How to make a smart camera pipeline

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About myself

The Chinese Univ. of HK
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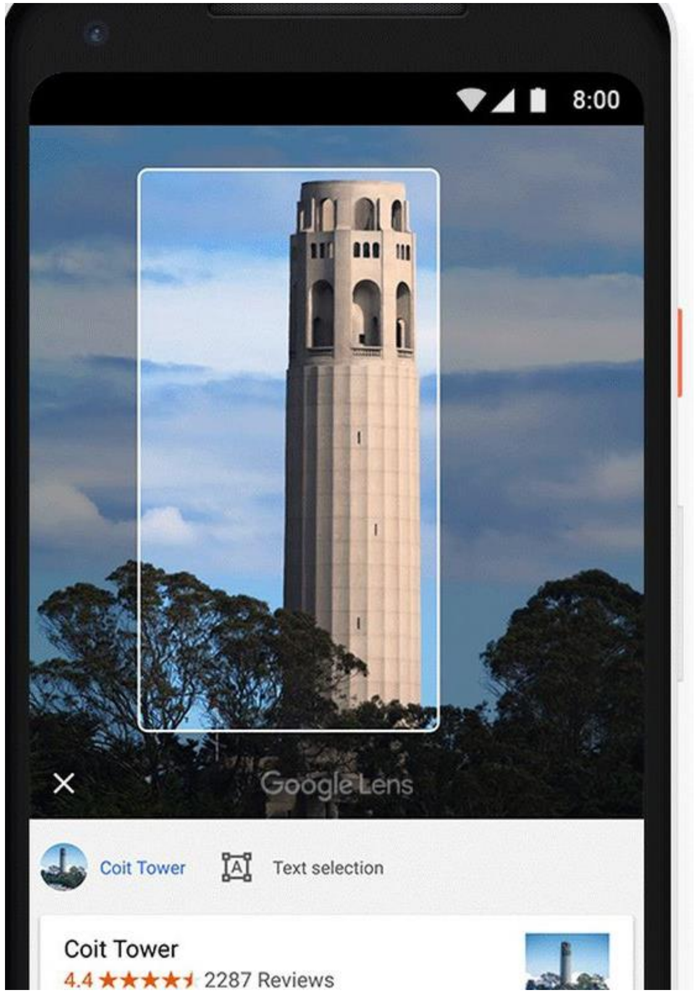
Google Research, Gcam
Staff Eng.
Manager: David Saleson
2017-2022

MIT
Ph.D.
Advisor: William T. Freeman
2012-2017

Smart camera = ML algorithms applied images?



Object detection

Face beautification
[Leyvand et al., 2006]

Camera may not capture visual signal for ML system

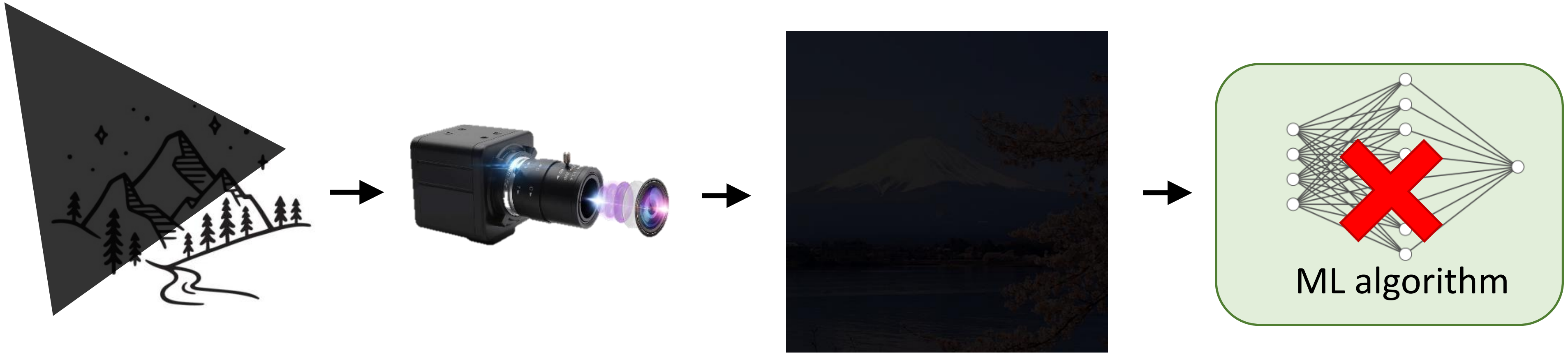
One frame

A frame 2s later

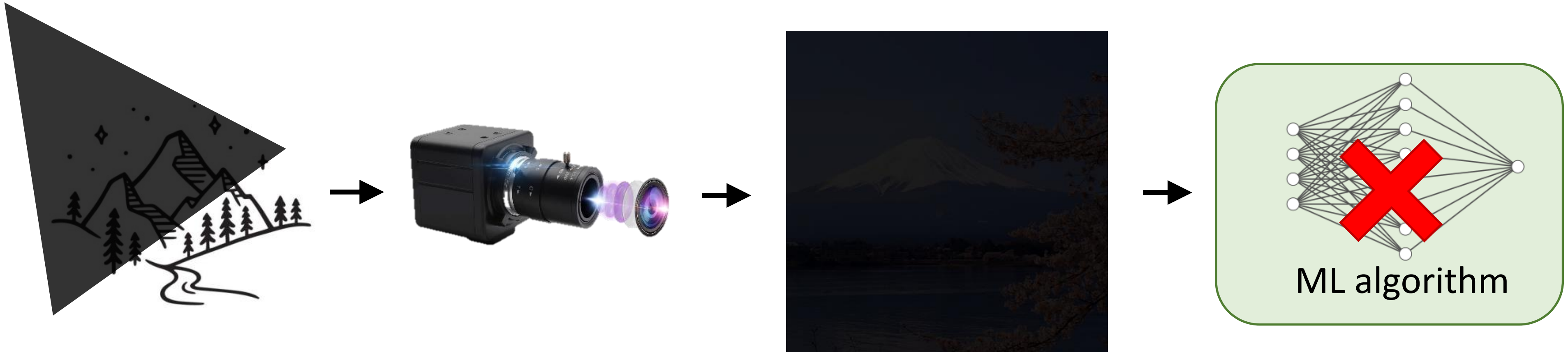
Images are too dark for ML to detect this biking person

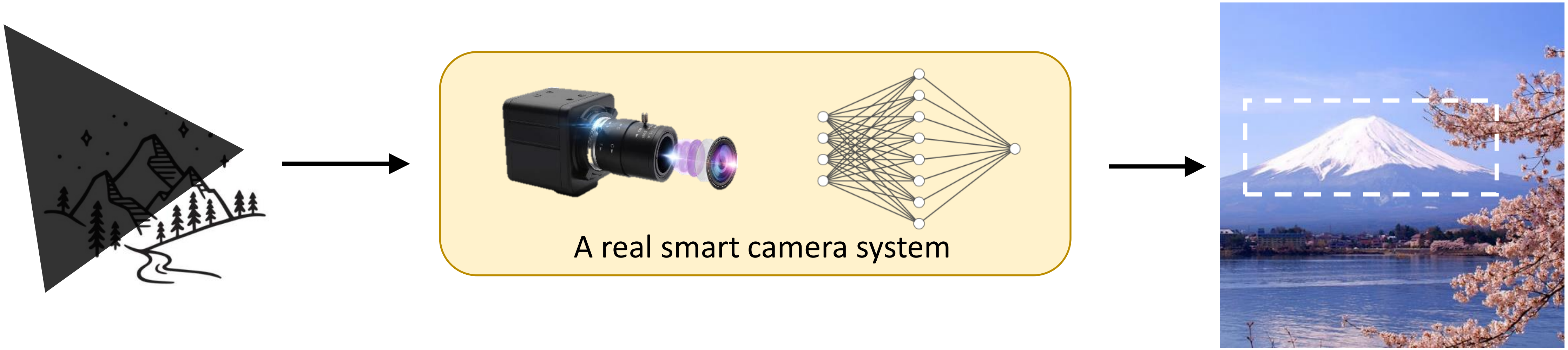
Video from a fatal car crash

Separate design may fail



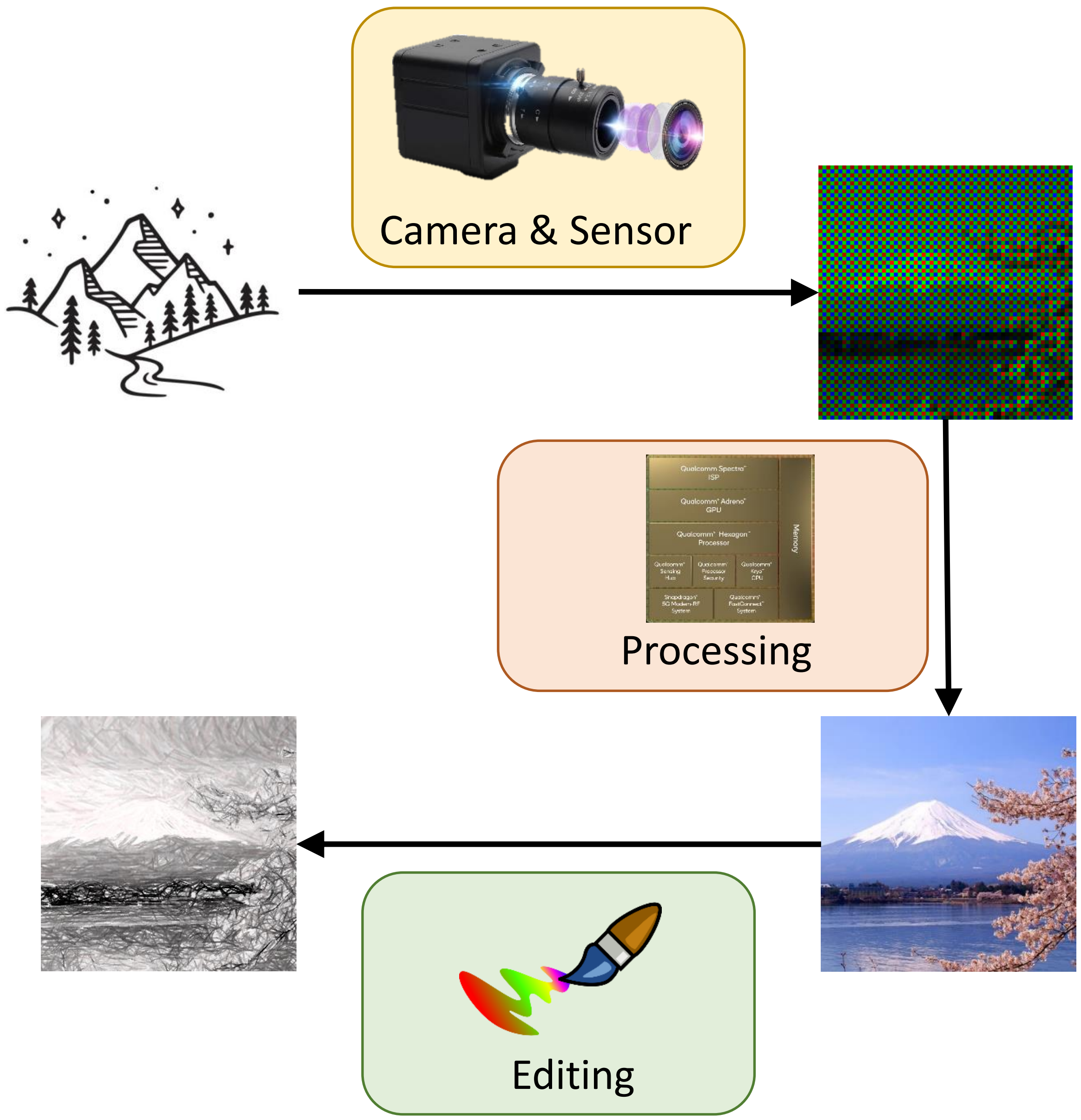
Machine learning embedded in the camera





Overview

- **Capturing**: multiple source fusion
- **Processing & editing**
  - **Training data:** synthetic data
  - **Network**: combine classic image processing algorithm and machine learning



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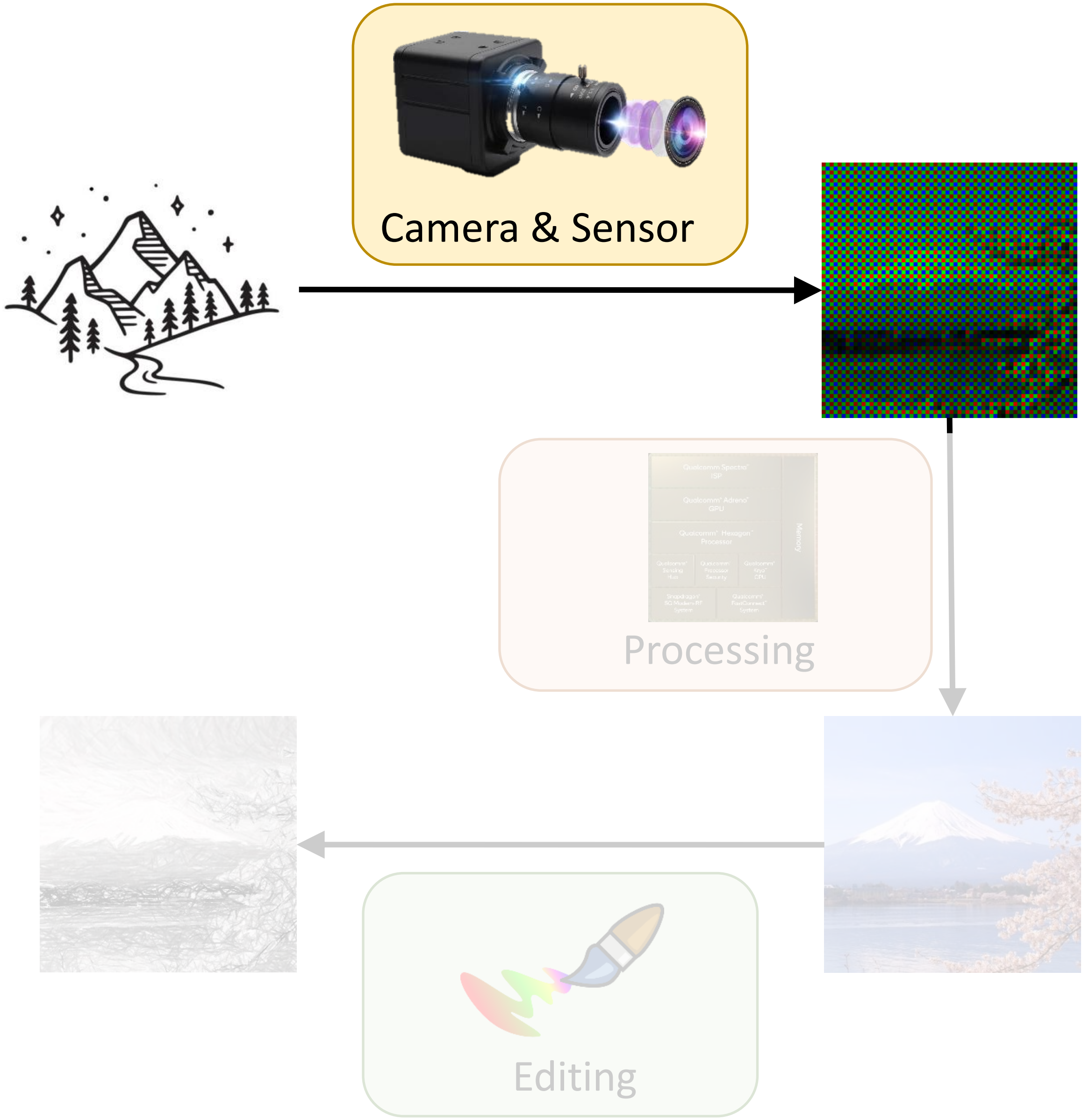
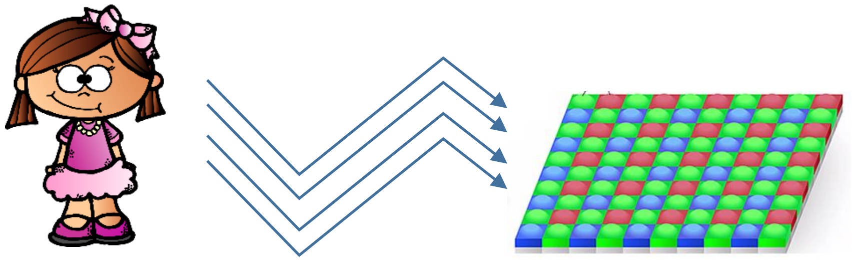


Image in lowlight

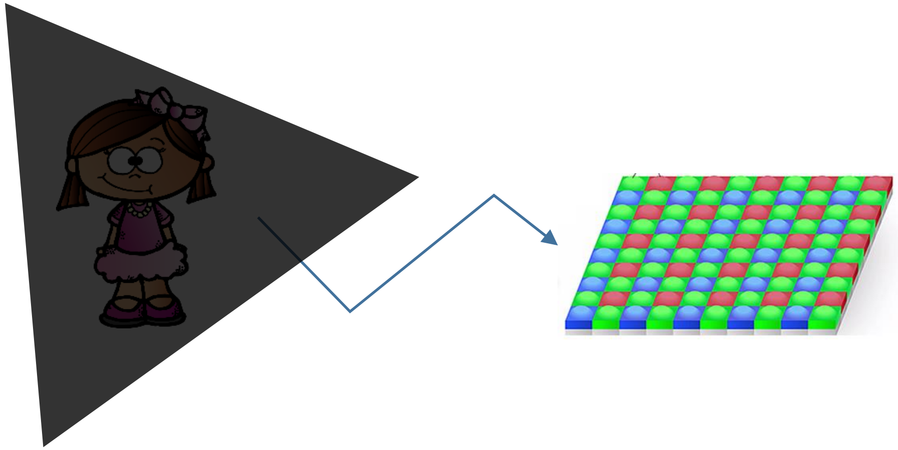
"Handheld Mobile Photography in Very Low Ligh“, SIGGRAPH Asia 2019

by our night sight algorithm

Not enough photons in lowlight

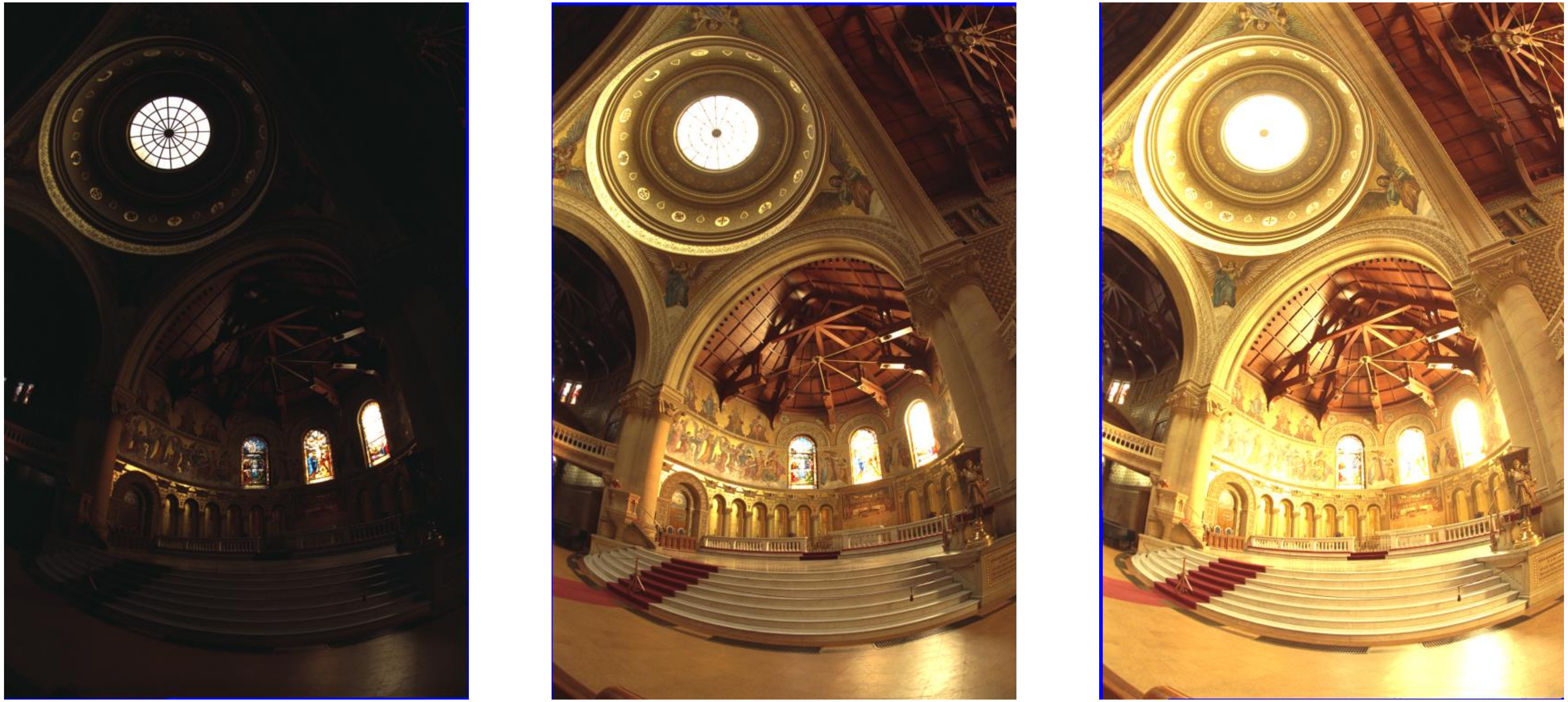


Good lighting



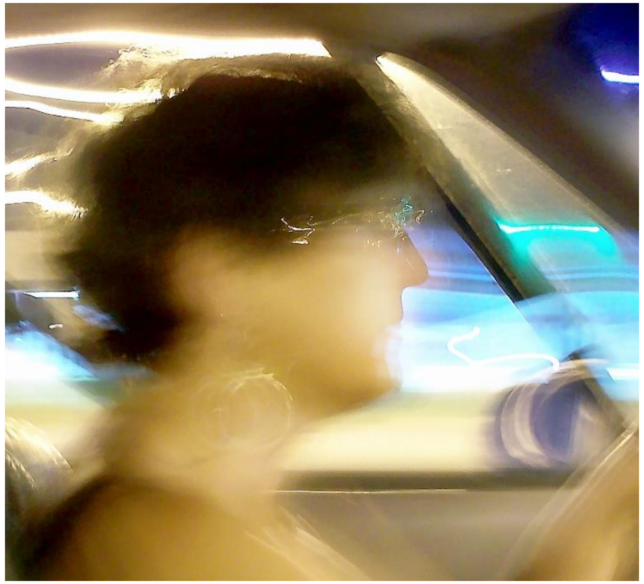
Lowlight

Exposure bracketing



[Debevec et al., 2007]
[Gallo and Sen 2016]

From long exposure to burst photography



Long-exposure

Motion blur

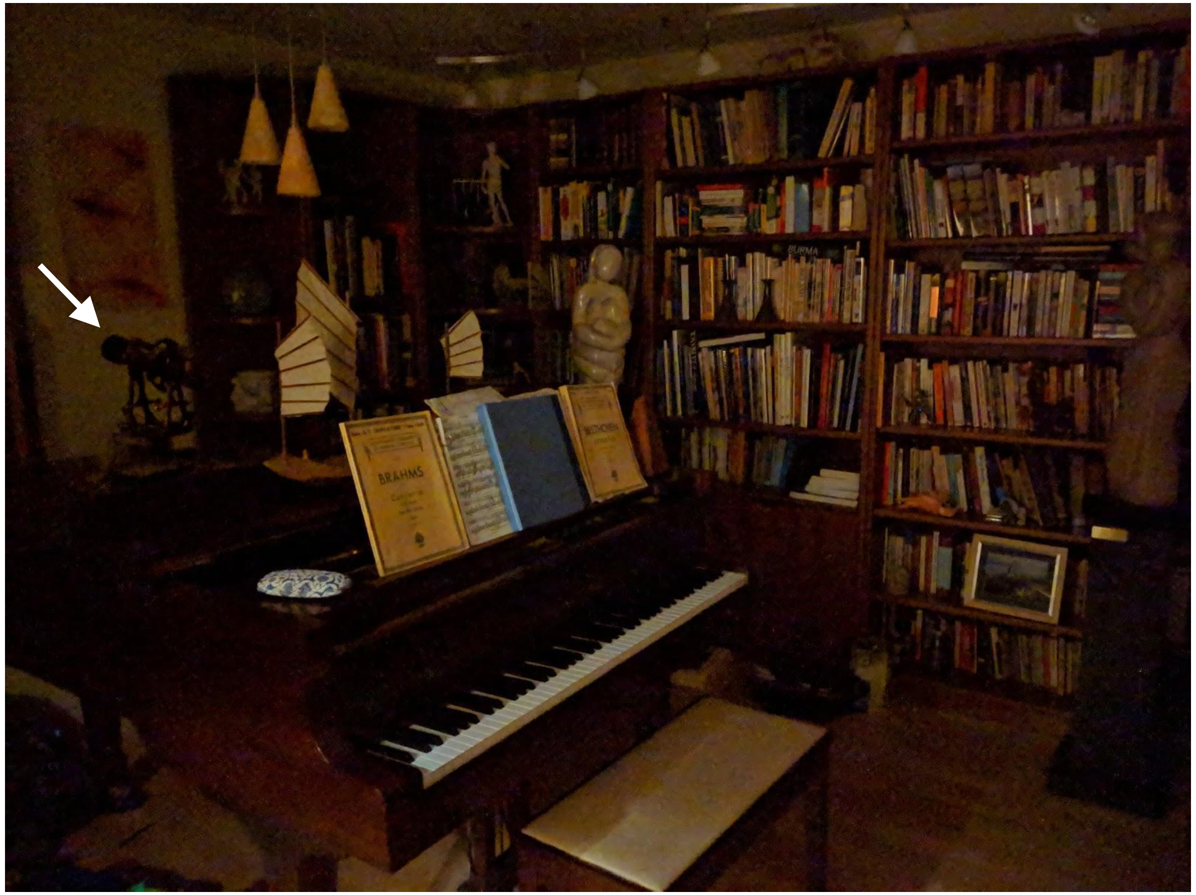
Burst photography

burst of short exposed frames

HDR+

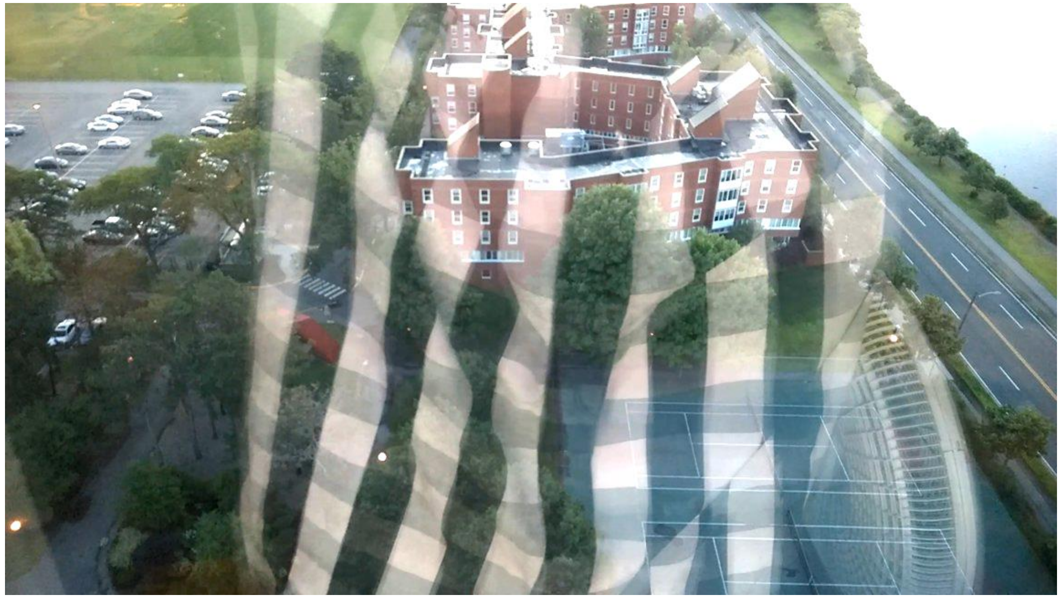
S. Hasinoff et al, "Burst photography for high dynamic range and low-light imaging on mobile cameras “, SIGGRAPH Asia 2016.

Night sight



O. Liba, et al., "Handheld Mobile Photography in Very Low Ligh“, SIGGRAPH Asia 2019.

Multiple captures also helps to remove reflection

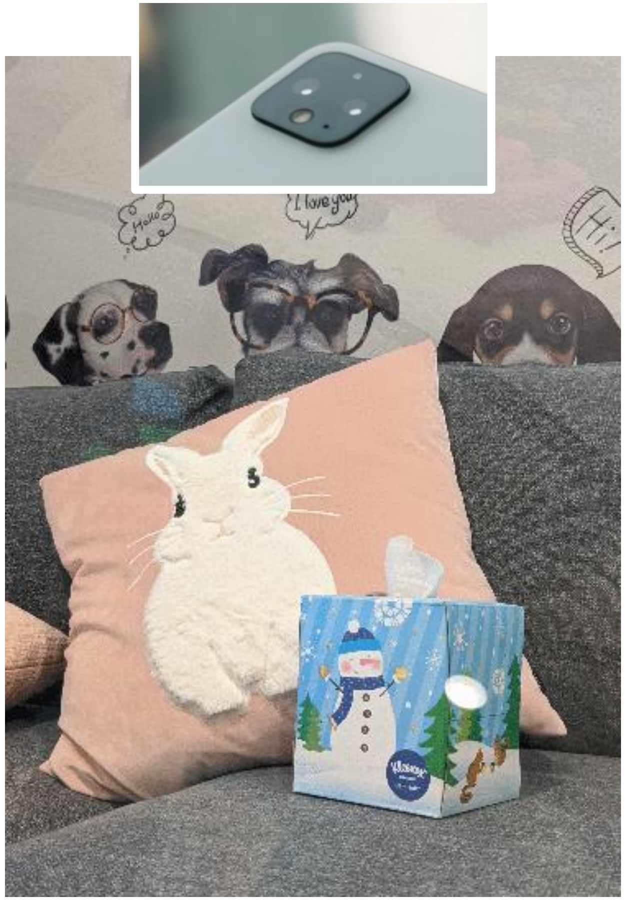


Images with reflection

Reflection-free image

T. Xue, et al., "A Computational Approach for Obstruction-Free Photography“, SIGGRAPH, 2015.

Reflection removal using stereo input

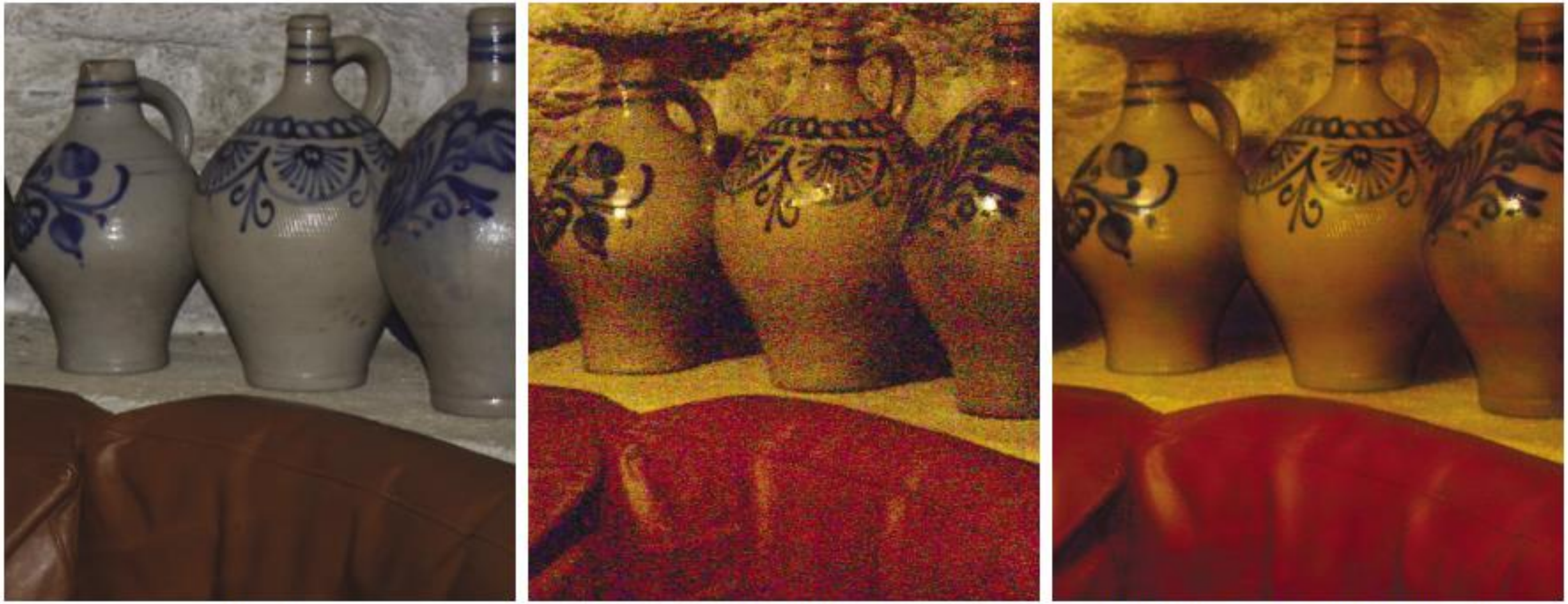


2 frames from stereo camera

Output

S. Niklaus et al., "Learned dual-view reflection removal“, WACV, 2021.

Flash / Non-flash Photography

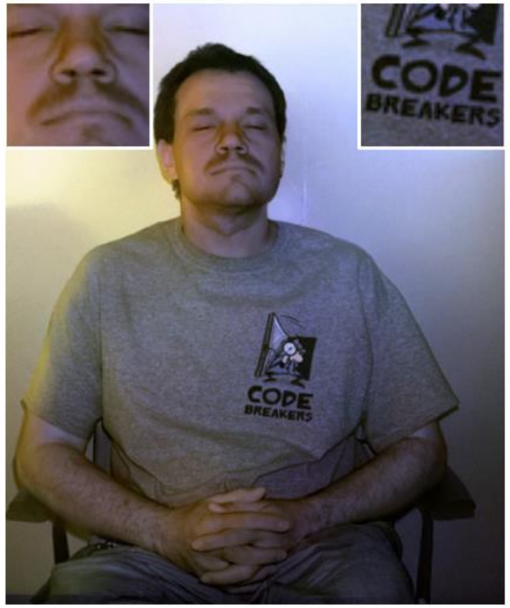


Flash　　　No-Flash　　　Detail Transfer with Denoising

G. Petschnigg et al., “Digital Photography with Flash and No-Flash Image Pairs”, SIGGRAPH 2004.

Stereoscopic Dark Flash for Low-light Photography

RGB IR (infrared)

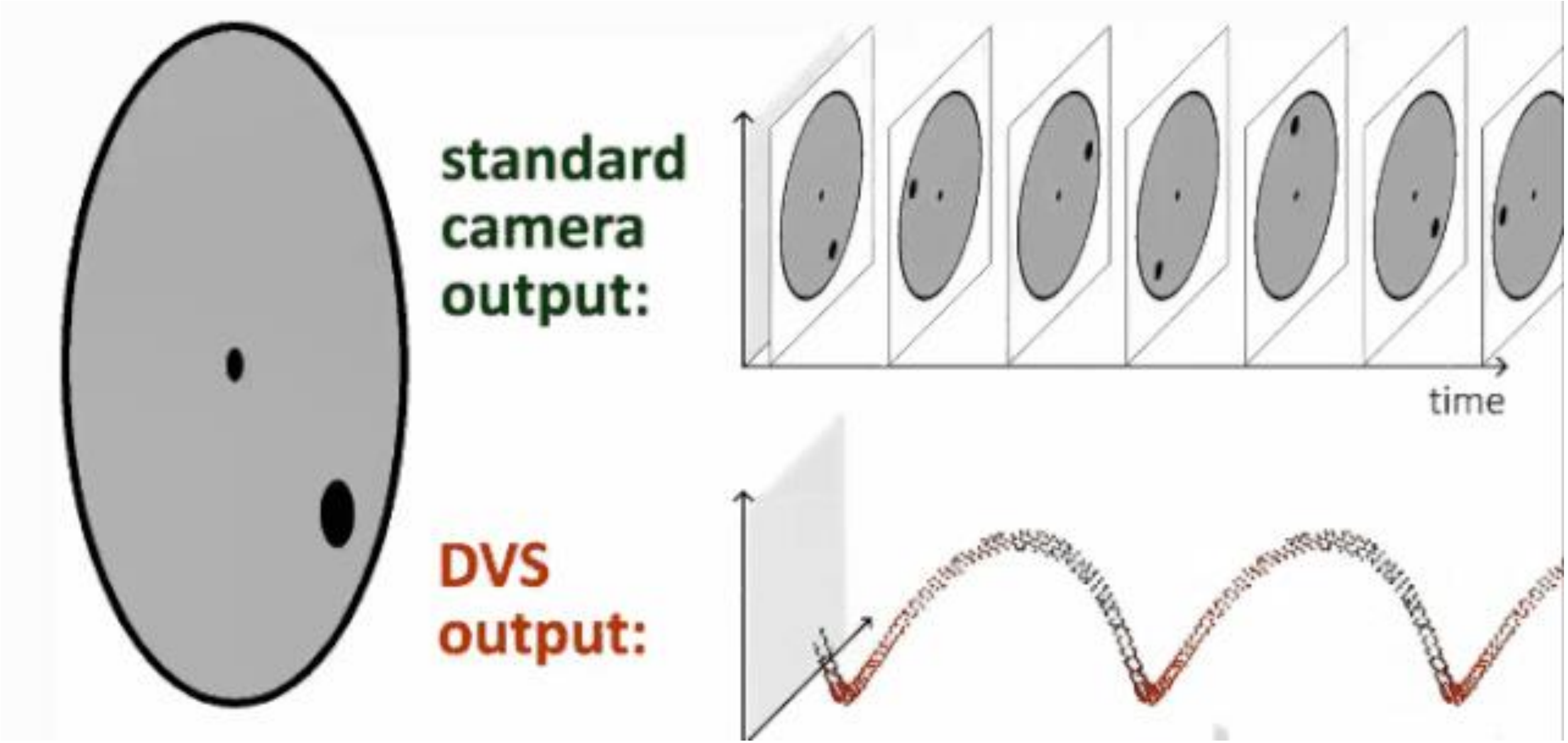


Merged result

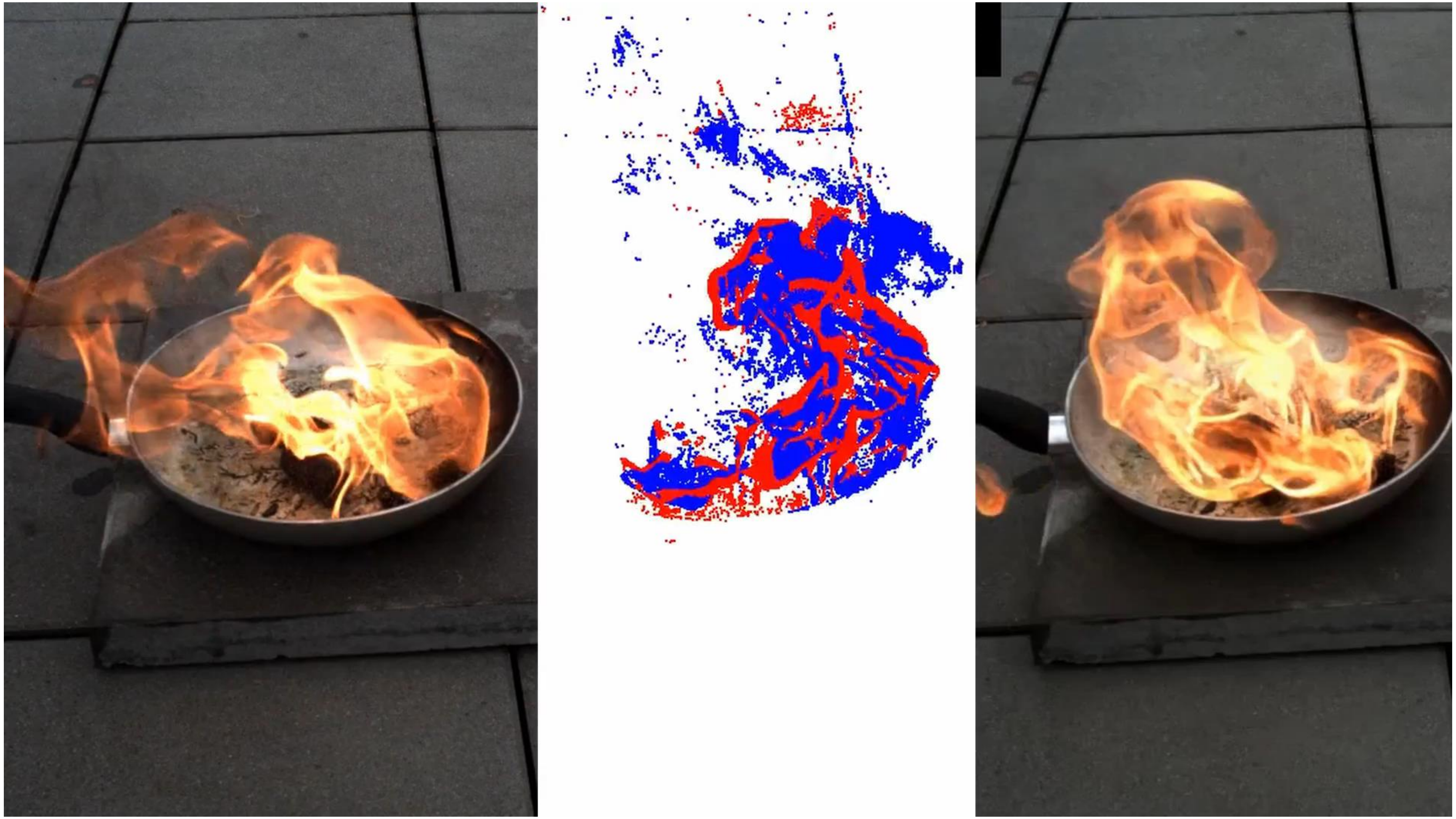
Jian Wang, Tianfan Xue, Jonathan T. Barron, Jiawen Chen

ICCP 2019

Event camera

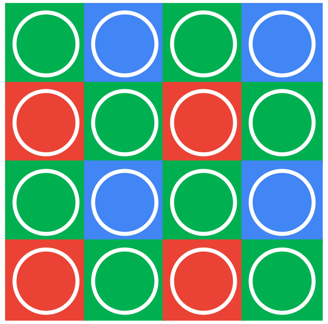


Use event camera to recover high-speed motion

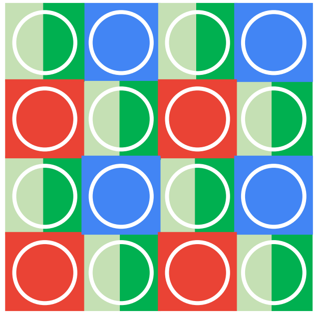


S. Tulyakov et al., “Time Lens: Event-based Video Frame Interpolation”, CVPR 2021.

Depth and debluring from DP images

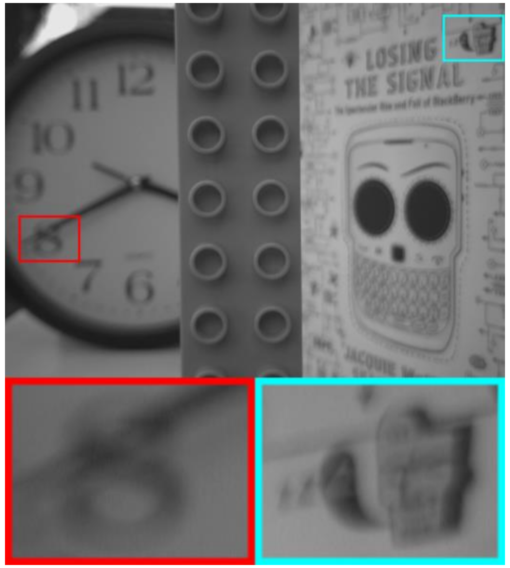


Regular sensor

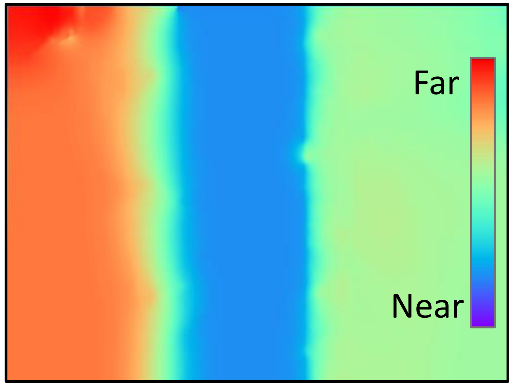


DP sensor

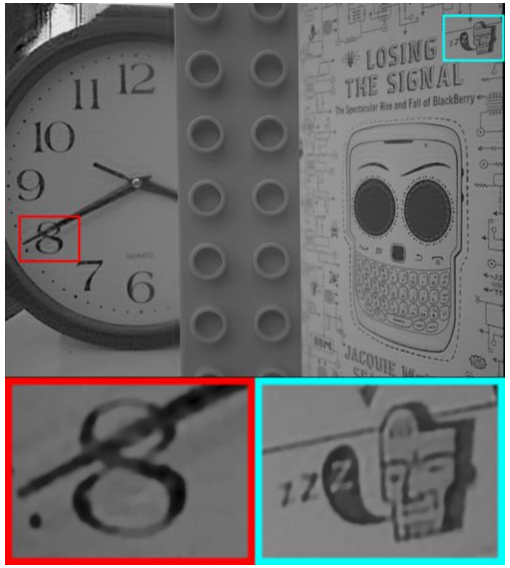
Input DP image



Depth map



All-in-focus image



Defocus Map Estimation and Deblurring from a Single Dual-Pixel Image

S. Xin, N. Wadhwa, T. Xue, J. T. Barron, P. P. Srinivasan, J. Chen, I. Gkioulekas, R. Garg

ICCV 2021

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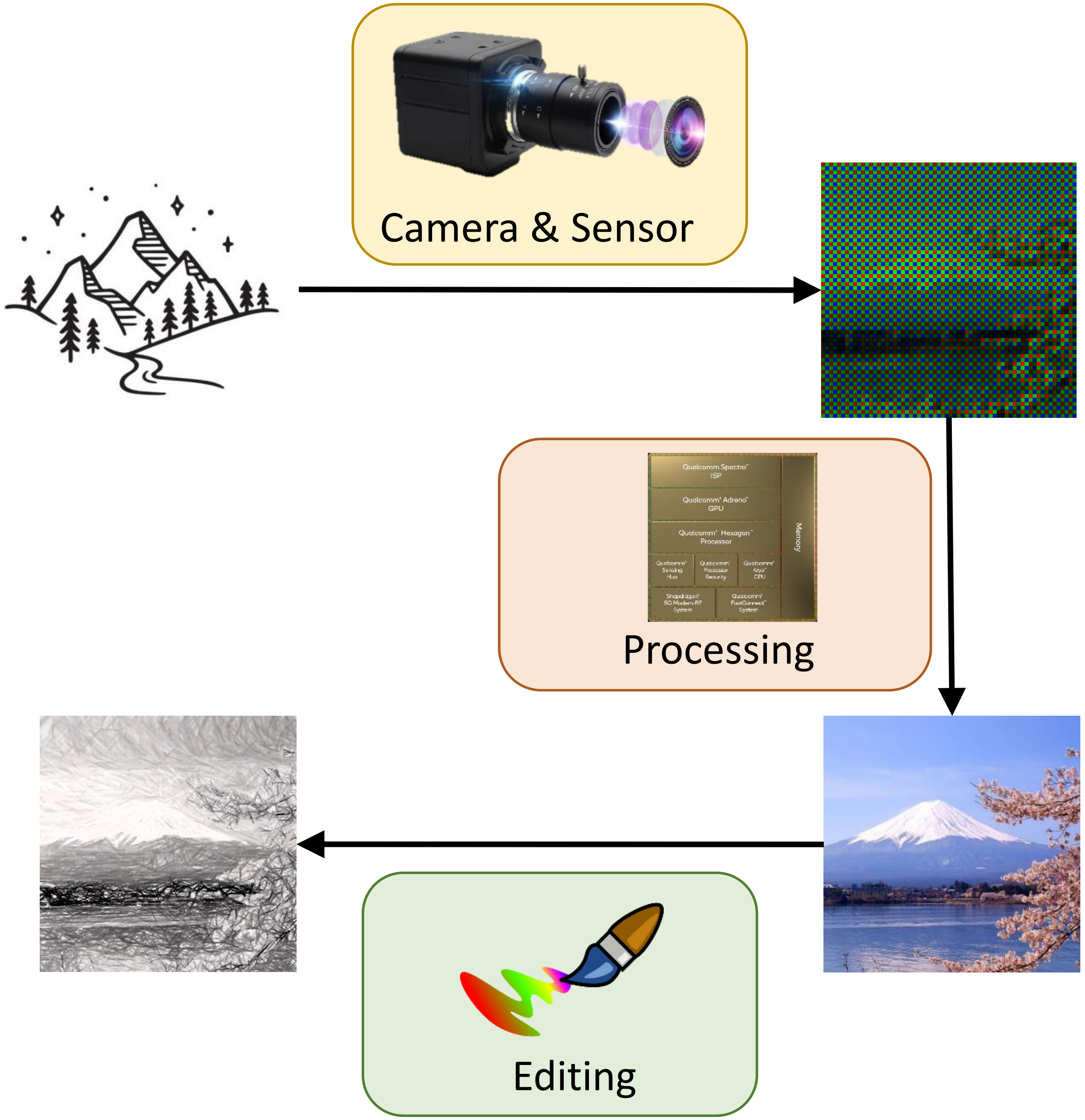
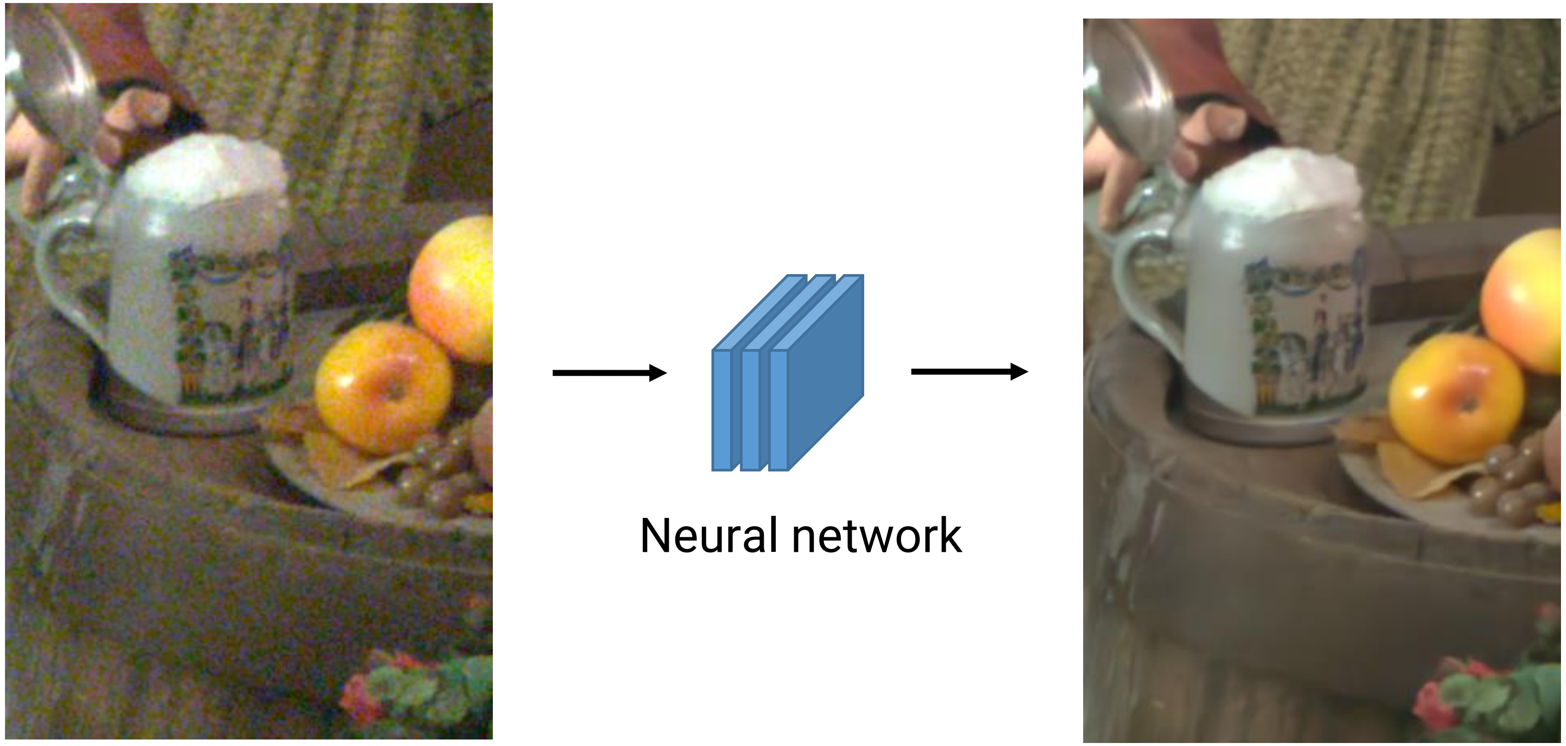


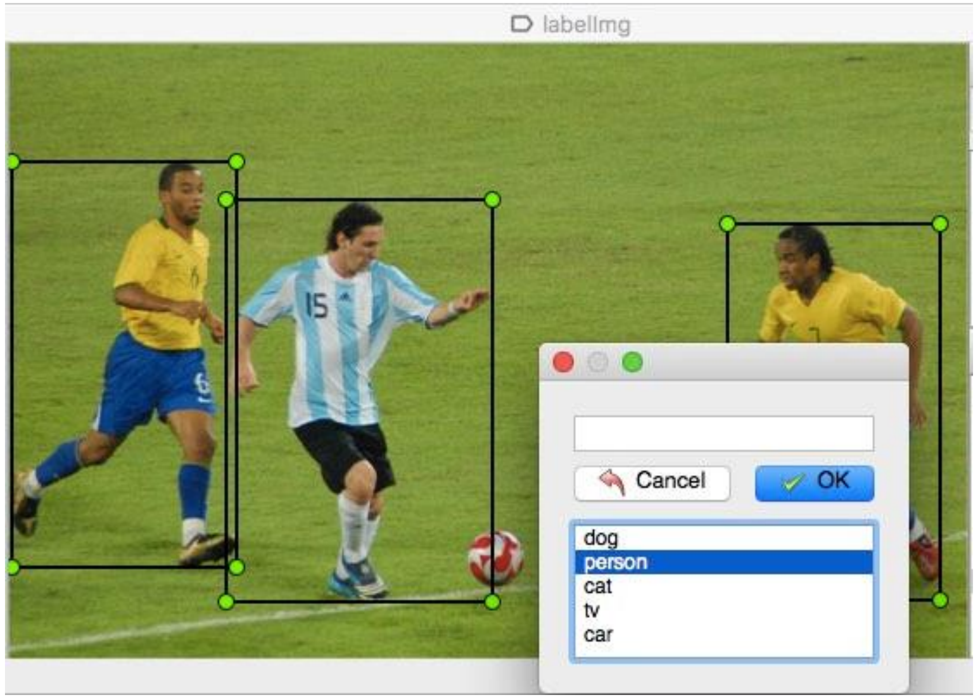
An input/output pair is needed for ML training



Noisy input

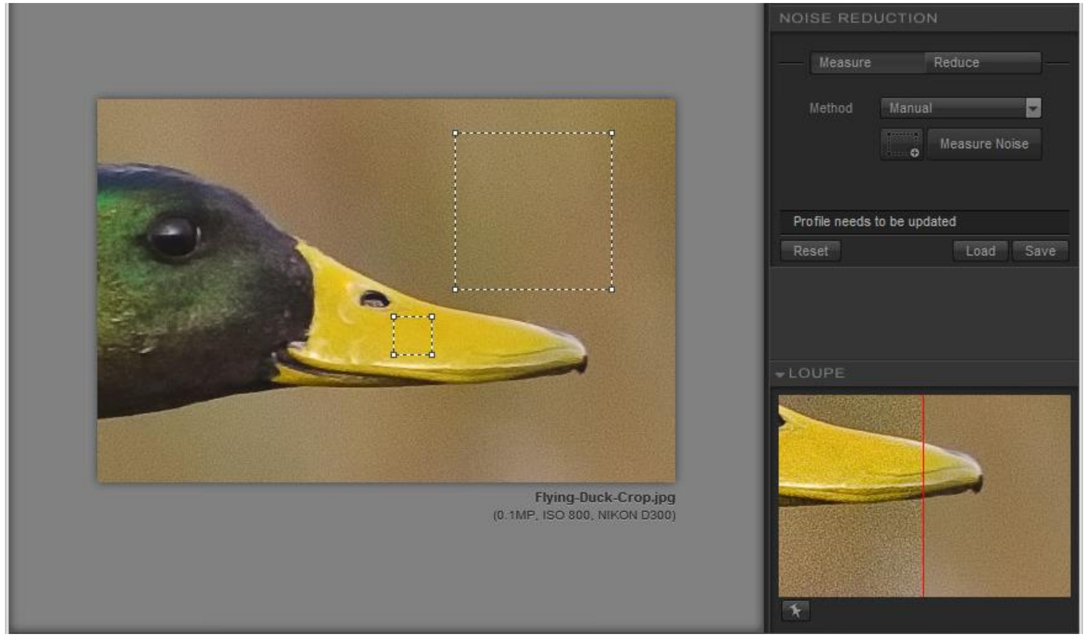
Denoised output

Ground truth output are hard to label



Labeling detection is easy.
few seconds / image

Image Credit: https://github.com/tzutalin/labelImg



Label denoising is hard:
few hours / image

Image Credit: Nik Collection

Capturing ground truth requires a lot of manual efforts

Collecting ground truth for denoising (<100/day)

Image Credit: [Chen et al. CVPR, 2018]

Devices differences

DSLR

Mobile camera

Webcam

List of Android smartphones

From Wikipedia, the free encyclopedia

This is a list of devices that run on the Android operating system.

This is a dynamic list and may never be able to satisfy particular standards for completeness. You can help by adding missing items with reliable sources.

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1077. ^ "Samsung Galaxy A40 - Full phone specifications". *GSMArena*.
1078. ^ "Samsung Galaxy A2 Core - Full phone specifications". *GSMArena*.
1079. ^ "Samsung Galaxy A20e - Full phone specifications". *GSMArena*.
1080. ^ "Samsung Galaxy A70 - Full phone specifications". *GSMArena*.
1081. ^ "Samsung Galaxy A80 - Full phone specifications". *GSMArena*.
1082. ^ "Samsung Galaxy A60 - Full phone specifications". *GSMArena*.
1083. ^ "Samsung Galaxy Xcover 4s - Full phone specifications". *GSMArena*.
1084. ^ "Samsung Galaxy A10e - Full phone specifications". *GSMArena*.
1085. ^ "Samsung Galaxy Note10 - Full phone specifications". *GSMArena*.
1086. ^ "Samsung Galaxy Note10+ - Full phone specifications". *GSMArena*.
1087. ^ "Samsung Galaxy A10s - Full phone specifications". *GSMArena*.
1088. ^ "Samsung Galaxy A30s - Full phone specifications". *GSMArena*.
1089. ^ "Samsung Galaxy A50s - Full phone specifications". *GSMArena*.
1090. ^ "Samsung Galaxy A90 5G - Full phone specifications". *GSMArena*.

1317. ^ "Xiaomi Mi Max - Full phone specifications". *GSMArena*.
1318. ^ "Xiaomi Mi 5s - Full phone specifications". *GSMArena*. Retrieved 2020-06-06.
1319. ^ "Xiaomi Mi 5s Plus - Full phone specifications". *GSMArena*. Retrieved 2020-06-06.
1320. ^ "Xiaomi Mi Note 2 - Full phone specifications". *GSMArena*.
1321. ^ "Xiaomi Mi Mix - Full phone specifications". *GSMArena*. Retrieved 2020-06-06.
1322. ^ "Xiaomi Mi 5c - Full phone specifications". *GSMArena*. Retrieved 2020-06-06.
1323. ^ "Xiaomi Mi 6 - Full phone specifications". *GSMArena*. Retrieved 2020-06-06.
1324. ^ "Xiaomi Mi Max 2 - Full phone specifications". *GSMArena*.
1325. ^ "Xiaomi Mi A1 (Mi 5X) - Full phone specifications". *GSMArena*. Retrieved 2020-06-06.
1326. ^ "Xiaomi Mi Note 3 - Full phone specifications". *GSMArena*.
1327. ^ "Xiaomi Mi Mix 2 - Full phone specifications". *GSMArena*. Retrieved 2020-06-06.
1328. ^ "Xiaomi Mi Mix 2S - Full phone specifications". *GSMArena*. Retrieved 2020-06-06.
1329. ^ "Xiaomi Mi A2 (Mi 6X) - Full phone specifications". *GSMArena*. Retrieved 2020-06-06.
1330. ^ "Xiaomi Black Shark - Full phone specifications". *GSMArena*.
1331. ^ "Xiaomi Mi 8 - Full phone specifications". *GSMArena*. Retrieved 2020-06-06.
1332. ^ "Xiaomi Mi 8 SE - Full phone specifications". *GSMArena*. Retrieved 2020-06-06.
1333. ^ "Xiaomi Mi 8 Explorer - Full phone specifications". *GSMArena*. Retrieved 2020-06-06.
1334. ^ "Xiaomi Mi Max 3 - Full phone specifications". *GSMArena*.
1335. ^ "Complete Specs". *GSMArena*. Retrieved 2020-06-30.
1336. ^ "Xiaomi Mi 8 Pro - Full phone specifications". *GSMArena*. Retrieved 2020-06-06.
1337. ^ "Xiaomi Mi 8 Lite - Full phone specifications". *GSMArena*. Retrieved 2020-06-06.
1338. ^ "Xiaomi Mi Mix 3 - Full phone specifications". *GSMArena*. Retrieved 2020-06-06.
1339. ^ "Complete Specs". *GSMArena*. Retrieved 2020-06-30.
1340. ^ "Complete Specs". *GSMArena*. Retrieved 2020-06-30.
1341. ^ "Xiaomi Mi 9 - Full phone specifications". *GSMArena*. Retrieved 2020-06-06.
1342. ^ "Xiaomi Mi 9 SE - Full phone specifications". *GSMArena*. Retrieved 2020-06-06.
1343. ^ "Complete Specs". *GSMArena*. Retrieved 2020-06-30.
1344. ^ "Xiaomi Mi Mix 3 5G - Full phone specifications". *GSMArena*. Retrieved 2020-06-06.
1345. ^ "Xiaomi Mi 9T - Full phone specifications". *GSMArena*. Retrieved 2020-06-06.
1346. ^ "Xiaomi Mi A3 - Full phone specifications". *GSMArena*. Retrieved 2020-09-04.
1347. ^ "Xiaomi Mi 9T Pro - Full phone specifications". *GSMArena*. Retrieved 2020-06-06.
1348. ^ "Complete Specs". *GSMArena*. Retrieved 2020-06-30.

Can we use images on the web

<100 images / day

No. of images uploaded to internet:
3,000,000,000,000 images / day

by Leon Seibert, Unsplash

Apply degeneration to images on the web

Input/output pairs

Clean images from web

Synthesize degeneration

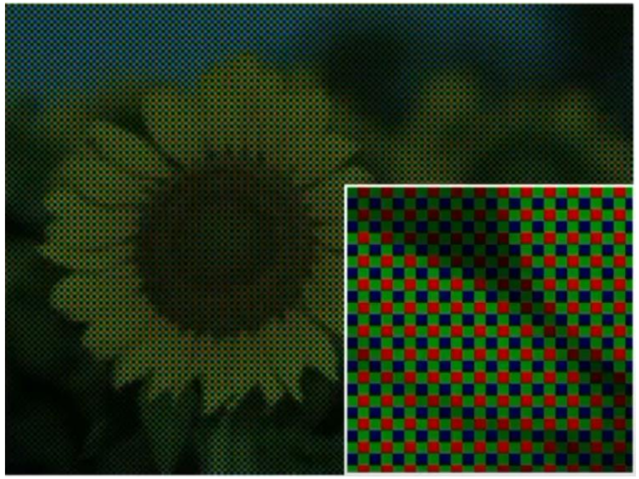
Degenerated images

Processing network

Recovered clean image

How to generate realistic degeneration?

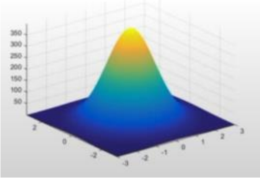
Real noise does not directly apply to sRGB



Raw image

Camera pipeline

sRGB image

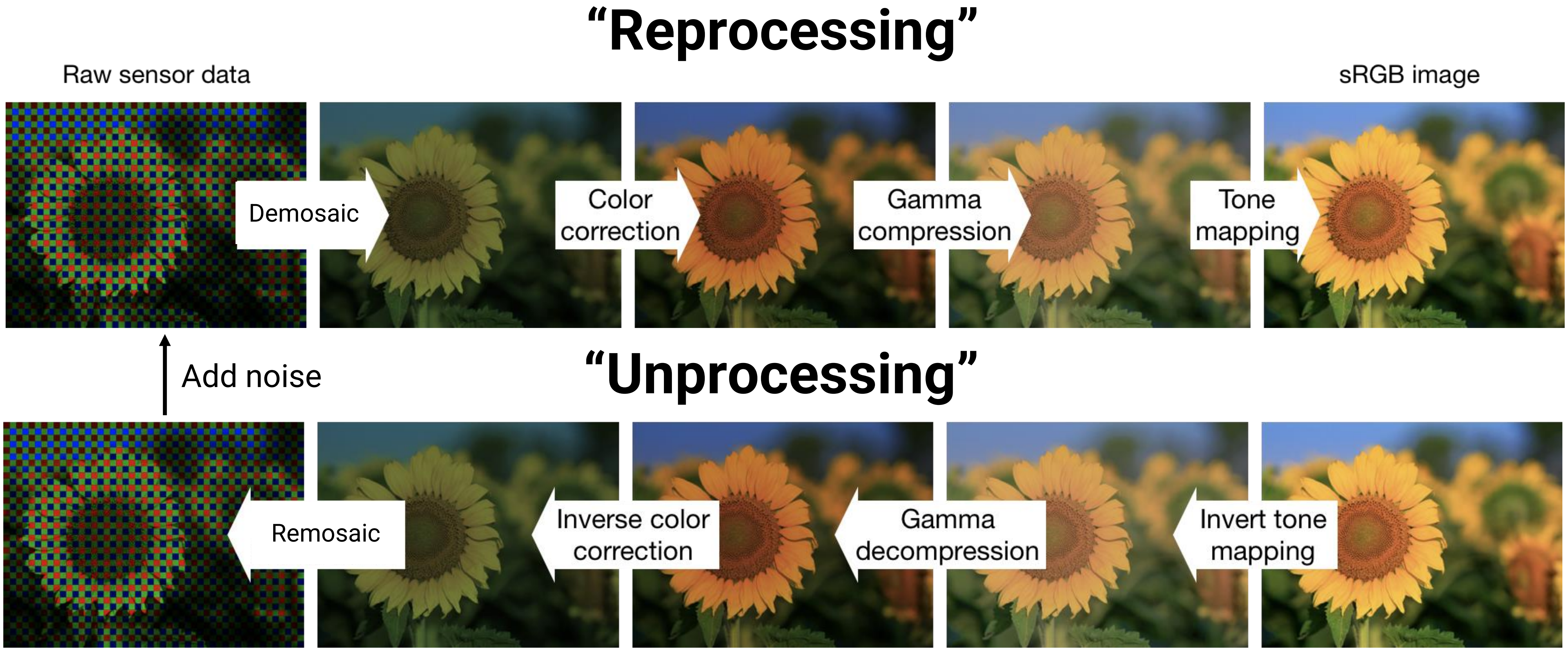


Noise

$$y \sim \mathcal{N}(\mu = x, \sigma^2 = \lambda_{read} + \lambda_{shot} x)$$

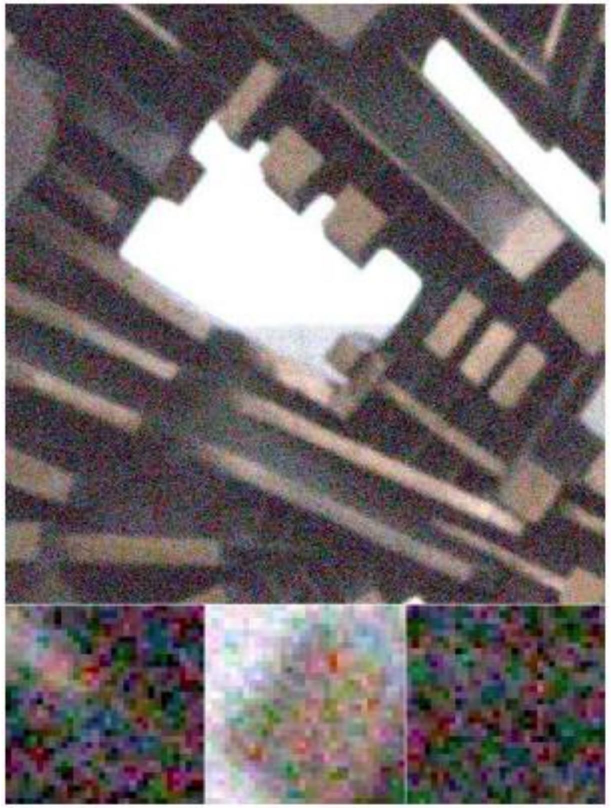
Noise model

Synthesize raw from sRGB

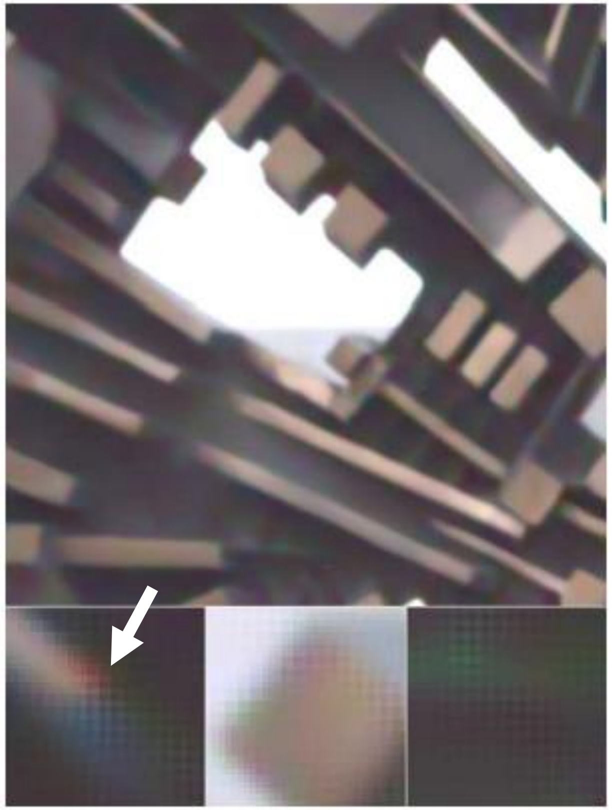


T. Brooks, B. Mildenhall, **T. Xue**, J. Chen, D. Sharlet, J. T. Barron, "Unprocessing images for learned raw denoising", CVPR, 2019

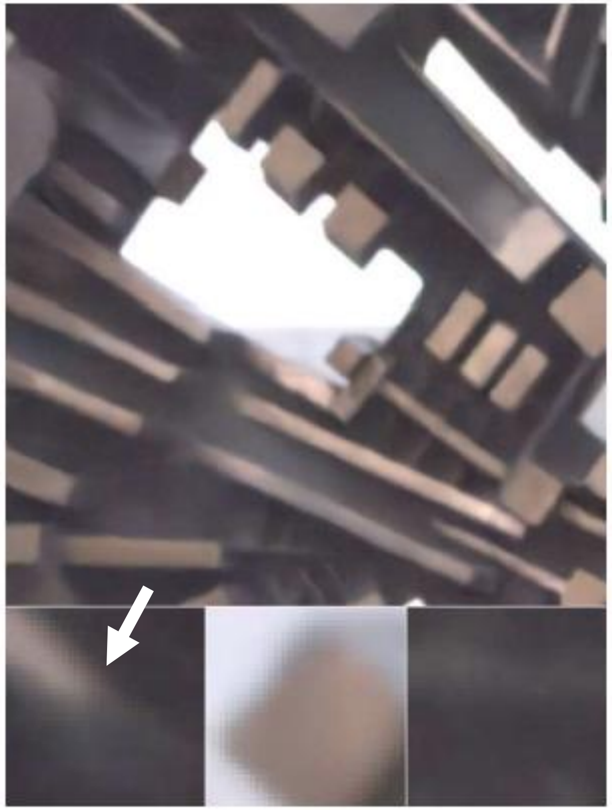
Unprocess improves the image quality



Noisy input

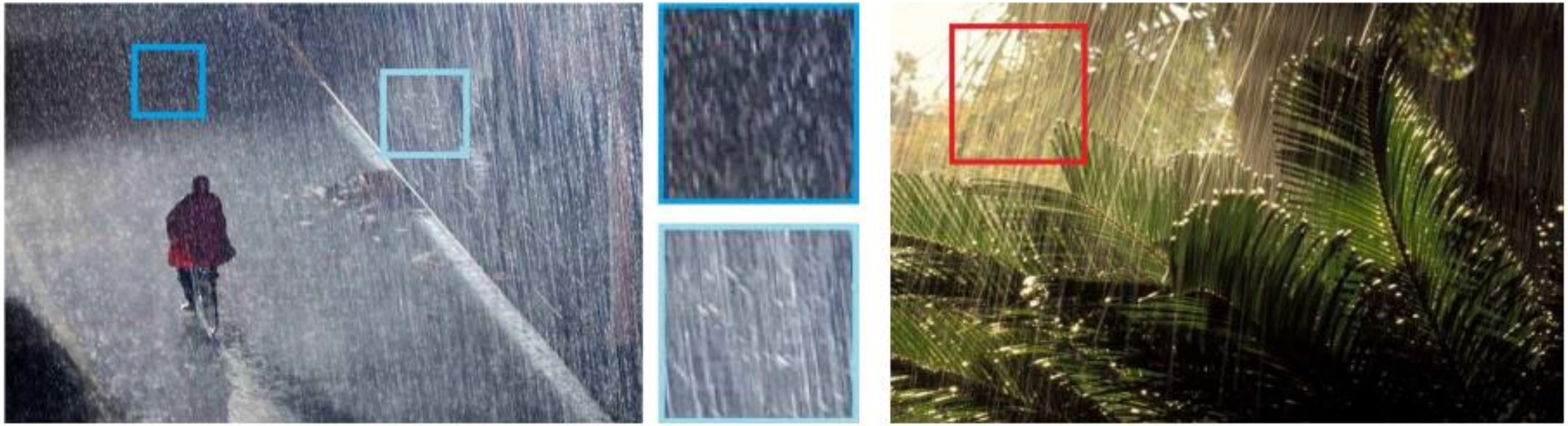


N3Net



Ours

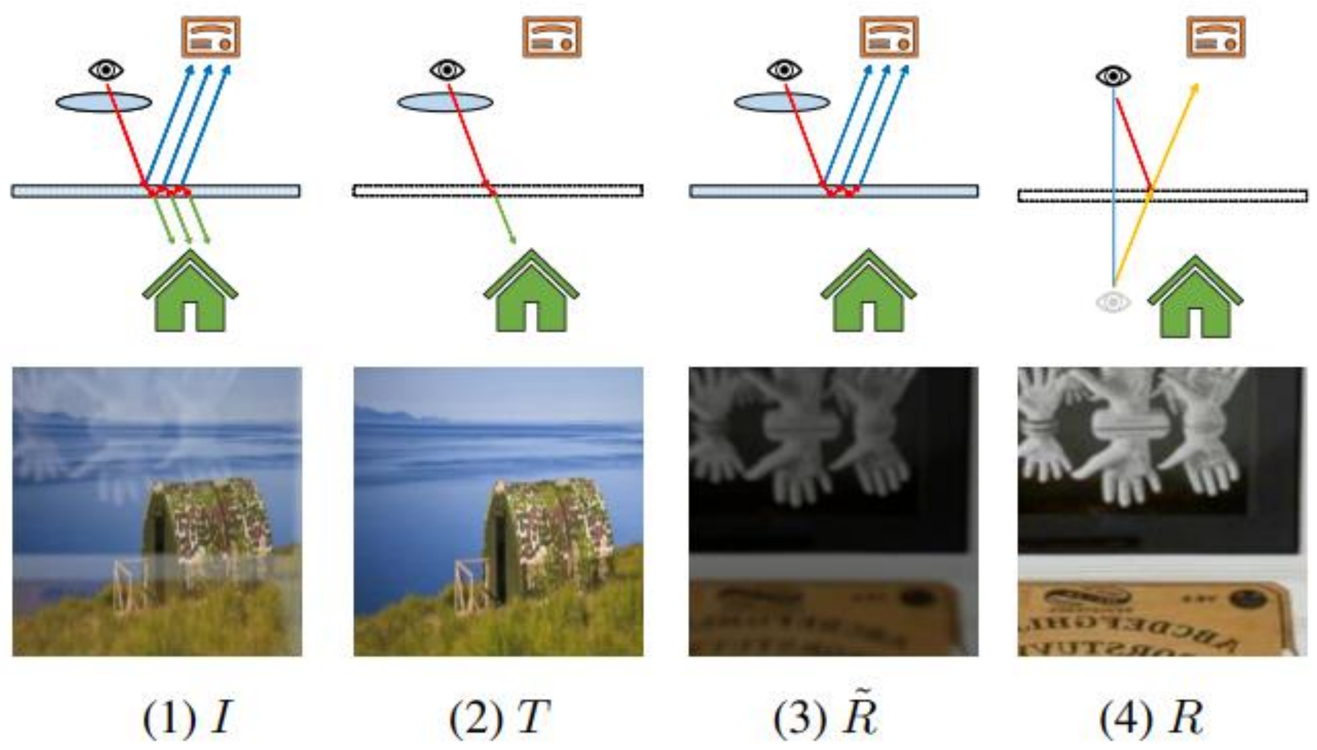
Simulate realistic rain drops

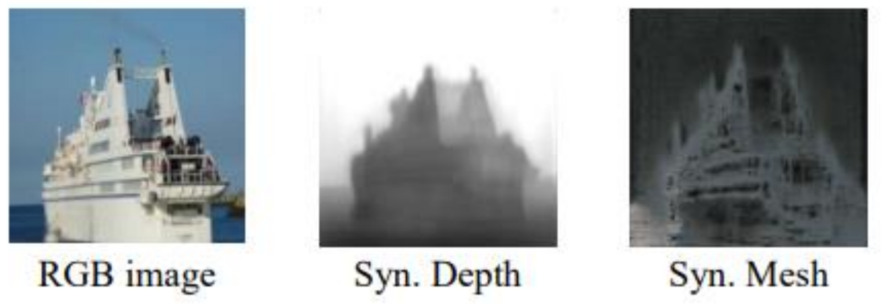


(a) Heavy rain. (b) Rain accumulation.

Yang et al., “Deep Joint Rain Detection and Removal from a Single Image”, 2017

Sometimes, it is important to understand 3D geometry in the simulation





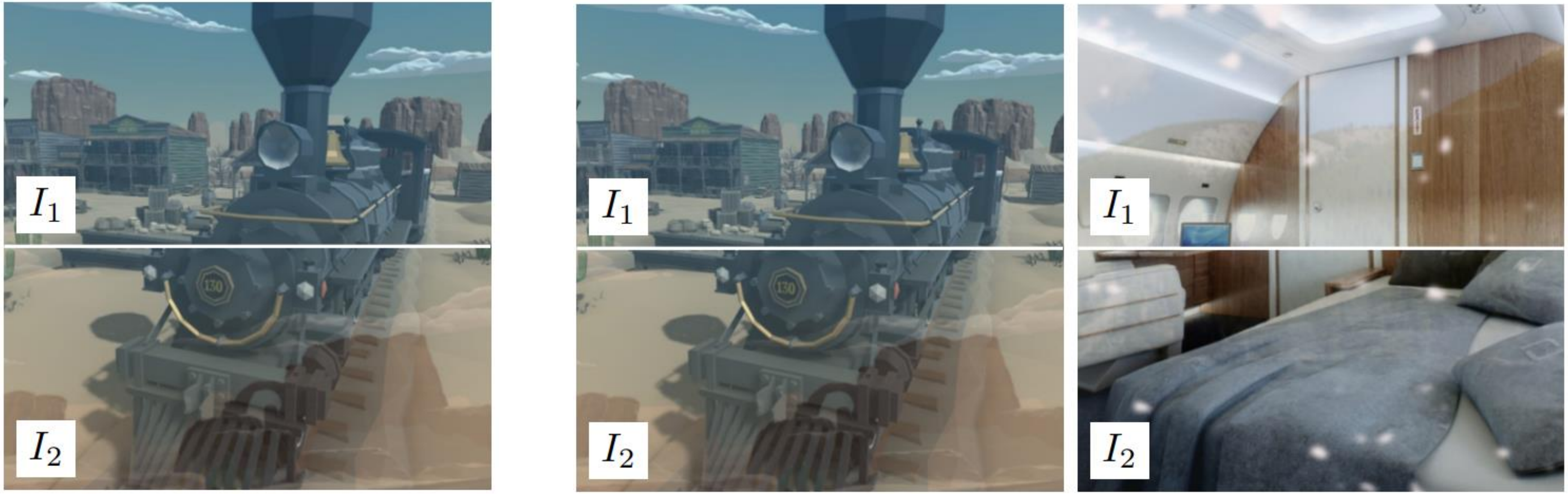
Symbol	Definition
T	Front scene image
R	Back scene image
$\tilde{R}$	Back scene image reflected by a glass
X^*	Predicted image of X
T/R	T or R

Kim et al., "Single Image Reflection Removal with Physically-Based Training Images", CVPR 2020

We can even resort to rendering engine

S. Niklaus et al., "Learned dual-view reflection removal“, WACV, 2021.

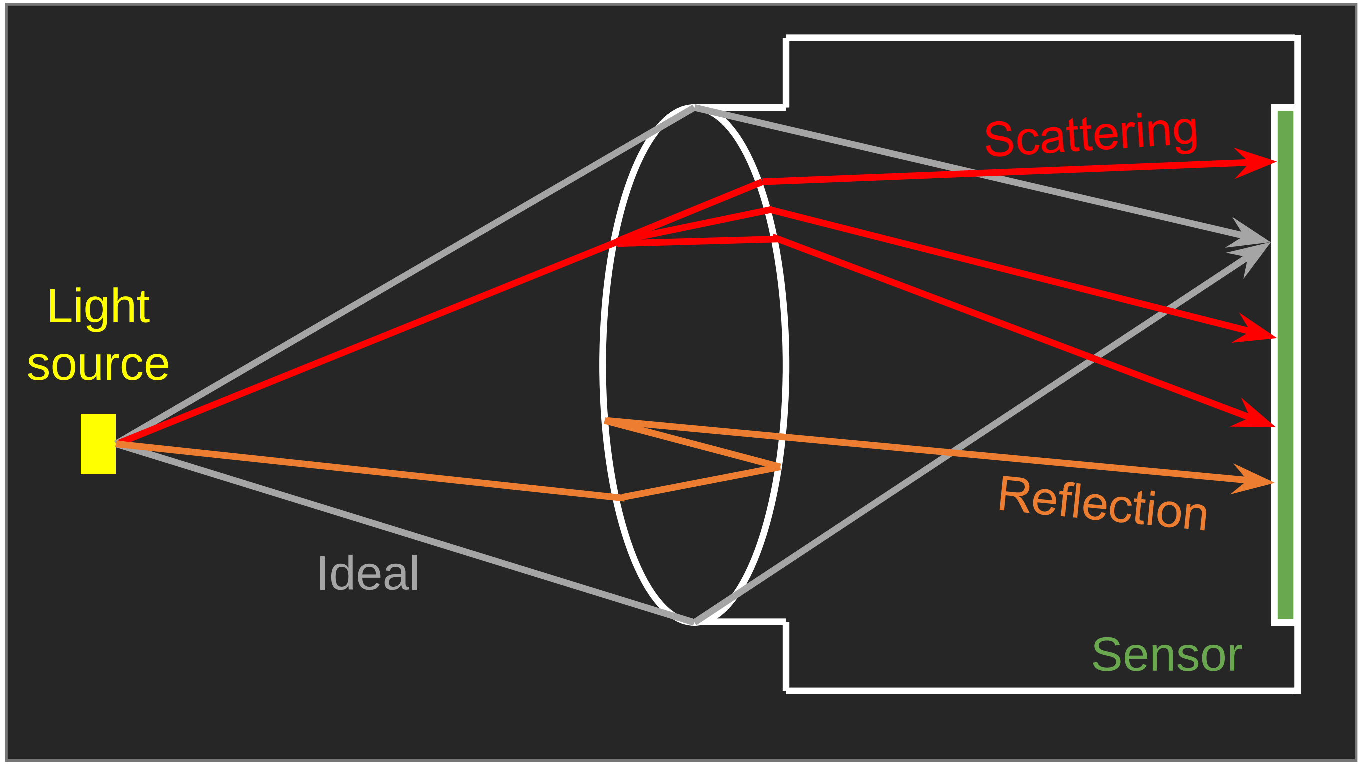
We can even resort to rendering engine



S. Niklaus et al., "Learned dual-view reflection removal“, WACV, 2021.

Lens flare

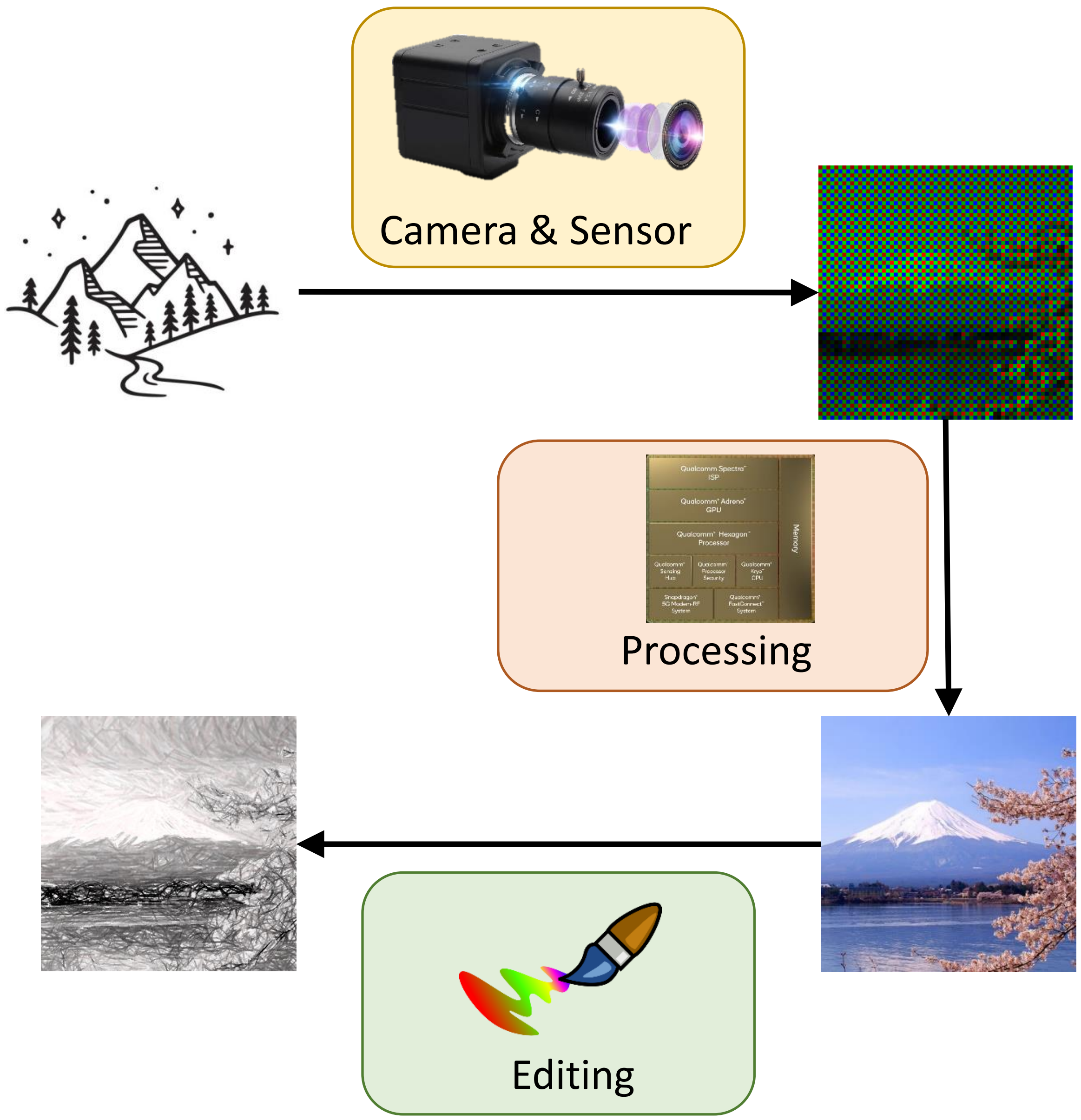
Flare formation



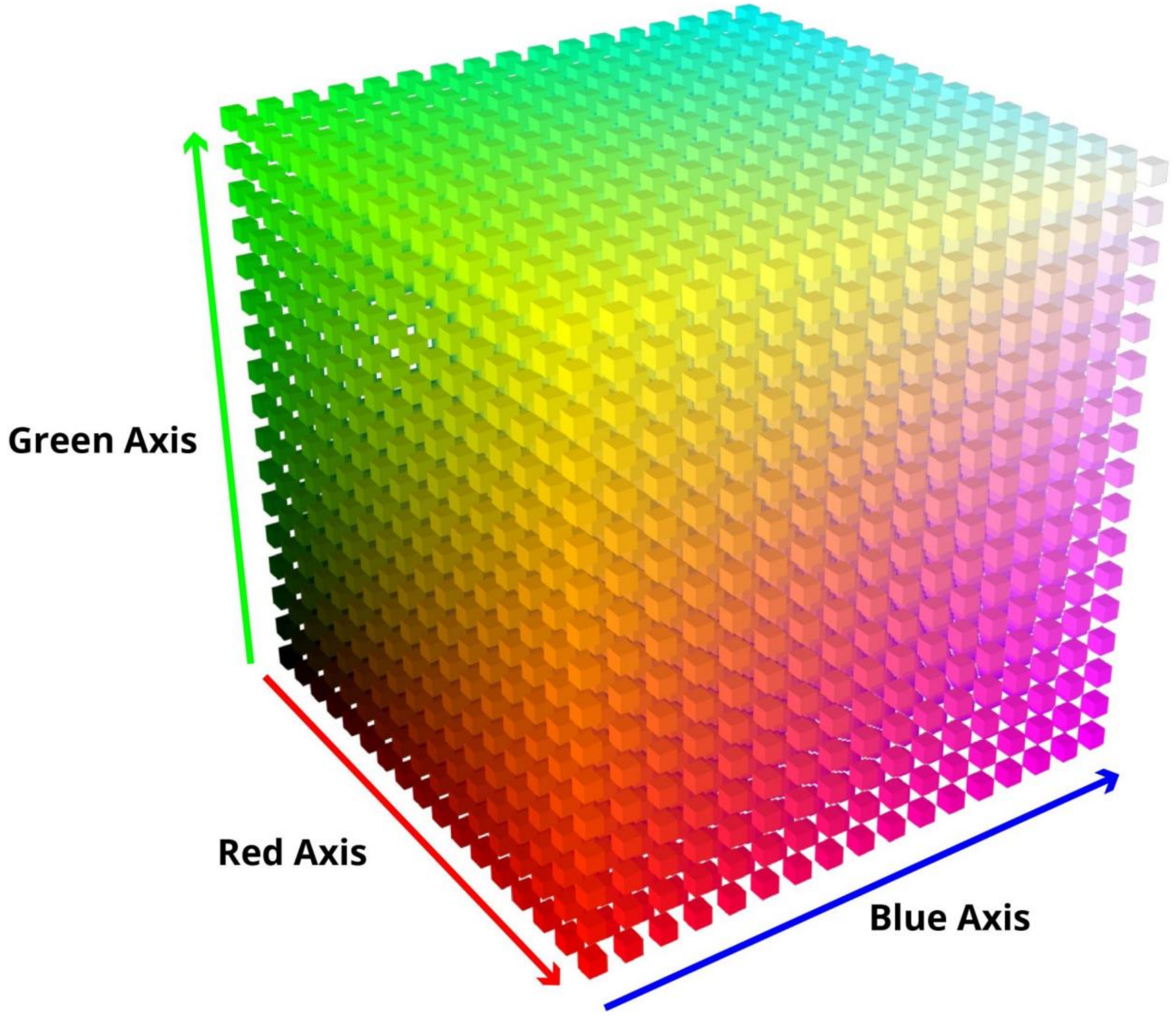
Wu et al,. “How to Train Neural Networks for Flare Removal”, ICCV 2021

Overview

- **Capturing**: multiple source fusion
- **Processing & editing**
  - **Training data:** synthetic data
  - **Network**: combine classic image processing algorithm and machine learning

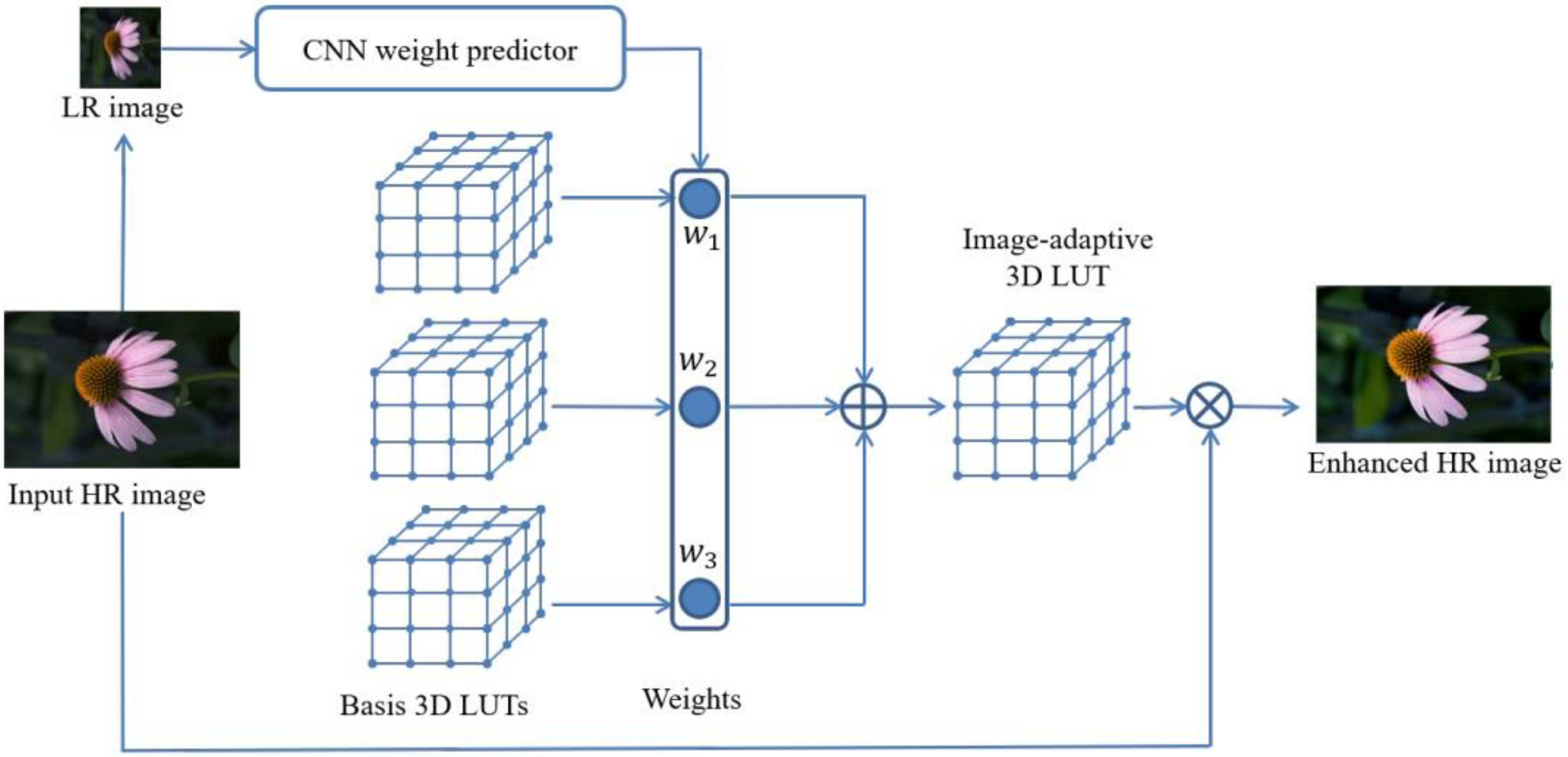


Representing point operation: 3D LUT



https://www.bromptontech.com/what-is-a-3d-lut/

Learning to enhance -> Learning 3D LUT

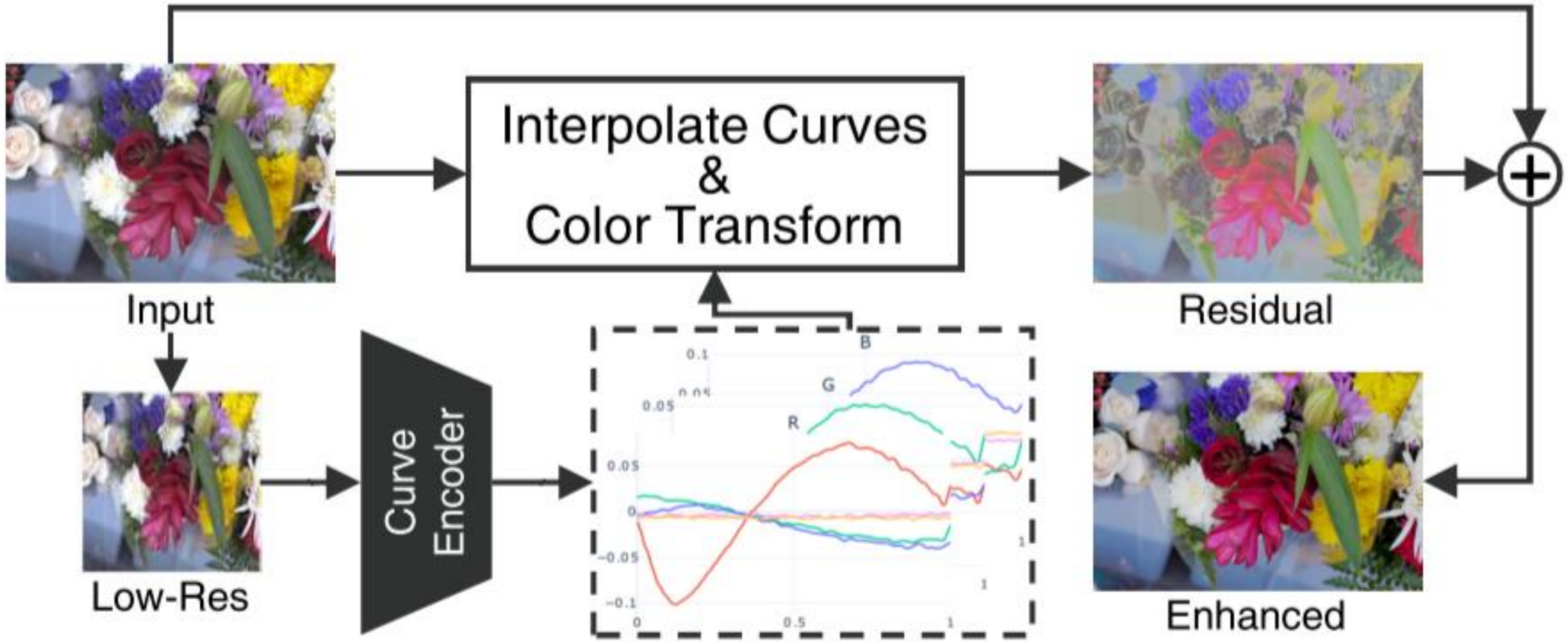


H. Zeng et al., "Learning Image-adaptive 3D Lookup Tables for High Performance Photo Enhancement in Real-time", T-PAMI, 2020

Learning 3D LUT significantly reduces the time cost

Resolution	1920×1080	3840×2160	6000×4000
Pix2Pix [49]	1.2e2	N.A.	N.A.
CycGAN [50]	5.6e2	N.A.	N.A.
DPE [7]	8.6e1	N.A.	N.A.
White-Box [9]	5.0e3	9.1e3	2.0e4
Dis-Rec [8]	2.5e4	1.1e5	3.3e5
UIE [11]	1.0e4	2.0e4	3.3e4
HDRNet [2]	4.5e1	2.1e2	5.9e2
UPE [10]	4.5e1	2.1e2	5.9e2
Ours	**0.64**	**1.66**	**3.76**

Image Enhancement: Using color tran. and global curve



Song et al, “StarEnhancer: Learning Real-Time and Style-Aware Image Enhancement”, ICCV 2021

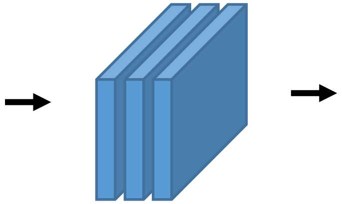
Direct prediction is expensive

[PhotoWCT: Li et al., ECCV 2018]
[WCT2: Yoo et al., ICCV 2019]
[LST: Li et al., CVPR 2019]

All of them are OOM when applied to 4MP image

Style image

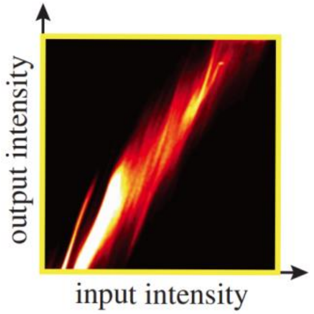
Input



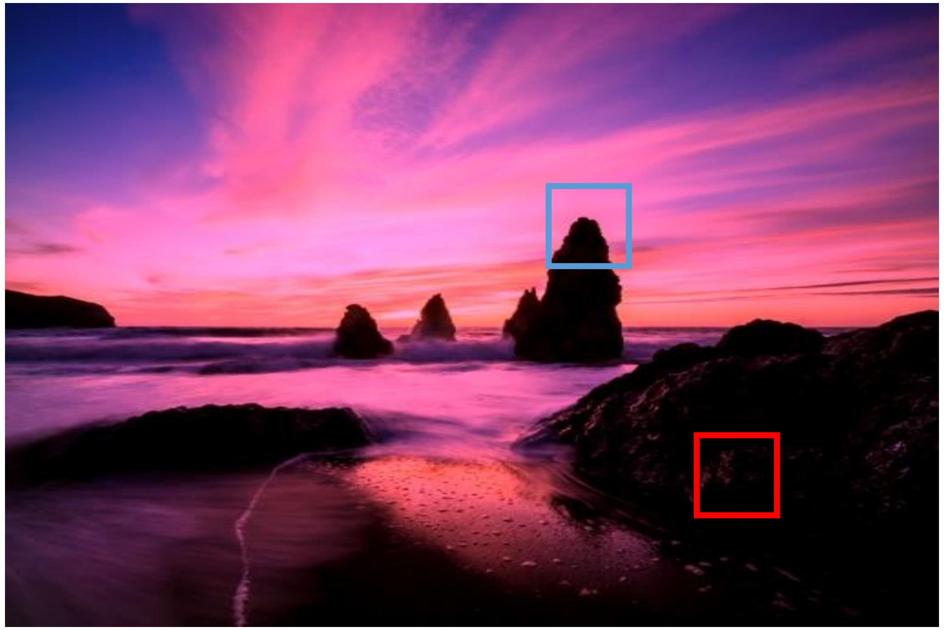
Neural network

Stylized output

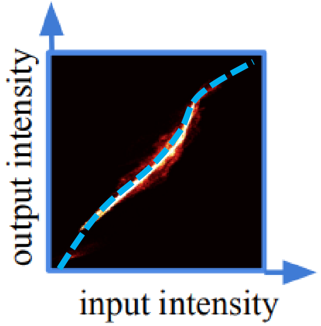
Can we approximate it using tone curves?

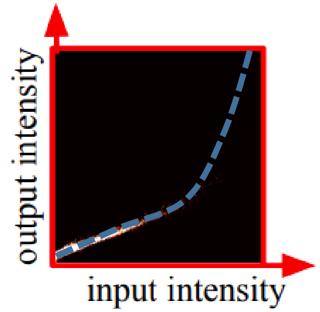


Input

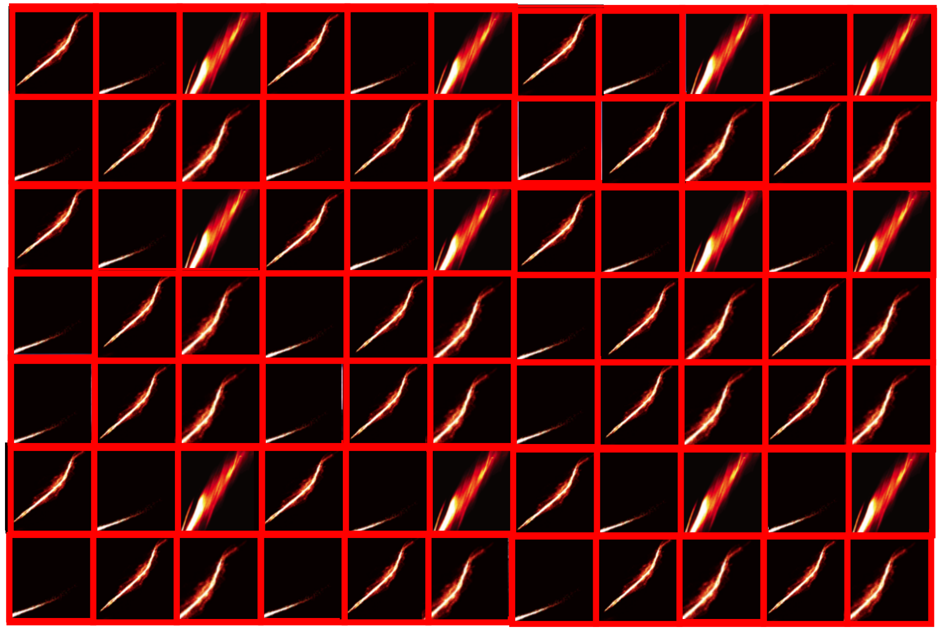


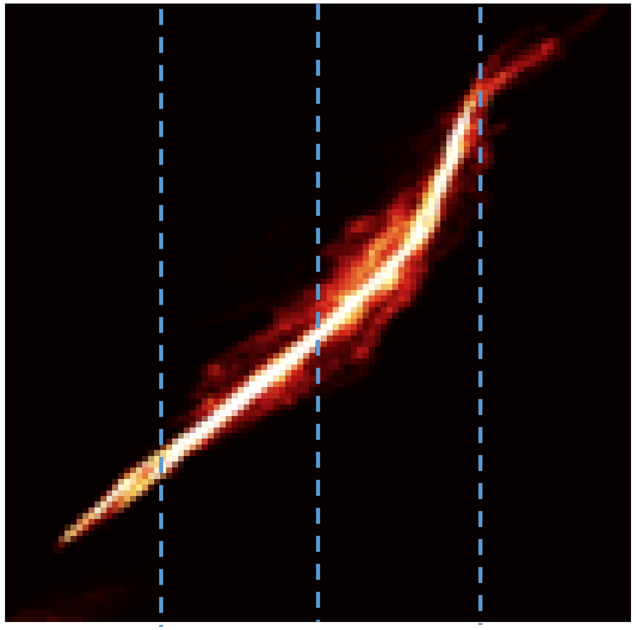
Stylized output

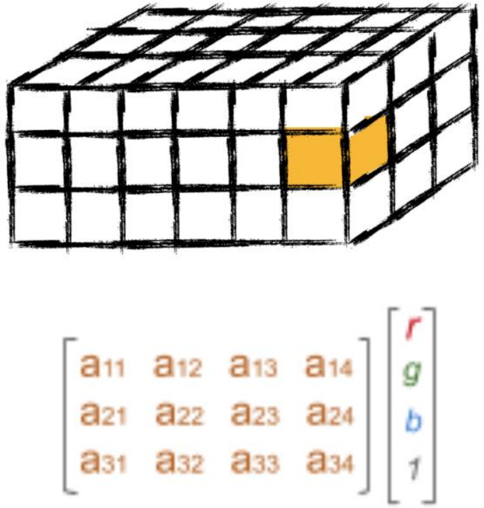




Model a set of tone curves as bilateral grid



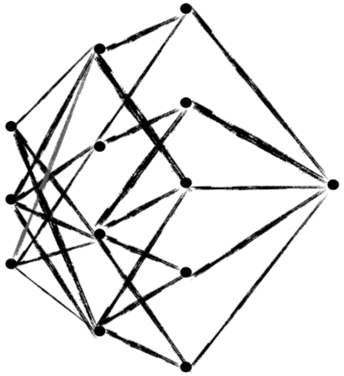


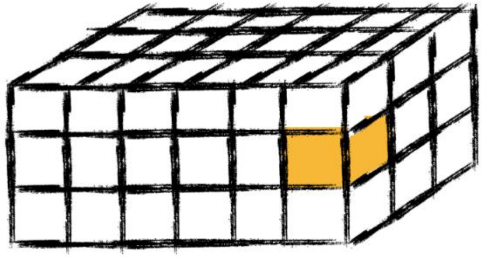


Bilateral grid

J. Chen, A. Adams, N. Wadhwa, S. Hasinoff, “Bilateral guided upsampling”, 2017
M. Gharbi, J. Chen, J. Barron, S. Hasinoff, F. Durand, “ Deep Bilateral Learning for Real-Time Image Enhancement”, SIGGRAPH 2017

Style transfer using a set of tone curves





$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \end{bmatrix} \begin{bmatrix} r \\ g \\ b \\ 1 \end{bmatrix}$$

Tone curves baked in bilateral grid

Low resolution: 256x256

Full resolution: 4Kx3K

Output

Apply

Input

X. Xia, M. Zhang, **T. Xue**, Z. Sun, H. Fang, B. Kulis, J. Chen, "Joint bilateral learning for real-time universal photorealistic style transfer", ECCV 2020

Performance

Image Size	PhotoWCT	LST	WCT^2	**Ours**
512×512	0.68s	0.25s	3.85s	**$<$ 5 ms**
1024×1024	1.51s	0.84s	6.13s	**$<$ 5 ms**
1000×2000	2.75s	OOM	10.94s	**$<$ 5 ms**
2000×2000	OOM	OOM	OOM	**$<$ 5 ms**
3000×4000	OOM	OOM	OOM	**$<$ 5 ms**

Latency

Mean Score	PhotoWCT	LST	WCT^2	**Ours**
Photorealism	2.02	2.89	**4.21**	4.14
Stylization	3.10	3.19	3.24	**3.49**
Overall quality	2.23	2.84	3.60	**3.79**

User study of visual quality


H&M
MACYS

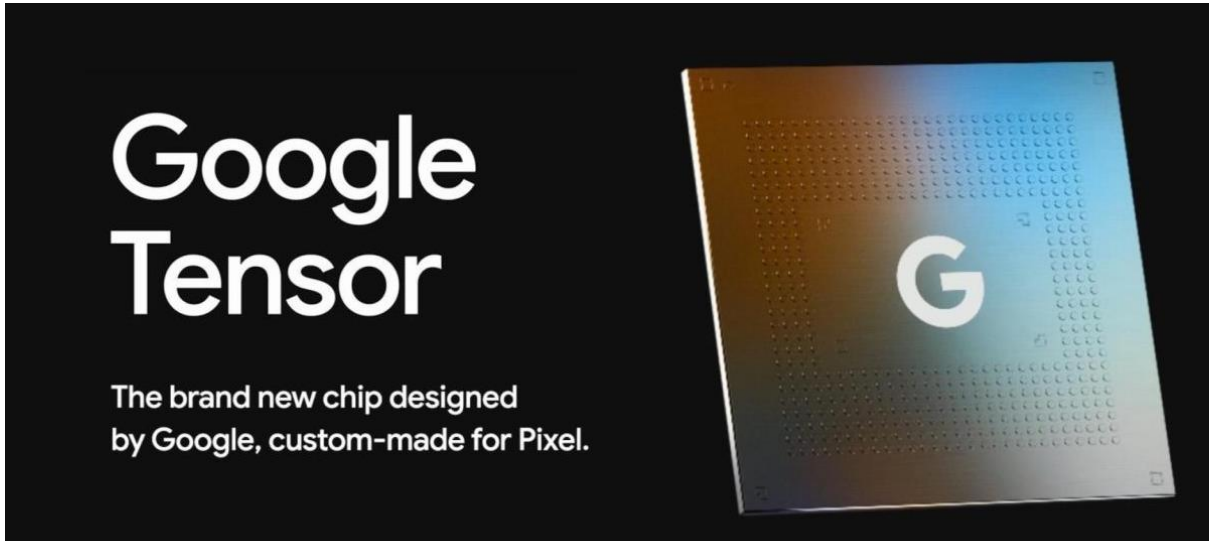
Results on 12MP image

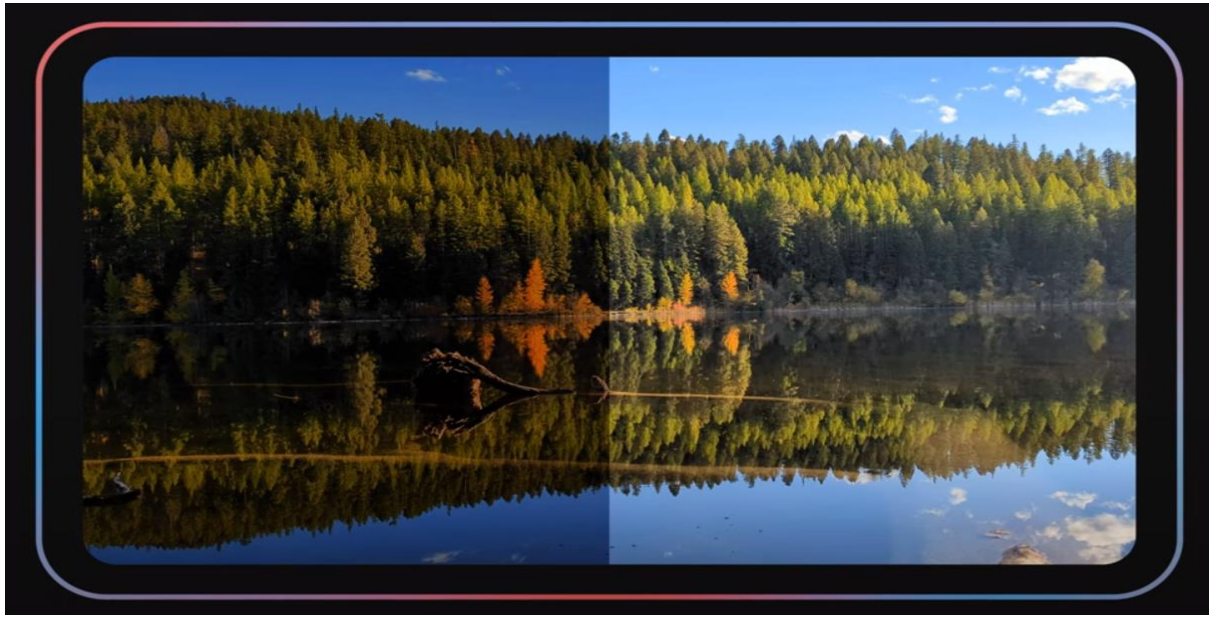
HDRnet tonemapping

12 megapixel 16-bit linear input (tone-mapped for visualization) | tone-mapped with HDR+ **400 – 600 ms** | processed with our algorithm **61 ms**, PSNR = **28.4 dB**

M. Gharbi, J. Chen, J. Barron, S. Hasinoff, F. Durand, “ Deep Bilateral Learning for Real-Time Image Enhancement”, SIGGRAPH 2017

Used by Google Tensor Chip



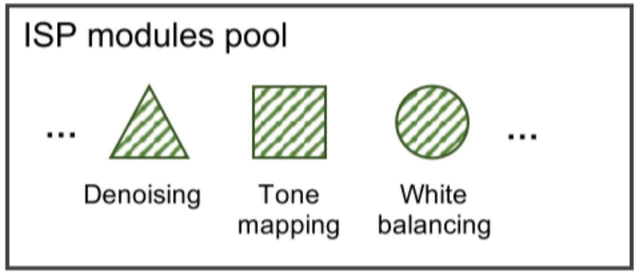


Denoising using spatially varying kernels

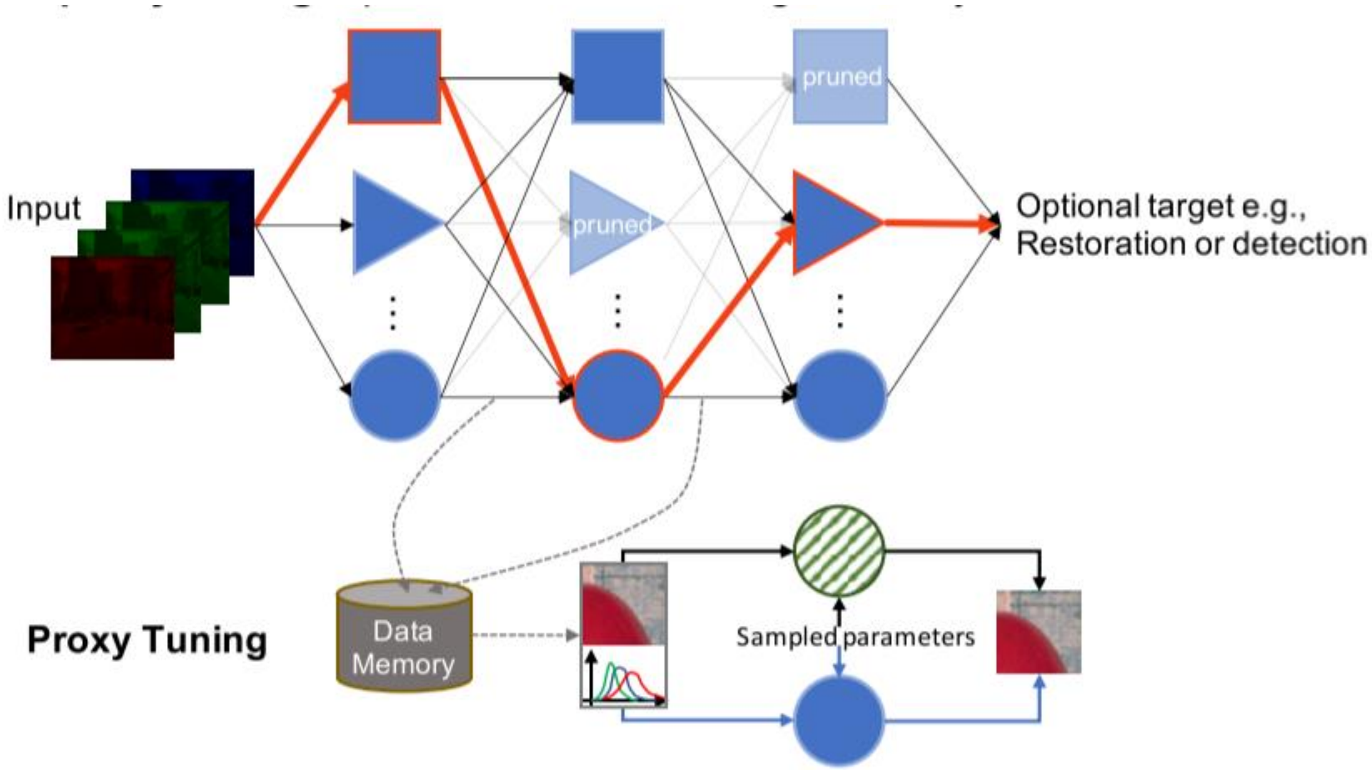
Input MalleConv Selected kernel 1 Selected kernel 2

Jiang et al, “Fast and High-quality Image Denoising via Malleable Convolutions”, ECCV 2022

We can even learn to reorder different modules



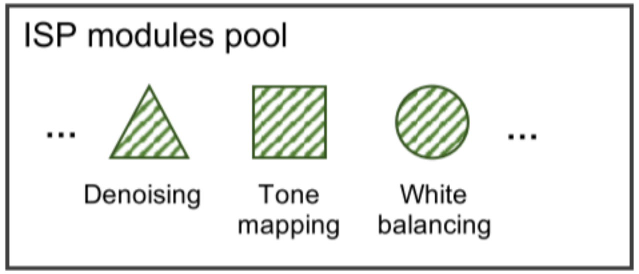
Basic camera modules



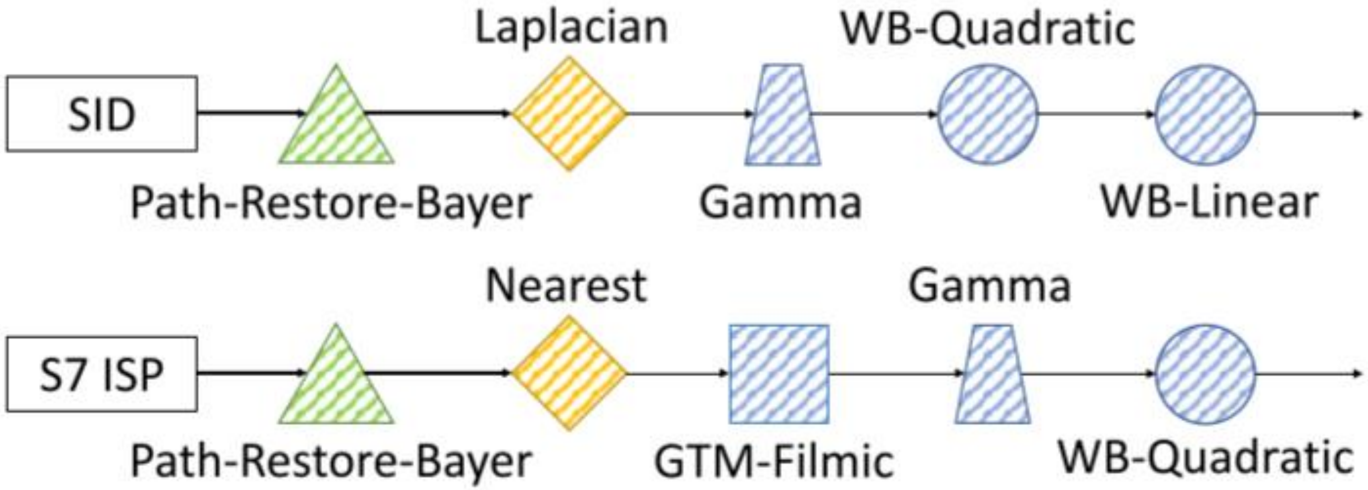
Learn a task-specific pipeline

K. Yu et al, “ReconfigISP: Reconfigurable Camera Image Processing Pipeline”, ICCV 2021

We can even learn to reorder different modules



Basic camera modules



Different task may need different pipelines

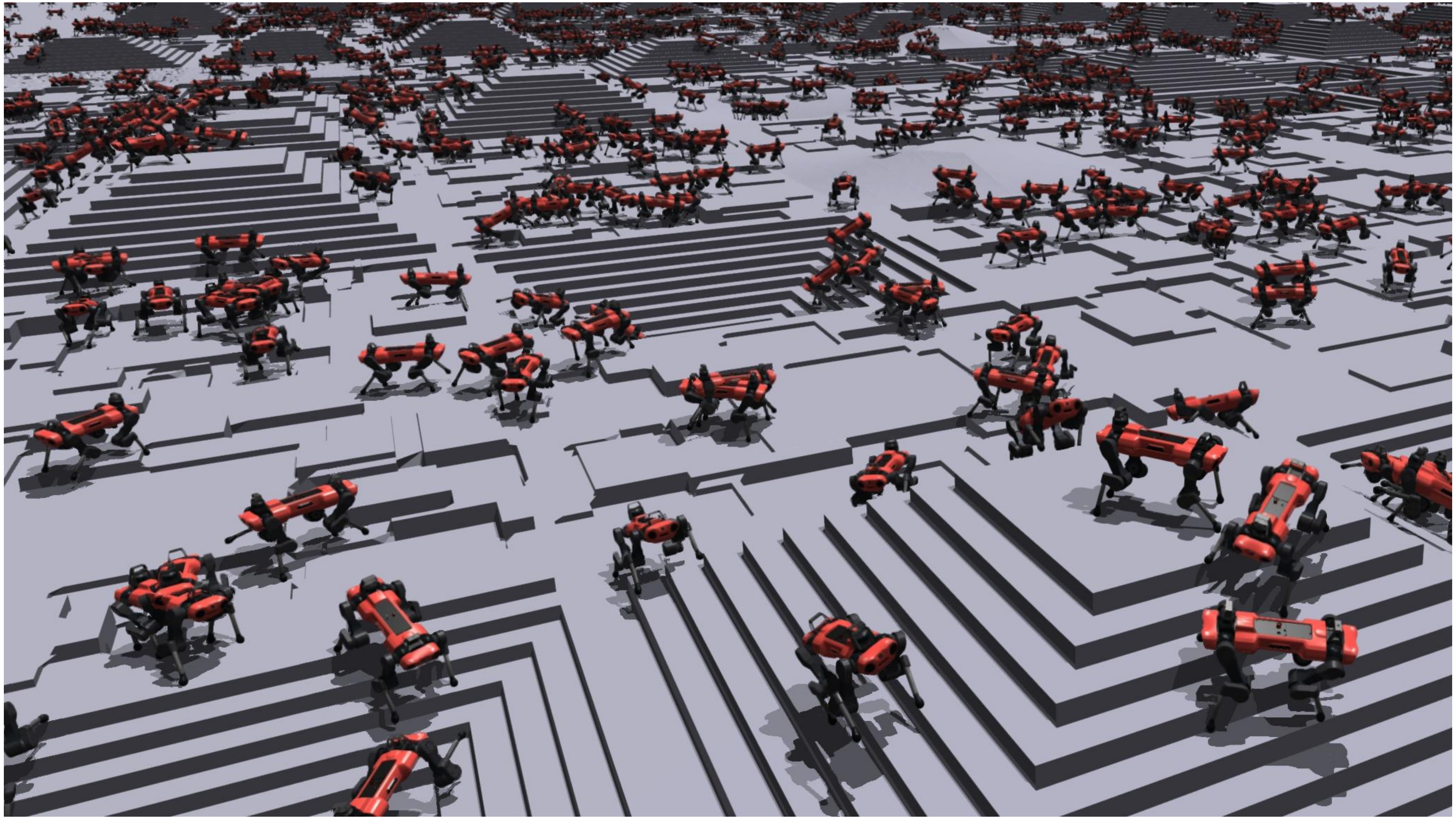
K. Yu et al, "ReconfigISP: Reconfigurable Camera Image Processing Pipeline", ICCV 2021

Future smart cameras research

Simulation is important to collect training data

Image credit: Tesla AI Day

Is there Isaac Gym for computational photography?



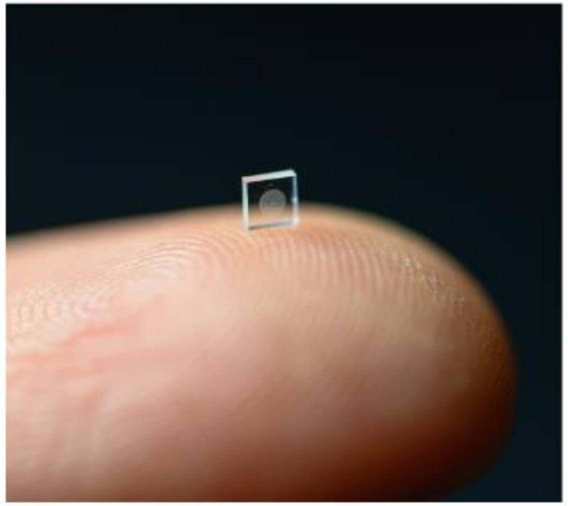
Issac Gym by NVIDIA, for robotic algorithm design

Computational Photography and Hardware

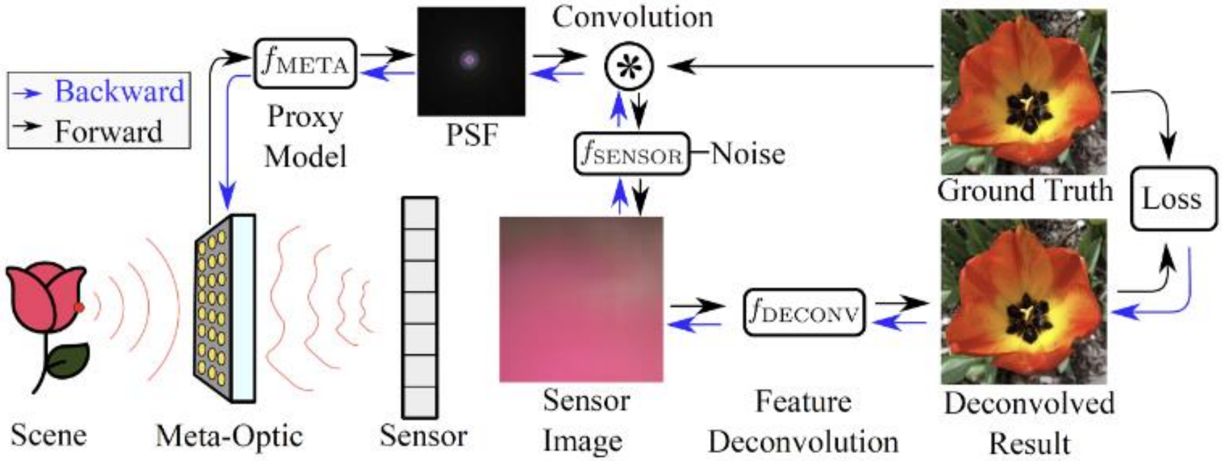
Image credit: https://bit.ly/2mmFtKP

Joint lens and algorithm design

Metasurface Close-up



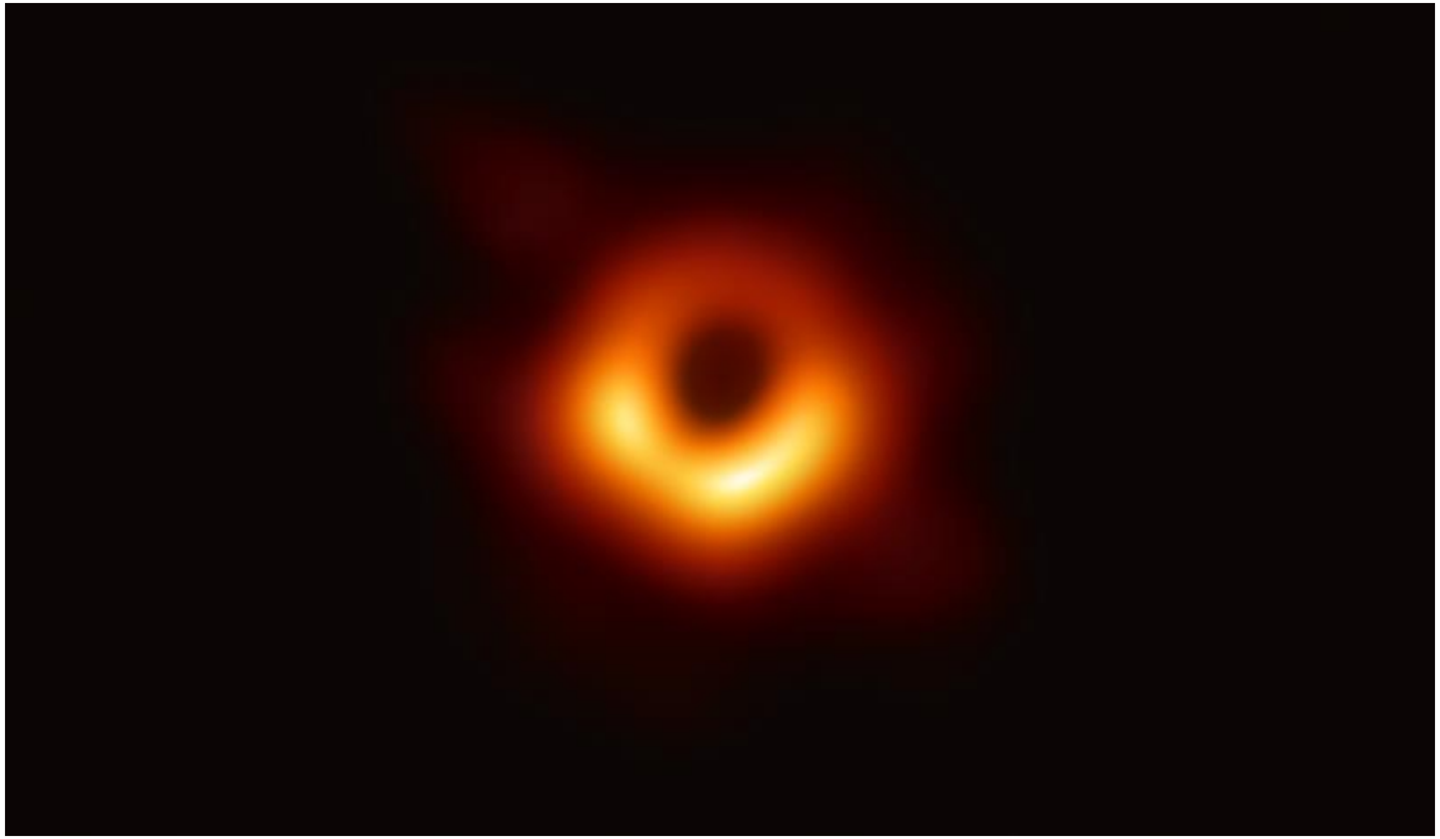
Learning Meta-Optics End-to-End



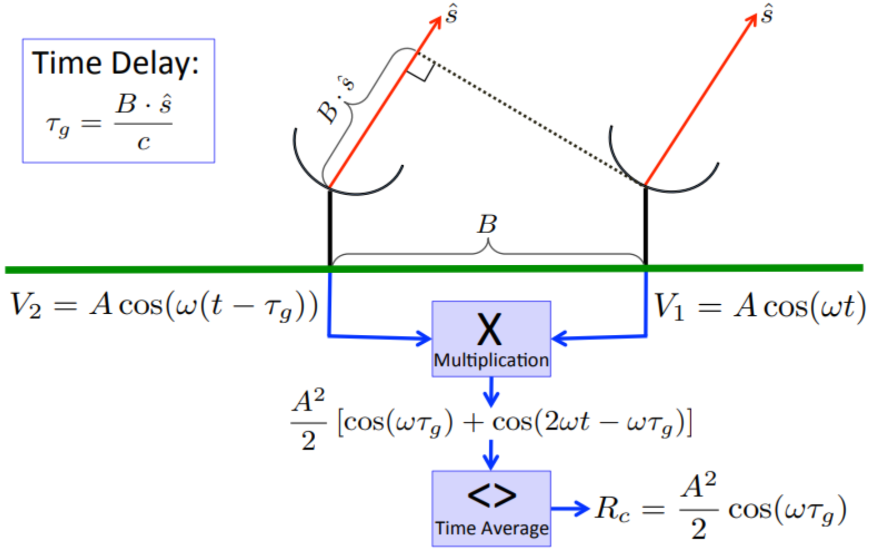
Neural Nano-Optics

Tseng et al., "Neural nano-optics for high-quality thin lens imaging", 2021

Camera is not only for better selfies



First black hole image
[image credit: NASA]



VLBI image formation

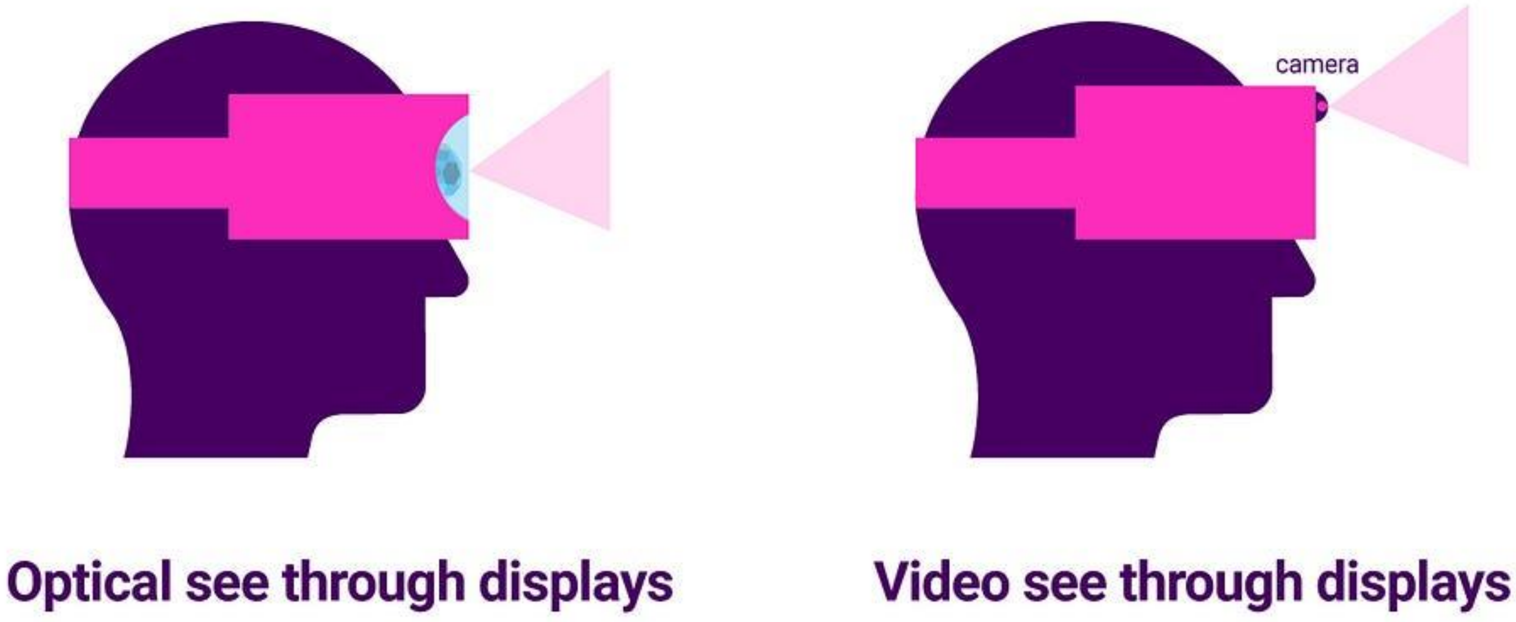
K. Bouman, “Computational Imaging for VLBI Image Reconstruction”, CVPR 2016

How VR may impact us

Can we capture more 3D content using our cameras?

B. Mildenhall et al., "NeRF: Representing Scenes as Neural Radiance Fields for View Synthesis", ECCV, 2020

Can cameras be as good as our eyes?



https://uxdesign.cc/augmented-reality-device-types-a7668b15bf7a

Can our algorithms be as fast as to deal with 8K60fps?

AIGC and Computational Photography

Where is the boundary between **editing** and **synthesis**

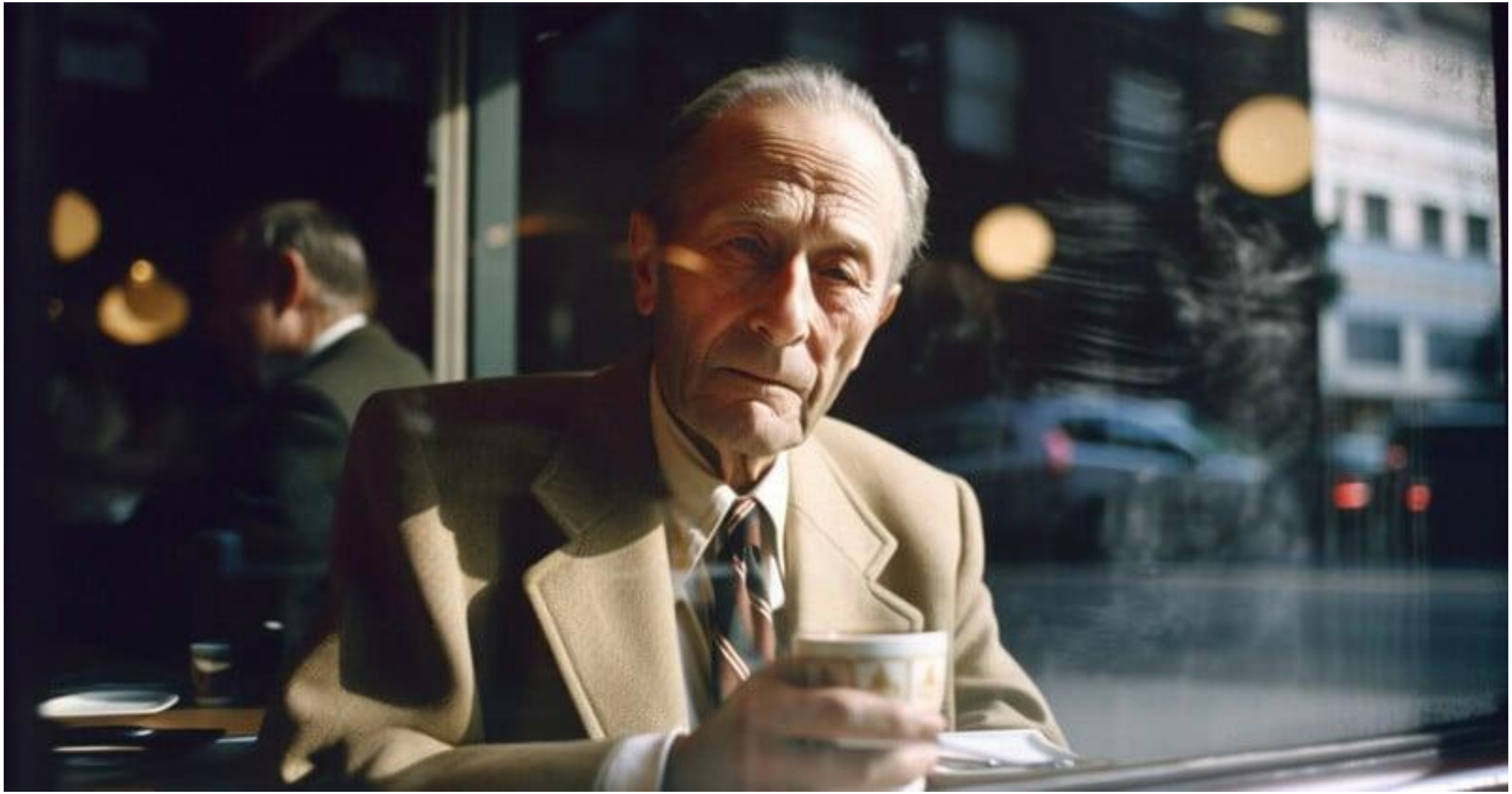
Which one is real, which one is fake?

https://www.bilibili.com/video/BV16M4y1q7B5

Where is the boundary between **editing** and **synthesis**

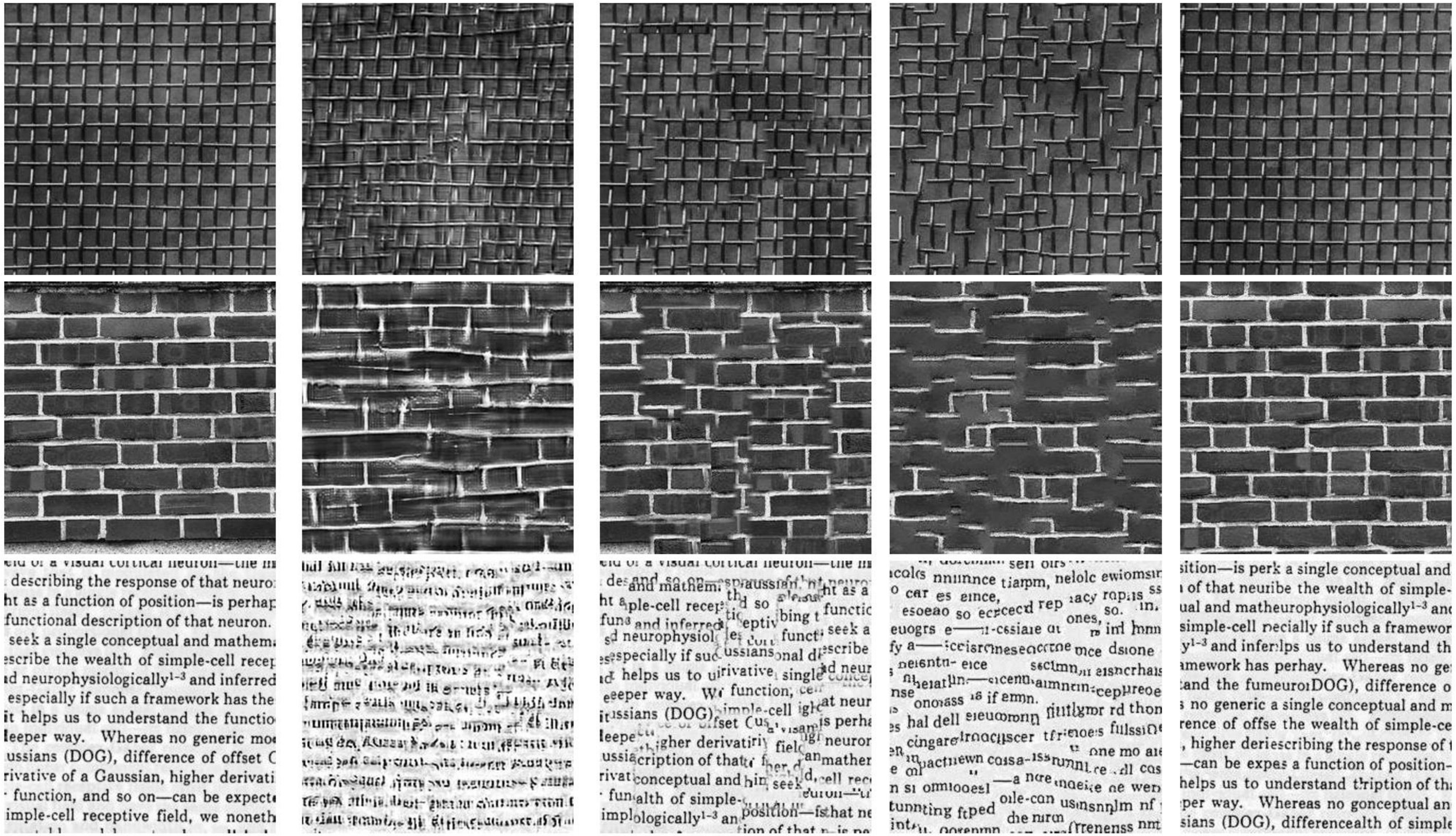
Robin et al., “High-Resolution Image Synthesis with Latent Diffusion Models”, CVPR 22.

Where is the boundary between **editing** and **synthesis**



Generated by Midjourney v5: https://petapixel.com/2023/03/17/midjourney-v5-creates-photorealistic-images-and-even-does-hands-correctly/

Where is the boundary between **editing** and **synthesis**



input texture | Portilla & Simoncelli [17] | Xu et.al. [21] | Wei & Levoy [20] | Image Quilting

A. Efros and W. T. Freeman, “Image quilting for texture synthesis and transfer”, CG 2001

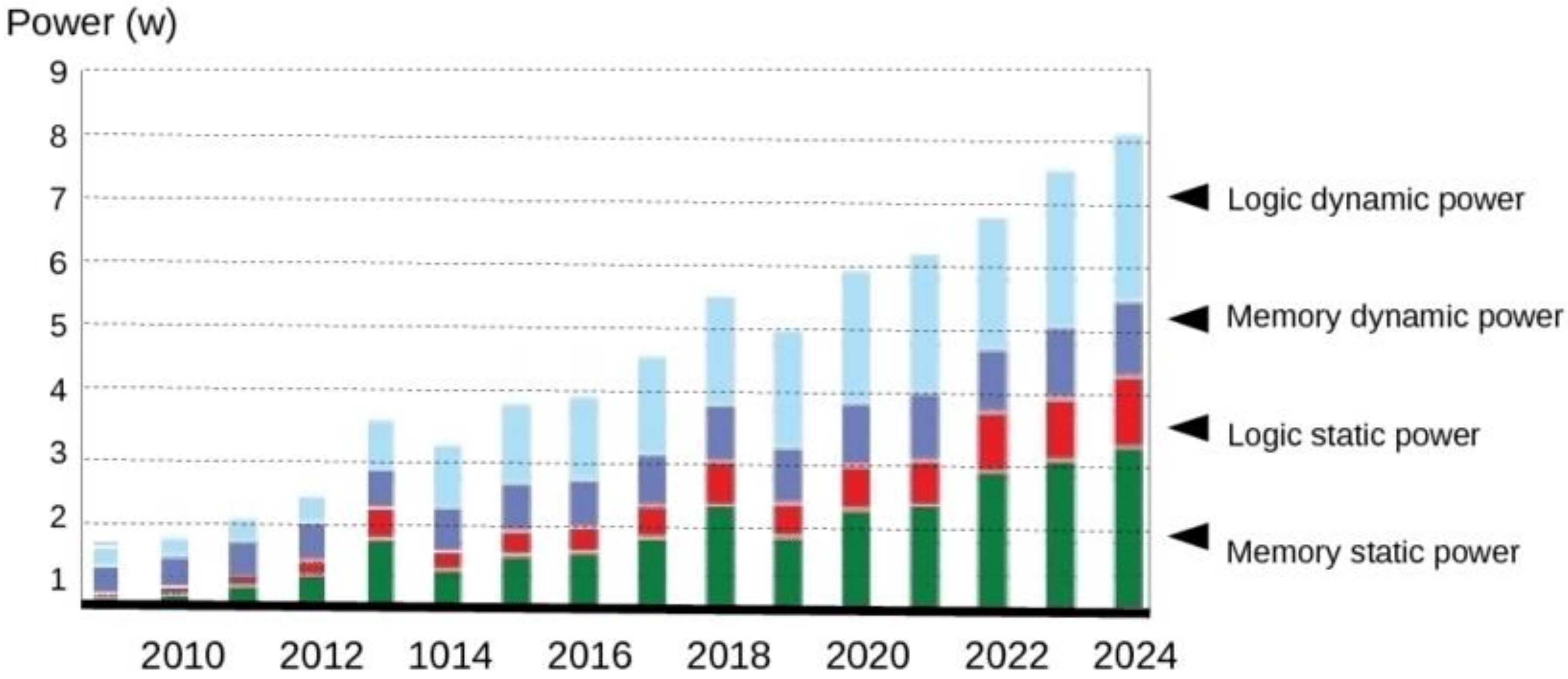
Do we even need a powerful lens?

Only less powerful camera hardware is needed in the future?

Cameras become **more powerful** in past 10y

Gap between academic research and industrial design

Industrial not only care quality, but also speed & power



SoC consumer portable power consumption

Yahia Benmoussa, “Performance and Energy Consumption Characterization and Modeling of Video Decoding on Multi-core Heterogenous Mobile SoC and their Applications”

High PSNR != Better Image

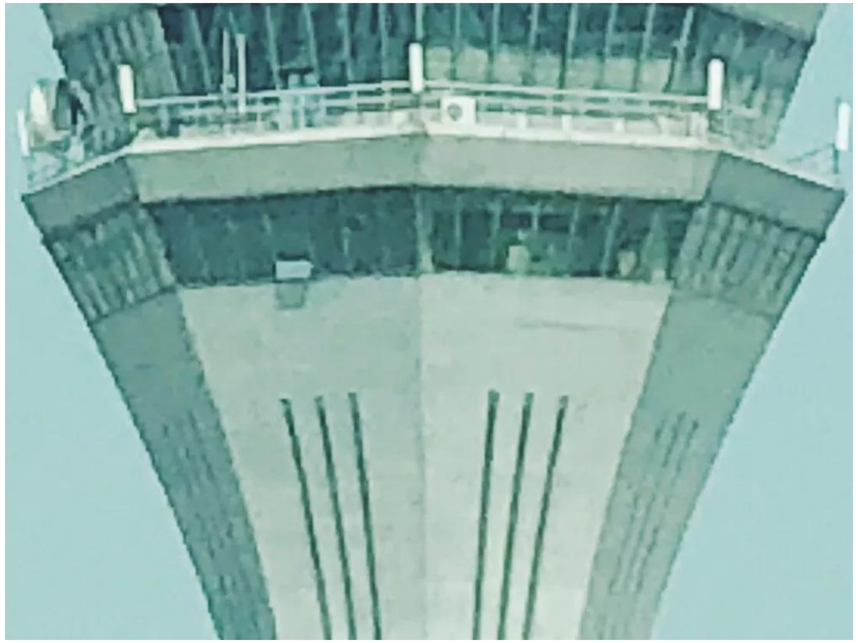
L., Christian, et al. "Photo-realistic single image super-resolution using a generative adversarial network." *CVPR*. 2017.

Diff users may even have diff preferences

3 experts gave very different tunings

Image credit: Adobe 5K

It is even hard to describe what is best



Some photographers don't like over-smoothed image, and call it "**like oil painting**"

Some photographers don't like HDR image, and call it "**Cartoon-look**"

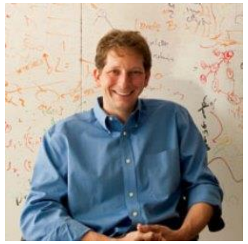
http://barney-streit.squarespace.com/blog/2013/6/5/good-hdr-bad-hdr

Collaborators and acknowledgement


Bill Freeman


Fredo Durand

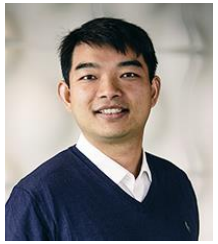

Antonio Torralba


Josh Tenenbaum


Michael Geosele


Rick Szeliski

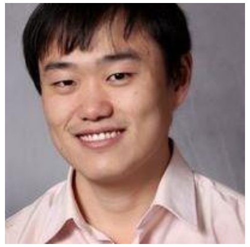

Daniel


Ce Liu


Orly Liba


Miki Rubinstein


Joseph Lim


Yuandong Tian


Hossein Mobahi


Jiajun Wu


Katie Bouman


Neal Wadhwa

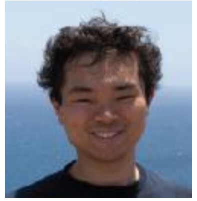

Chengkai Zhang


Yun-Ta Tsai


Jon Barron


Sam Hasinoff


Dillon Sharlet


Jiawen Chen


Xide Xia


Zheng Sun


Kiran Murthy


Marc Levoy


Shumian Xin


Pratul Srinivasan


Ioannis Gkioulekas


Rahul Garg


Jian Wang


Qiurui He


Brian Kulis


Simon Niklaus


Paul Debevec


Xiuming Zhang

Q&A