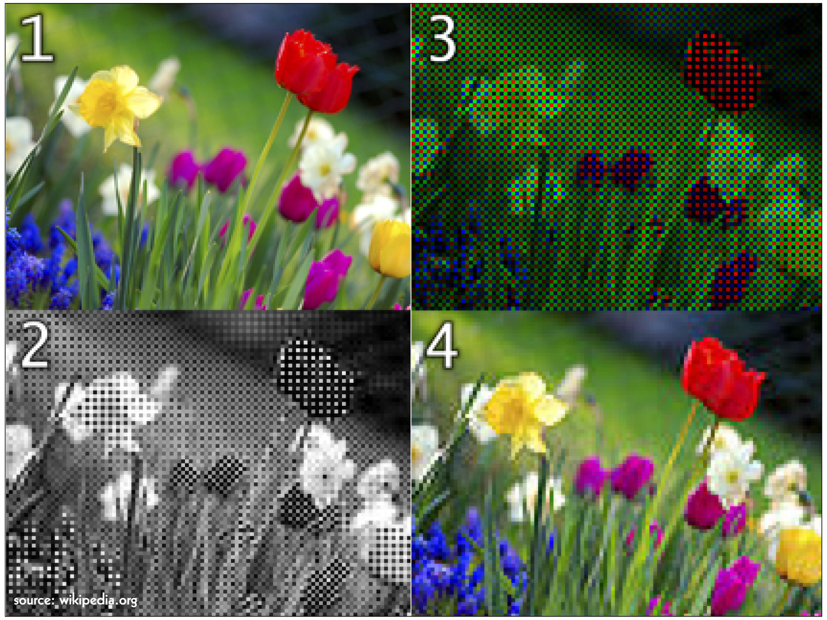


Bayer



source: wikipedia.org



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0111010100101010100010110101011110
0001110101010101010100001011101010
0110101010010101010001011010101111
0010101010101010000101110101010000
0111010100101010100010110101011110
0101010101010101000010111010100110
1001011101010010101010001011010101
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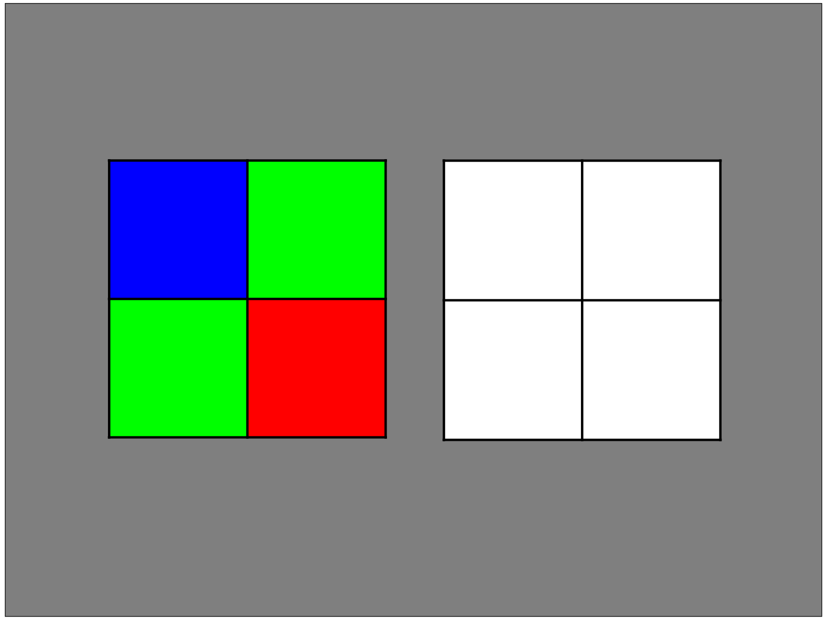

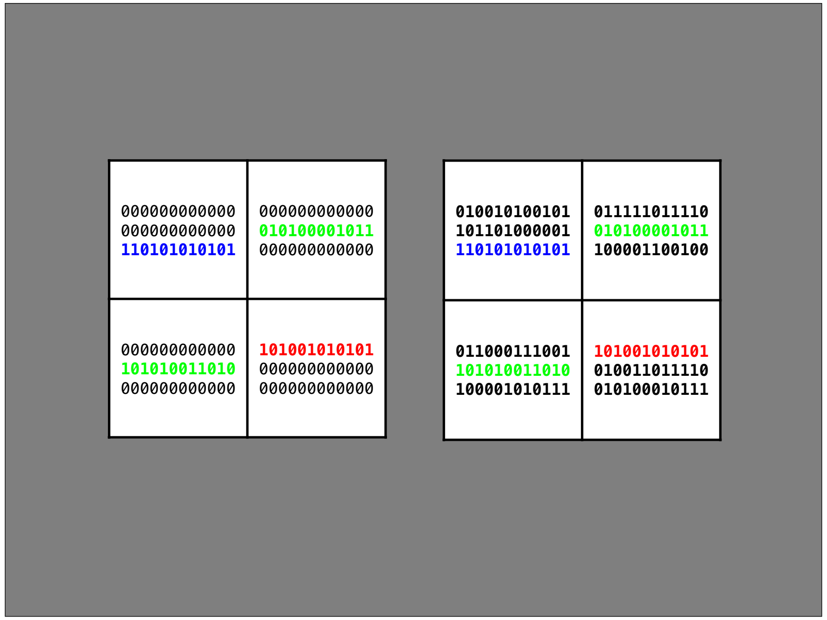
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000000000000
110101010101
000000000000
010100001011
000000000000
000000000000
101010011010
000000000000
101001010101
000000000000
000000000000
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101101000001
110101010101
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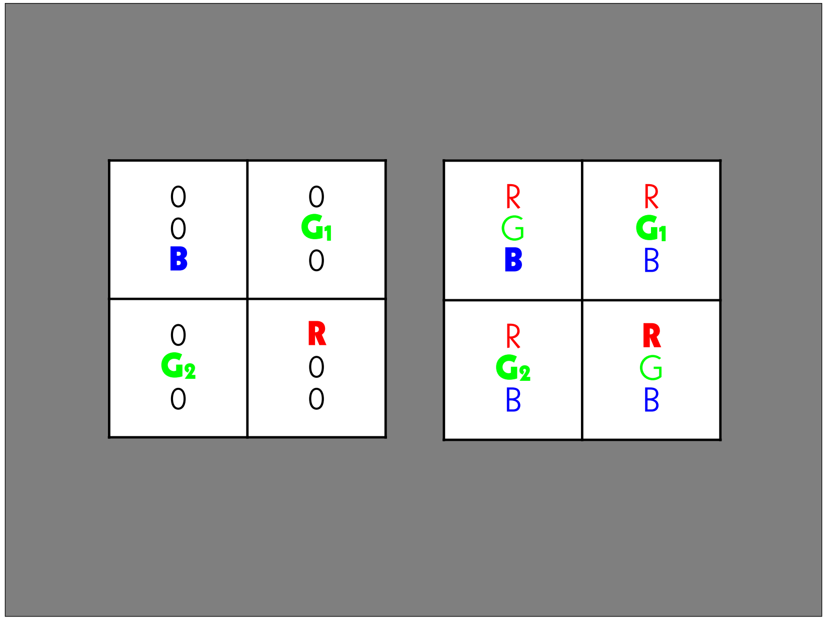
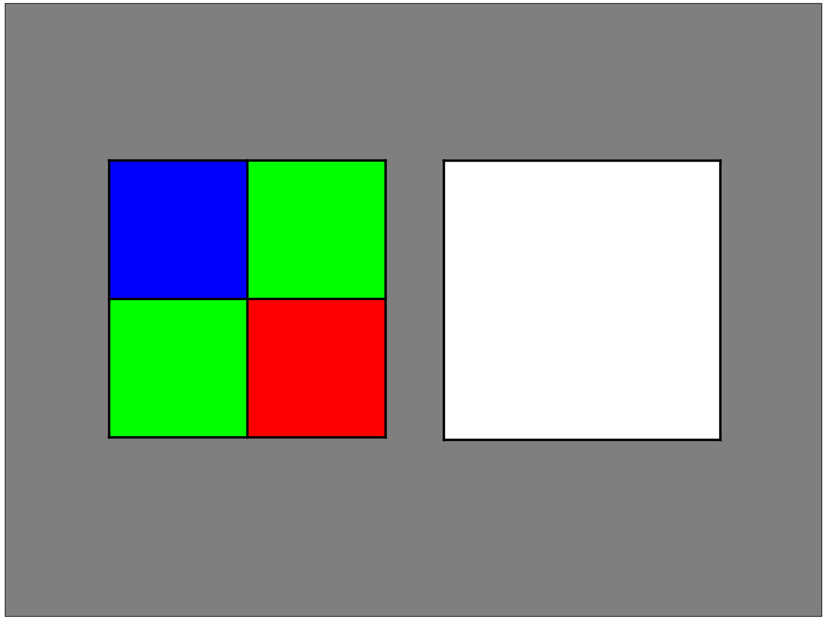
010011011110
010100010111

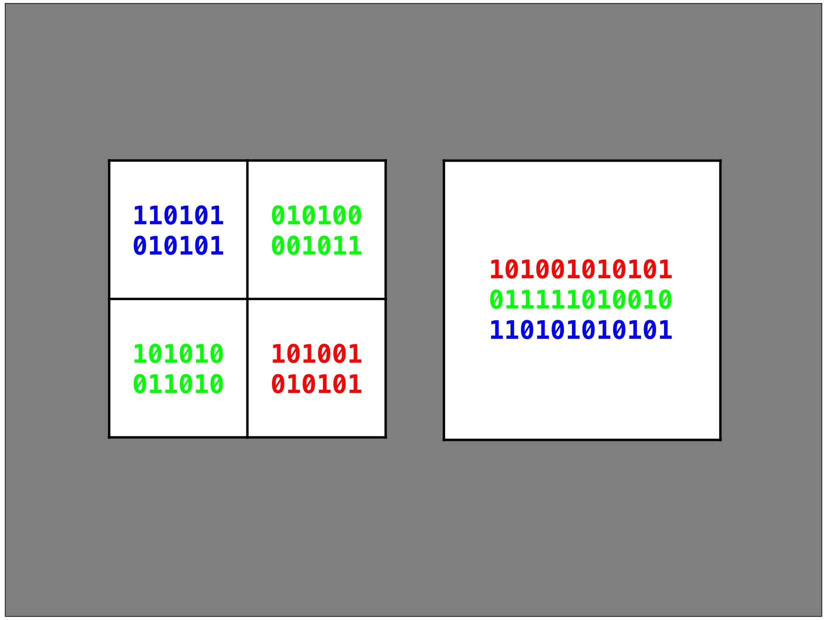
45


0 0 B
0 G1 0
0 G2 0
R 0 0
R G B
R G1 B
R G2 B
R G B

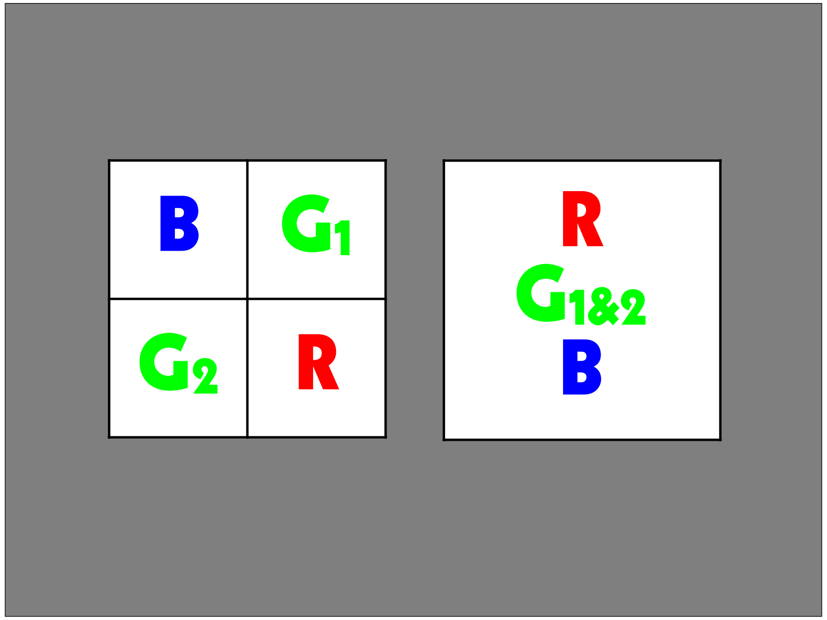
46



47


110101
010101
010100
001011
101010
011010
101001
010101
101001010101
011111010010
110101010101

48



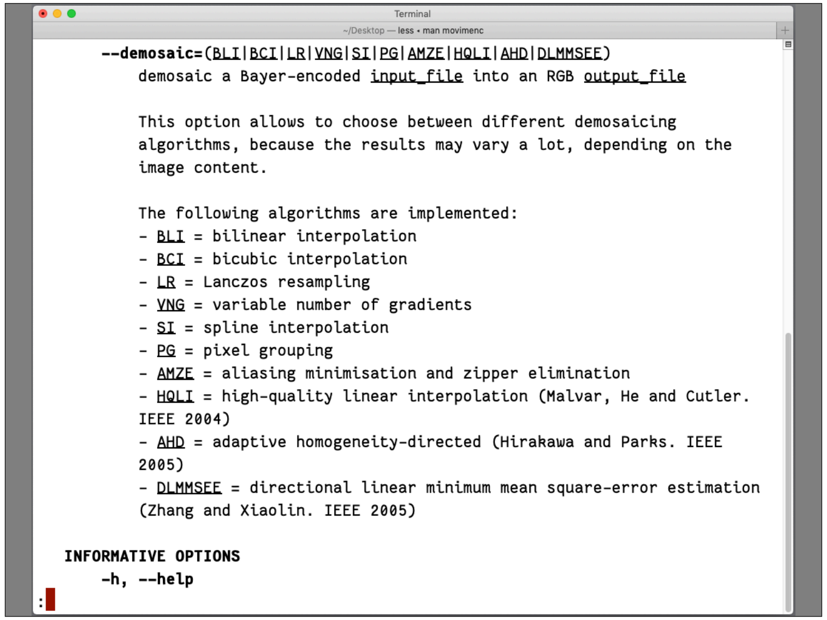
Bayer-Daten benützen

digitales Aufblasen auf RGB

- die generierten Daten werden verdreifacht
- die Datei hat die volle Sensorauflösung
- nur ein Drittel der Daten ist real

digitale Reduktion auf RGB

- drei Viertel der generierten Daten sind gespeichert
- die Datei hat die halbe Sensorauflösung
- alle Daten sind real



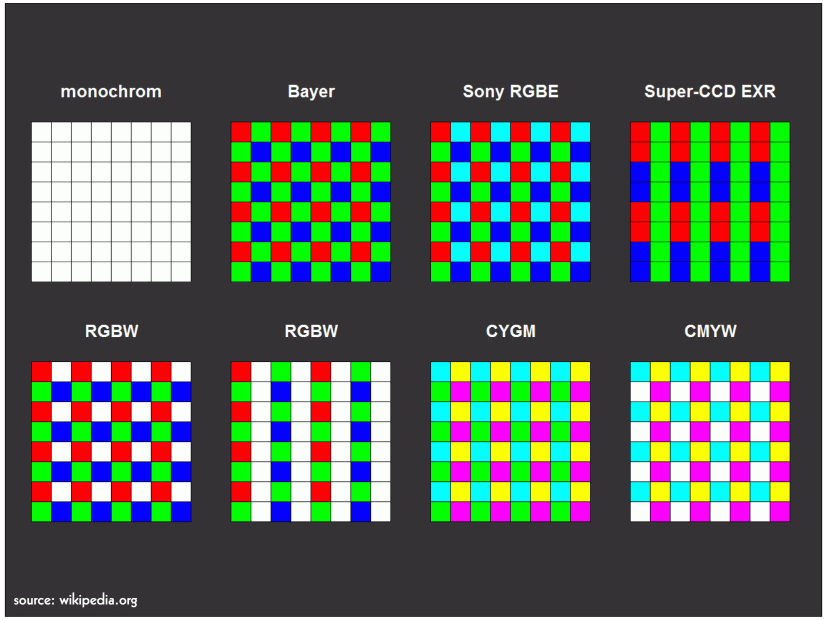
```
Terminal
~/Desktop — less • man movimenc

       --demosaic=(BLI|BCI|LR|VNG|SI|PG|AMZE|HQLI|AHD|DLMMSEE)
           demosaic a Bayer-encoded input_file into an RGB output_file

           This option allows to choose between different demosaicing
           algorithms, because the results may vary a lot, depending on the
           image content.

           The following algorithms are implemented:
           - BLI = bilinear interpolation
           - BCI = bicubic interpolation
           - LR = Lanczos resampling
           - VNG = variable number of gradients
           - SI = spline interpolation
           - PG = pixel grouping
           - AMZE = aliasing minimisation and zipper elimination
           - HQLI = high-quality linear interpolation (Malvar, He and Cutler.
           IEEE 2004)
           - AHD = adaptive homogeneity-directed (Hirakawa and Parks. IEEE
           2005)
           - DLMMSEE = directional linear minimum mean square-error estimation
           (Zhang and Xiaolin. IEEE 2005)

   INFORMATIVE OPTIONS
       -h, --help
:
```

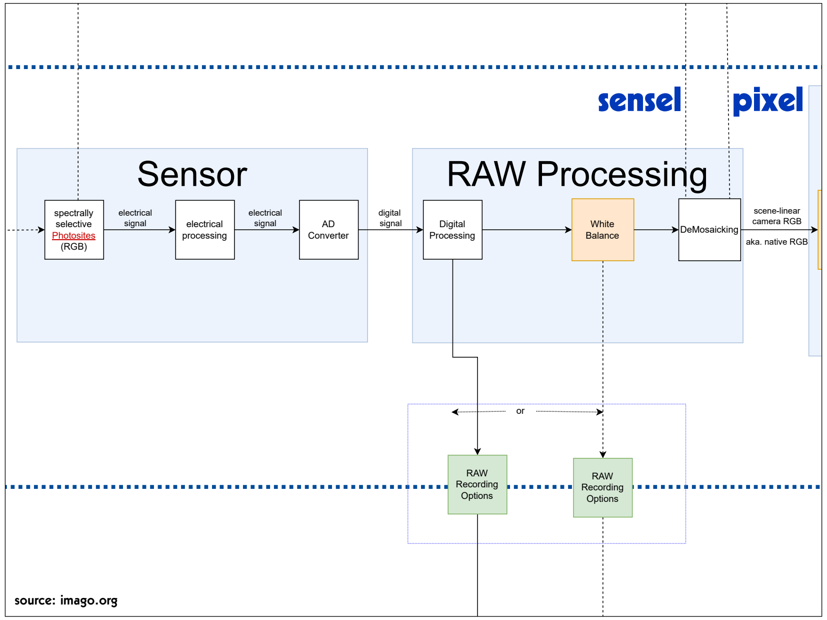
Proposed Terminology

pixel

= picture element

sensel

= sensor element



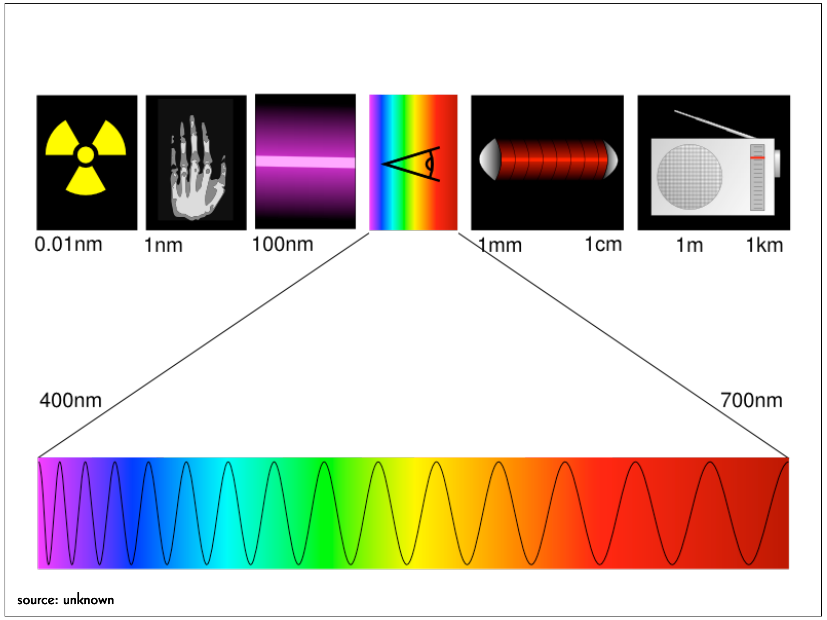
source: imago.org

Bayer-Daten speichern

- pixel values generated by one de-mosaicking algorithm (digital blow-up)
- pixel values generated by mixing two green sensel values into one (digital reduction)
- raw sensel values

Normlicht

- D50
- D55
- D65
- D75


0.01nm
1nm
100nm
1mm
1cm
1m
1km
400nm
700nm
source: unknown

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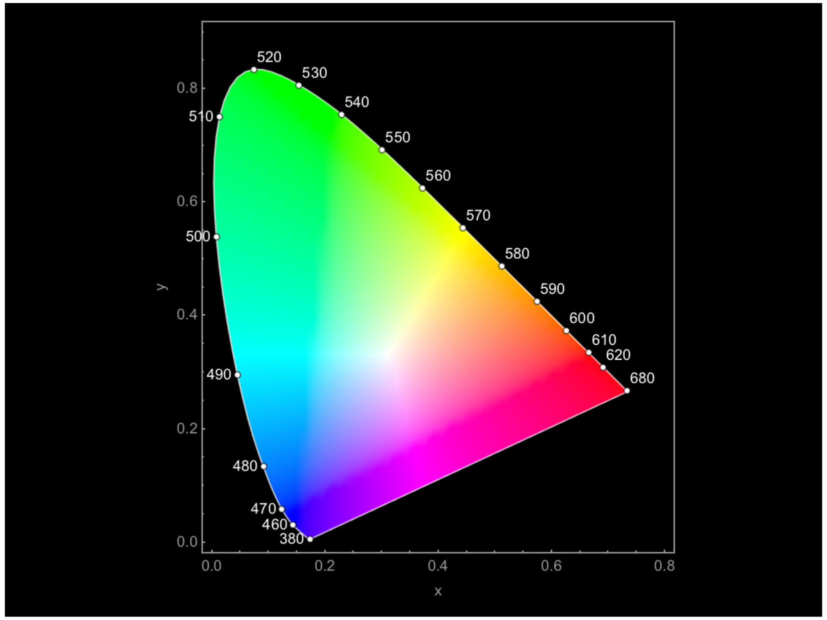
520
530
540
550
560
570
580
590
600
610
620
680
510
500
490
480
470
460
380
0.8
0.6
0.4
0.2
0.0
y
0.0
0.2
0.4
0.6
0.8
x

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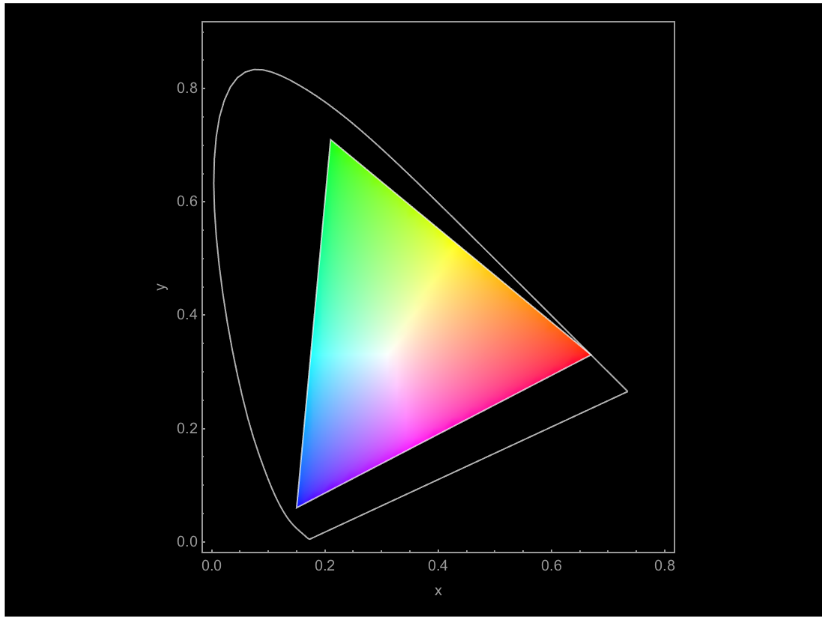
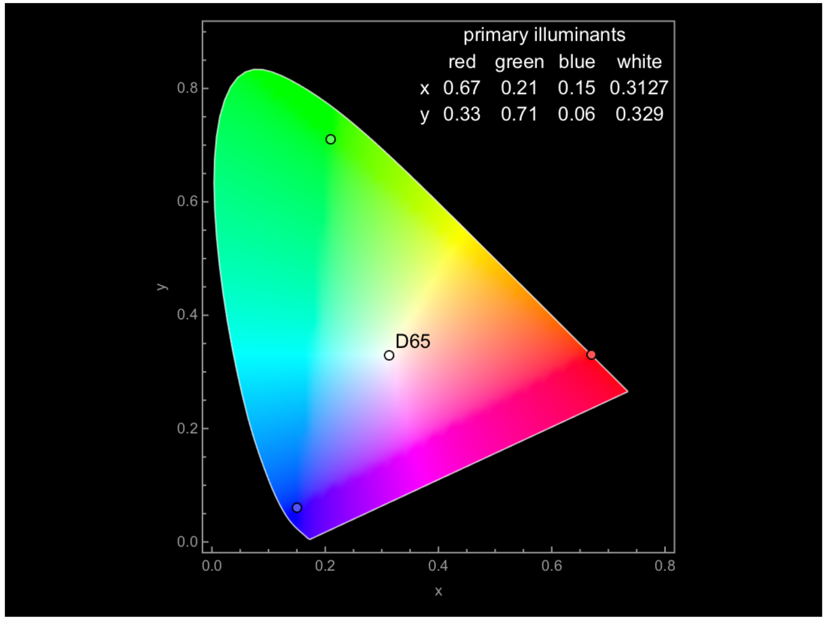

0.8
0.6
0.4
0.2
0.0
y
0.0
0.2
0.4
0.6
0.8
x

59


primary illuminants
red green blue white
x 0.67 0.21 0.15 0.3127
y 0.33 0.71 0.06 0.329
D65
0.8
0.6
0.4
0.2
0.0
y
0.0
0.2
0.4
0.6
0.8
x

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Dateiaufbau

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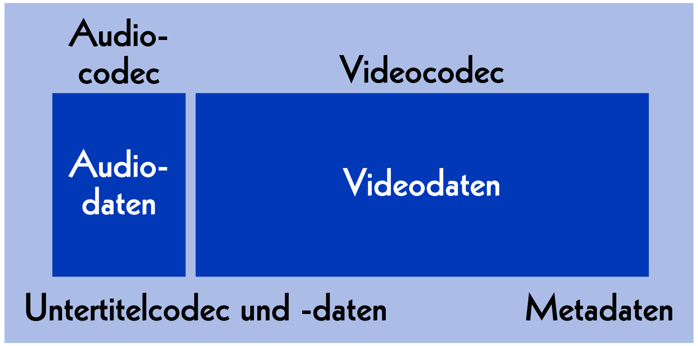
Dateiaufbau

Container (Wrapper)



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Container für Datenfluss

- MP4
- QuickTime (.mov)
- AVI
- MXF
- Matroska (.mkv)
- Flash

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Container für Einzelbilder

- Ordner
- TAR
- ZIP
- MXF
- Matroska (.mkv)
- CinemaDNG
- Motion JPEG

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Audiocodec

- WAVE
- BWF
- AAC
- MP3
- FLAC

Videocodec (Archiv)

Einzelbilder

- TIFF
- DPX
- JPEG 2000
- OpenEXR
- DNG

Datenfluss

- $Y'C_BC_R$ 8 bit
- $Y'C_BC_R$ 10 bit
- HuffYUV
- FFV1

Videocodec (Mezzanine)

- ProRes 422, ProRes 4444, ProRes RAW
- DNxHD, DNxHR
- CineForm RAW
- Blackmagic RAW

Videocodec (Zugang)

- H.264 (AVC)
- H.265 (HEVC)
- H.266 (VVC)
- AV1

RAW data are cooked.

Audiodaten

- pcm_s16le
- pcm_s24le
- pcm_s32le

Videodaten

- rgb48le
- yuv444p16le
- rgb24
- yuv422p10le
- rgb72le
- uyvy422
- yuv420p
- yuv444p24le
- bayer_bggr16le
- bayer_bggr24le

What is inside my DPX?

- log neg encoding
- log RGB encoding or quasi-log encoding
- gamma encoding or power function encoding
- scene-linear encoding

Dateiformate

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Grundsätze

- **Ein Archiv muss seine Dateien pflegen und handhaben können.**

- Open Source
- einfache Bedienung und ausführliche Dokumentation
- weite Verbreitung

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Formate für verschiedene Anwendungszwecke

Archivmasterformat
→ zur Erhaltung und Archivierung

Mezzanine-Format
→ zur Bearbeitung und Postproduktion

Distributionsformat
→ zur Verbreitung und Zugänglichmachung

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Elena Rossi-Snook:

Archiving without access isn't preservation, it's hoarding.

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Archivmaster (heute)

Einzelbilder («Film»)
- Ordner, TIFF, 2K oder 4K, RGB, 16 bit
- MXF, DPX, 2K oder 4K, R'G'B', 10 bit

Datenfluss («Video»)
- AVI, «raw», HD, $Y'C_BC_R$ 4:2:2, 10 bit
- Matroska, FFV1, HD, $Y'C_BC_R$ 4:2:2, 10 bit

Ton
- BWF, 96 kHz, 24 bit
- FLAC, 96 kHz, 24 bit

Mezzanine (heute)

Bild
- ProRes 4444, 2K
- DNxHR, 2K
- ProRes 422 HQ, HD
- DNxHD 175x, HD

Ton
- BWF, 48 kHz, 24 bit
- WAVE, 48 kHz, 24 bit

Zugang (heute)

MP4

Bild
- H.264, SD, $Y'C_BC_R$ 4:2:0, 8 bit, lossy
- H.264, «HD», $Y'C_BC_R$ 4:2:0, 8 bit, lossy

Ton
- AAC, 44.1 kHz, 16 bit
- AAC, 48 kHz, 16 bit

Archivmaster und Mezzanine

Einzelbilder («Film»)
- Matroska, FFV1, 4K oder 2K, R'G'B', 12 bit
- Matroska, FFV1, 4K oder 2K, RGB, 16 bit

Datenfluss («Video»)
- Matroska, FFV1, «HD», $Y'C_BC_R$ 4:4:4, 12 bit
- Matroska, FFV1, «HD», $Y'C_BC_R$ 4:4:4, 10 bit

Ton
- Matroska, FLAC, 192 kHz, 24 bit

Zugang

MP4

Bild

- H.264, «HD», Y′CBCR 4:2:0, 8 bit
- H.265, «HD», Y′CBCR 4:2:0, 8 bit
- H.266, «HD», Y′CBCR 4:2:0, 8 bit
- AV1, «HD», Y′CBCR 4:2:0, 8 bit

Ton

- AAC, 96 kHz, 16 bit
- AAC, 48 kHz, 16 bit

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Bibliografie

Reto Kromer: **Matroska and FFV1: One File Format for Film and Video Archiving?**, in «Journal of Film Preservation», Nr. 96 (April 2017), FIAF, Brüssel, Belgien, S. 41–45

→ https://retokromer.ch/publications/JFP_96.html

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Vor- und Nachteile

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Container

- Ordner
- TAR
- ZIP
- MXF
- Matroska
- AXF

Codec

- TIFF
- DPX
- JPEG 2000
- FFV1
- OpenEXR
- CineForm RAW
- ProRes RAW
- Blackmagic RAW

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	Vorteile	**Nachteile**
TIFF DPX OpenEXR	Daten leichter zu bearbeiten	grössere Dateien
JPEG 2000 FFV1	kleinere Dateien	Daten komplexer zu bearbeiten

Eine Brücke zwischen den zwei Welten

RAWcooked (CLI)

→ mediaarea.net/RAWcooked

RAWcooked

- encoding into Matroska container using FFV1 video codec and FLAC audio codec
- significantly fewer files
- all metadata preserved
- decoding with bit-by-bit reversibility
- possibility to embed sidecar files such as checksum manifest, LUT, XML and PDF
- compatibility with media players

MXF-Container (.mxf)

Videocodec

- DPX
- JPEG 2000
- DNxHD, DNxHR
- ProRes 422, ProRes 4444

SMPTE RDD 48:2018

SMPTE REGISTERED DISCLOSURE DOCUMENT

MXF Archive and Preservation Format Registered Disclosure Document

Page 1 of 113

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This document is NOT a Standard, Recommended Practice or Engineering Guideline, and does NOT imply a finding or representation of the Society.

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All other inquiries in respect of this document, including inquiries as to intellectual property requirements that may be attached to use of the disclosed technology, should be addressed to the proponent identified below.

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MXF / DPX

MXF
→ SMPTE RDD 48:2018

DPX
→ SMPTE ST 268M:2015

MXF / JPEG 2000

MXF
→ SMPTE RDD 48:2018

JPEG 2000
→ ISO/IEC 15444-1:2019
→ usw.

MXF / DNx

MXF
→ SMPTE RDD 48:2018

DNxHD, DNxHR
→ nicht veröffentlicht

MXF / ProRes

MXF
→ SMPTE RDD 48:2018

ProRes 422, ProRes 4444
→ SMPTE RDD 36:2015

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SMPTE RDD 36:2015

SMPTE REGISTERED DISCLOSURE DOCUMENT

Apple ProRes Bitstream Syntax and Decoding Process

Page 1 of 39 pages

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Matroska-Container (.mkv)

Videocodec

- FFV1
- ProRes 422, ProRes 4444

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Matroska / FFV1

Matroska (.mkv)
→ IETF RFC 9559

FFV1
→ IETF RFC 9043

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Stream: Internet Engineering Task Force (IETF)
RFC: 9043
Category: Informational
Published: August 2021
ISSN: 2070-1721
Authors: M. Niedermayer D. Rice J. Martinez

RFC 9043
FFV1 Video Coding Format Versions 0, 1, and 3

Abstract

This document defines FFV1, a lossless, intra-frame video encoding format. FFV1 is designed to efficiently compress video data in a variety of pixel formats. Compared to uncompressed video, FFV1 offers storage compression, frame fixity, and self-description, which makes FFV1 useful as a preservation or intermediate video format.

Status of This Memo

This document is not an Internet Standards Track specification; it is published for informational purposes.

This document is a product of the Internet Engineering Task Force (IETF). It represents the consensus of the IETF community. It has received public review and has been approved for publication by the Internet Engineering Steering Group (IESG). Not all documents approved by the IESG are candidates for any level of Internet Standard; see Section 2 of RFC 7841.

Information about the current status of this document, any errata, and how to provide feedback on it may be obtained at https://www.rfc-editor.org/info/rfc9043.

Matroska / ProRes

Matroska (.mkv)
→ IETF RCF 9559

ProRes 422, ProRes 4444
→ SMPTE RDD 36:2015

OpenEXR-Dateiformat (.exr)

OpenEXR
→ 3-Klausel-BSD-Lizenz
→ nicht von einer offiziellen Stelle normiert

Umwandlungen

$$
\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1.140251 \\ 1 & -0.393931 & -0.580809 \\ 1 & 2.028398 & 0 \end{bmatrix} \cdot \begin{bmatrix} Y'_{601} \\ U \\ V \end{bmatrix}
$$

$$
\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \begin{bmatrix} 1 & 0.956295 & 0.621025 \\ 1 & -0.272558 & -0.646709 \\ 1 & -1.104744 & 1.701157 \end{bmatrix} \cdot \begin{bmatrix} Y'_{601} \\ I \\ Q \end{bmatrix}
$$

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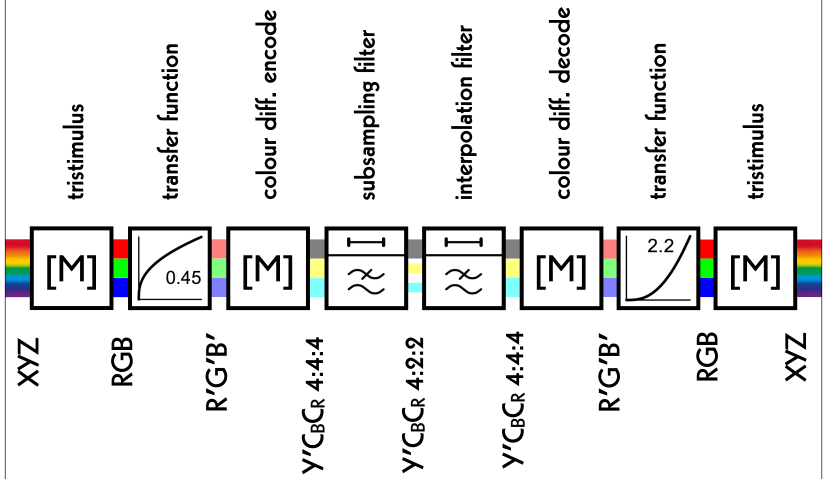

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Dateiumwandlungen

- demultiplexen
- decodieren
- ändern
- codieren
- multiplexen

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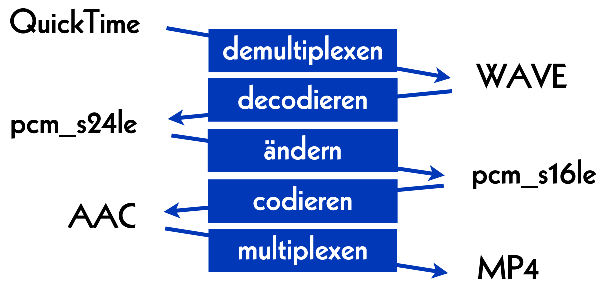
Beispiel: Ton



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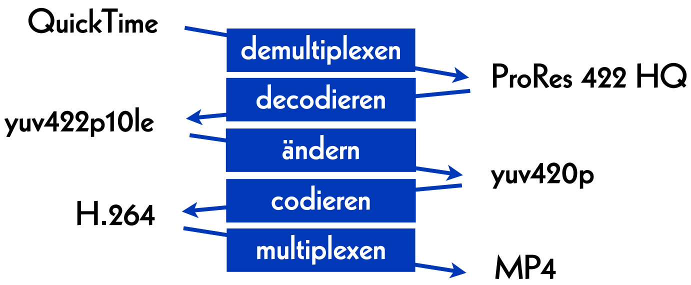
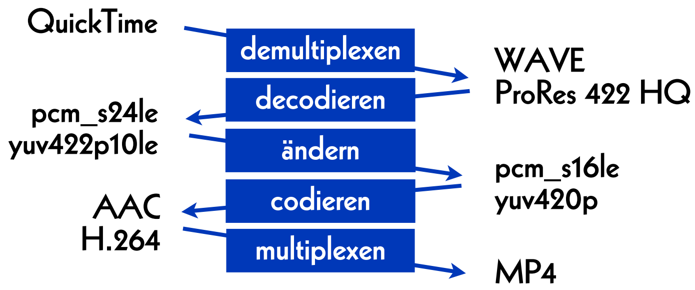
Beispiel: Bild



Beispiel: Bild und Ton



Datenwartung

Plan the Next Migration

- file naming
- barcodes
- checksums
- write the full index onto the cartridge
- technical metadata
- code to retrieve the files

File Naming (example)

- title_codec.container
- title_codec_container_algorithm.txt

- film_H264.mp4
- film_H264_mp4_md5.txt

Checksums

cryptographic

- MD5
- SHA-1
- SHA-256
- SHA-512

non-cryptographic

- CRC-32
- xxHash 32
- xxHash 64
- xxHash 128

Longterm

- storage of the cartridges
- three copies …
- … in geographically distant locations
- data integrity check
- data migration
- availability of LTO decks

Data Migrations

2014

- our internal archive from LTO-4 to LTO-6 (5.7 PB)

2014–2025

- a hundred data migrations for clients

2021

- our internal archive from LTO-6 to LTO-8 (25.2 PB)

Reading

Reto Kromer: **On the Bright Side of Data Migrations**, in «IASA Journal», n. 49 (December 2018), IASA, p. 18–22

→ retokromer.ch/publications/IASA_49.html

read | script | write

script to modify

- container
- codec
- both container and codec
- metadata
- filename

#1: ProRes-born Content

from:

- ProRes stored in a QuickTime (.mov) container

to:

- ProRes stored in a Matroska (.mkv) container

Update the Container

→ read file from source LTO

→ demultiplex file

- ProRes 422, 10 bit [yuv422p10le]
- ProRes 4444, 10 bit [yuv444p10le or yuva444p10le] or 12 bit [yuv444p12le]

→ multiplex file

→ write file to destination LTO

#2: Video

from:

- AVI / 8-bit and 10-bit uncompressed
- MOV / 8-bit and 10-bit uncompressed
- MP4 / 8-bit and 10-bit uncompressed

to:

- Matroska / FFV1

Container and Codec

→ read file from source LTO
→ demultiplex file
→ decode file

- $Y'C_BC_R$, 4:2:2, 8 bit, uyvy422

→ encode file
→ multiplex file
→ write file to destination LTO

Container and Codec

→ read file from source LTO
→ demultiplex file
→ decode file

- $Y'C_BC_R$, 4:2:2, 10 bit, yuv422p10le

→ encode file
→ multiplex file
→ write file to destination LTO

#3: Filename

from:

- Title_YUV422.mkv

to:

- Title_YCbCr422_9d5084b5b0a08d5022b39e0e75241d12.mkv

Always remember:

To do nothing is **never** an option!

Danksagung (1)

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