Audiovisuelle Dateiformate

Reto Kromer • AV Preservation by reto.ch

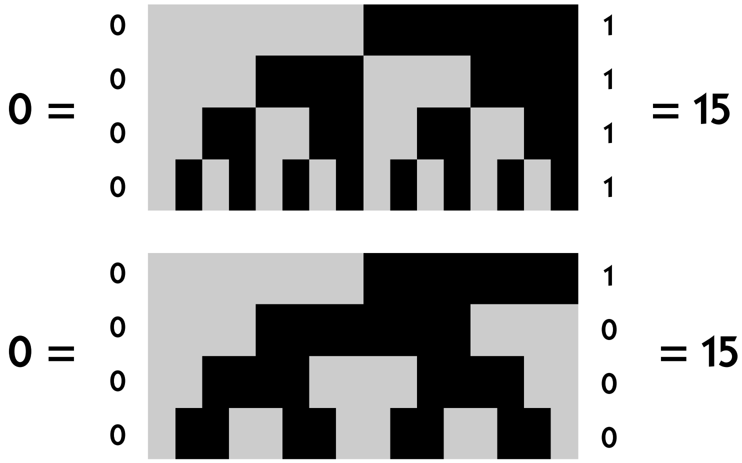
Einführung in FFmpeg
Lichtspiel / Kinemathek Bern
12. Februar 2026

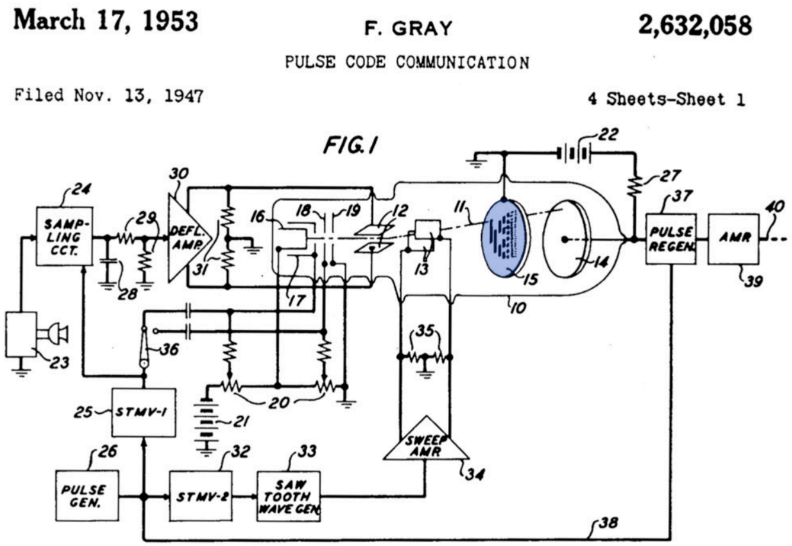
Inhalt

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

Digitaler Ton

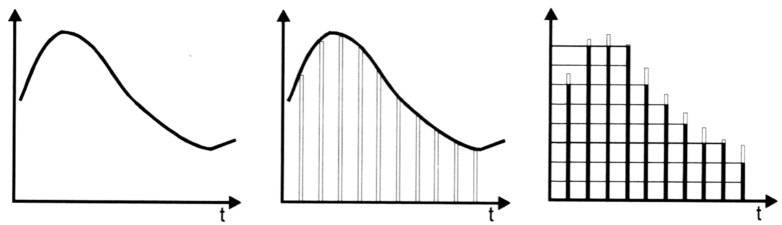
Frank Gray (1887–1969)





Digitaler Ton

- Abtastung
- Quantisierung
- Kompression



Digitalisierung = Abtastung + Quantisierung

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.

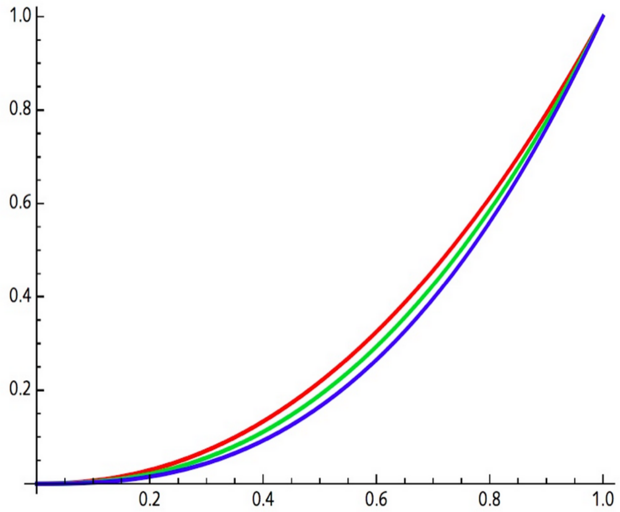
Quantisierungsauflösung

- 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

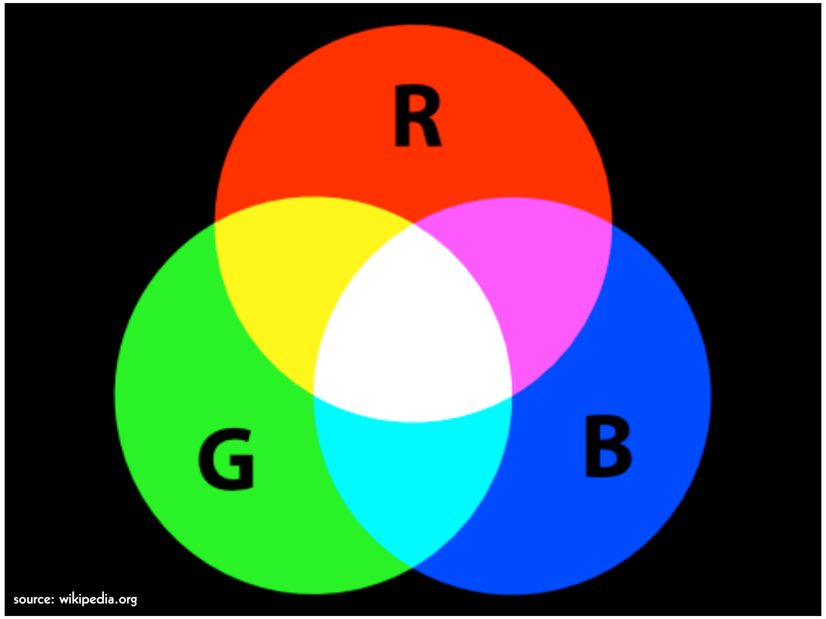
«Mittelgrau»

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

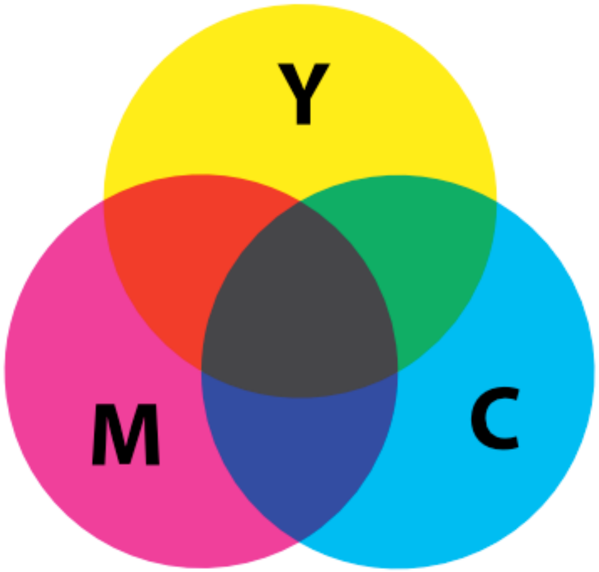


Farbraum

- 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



source: wikipedia.org

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

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

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

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

21

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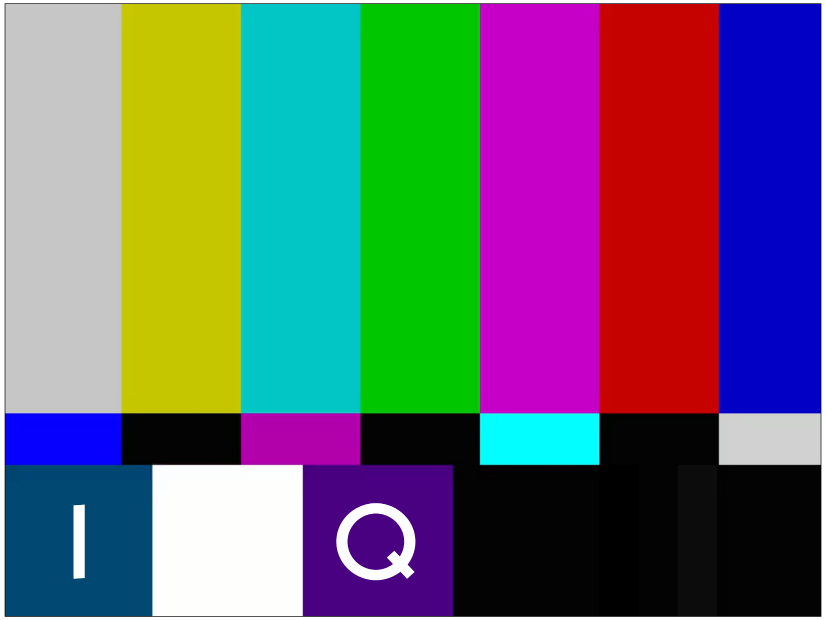
RGB24

00000000 00000000 00000000	11111111 00000000 00000000	00000000 11111111 00000000	00000000 00000000 11111111
00000000 11111111 11111111	11111111 00000000 11111111	11111111 11111111 00000000	11111111 11111111 11111111

23



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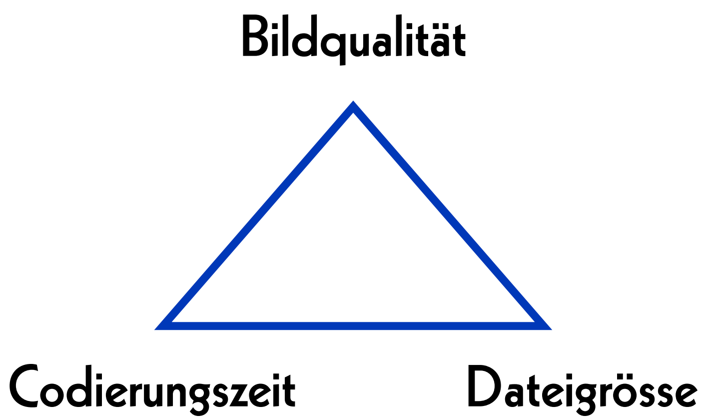

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Kompression

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

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Nicht komprimiert

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

Beispiele: TIFF, DPX, DNG, OpenEXR

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Verlustfrei komprimiert

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

Beispiele: JPEG 2000, FFV1

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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

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Farbunterabtastung

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

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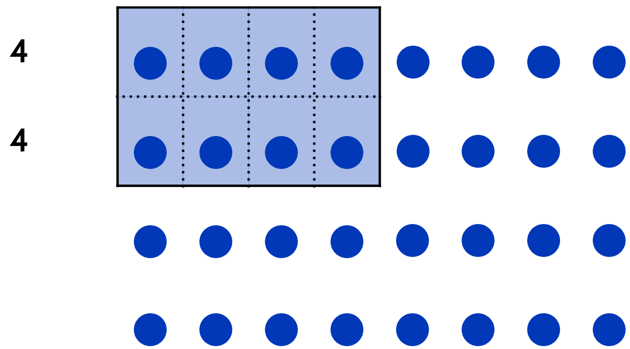
4:4:4



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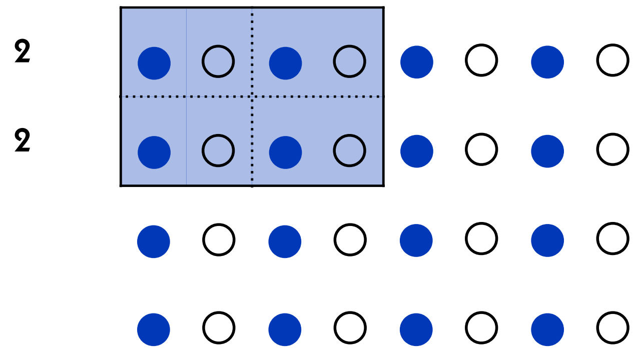
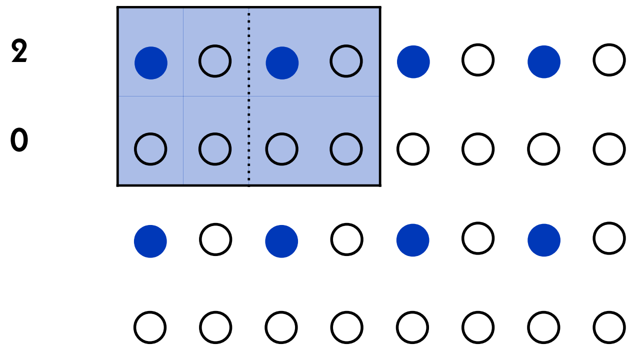
4:2:2

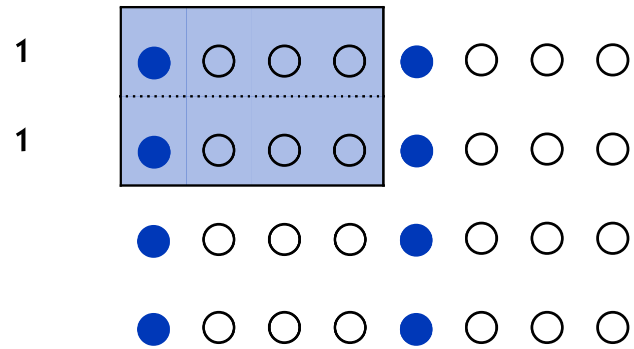


32

4:2:0



4:1:1



Komprimiert generiert

- sowohl für Aufnahme als auch für Postproduktion optimiert

Beispiele: CineForm RAW, ProRes RAW, Blackmagic RAW

Unbequeme Tatsachen

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

Bryce E. Bayer (1929–2012)

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United States Patent [19] — [11] **3,971,065**

Bayer — [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

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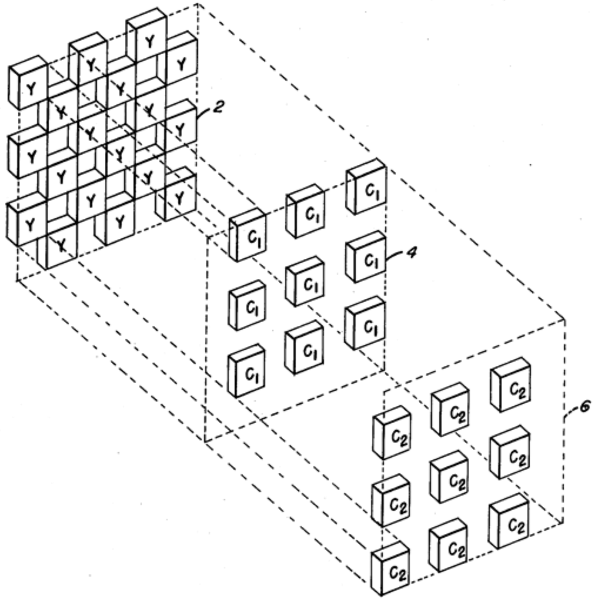

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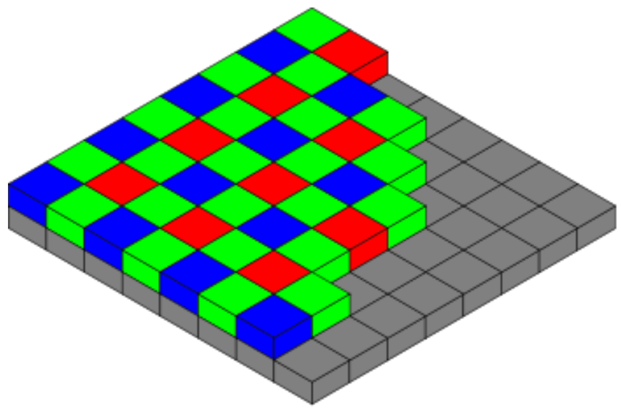
Bayer



source: wikipedia.org

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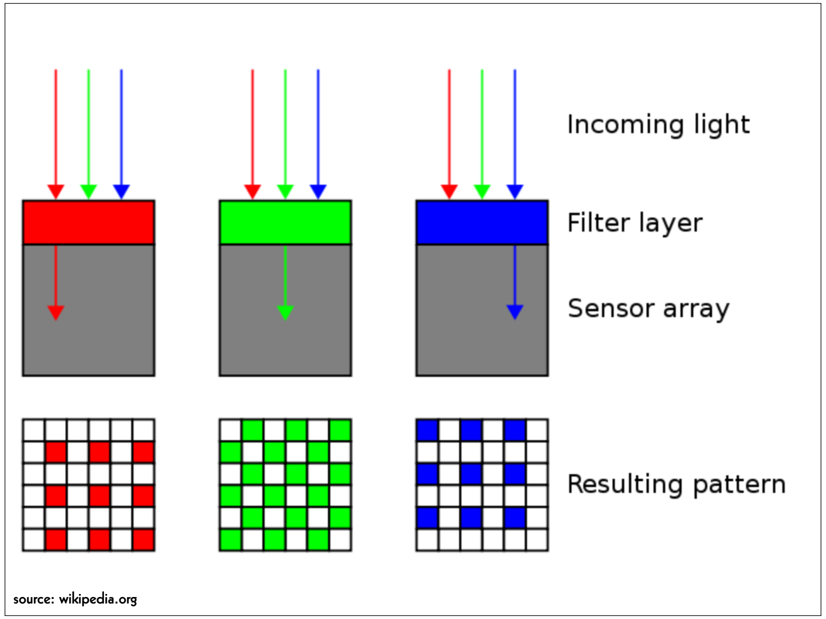

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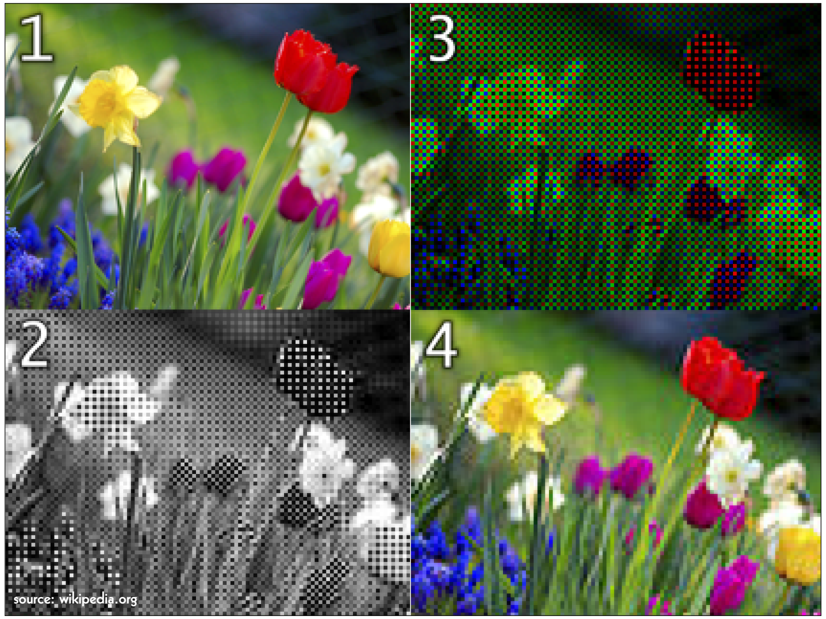

42

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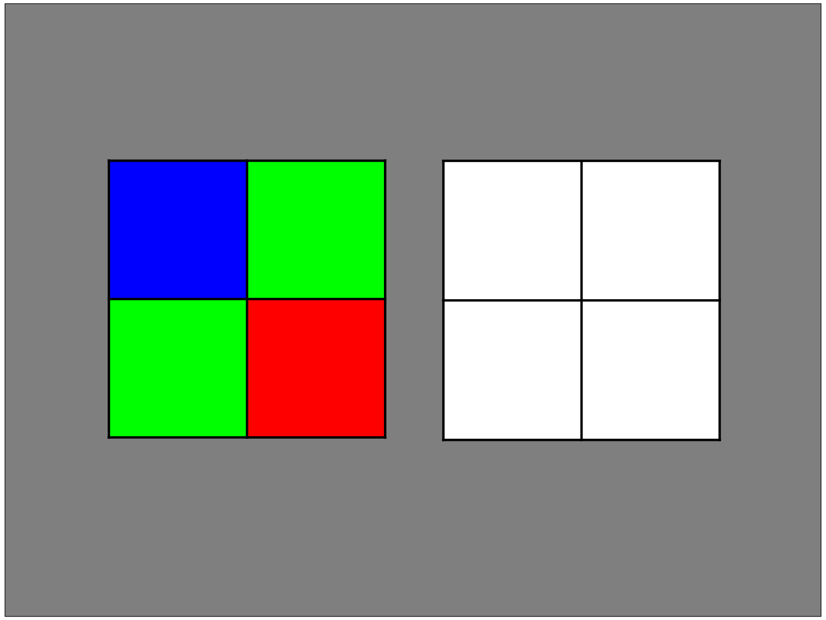

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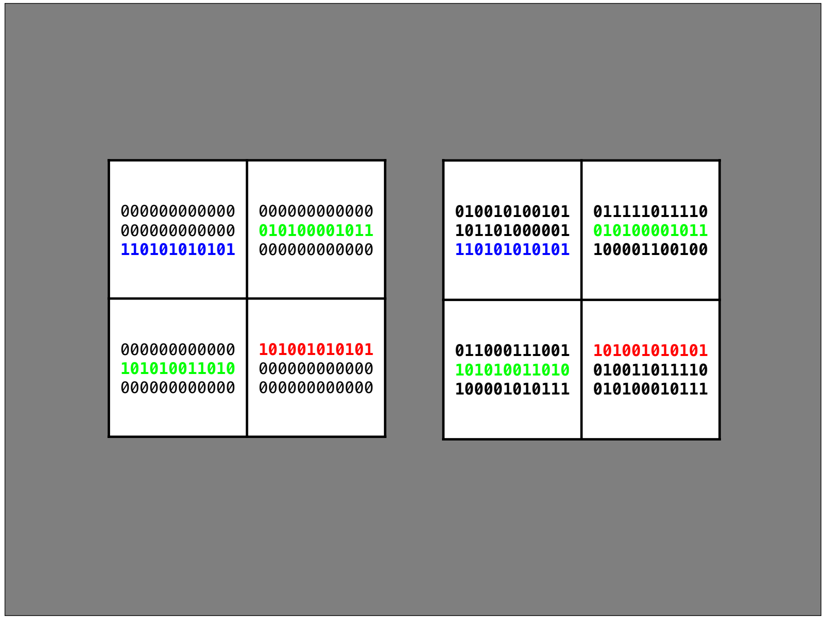
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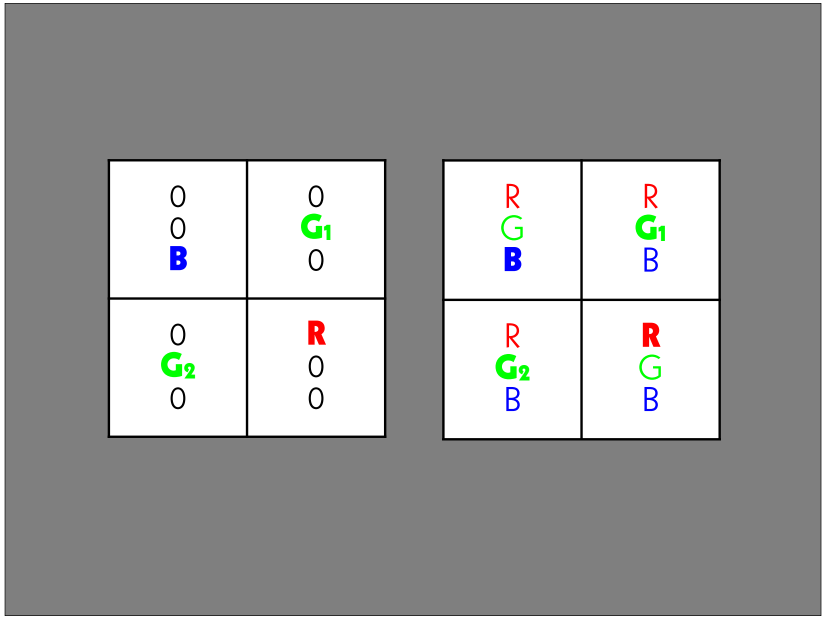
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0
B
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G1
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R
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B
R
G
B

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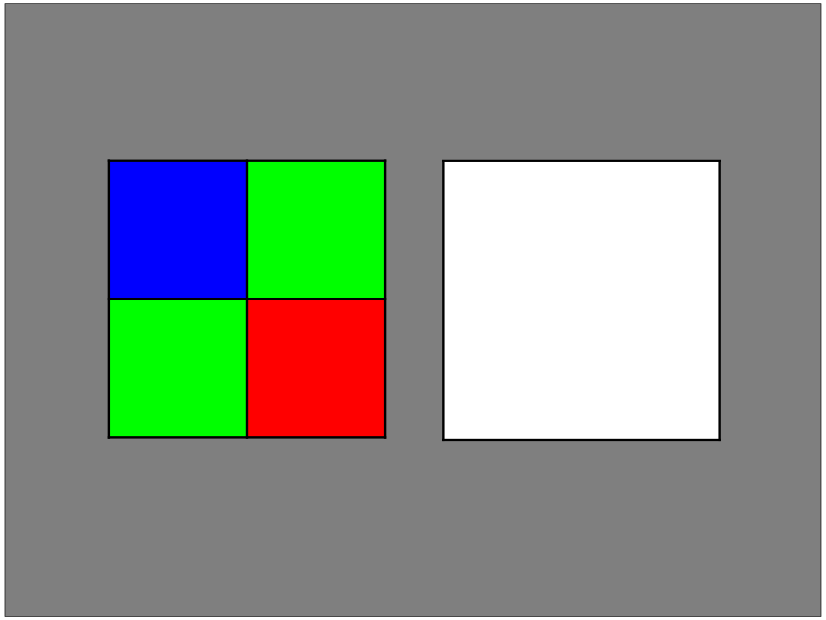

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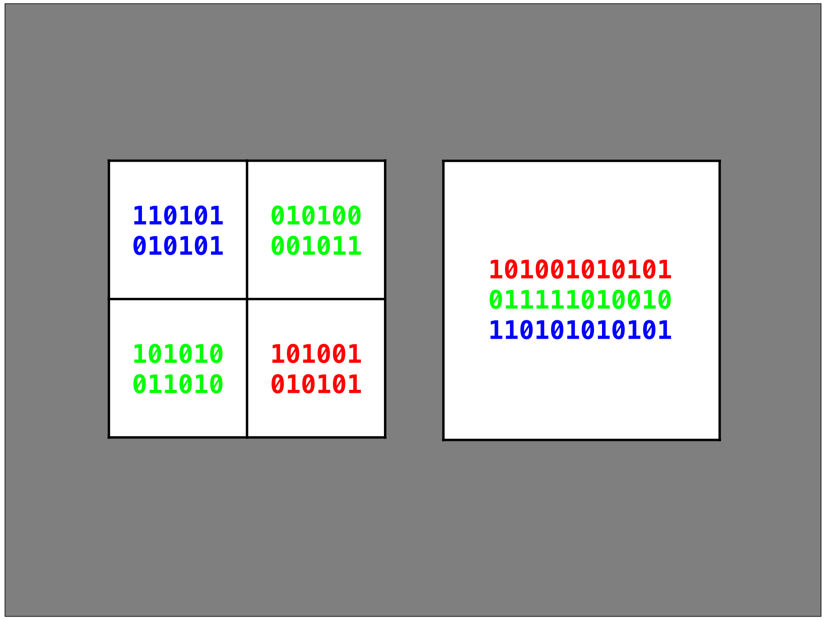
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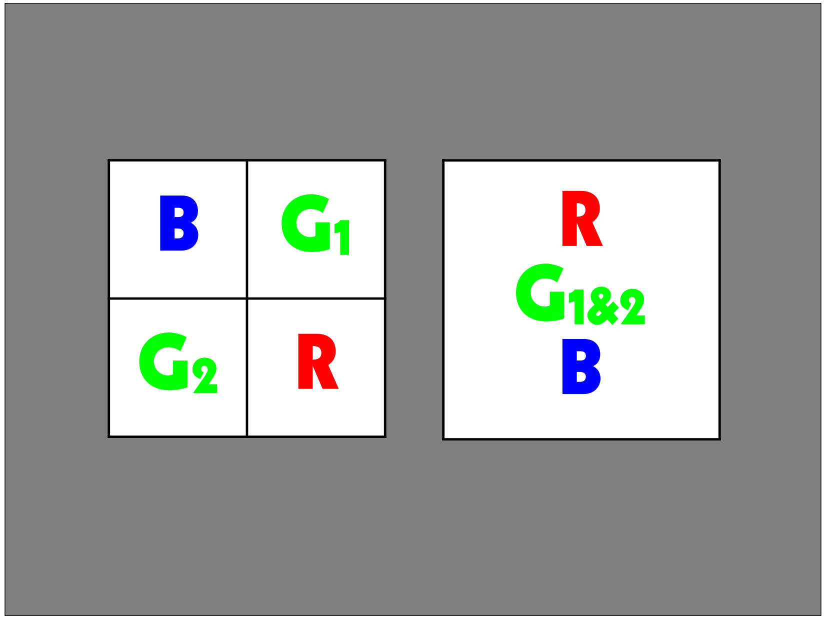


Bayer-Daten benützen

digitales Aufblasen auf RGB

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

digitale Reduktion auf RGB

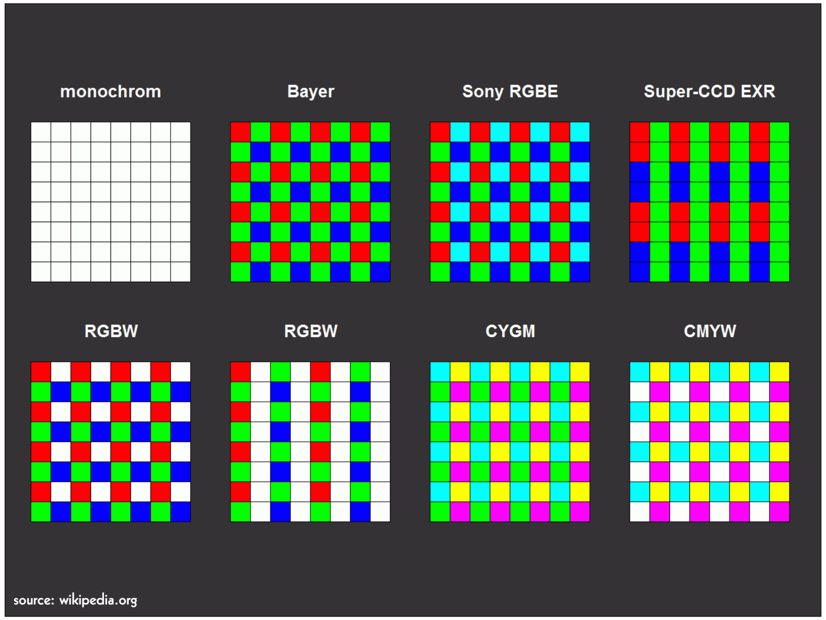
- drei Viertel der generierten Daten sind gespeichert
- die Datei hat die halbe Sensorauflösung
- die gesamten Daten sind real

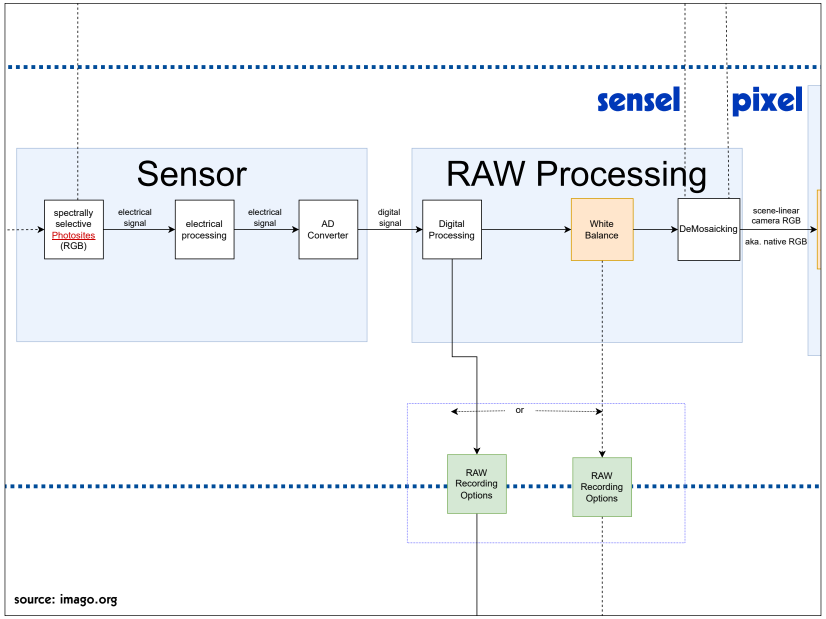

```
    --demosaic=(BLI|BCI|LR|VNG|SI|PG|AMZE|HQLI|AHD|DLMMSEE)
        demosaic a Bayer-encoded input_file into an RGB output_file

        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
:
```



source: imago.org

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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

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Normlicht

- D50
- D55
- D65
- D75

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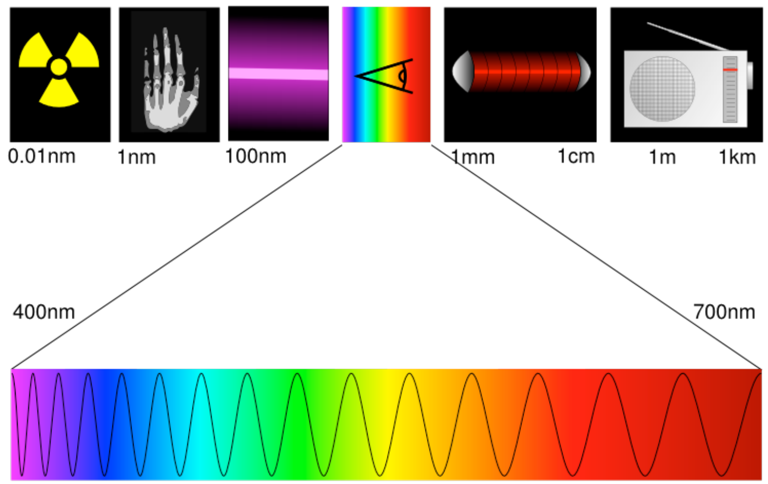

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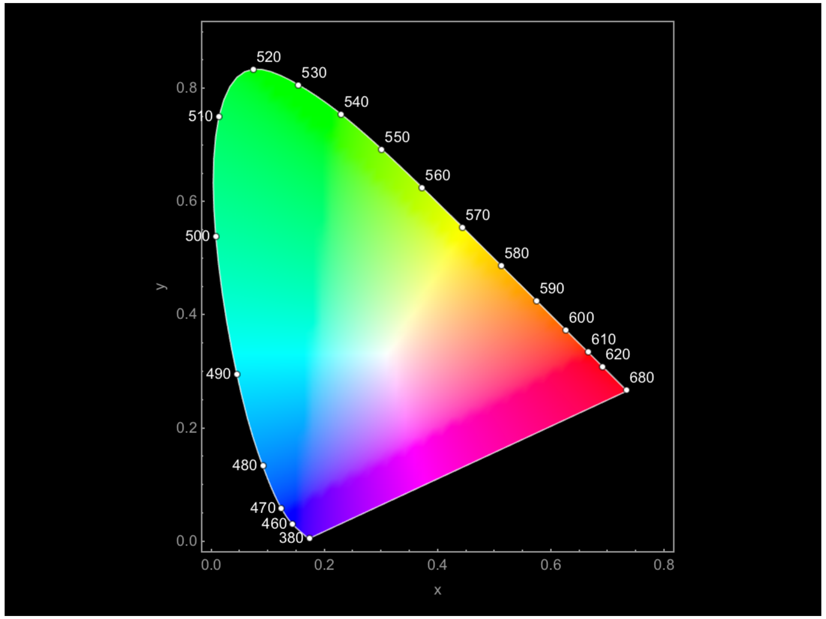

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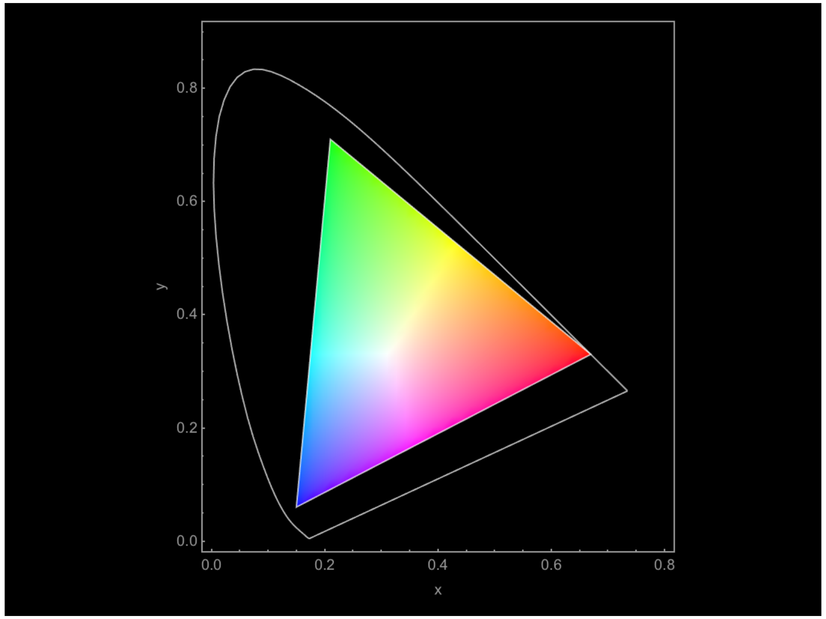

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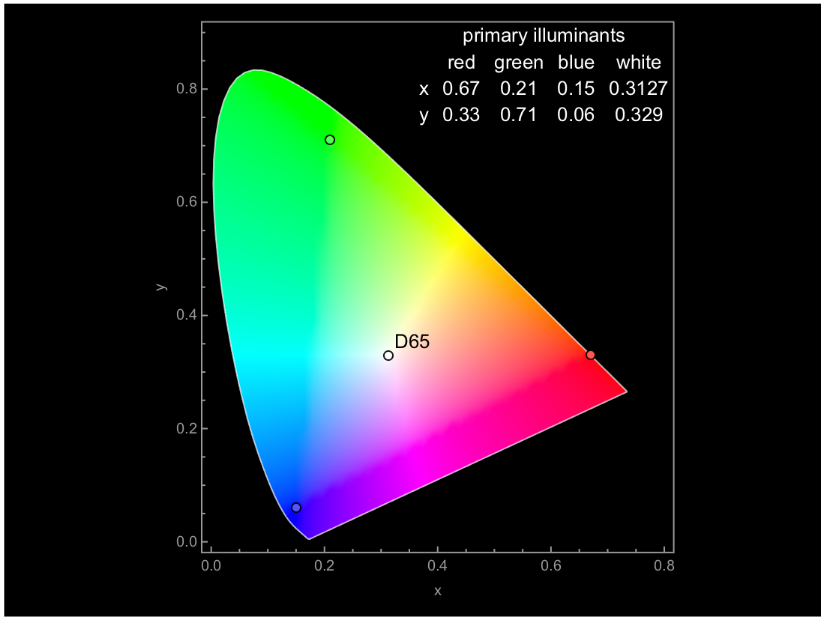

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Dateiaufbau

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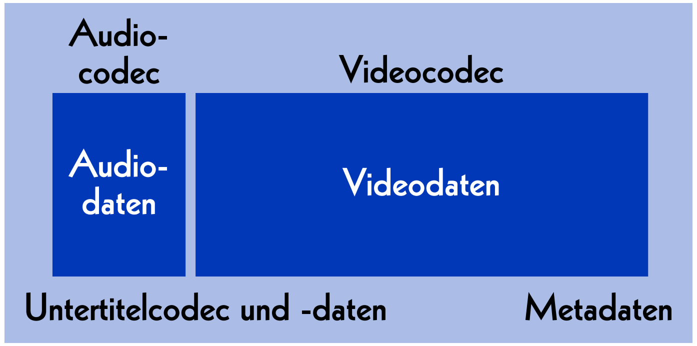
Dateiaufbau

Container (Wrapper)



Container für Datenfluss

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

Container für Einzelbilder

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

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

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

Grundsätze

- **Ein Archiv muss seine Dateien pflegen und handhaben können.**
- Open Source
- einfache Bedienung und ausführliche Dokumentation
- weite Verbreitung

Formate für verschiedene Anwendungszwecke

Archivmasterformat
→ zur Erhaltung und Archivierung

Mezzanine-Format
→ zur Bearbeitung und Postproduktion

Distributionsformat
→ zur Verbreitung und Zugänglichmachung

Elena Rossi-Snook:

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

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», $Y'C_BC_R$ 4:2:0, 8 bit
- H.265, «HD», $Y'C_BC_R$ 4:2:0, 8 bit
- H.266, «HD», $Y'C_BC_R$ 4:2:0, 8 bit
- AV1, «HD», $Y'C_BC_R$ 4:2:0, 8 bit

Ton

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

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

Vor- und Nachteile

Container

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

Codec

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

	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

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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

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MXF-Container (.mxf)

Videocodec

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

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SMPTE RDD 48:2018

SMPTE REGISTERED DISCLOSURE DOCUMENT

MXF Archive and Preservation Format Registered Disclosure Document

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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.

Proponent Contact Information:
Kate Murray
Library of Congress
101 Independence Ave, S.E.
Washington, DC 20540-1300

Email: kmur@loc.gov

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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

SMPTE RDD 36:2015

SMPTE REGISTERED DISCLOSURE DOCUMENT

Apple ProRes Bitstream Syntax and Decoding Process

Page 1 of 39 pages

The attached document is a Registered Disclosure Document prepared by the sponsor identified below. It has been examined by the appropriate SMPTE Technology Committee and is believed to contain adequate information to satisfy the objectives defined in the Scope, and to be technically consistent.

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

Every attempt has been made to ensure that the information contained in this document is accurate. Errors in this document should be reported to the proponent identified below, with a copy to eng@smpte.org.

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.

Proponent contact information:

ProRes Program Office
Apple Inc.
1 Infinite Loop, MS: 77-2YAK
Cupertino, CA 95014
USA

Email: ProRes@apple.com

Matroska-Container (.mkv)

Videocodec

- FFV1
- ProRes 422, ProRes 4444

Matroska / FFV1

Matroska (.mkv)
→ IETF Internet Draft

FFV1
→ IETF RFC 9043

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 Internet Draft

ProRes 422, ProRes 4444
→ SMPTE RDD 36:2015

OpenEXR-Dateiformat (.exr)

OpenEXR

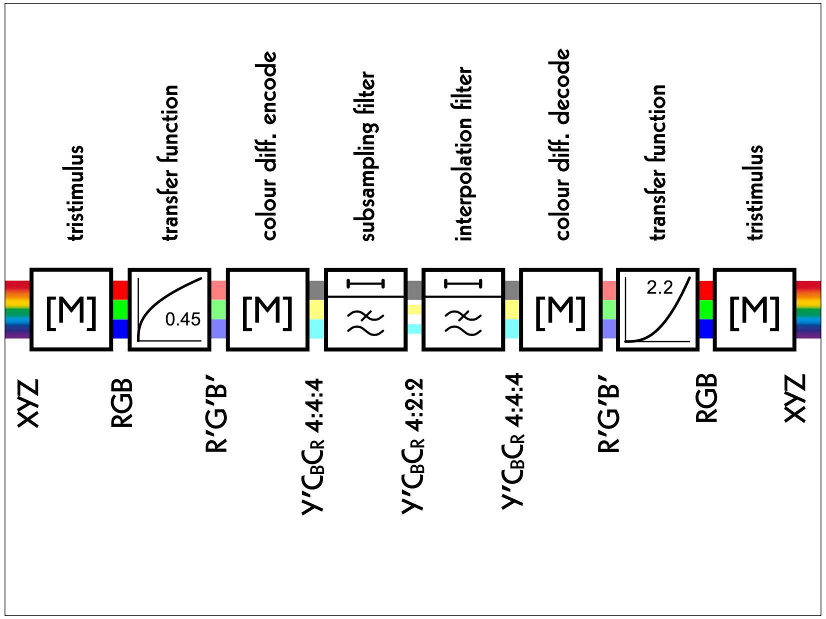
→ 3-Klausel-BSD-Lizenz

→ 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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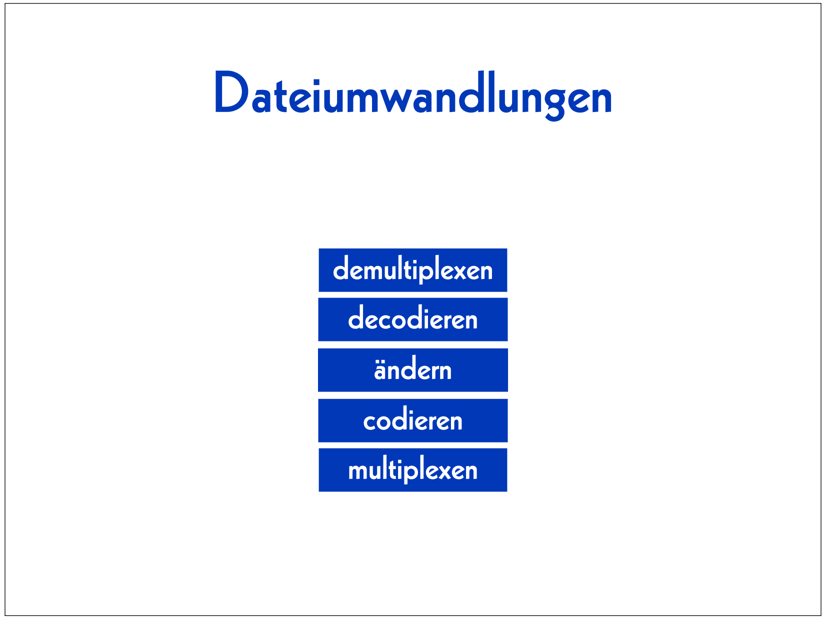
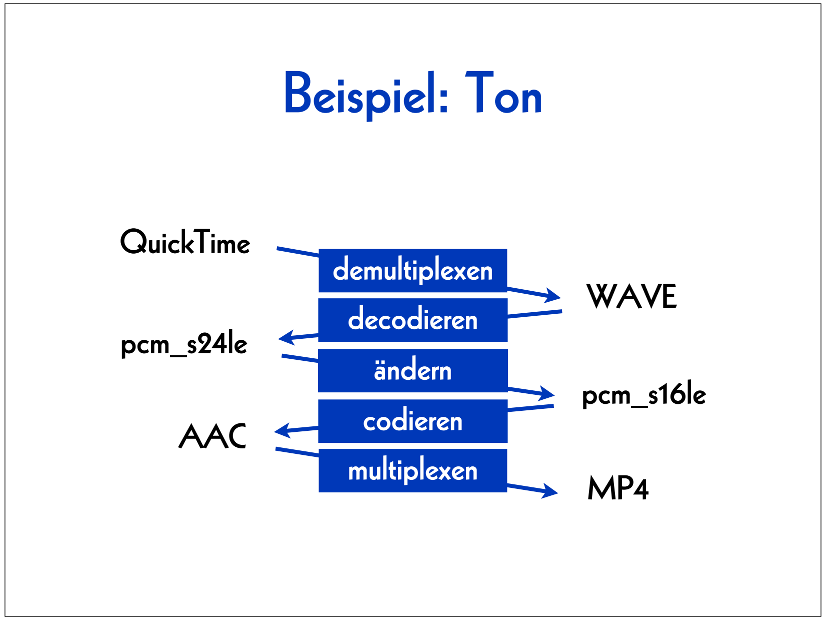
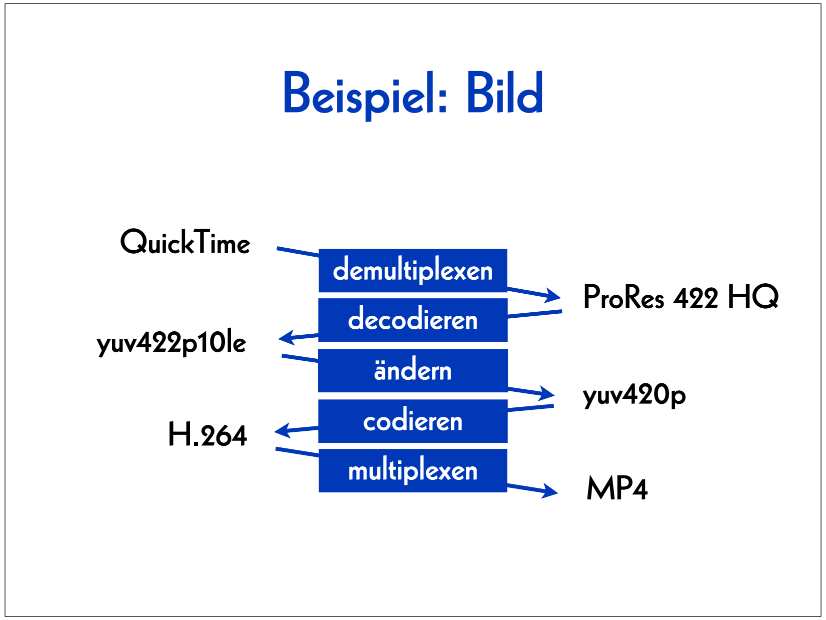


102



103



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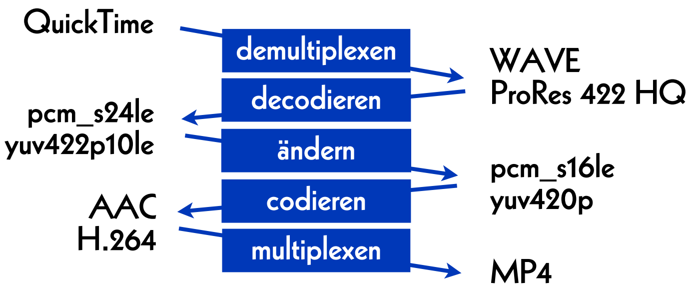
Beispiel: Bild und Ton



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)

2014–2021

- two dozen 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

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#1: ProRes-born Content

from:

- ProRes stored in a QuickTime (.mov) container

to:

- ProRes stored in a Matroska (.mkv) container

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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

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#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

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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!

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AV Preservation by

reto.ch

Sandrainstrasse 3/7
3007 Bern
Switzerland

reto.ch
info@reto.ch