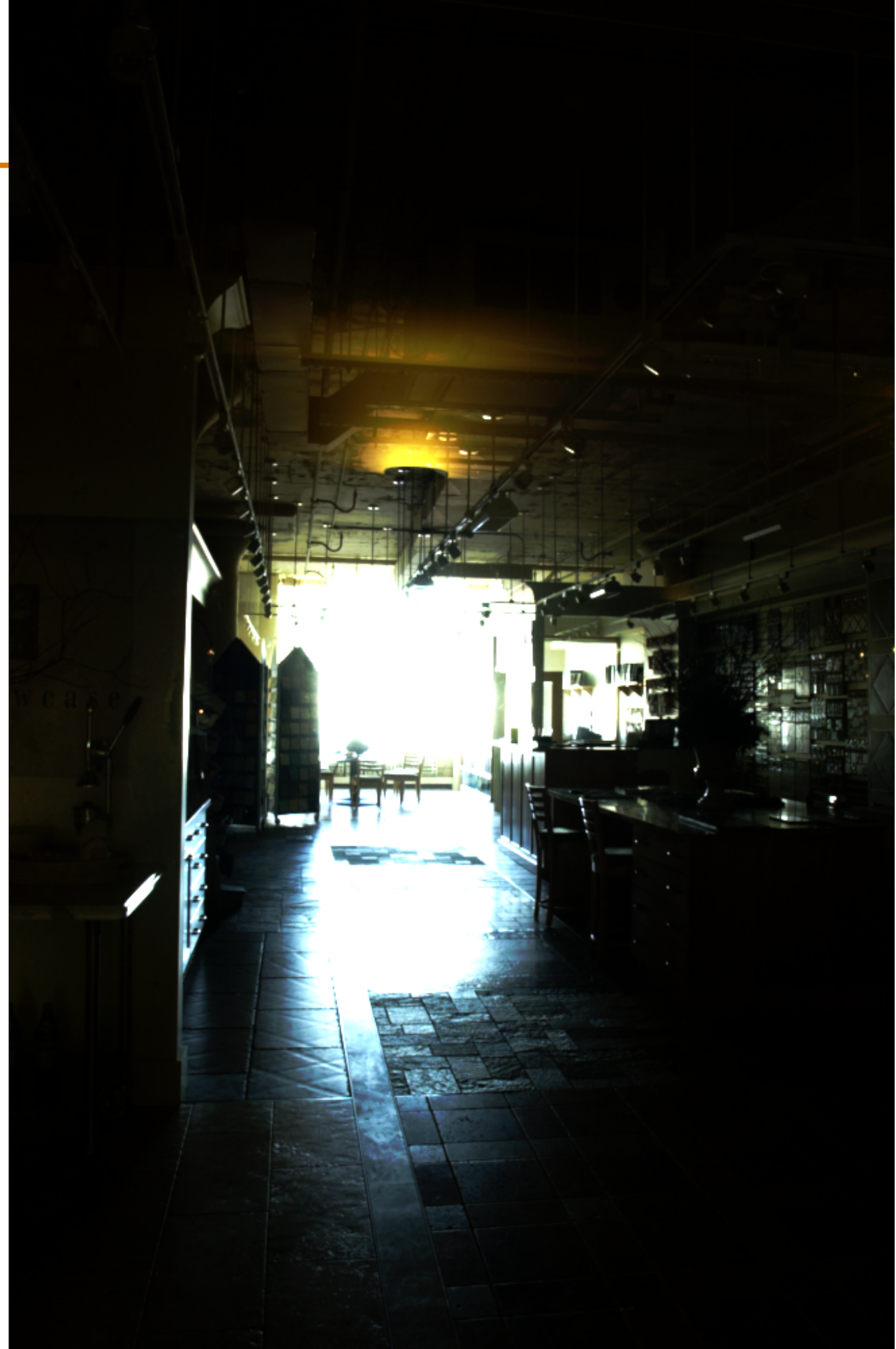
High-Dynamic-Range Imaging & Tone Mapping

Fredo Durand
MIT EECS 6.8370/6.8371

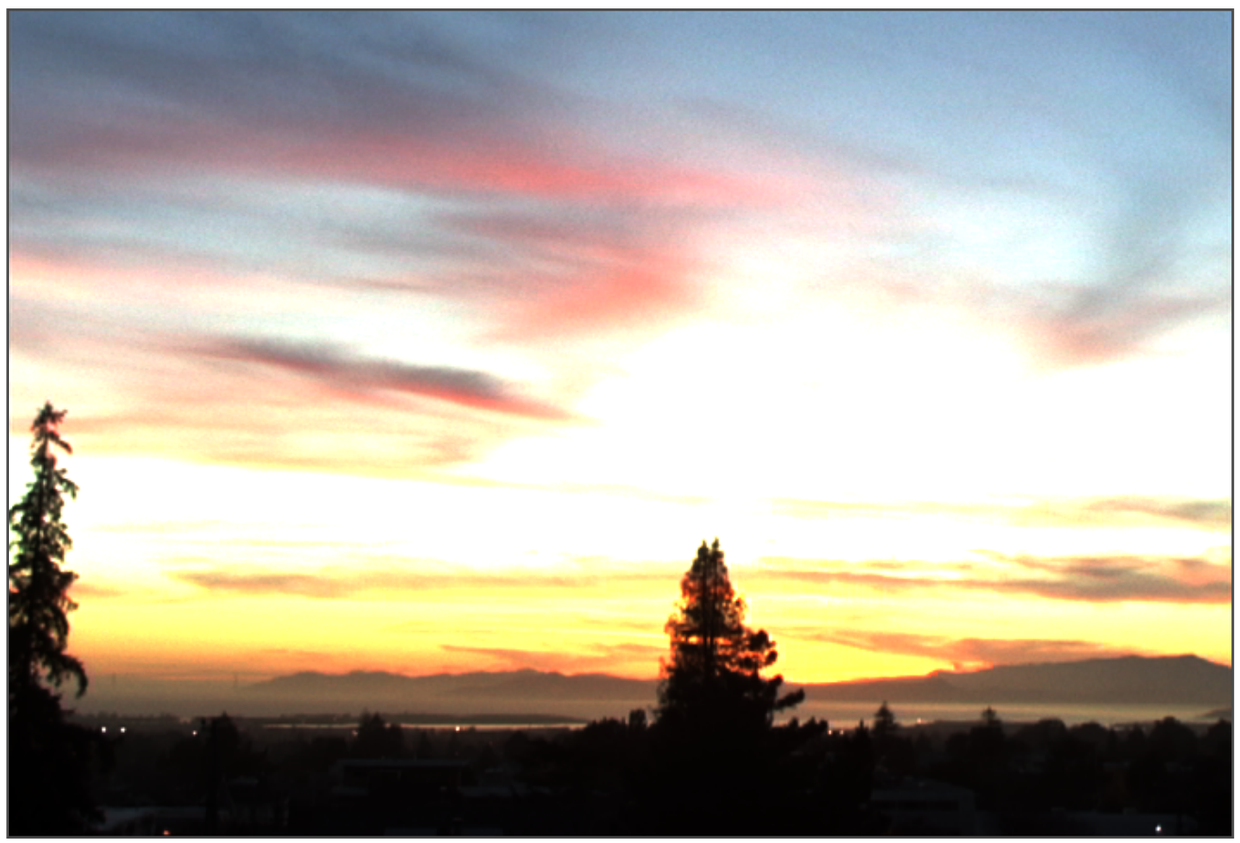
The dynamic range challenge

Examples

- **Inside is too dark**
- **Outside is too bright**

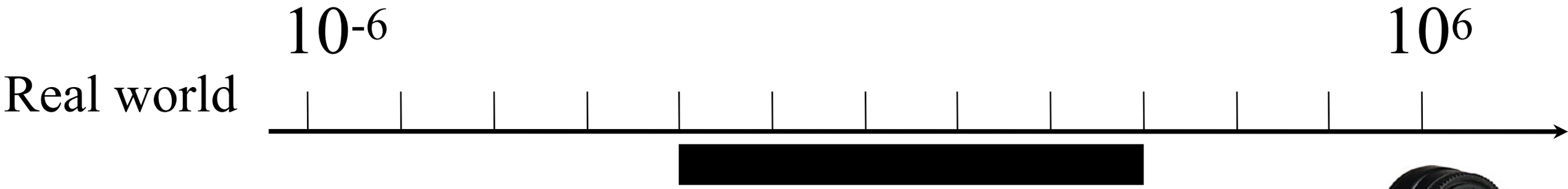


- **Sun overexposed**
- **Foreground too dark**



Real world dynamic range

- **Eye can adapt from ~ 10^{-6} to 10^{6} cd/m²**
- **Often 1 : 100,000 in a scene**

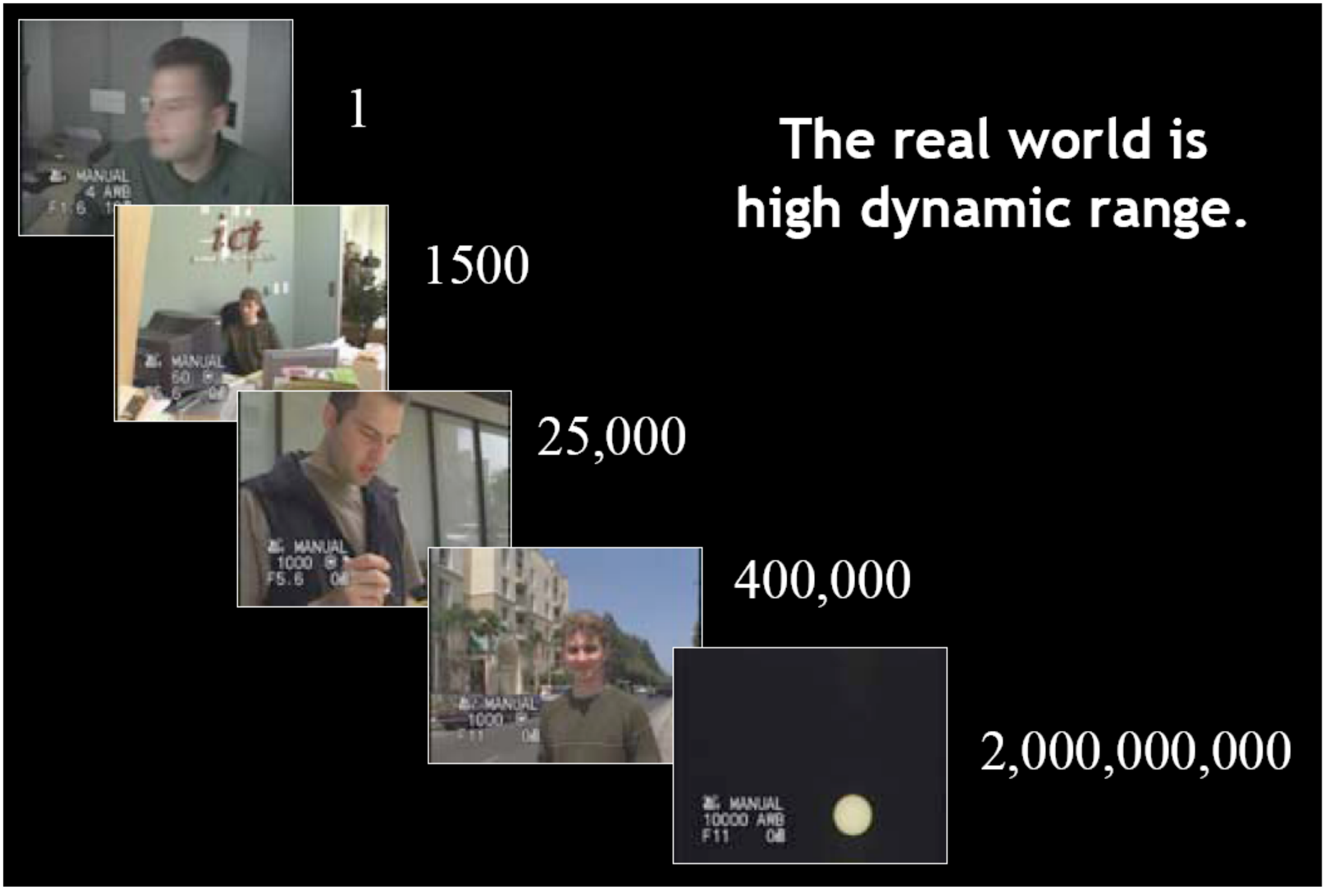




spotmeter

The world is high dynamic range

- **Slide from Paul Debevec**

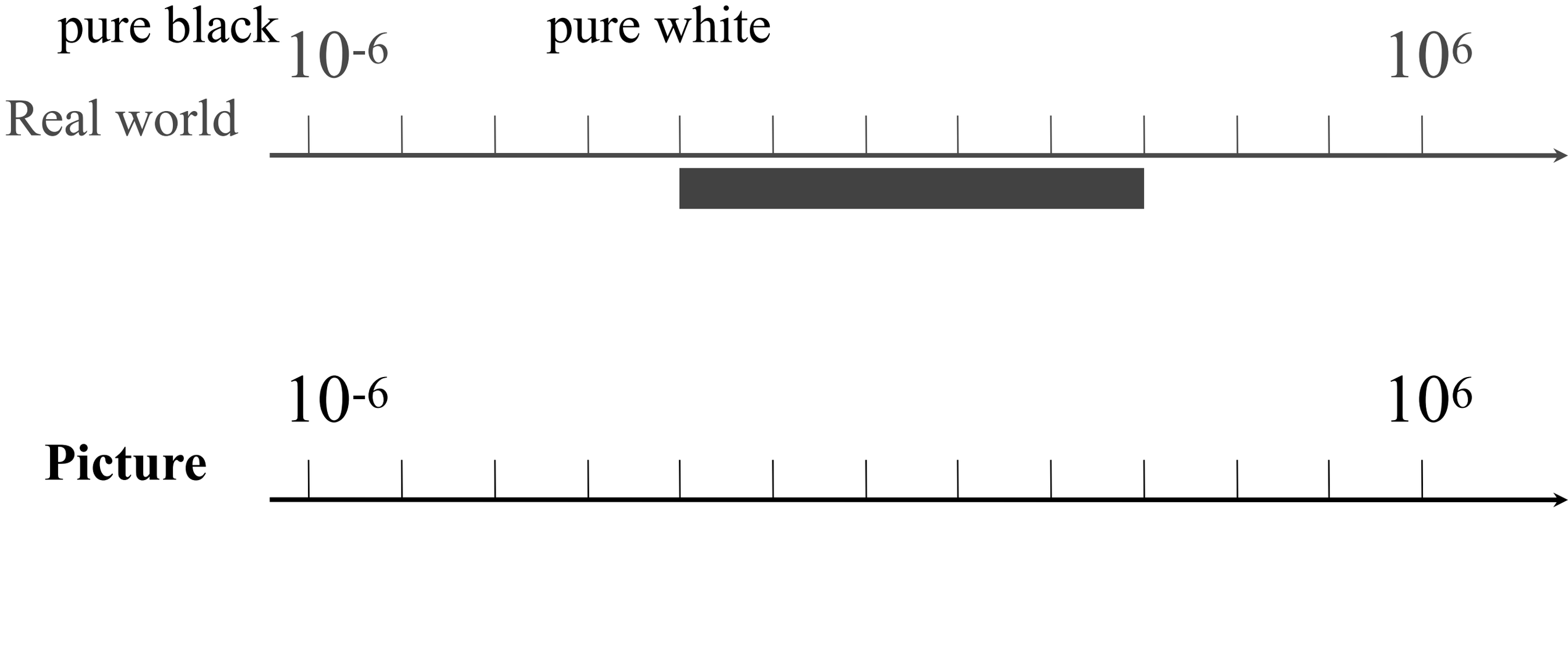


Picture dynamic range: Guess!



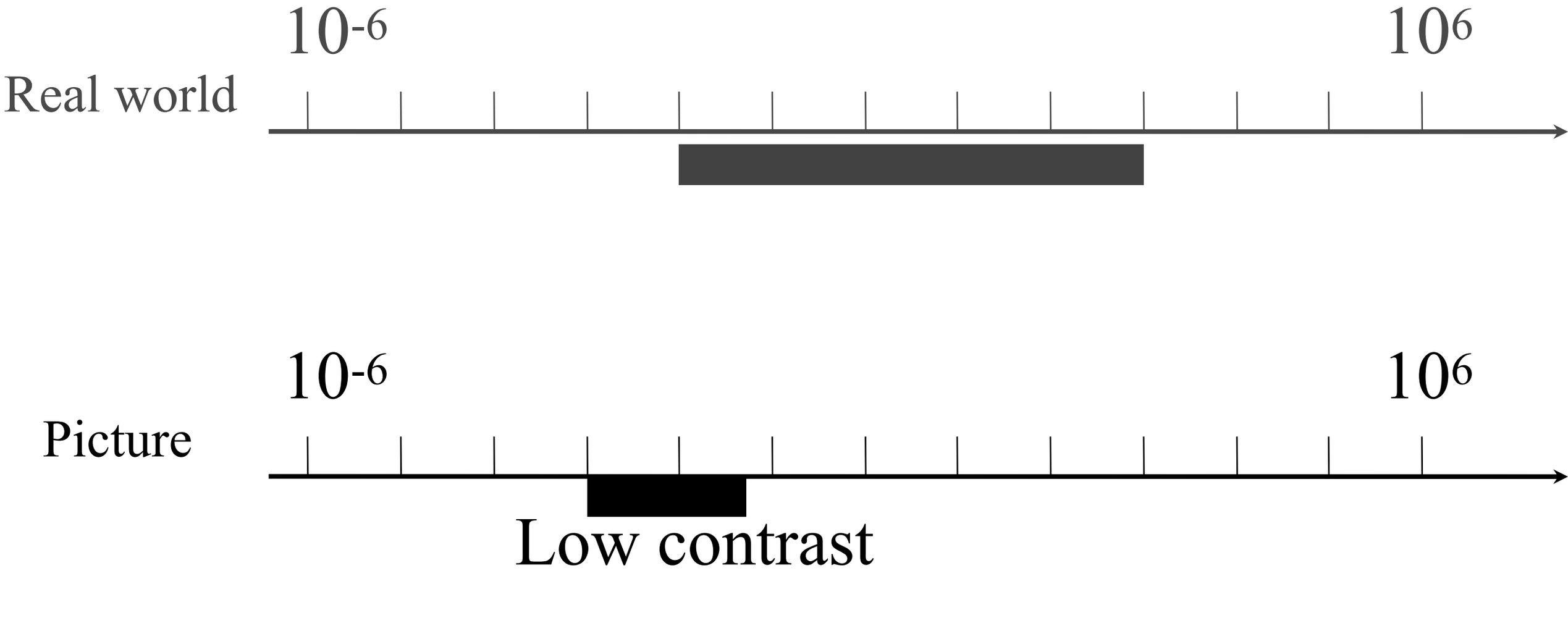
pure black

pure white



Picture dynamic range

- **Typically 1: 20 or 1:50**
  - Black  is ~ 50x darker than white
- **Max 1:500**



The dynamic range problem

- media (approximate and debatable)

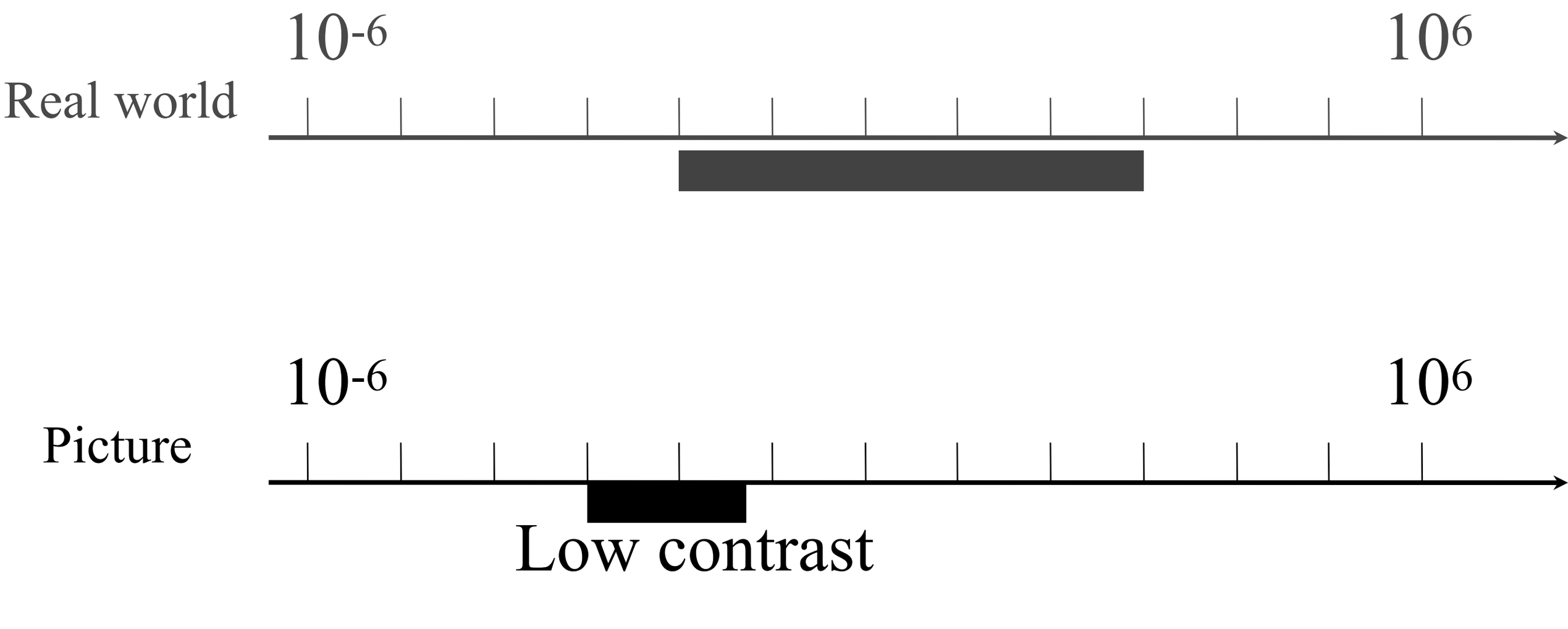
10:1	photographic print (higher for glossy paper)
20:1	artist's paints
200:1	slide film
500:1	negative film
1000:1	LCD display
2000:1	digital SLR (~11 bits)

- challenges
  - choosing which 6-12 bits of the world to include in your photograph (cell phone to professional SLR, respectively)
  - metering the world to help you make this decision, since the world has more dynamic range than any light meter
  - compressing 12 bits into 4 bits for print, or 10 for LCD
    - this is the *tone mapping* problem

© 2010 Marc Levoy

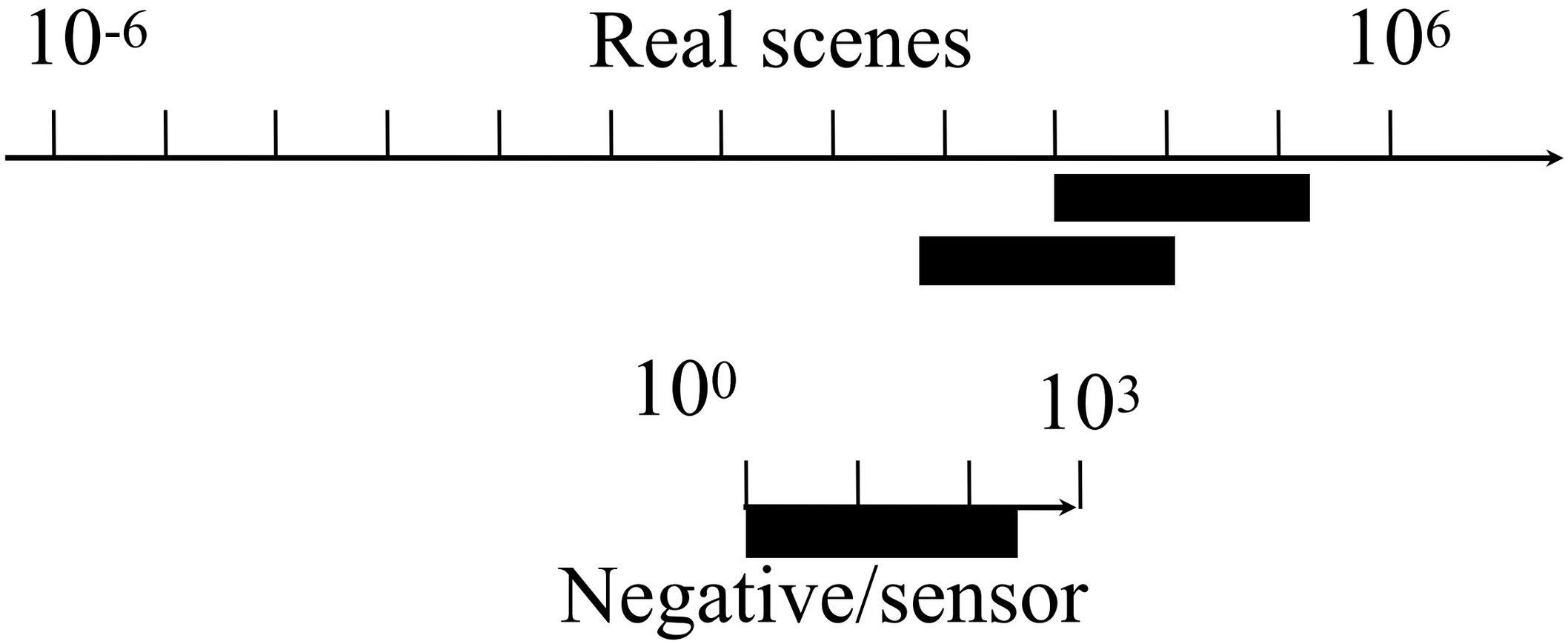
Picture dynamic range

- **Typically 1: 20 or 1:50**
  - Black  is ~ 50x darker than white



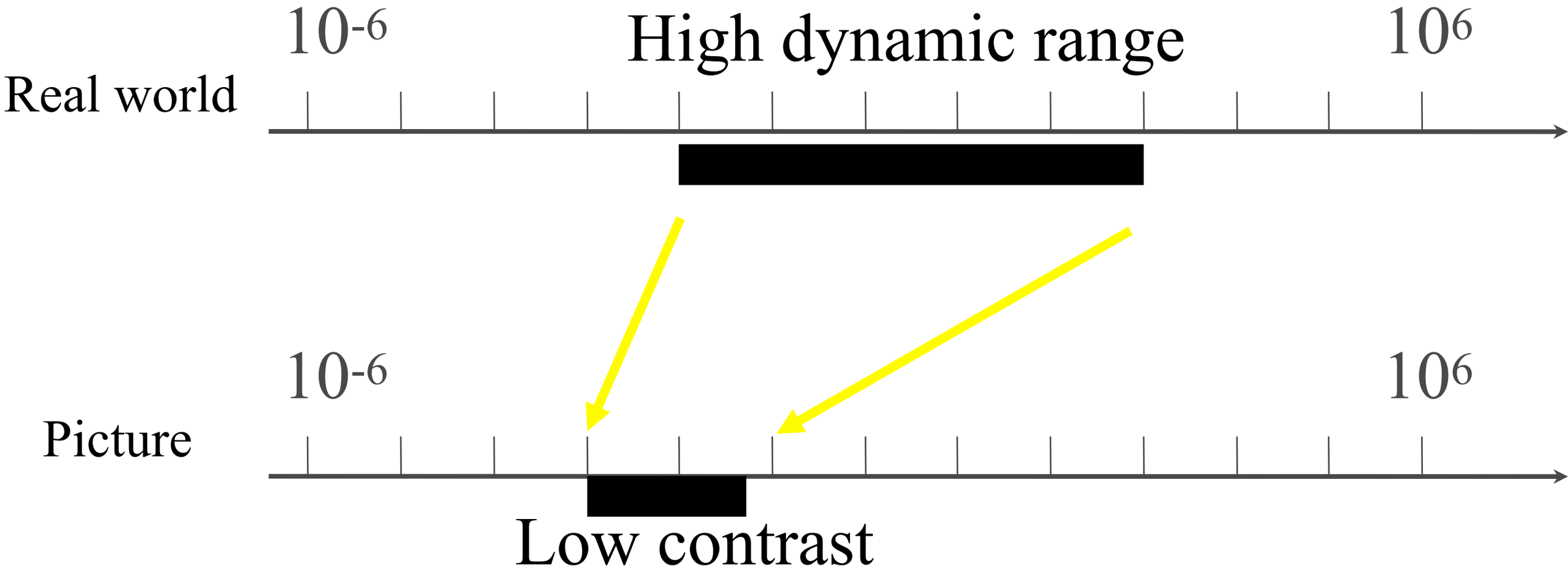
Problem 1: record the information

- **The range of illumination levels that we encounter is 10 to 12 orders of magnitudes**
- **Negatives/sensors can record 2 to 3 orders of magnitude**



Problem 2: Display the information

- **Match limited contrast of the medium**
- **Preserve details**



Without HDR & tone mapping



With HDR & tone mapping



- **http://www.stuckincustoms.com/2011/04/30/hdr-before-after/**





- **http://fstoppers.com/best-technique-for-shooting-interiors-hdr-or-flash**

Best Technique for Shooting Interiors: HDR or Flash?

Have you ever tried to shoot an interior photograph and have it look like the shots in magazines or high end property brochures? If so then you probably know there are two routes to go: HDR or Flash. Photographer **Dom Bower** recently made a video showing the differences in both techniques and how you can combine them both to create a sort of hybrid image. Keep in mind that Dom is only using one single speedlight directly above the camera. Many of the amazing images you see for high end hotels and expensive properties often have dozens of light sources accenting very specific elements in the image. What techniques have you guys used in your interior photos? If you have examples, feel free to post your images in the comments below and check out Dom's final photos in the **full post**.

32 Tweet 71 Share



Can be extreme

- **By Anthony Wong, http://abduzeedo.com/20-beautiful-hdr-pictures-part-3**



Not always cheesy



By Alexandre Buisse

http://luminous-landscape.com/essays/hdr-plea.shtml

Not always cheesy



By Alexandre Buisse

http://luminous-landscape.com/essays/hdr-plea.shtml

Plan

- **Multiple-exposure High-Dynamic-Range imaging**



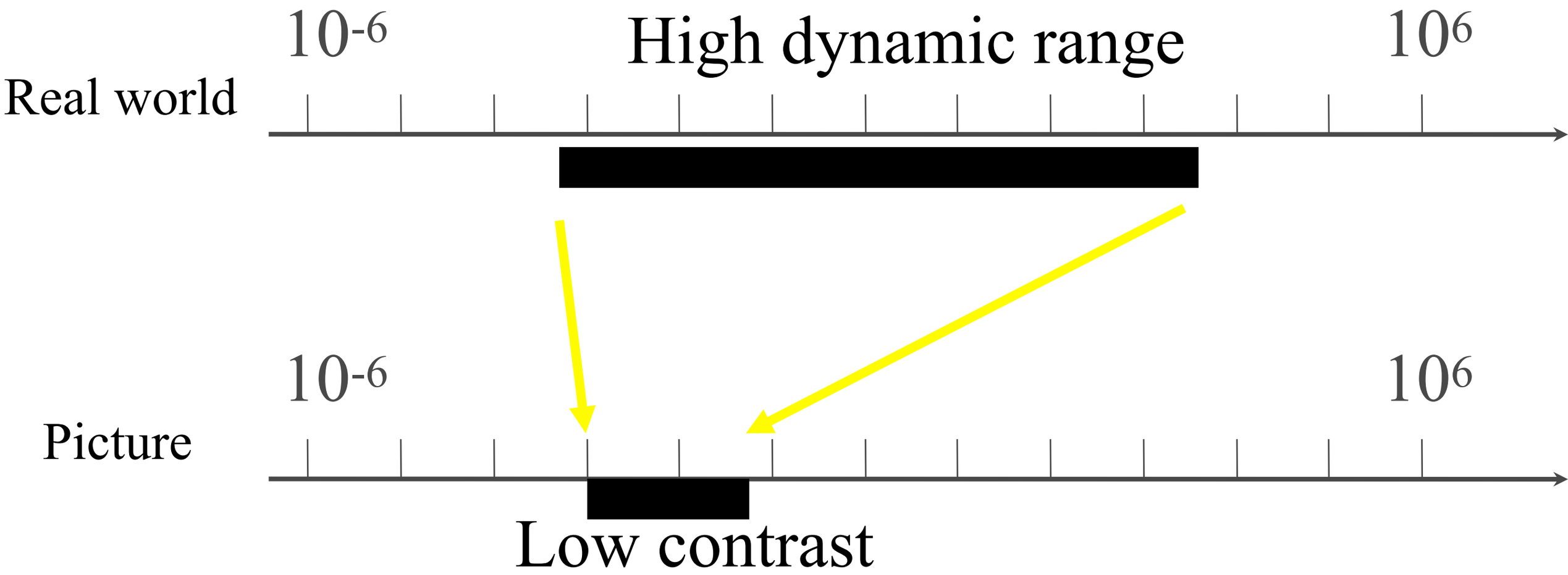
- **Tone mapping using the bilateral filter**



Multiple exposures

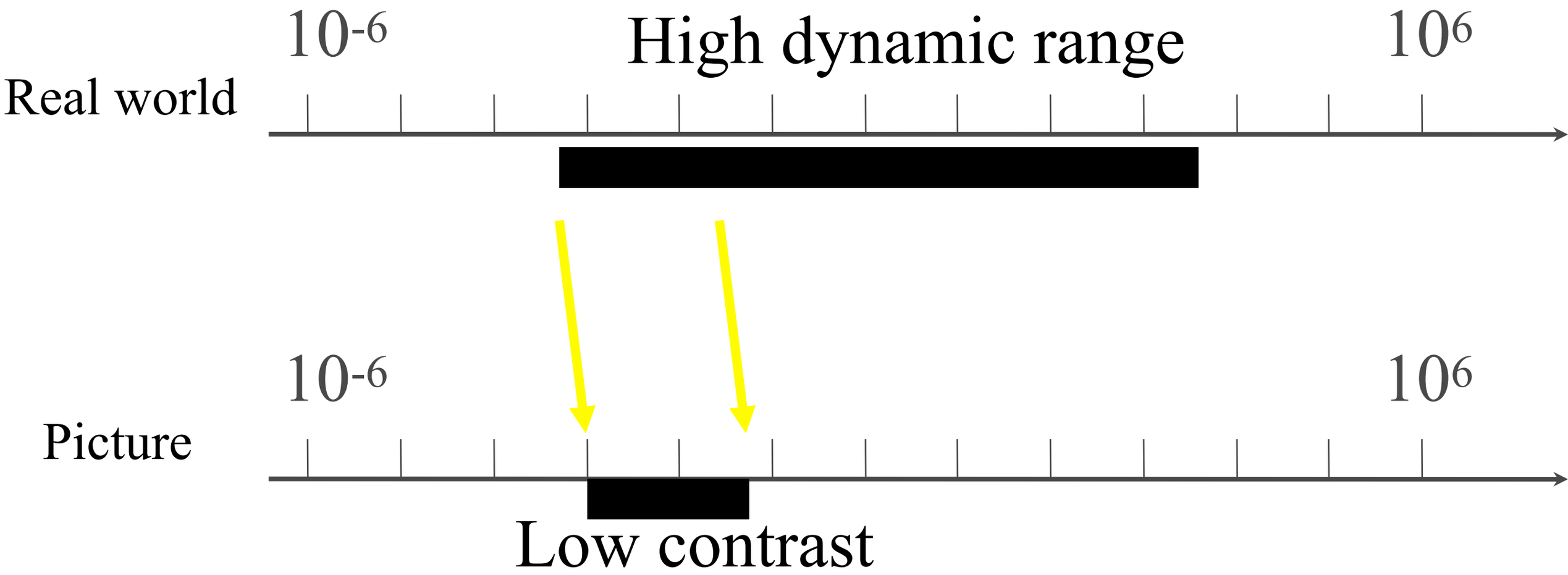
Multiple exposure photography

- **Sequentially measure all segments of the range**



Multiple exposure photography

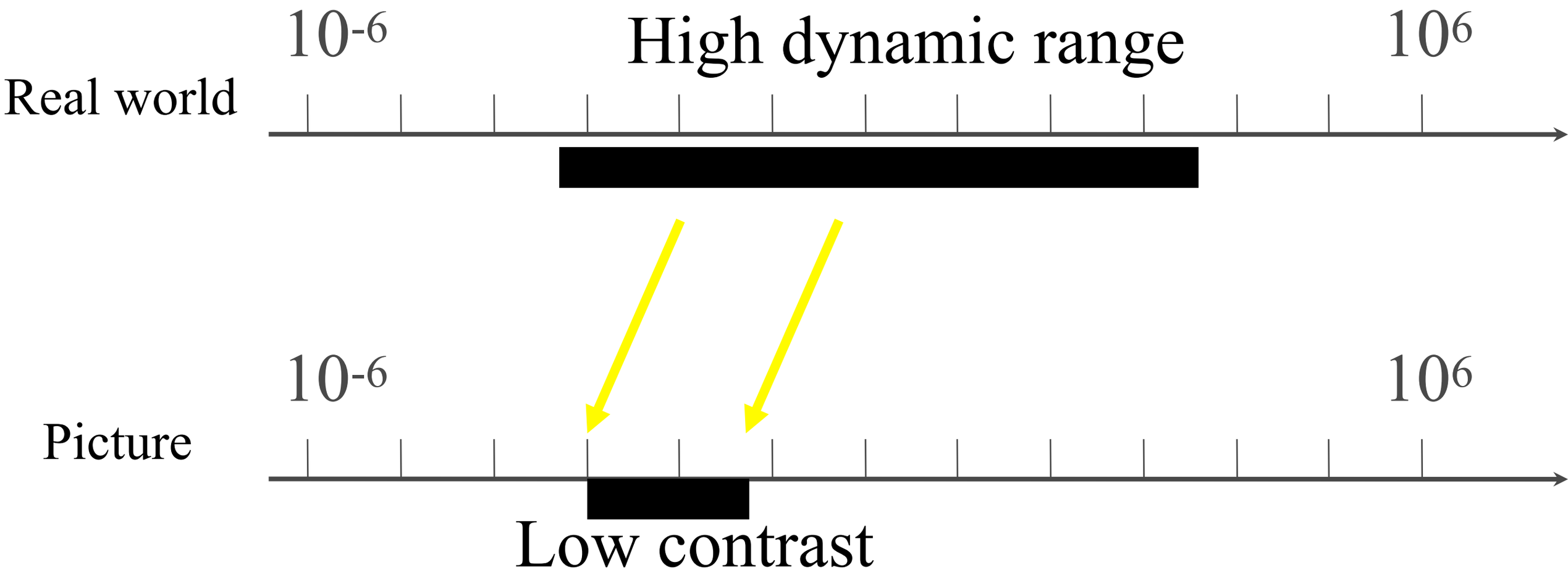
- **Sequentially measure all segments of the range**





Multiple exposure photography

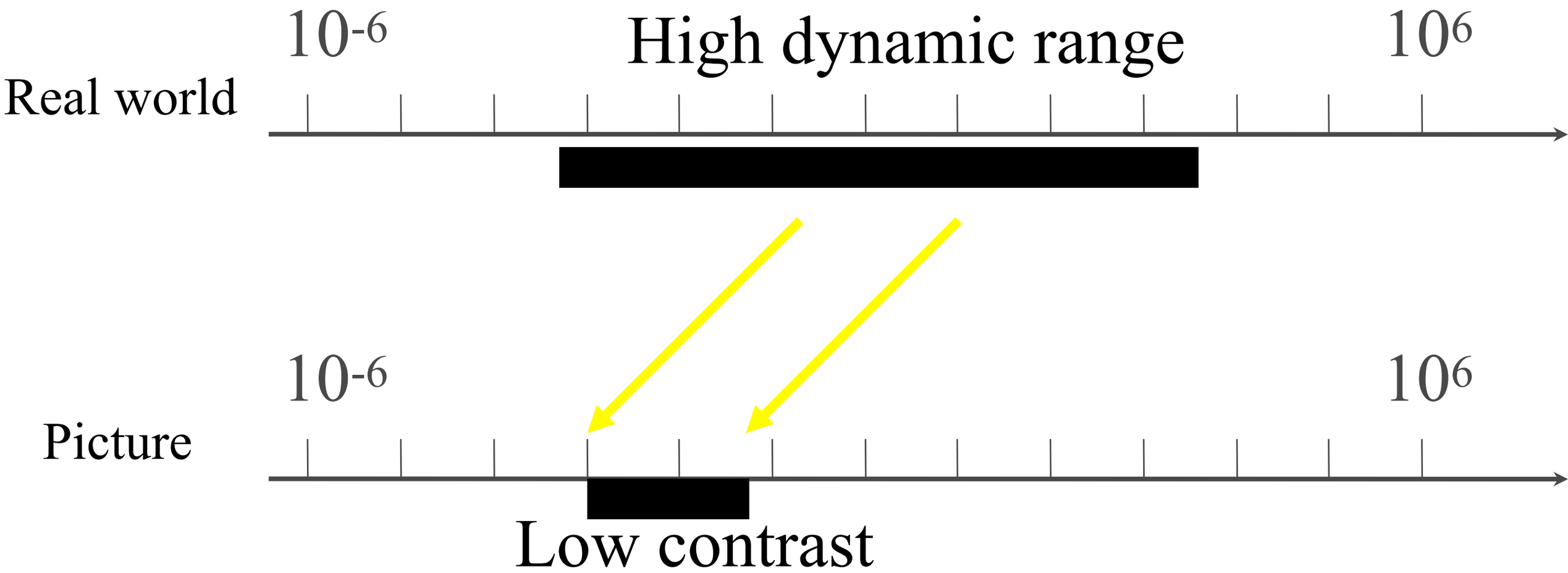
- **Sequentially measure all segments of the range**

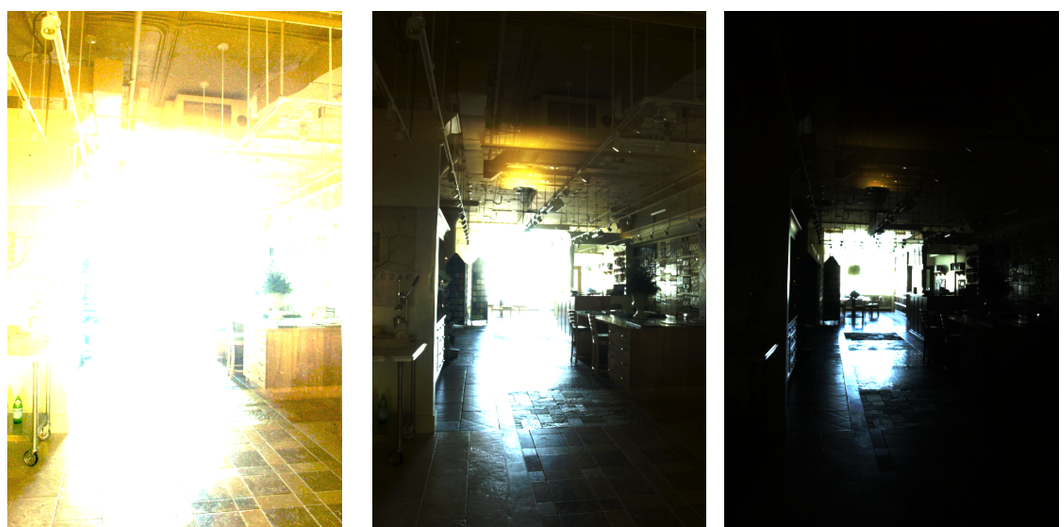




Multiple exposure photography

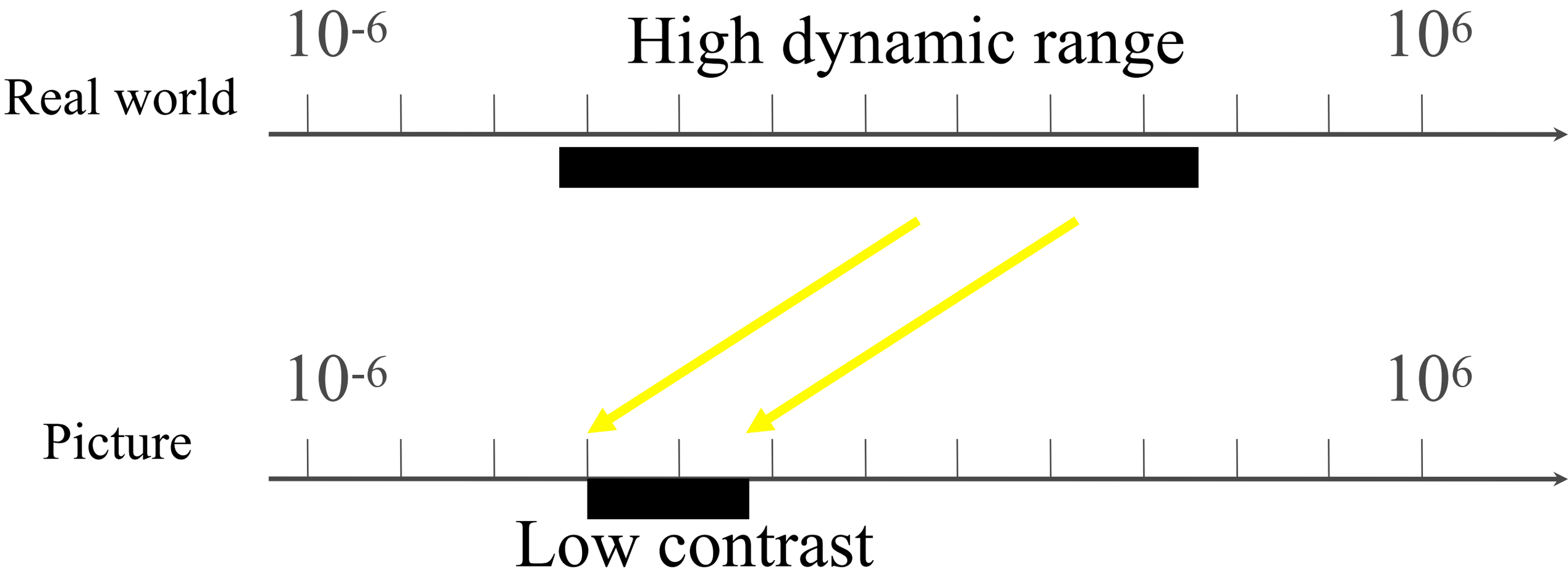
- **Sequentially measure all segments of the range**





Multiple exposure photography

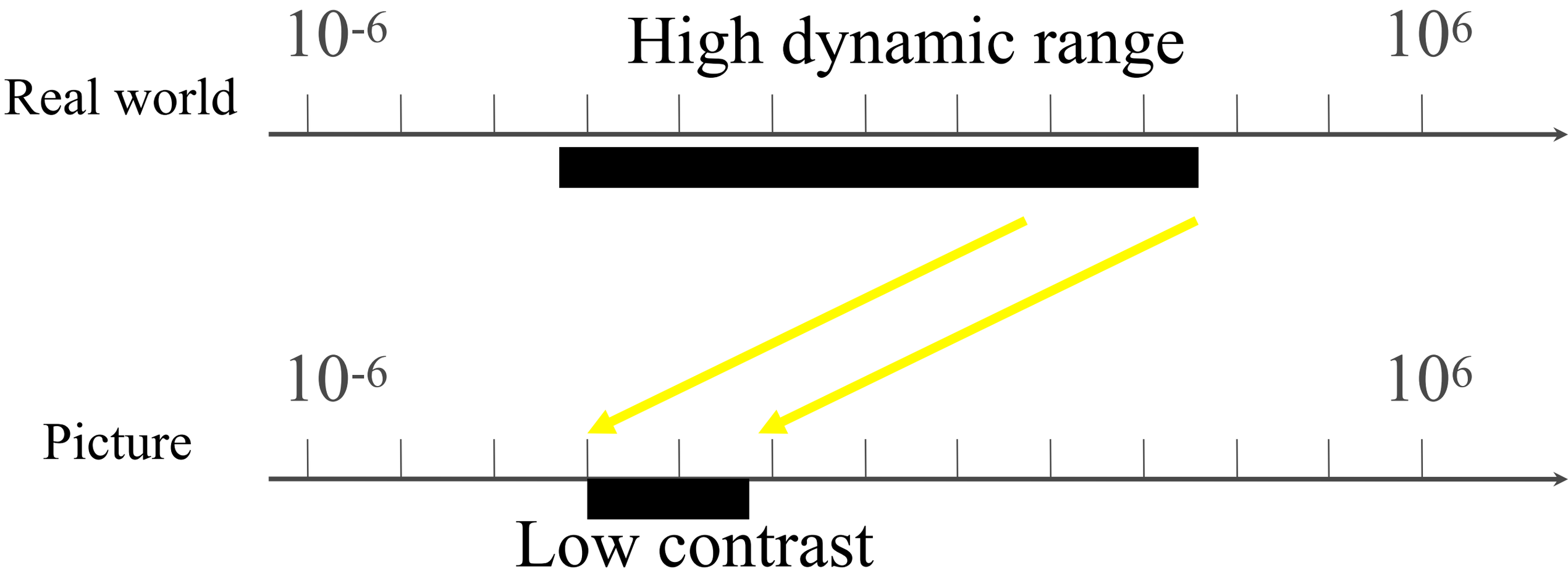
- **Sequentially measure all segments of the range**

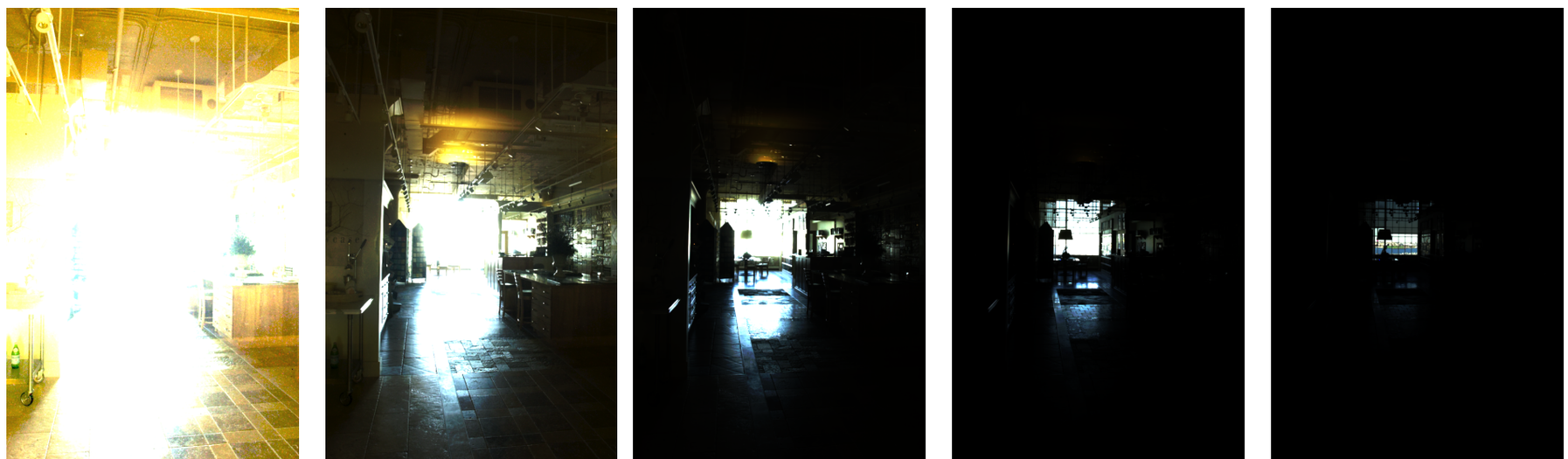




Multiple exposure photography

- **Sequentially measure all segments of the range**

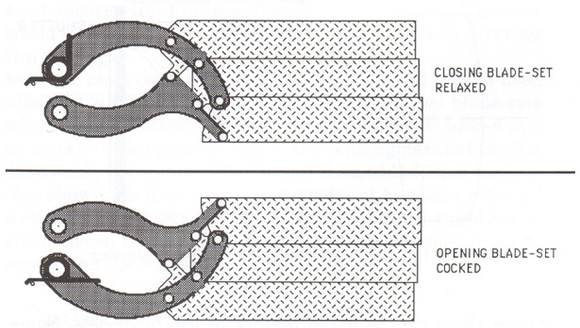




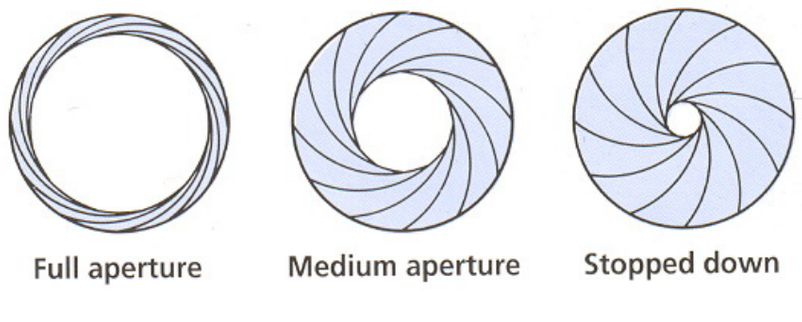
How do we vary exposure?

How do we vary exposure?

- **Options:**
  - Shutter speed



  - Aperture



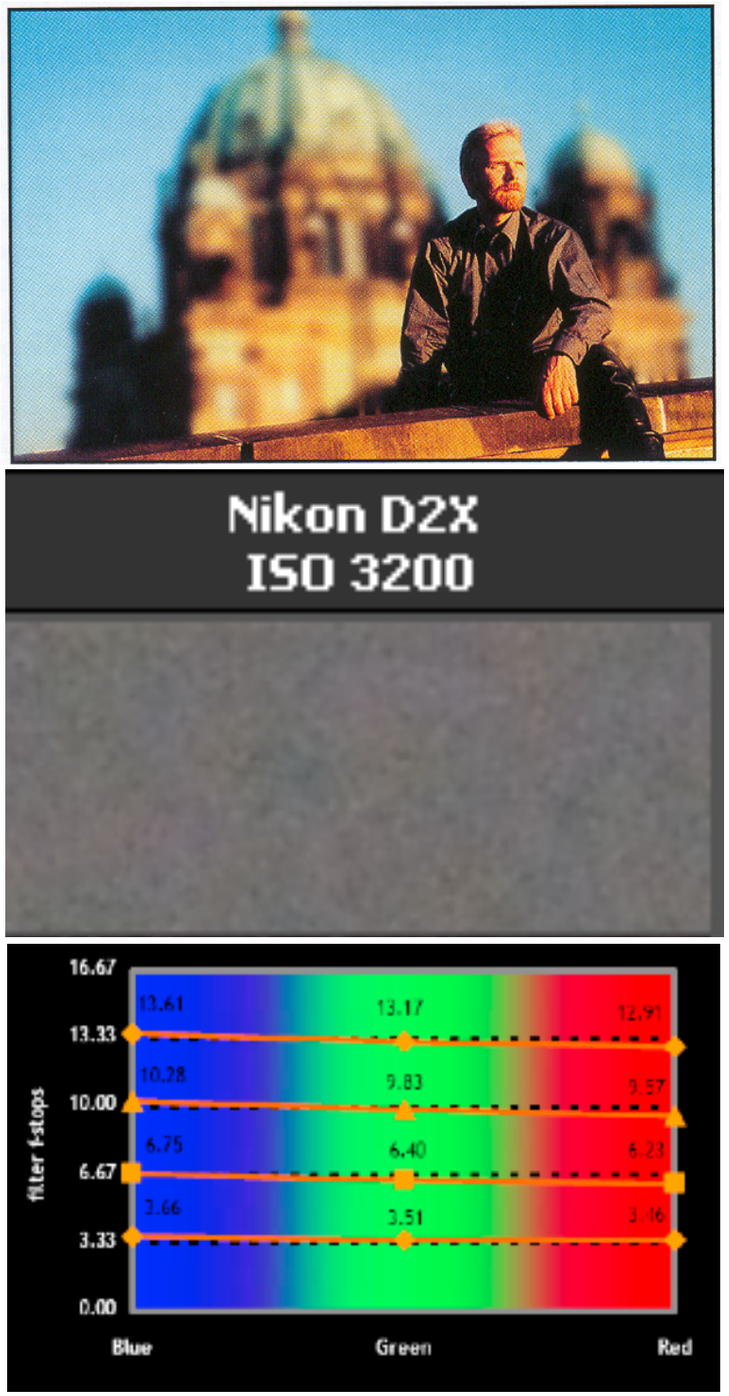
  - ISO
  - Neutral density filter



Slide inspired by Siggraph 2005 course on HDR

Tradeoffs

- **Shutter speed**
  - Range: ~30 sec to 1/4000sec (6 orders of magnitude)
  - Pros: reliable, linear
  - Cons: sometimes noise for long exposure
- **Aperture**
  - Range: ~f/1.4 to f/22 (2.5 orders of magnitude)
  - Cons: changes depth of field
  - Useful when desperate
- **ISO**
  - Range: ~100 to 1600 (1.5 orders of magnitude)
  - Cons: noise
  - Useful when desperate
- **Neutral density filter**
  - Range: up to 4 densities (4 orders of magnitude) & can be stacked
  - Cons: not perfectly neutral (color shift), not very precise, need to touch camera (shake)
  - Pros: works with strobe/flash, good complement when desperate



Slide after Siggraph 2005 course on HDR

Gustave Le Gray, 1857

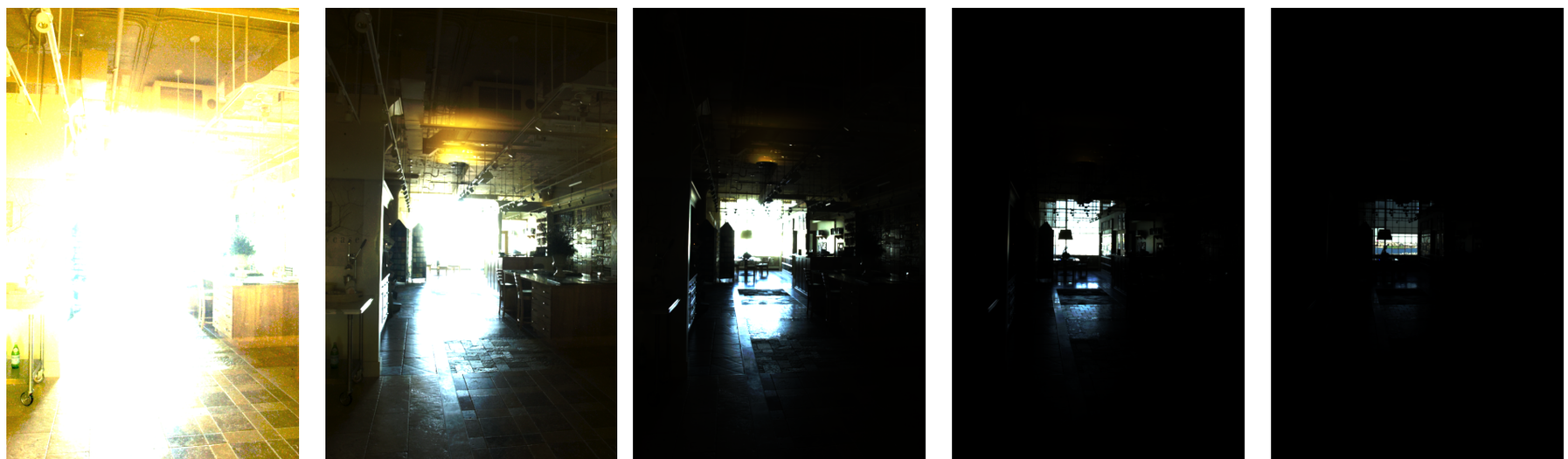
- http://www.metmuseum.org/collection/the-collection-online/search/283124



HDR merging: linear case

Problem statement

- **We have N images**
  - Images are encoded linearly
  - Only the exposure changes: no motion
- **We want 1 single HDR image**
  - encoded with same Image class
  - one value per x, y, c
  - values may be >1



Getting linear images

- http://www.mit.edu/~kimo/blog/linear.html
- http://www.luminous-landscape.com/forum/index.php?topic=25064
- http://www.guillermoluijk.com/tutorial/dcraw/index_en.htm
- ./dcrawx86 -v -H 0 -g 2.2 0 -o 1 DSC_*nef

Image formation: photons to floats

- Scene radiance L(x,y) reaches the sensor at a pixel x, y
- Value of pixel?
  - depends on shutter speed, aperture, ISO
    - multiplicative factor
  - clips if >1
  - noise gets added



Image formation

- Scene radiance L(x,y) reaches the sensor at a pixel x, y
- For each image i,
  radiance gets multiplied by exposure factor k_i
  - depends on shutter speed, ISO, etc
- **Noise n gets added**
- **values above 1 get clipped**
  - depends on photosite well capacity

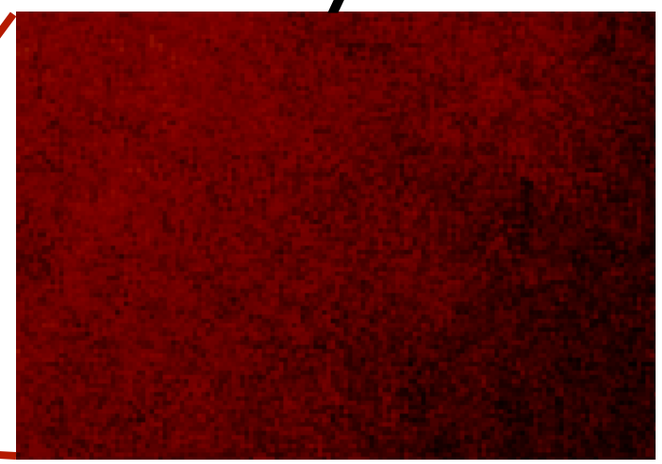
$$I_i(x, y)=\text{clip}(k_i\, L(x,y)+n)$$

Dynamic range

- In the highlights, we are limited by clipping
  - Value >1 saturate to 1
- In the shadows, we are limited by noise



Brightened many times



Merging HDR

$$I_i(x, y)=clip(k_i\ L(x,y)+n)$$



Merging HDR

$$I_i(x, y)=clip(k_i\ L(x,y)+n)$$

- For each pixel
  - figure out which images are useful
  - scale values appropriately according, ideally, to ki
  - Voila!



Questions?

$$I_i(x, y)=\text{clip}(k_i\, L(x,y)+n)$$

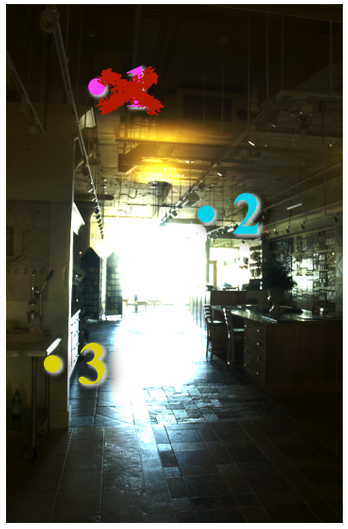
- For each pixel
  - figure out which images are useful
  - scale values appropriately according, ideally, to ki
  - Voila!



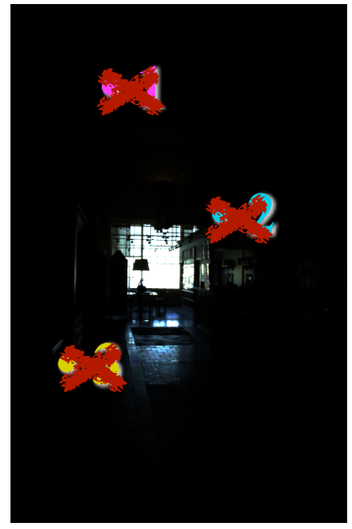
Which images are useful

- Eliminate clipped pixels
  - e.g. >0.99
- Eliminate pixels that are too dark / too noisy
  - e.g. <0.002





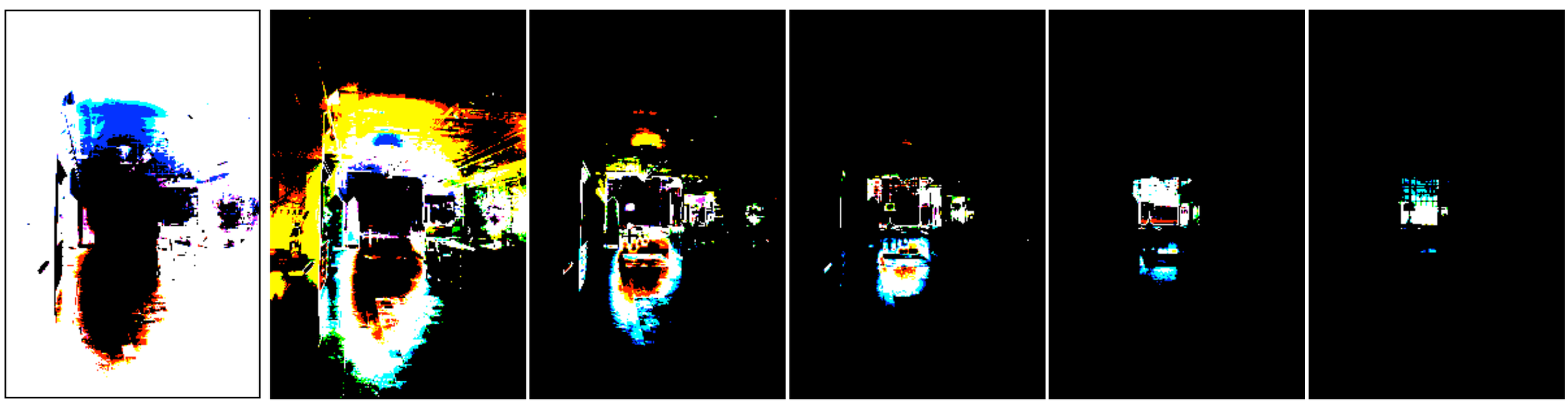






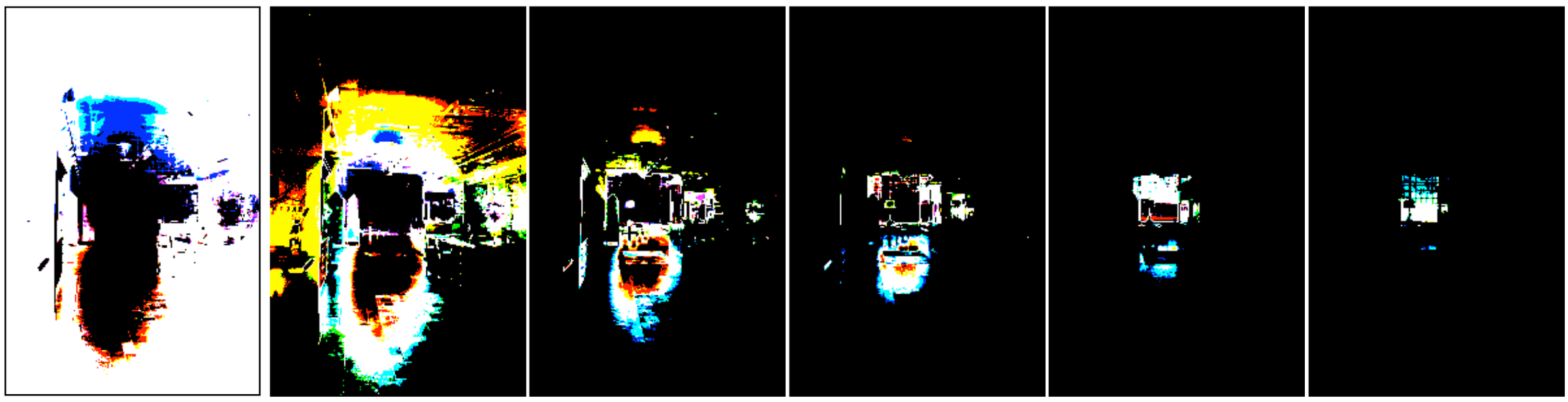
Eliminate bad pixels

- In PSet 5
- We compute a weight map for each image
- We use binary weights (0 or 1)
  - But can be extended to full scalar
  - In particular for better handling noise
- Weights can be different for different channels



Weight map

- We compute a weight map for each image



Assembling HDR

Assembling HDR

- **Figure out scale factor between images**
  - From exposure data
  - Or by looking at ratios $I_i(x,y)/I_j(x,y)$
    - but only when both are good
- **Compute weight map w_i for each image**
- **Reconstruct full image using weighted combination per pixel**

$$out(x,y) = \frac{1}{\sum w_i(x,y)} \sum w_i(x,y) \frac{1}{k_i} I_i(x,y)$$

Computing ki











Computing ki

- compute ki/kj for adjacent exposures
- just look at ratio of corresponding pixels
  - only for useful pixels



Computing ki in pset 5

- Only up to global scale factor
- Actually compute ki/kj for pairs of images
- Focus on pixels where
  - no clipping occurs & noise is negligible
- Ii(x, y)=ki L(x,y)
- get ki/kj by considering Ii/Ij
- If linearity holds, should be the same for all pixels
- Use median for extra robustness

Computing ki in pset 5

$$I_i(x, y)=\text{clip}(k_i\, L(x,y)+n)$$

- Only up to global scale factor, e.g. ki/k0
- Actually compute ki/kj for pairs of images
- ki/kj=median(Ii(x,y)/Ij(x,y)
  - for pixels st. wi(x,y)>0 AND wj(x,y)>0

- **Then compute ki/k0 by chaining these ratios**

Cleaner way

- You could use a (robust) regression to avoid computing ratios
- Would also make it easy to directly model uncertainty due to noise

- Also generalizes to full non-linear response
  - See Debevec and Malik 96

Special cases

- Some pixels might be underexposed or overexposed in **all** images
- Simple solution: don’t eliminate dark pixels in the brightest image or bright pixels in the darkest one.
  - Pay attention: dark pixels in the brightest (and vice versa), not other way around.
  - Careful is you implement it by changing the thresholds that values 0.0 (resp. 1.0) are actually kept



I call this the brightest image









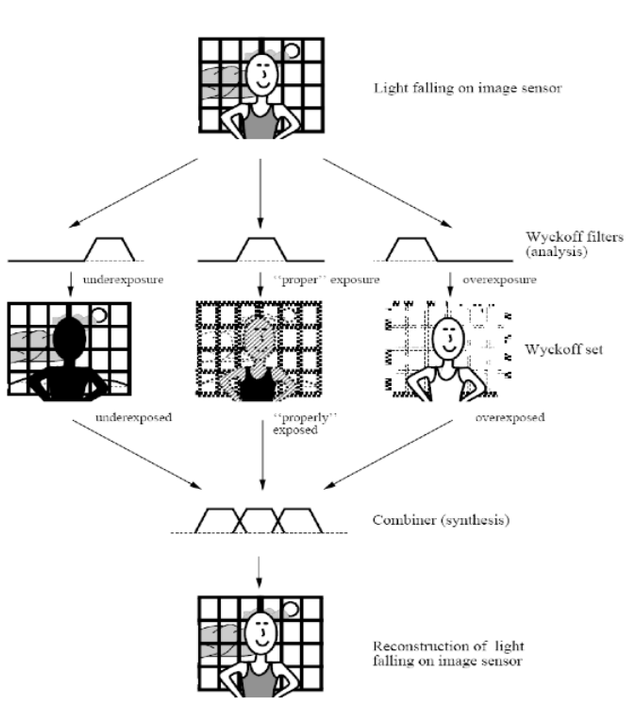
I call this the darkest image

In the end: HDR image

- Encoded with same image class
- One single float value per x, y, c
- numbers may be >1

HDR combination papers

- **Steve Mann http://genesis.eecg.toronto.edu/wyckoff/index.html**
- **Paul Debevec http://www.debevec.org/Research/HDR/**
- **Mitsunaga, Nayar , Grossberg http://www1.cs.columbia.edu/CAVE/projects/rad_cal/rad_cal.php**
- **http://people.csail.mit.edu/hasinoff/hdrnoise/**

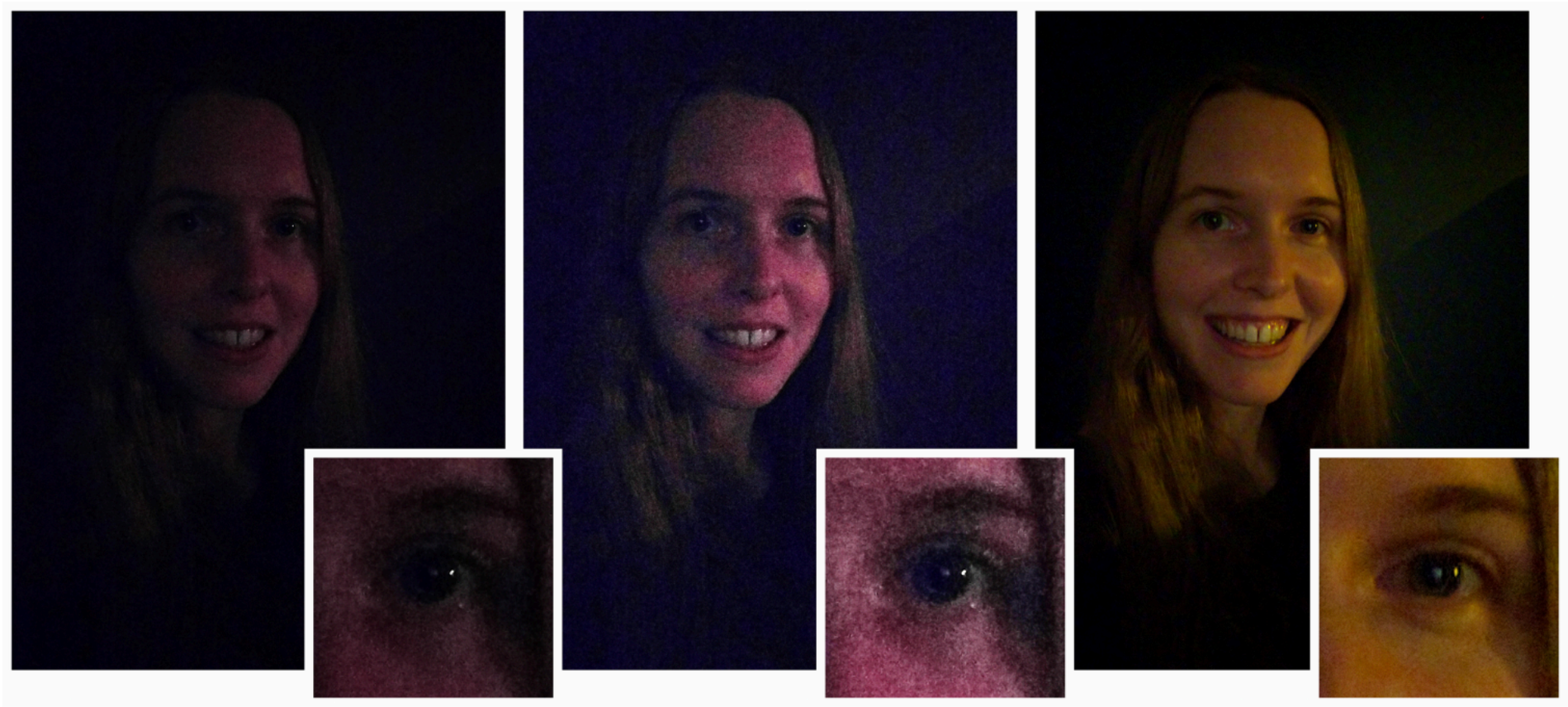


HDR+ on Android

- http://static.googleusercontent.com/media/hdrplusdata.org/en//hdrplus.pdf
- https://ai.googleblog.com/2018/02/introducing-hdr-burst-photography.html

Burst photography for high dynamic range and low-light imaging on mobile cameras

Samuel W. Hasinoff Dillon Sharlet Ryan Geiss Andrew Adams
Jonathan T. Barron Florian Kainz Jiawen Chen Marc Levoy
Google Research



Traditional Darkroom

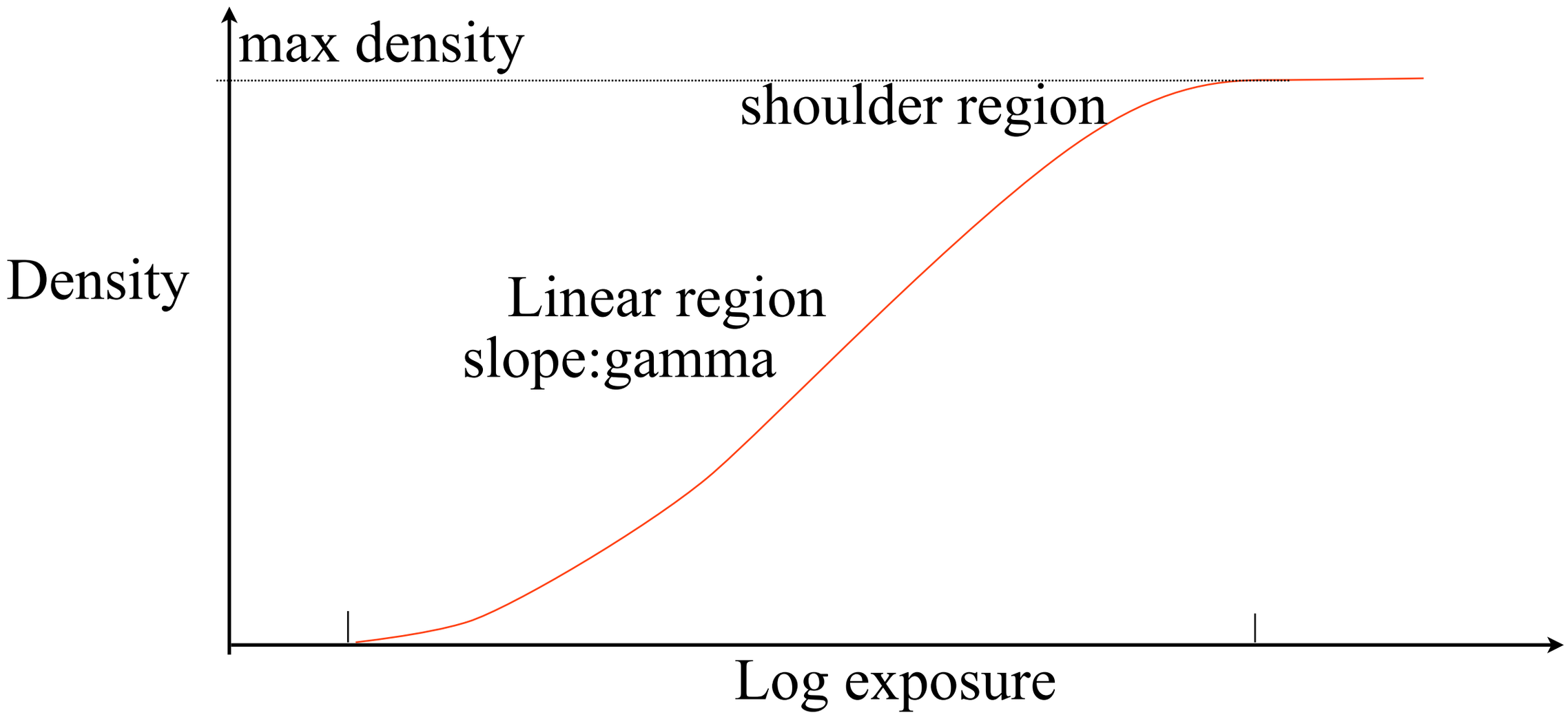
Limited dynamic range can be good!

- **W. Eugene Smith photo of Albert Schweitzer**
- **5 days to print!**
- **Things can be related because the intensity is more similar**
- **Balance, composition**



Negative and response curve

- **Negatives typically afford 3 orders of magnitude**
- **More than printing paper**
- **shoulder region provides a little more dynamic range (but less precision there)**



Response curve manipulation

- **Traditional photography**
  - Chemicals and duration of development
  - Paper grade (~γ)
  - Flashing the paper before printing
  - Various chemicals on paper
  - Note: you have one curve for negative, one for paper
    Usually they have inverse gamma (but not strictly, enables contrast control)
- **Digital**
  - Curve tool

Photoshop curves

- **Specify an arbitrary remapping curve**
- **Especially useful for black and white**

How the Curves Work

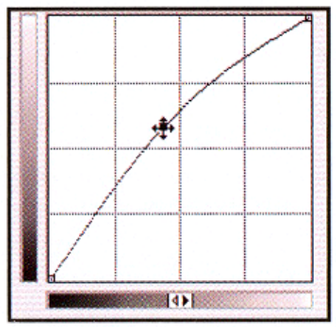
The Curves dialog box for every image opens with a straight diagonal line (see box, above). The midpoint of the line is 128, middle gray; 0, at the bottom left, is pure black; 255, at the top right, is pure white.

Cursor is first a crosshair

and becomes a grab tool once a point is selected.

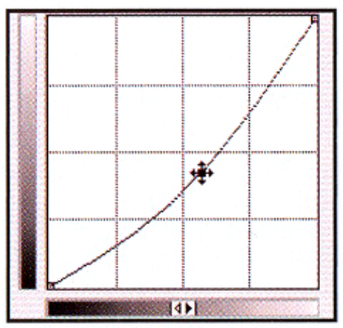


Original image



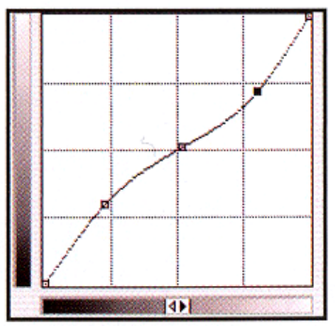


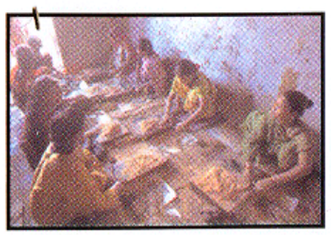
Click on the middle of the line and drag the curve up to lighten the image overall. See how all the points on the line except black and white have changed?



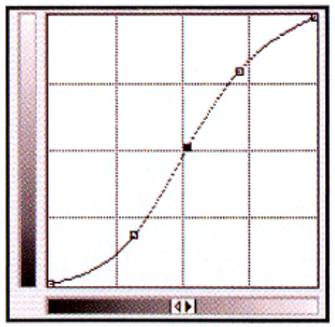


Moving the midpoint down darkens the image overall. Again, all the points on the line—and in the image—have changed, but the black and white points are intact.



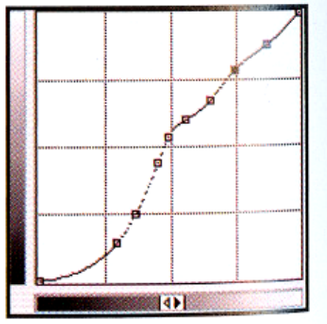


A downward pull in the highlights and an upward pull in the shadows lowers contrast. Here, the midpoint is not moved, so midtones are not affected.





Pulling the shadows down and the highlights up increases contrast. Here also, the midpoint is unchanged, but it can be moved as well.





You can place many points on a curve to adjust any narrow range of tones between two points.

From Photography by London et al.

Examples of curves

- **Brighten**
- **Darken**
- **Contrast**

Chemical curves: developt time

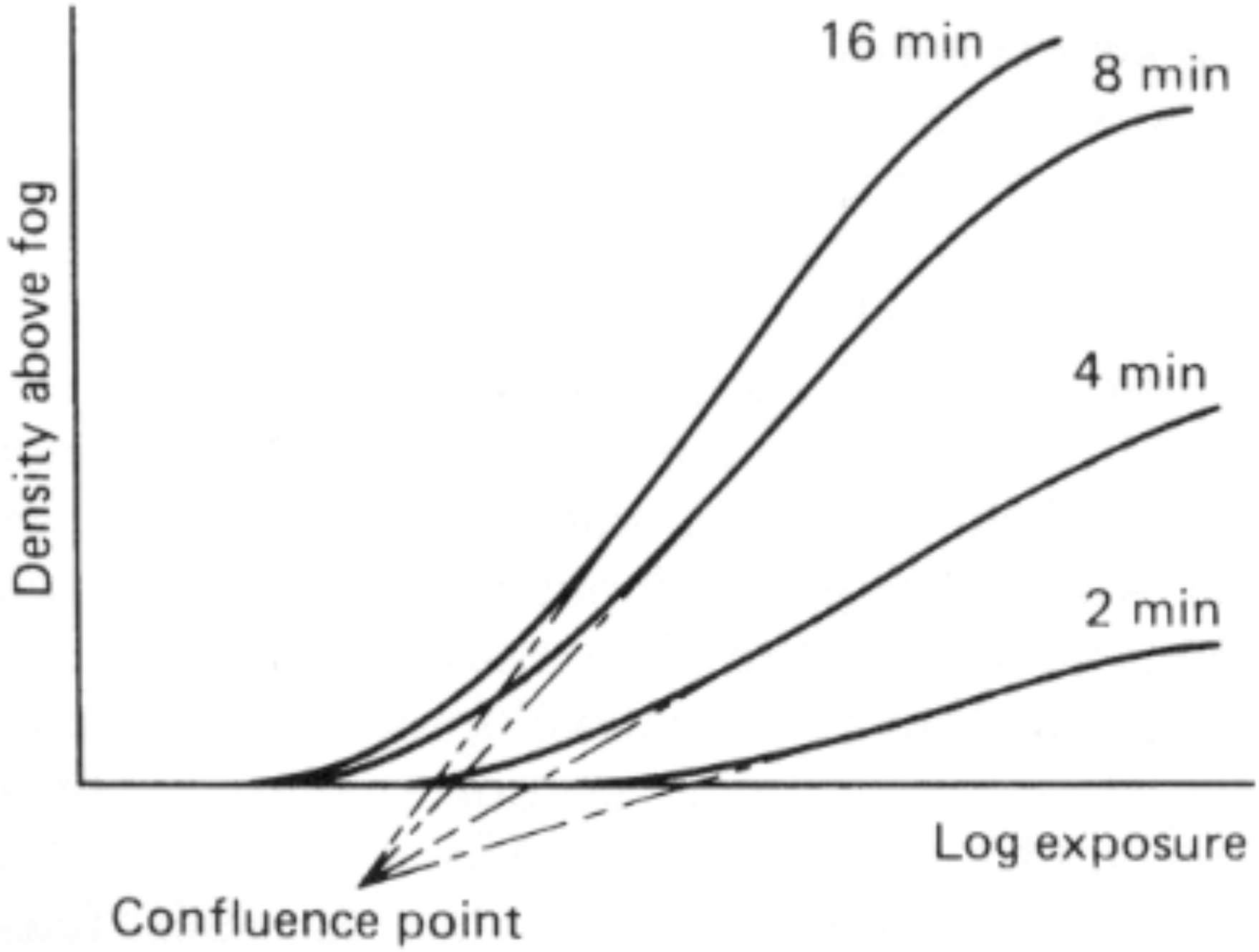
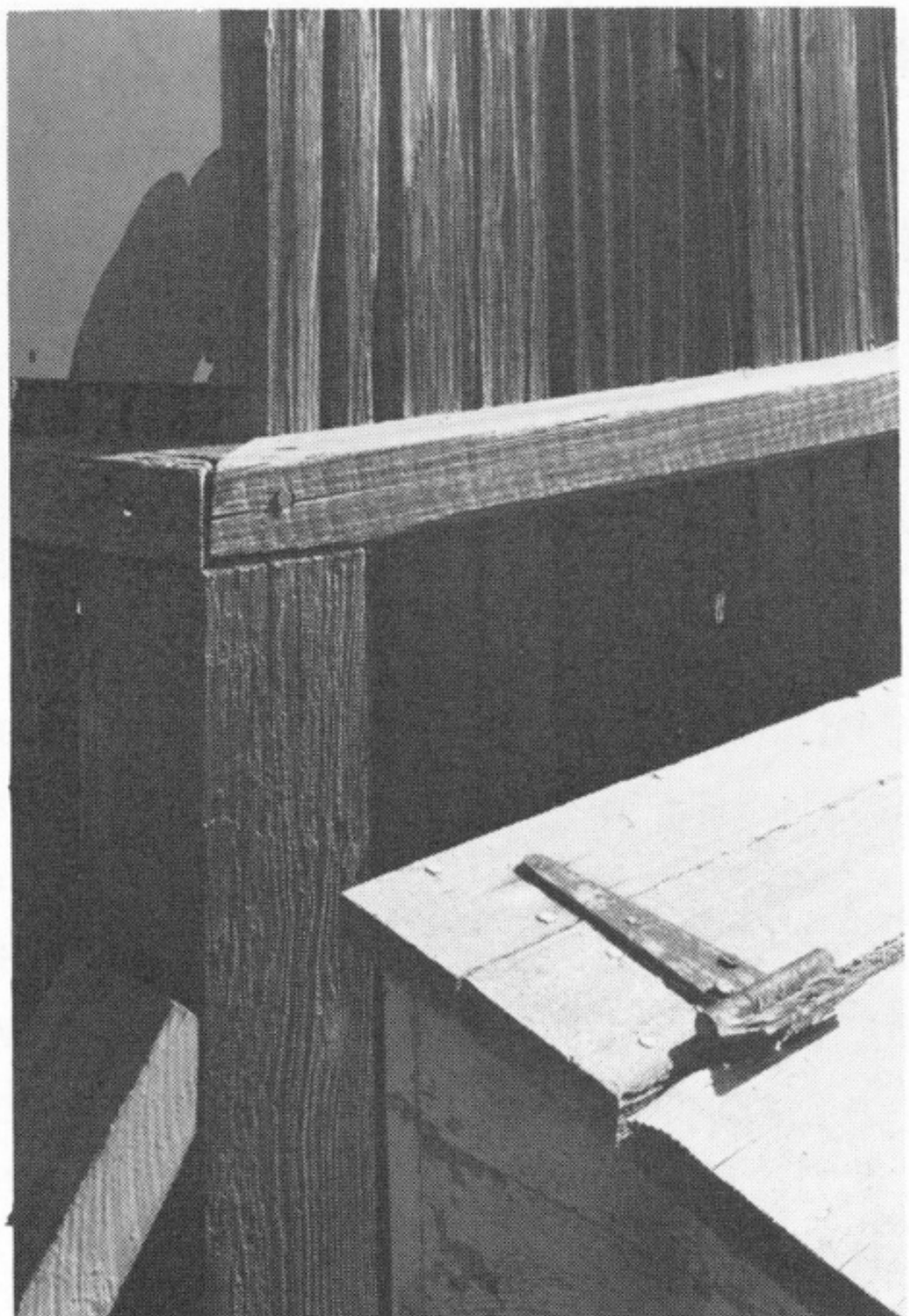


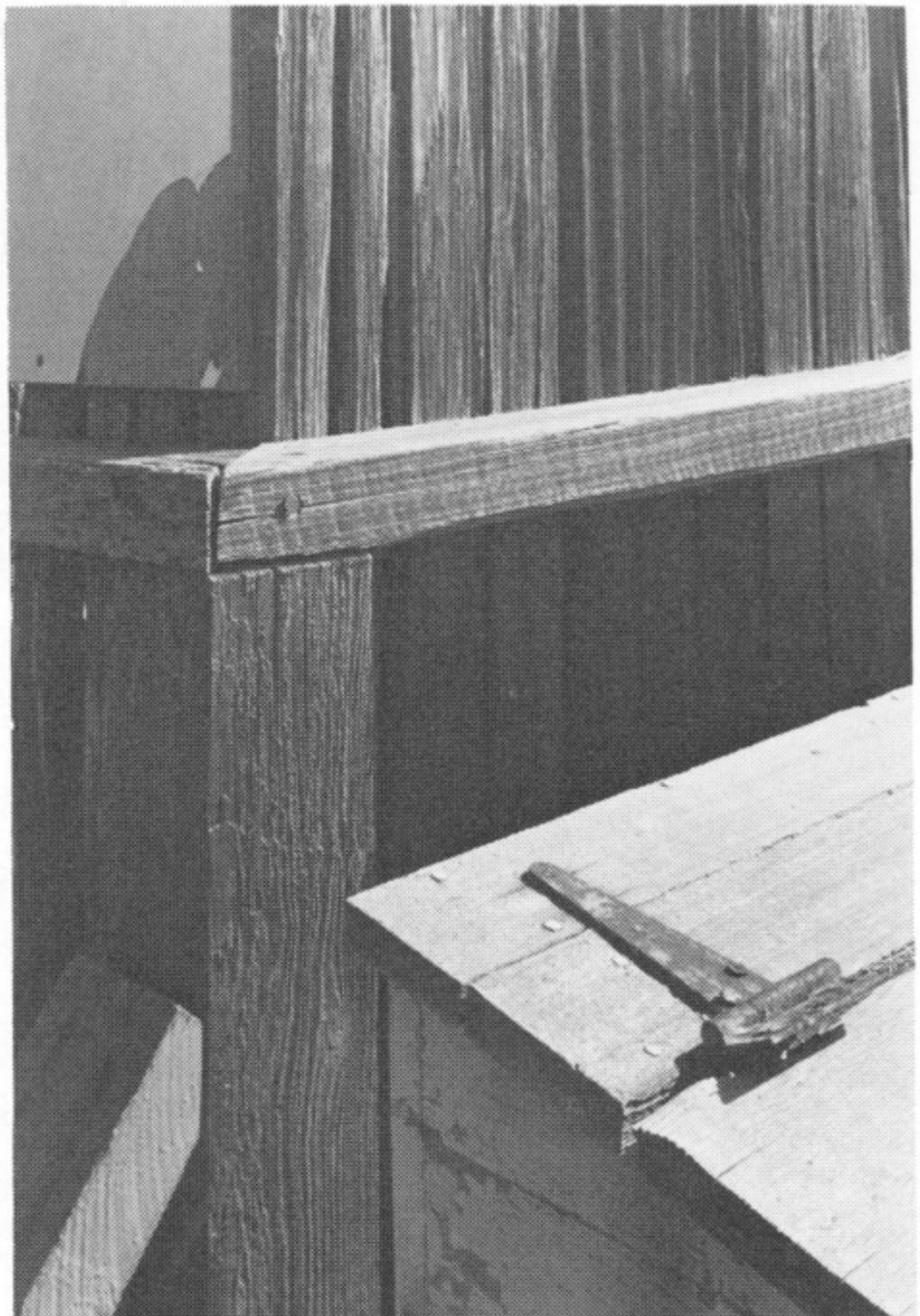
Figure 15.8 Effect of development time on characteristic curve of current sensitive materials

From The Manual of Photography, Jacobson et al.

Reduced development



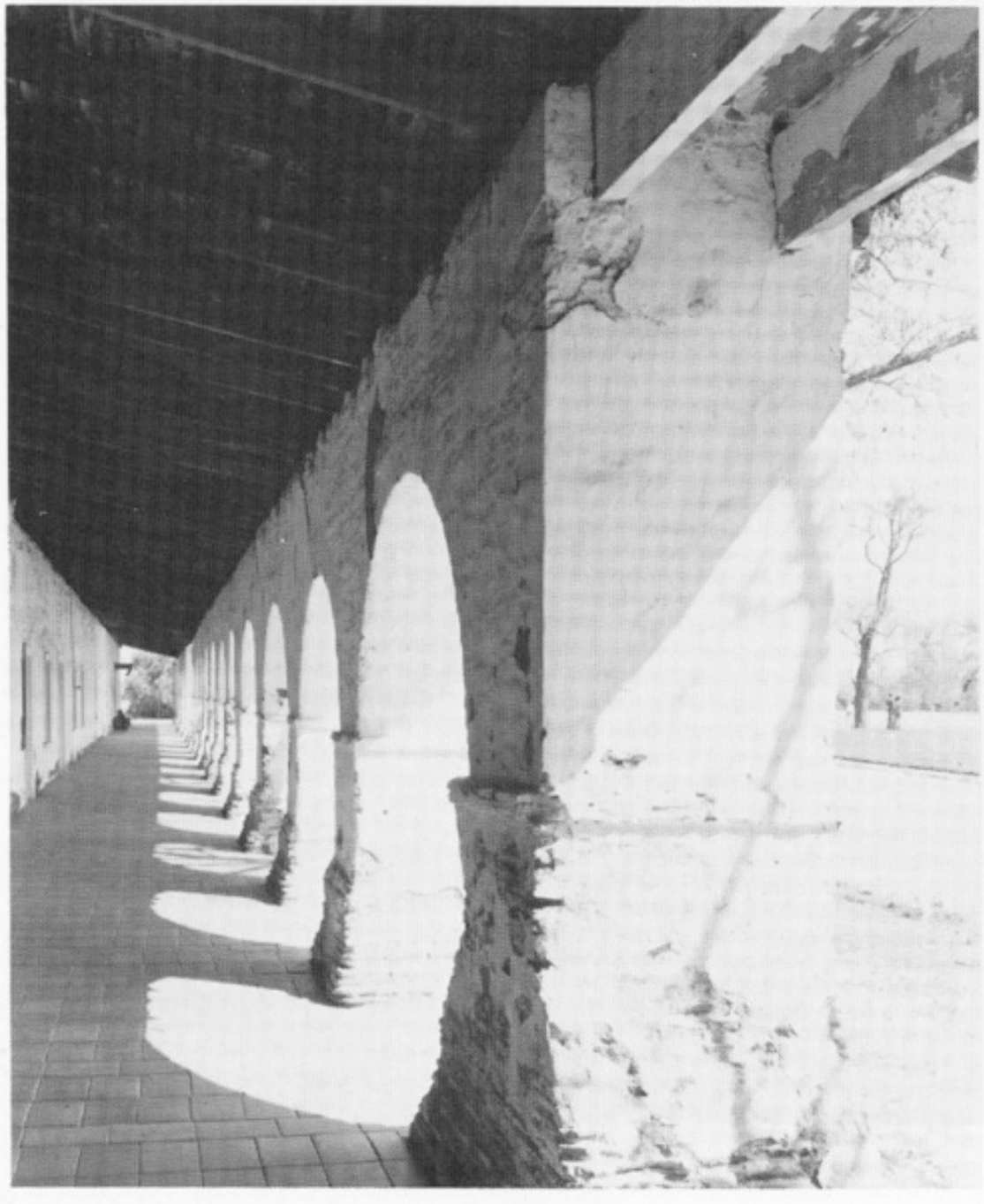
Normal development



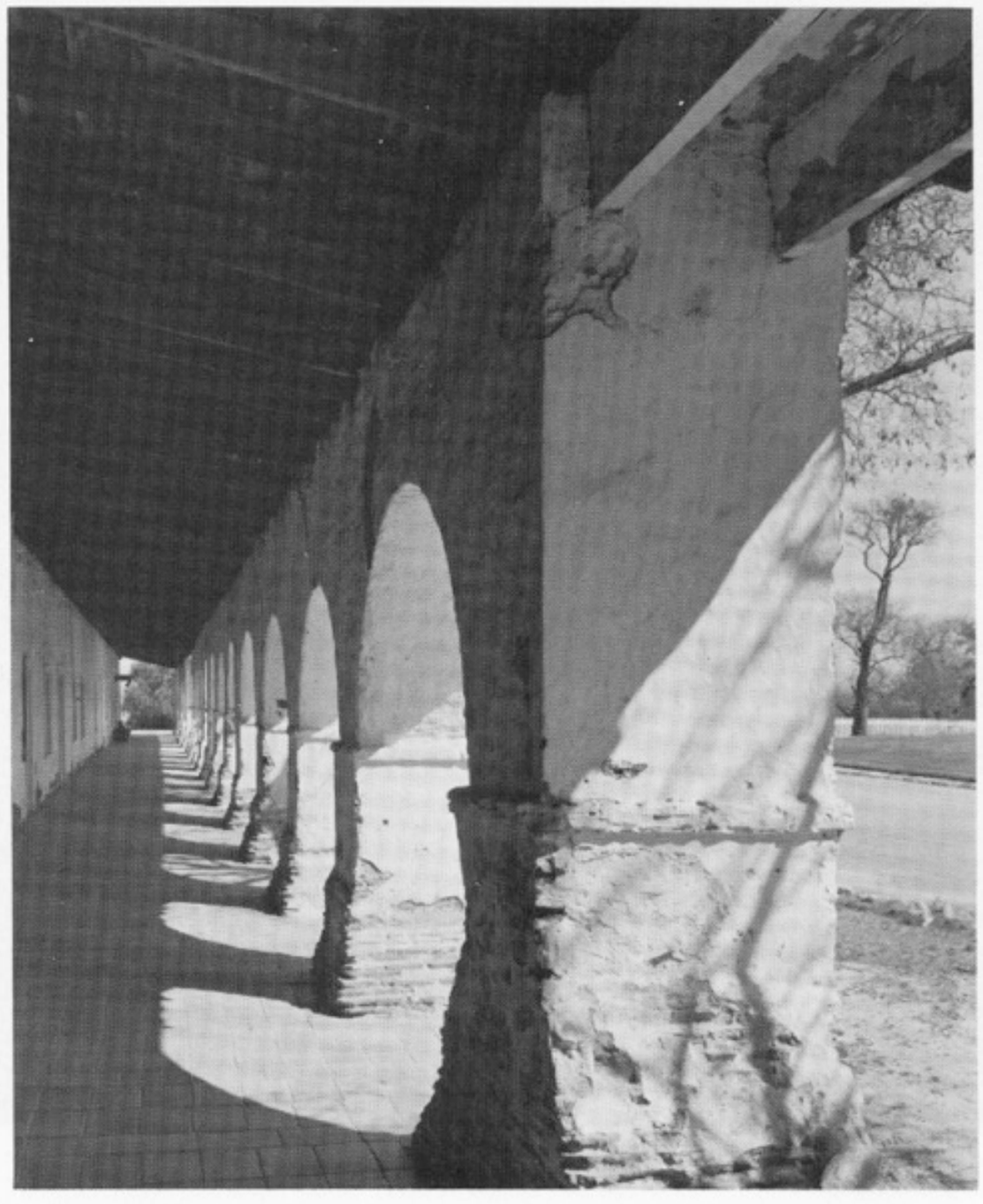
Contraction (short development)

Source: Ansel Adams

Two solutions



One development solution

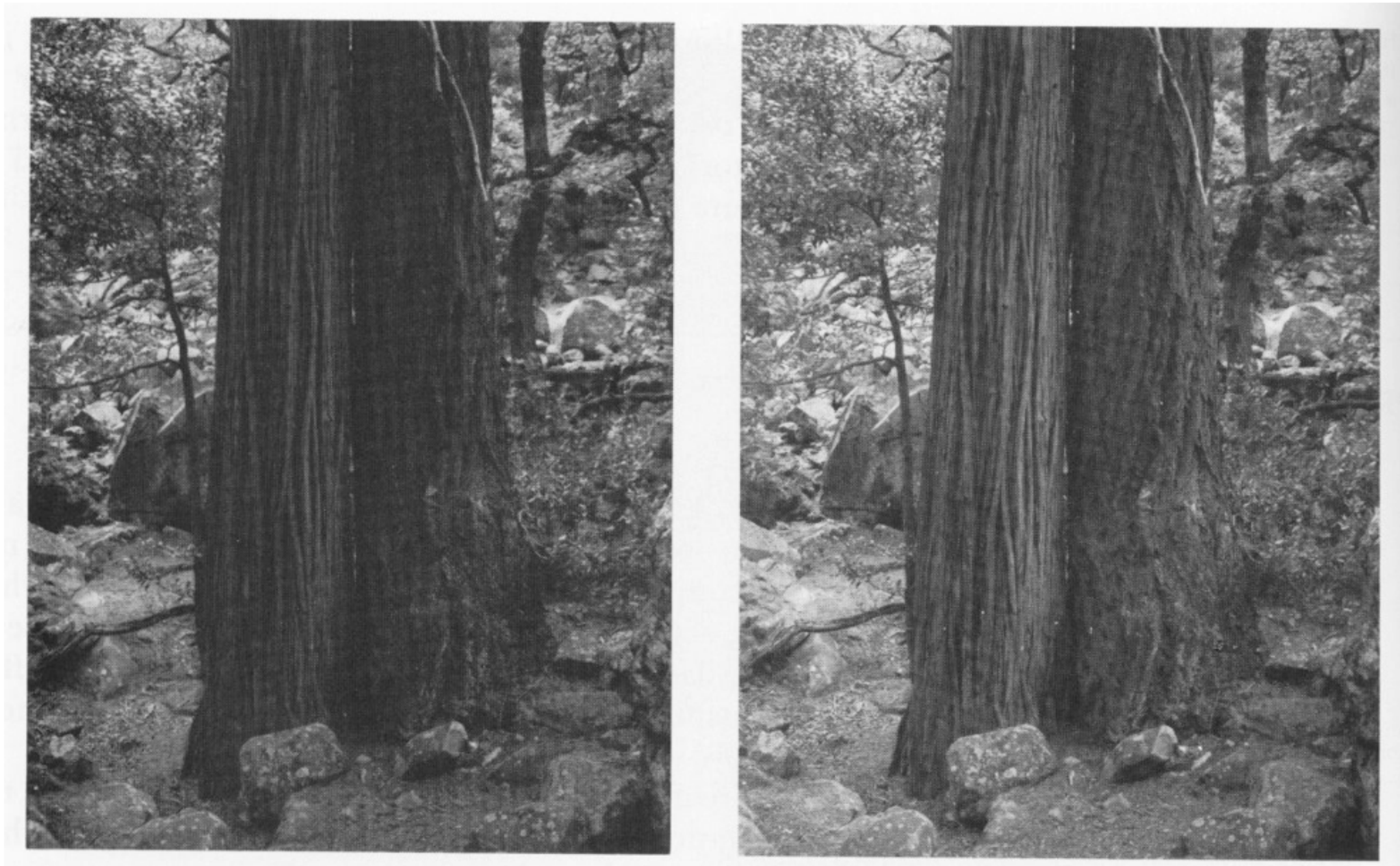


Two development solution:
the dark areas are the same,
but bright areas are different

Source: Ansel Adams

Pre-exposure

- **Briefly expose negative to a uniform light**
- **Raises the values of everything (in particular puts dark values above the low-contrast toe of response curve)**



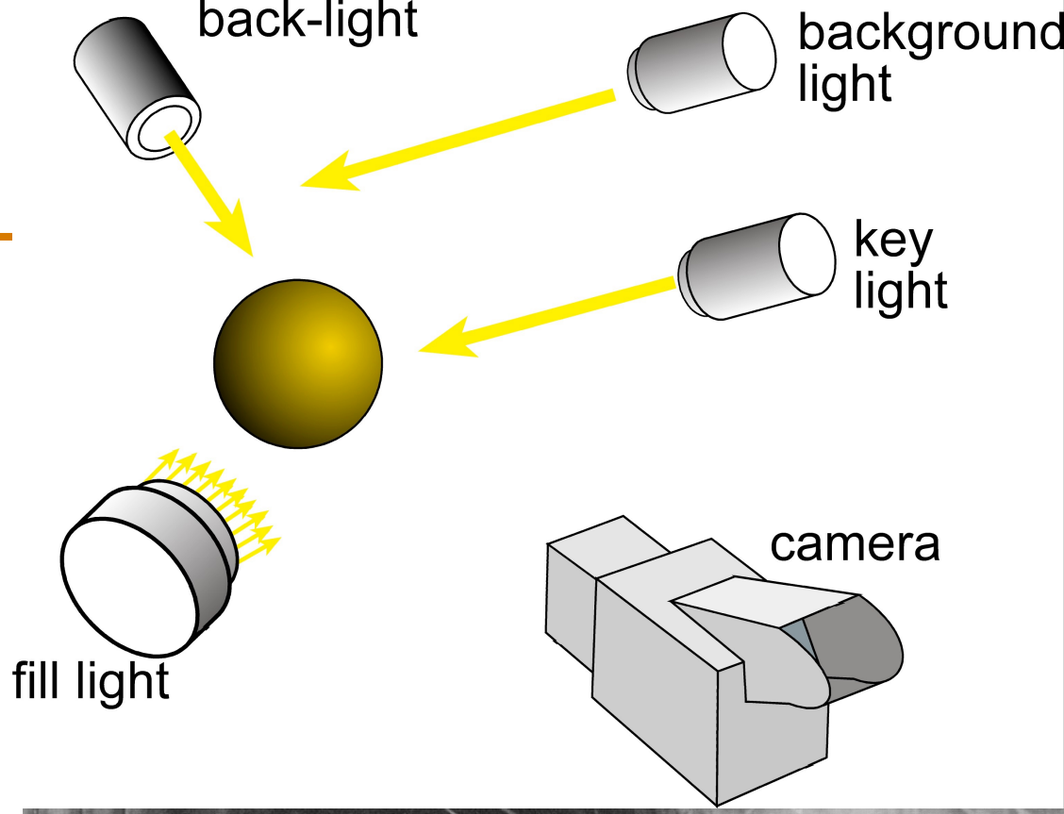
Without pre-exposure

With pre-exposure

Source: Ansel Adams

Lighting

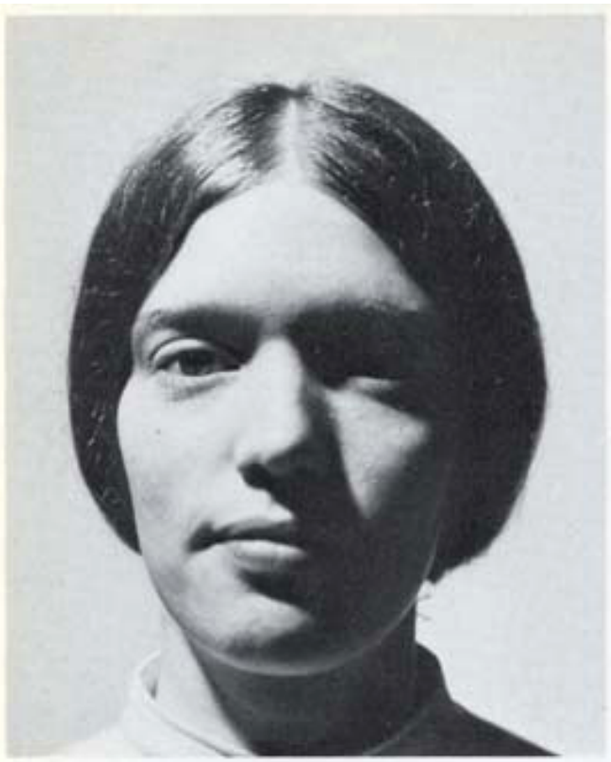
- **E.g. 3-point lighting**
  - Reduce dynamic range
  - Emphasize silhouettes
    ! 3D cues



- **Goals of lighting:**
  - Manage dynamic range
  - Reveal shape, layout, material
  - Tell story



Portrait lighting



Main light



Fill-in light



Accent light



Background light



Without flash



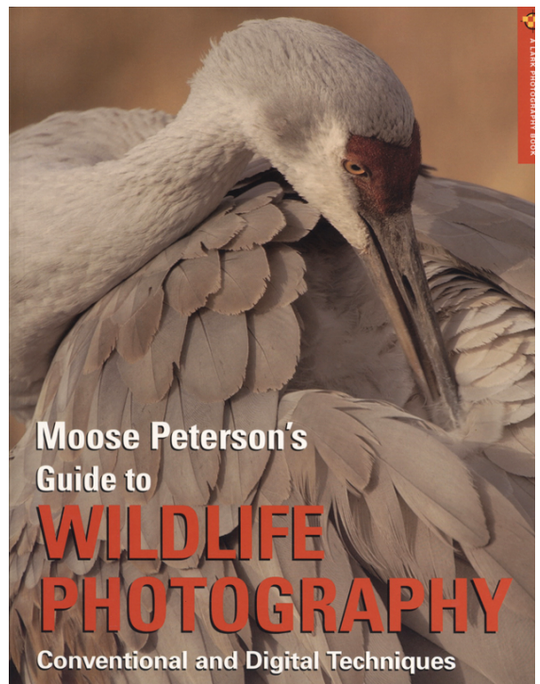
With fill flash



Fill-in flash

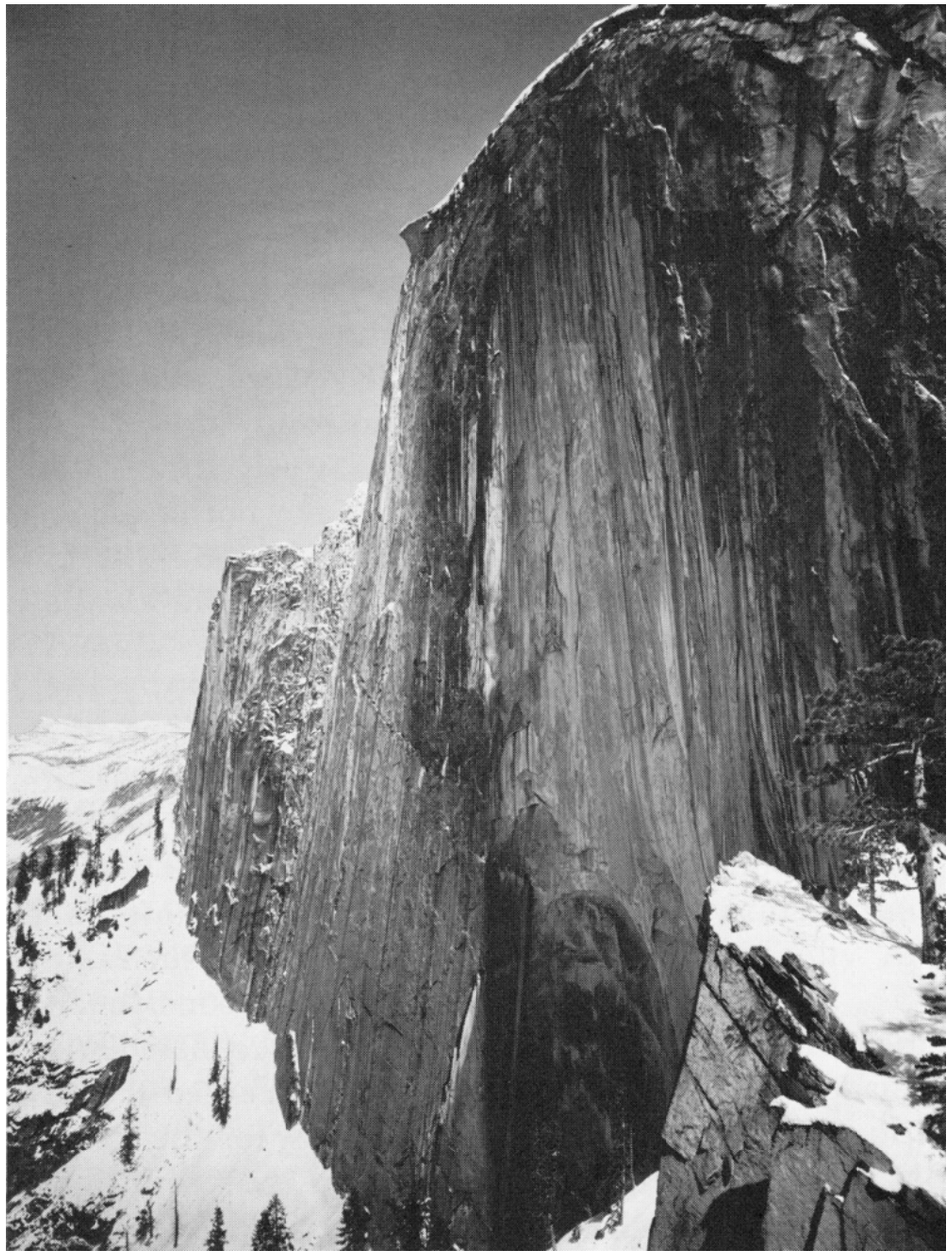




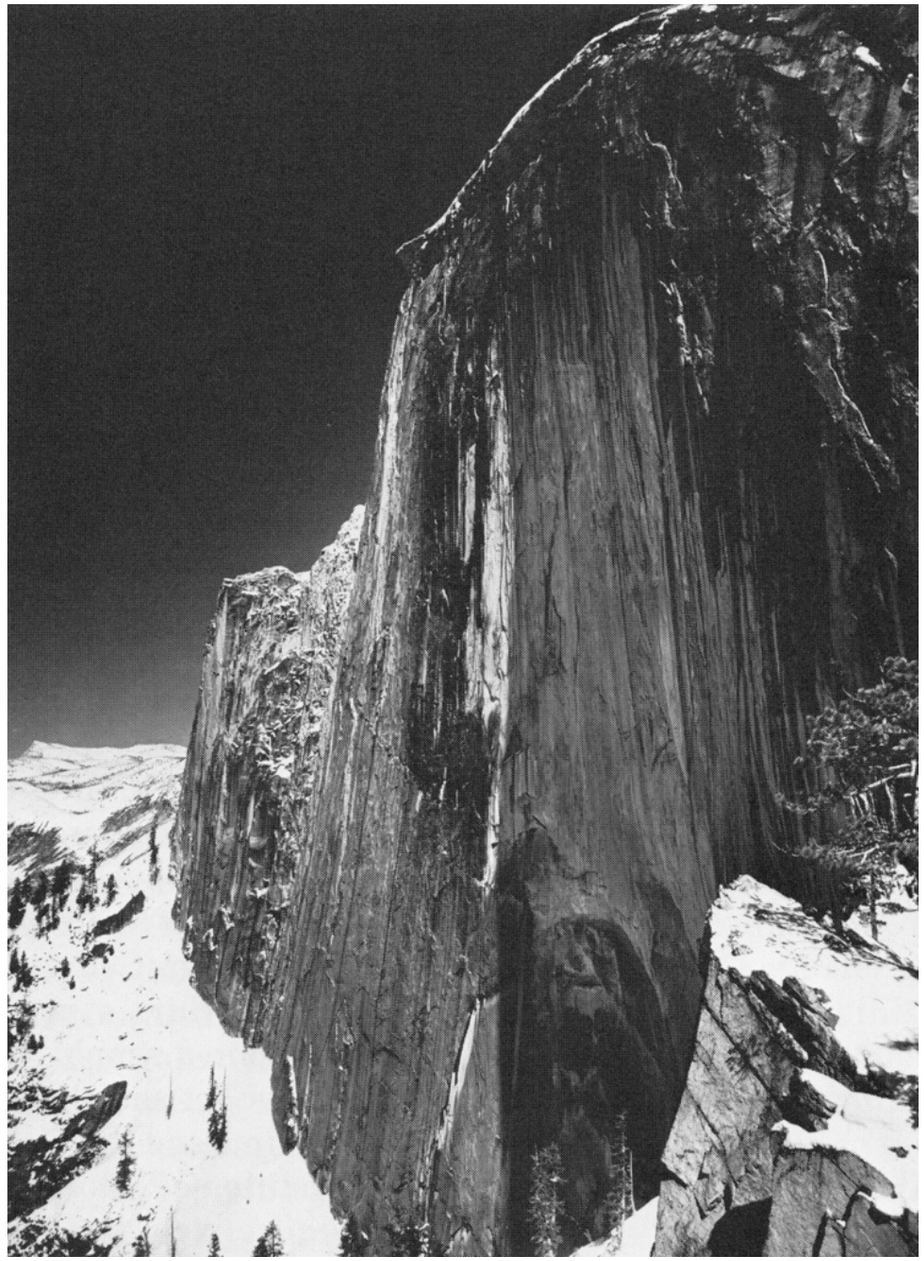


Filtering: black and white

- **Red/orange/yellow filters darken the sky**



No filter



With red filter

Source: Ansel Adams

Graduated neutral density



No filter: sky is too bright



Vertical neutral density gradient

Graduated ND & landscape

- **Art Wolfe: In the late evening light, I composed this image using a graduated neutral-density filter to bring the overall exposure into alignment, thus preserving the detail in the clouds in the sky and the reflections on the water.**



Portage Lake, Horizontal

http://www.artwolfe.com/

Graduated ND & landscape

- **Art Wolfe: Here I had to use a combination of filters and settings that greatly reduced my chance of success. I used my zoom to bring in Denali and the moose. A polarizing filter brought out the rich colors of the tundra and darkening the sky and a graduated, neutral-density filter to bring the entire scene into the same exposure.**



Denali Autumn

http://www.artwolfe.com/

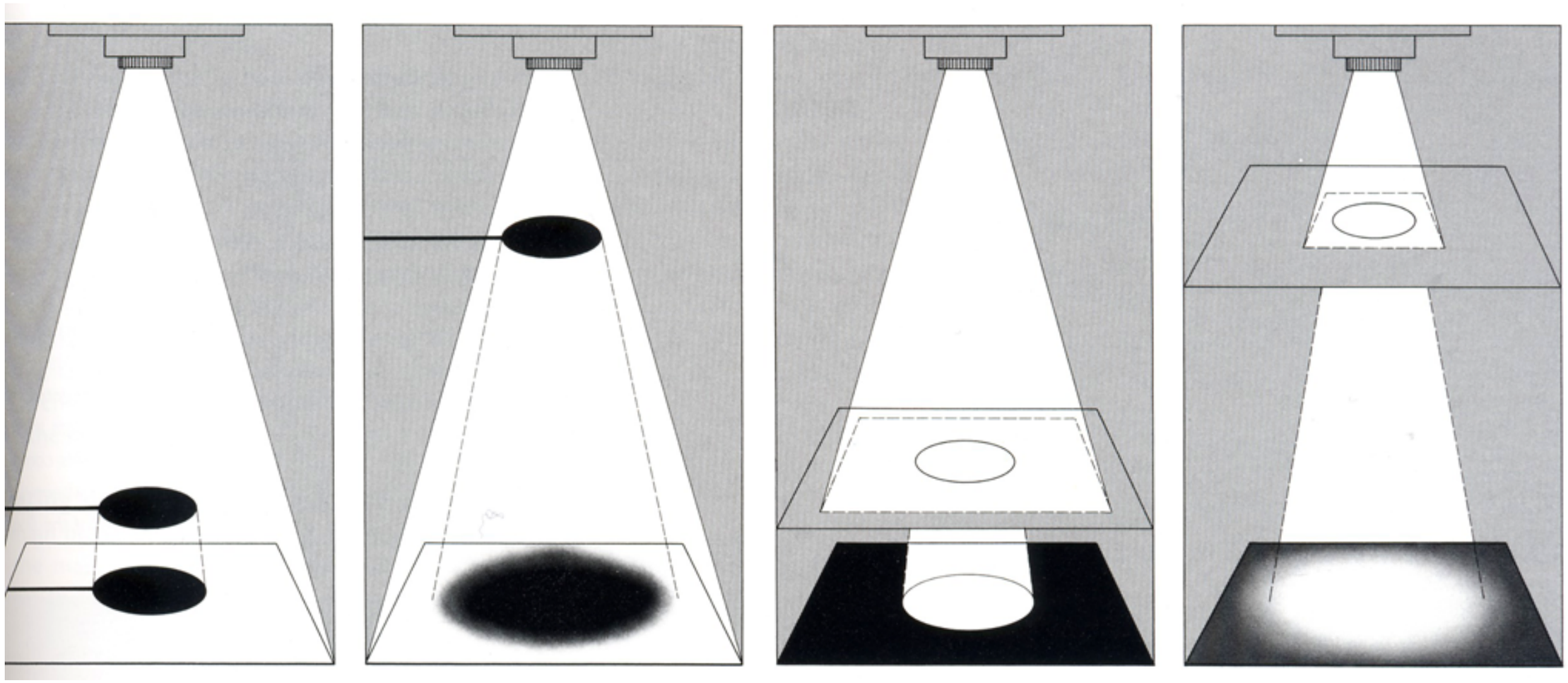
Alternative: Black card

- **http://hanjies.blogspot.com/2009/10/black-card-photography-part-i.html**
- 



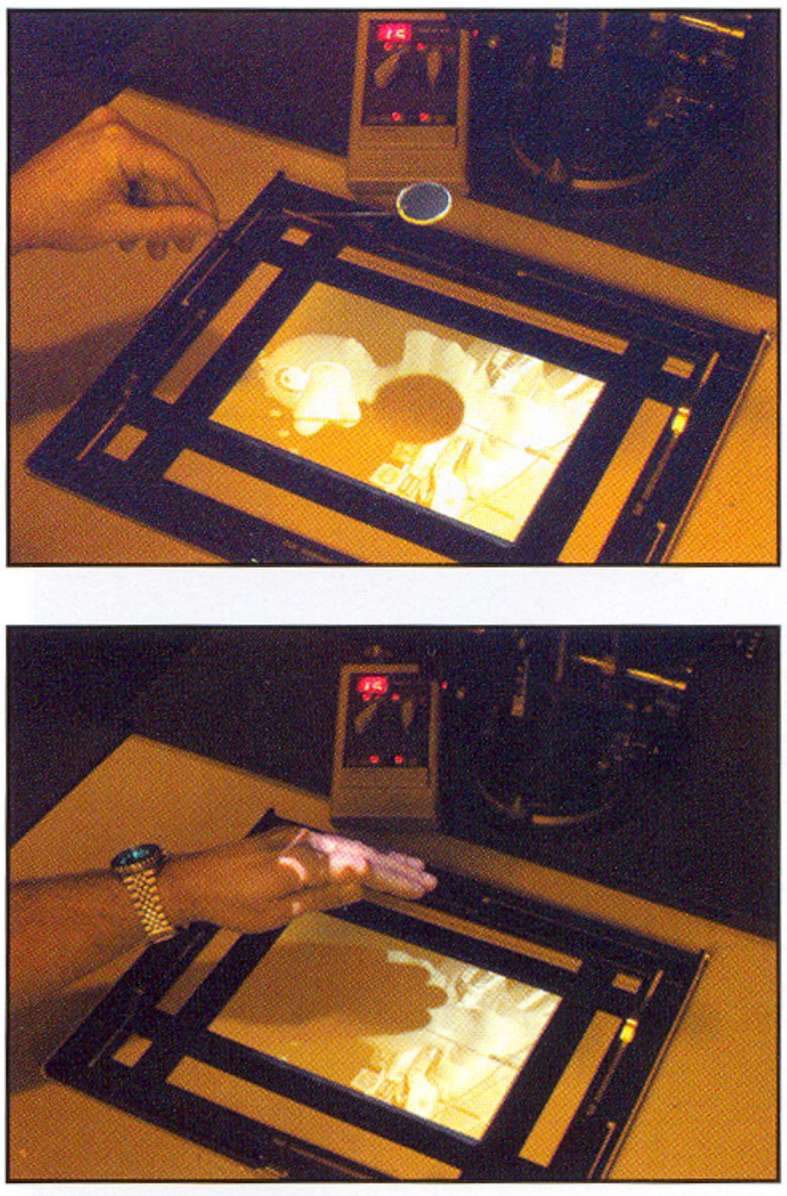
Dodging and burning

- **During the print**
- **Hide part of the print during exposure**
  - Makes it brighter

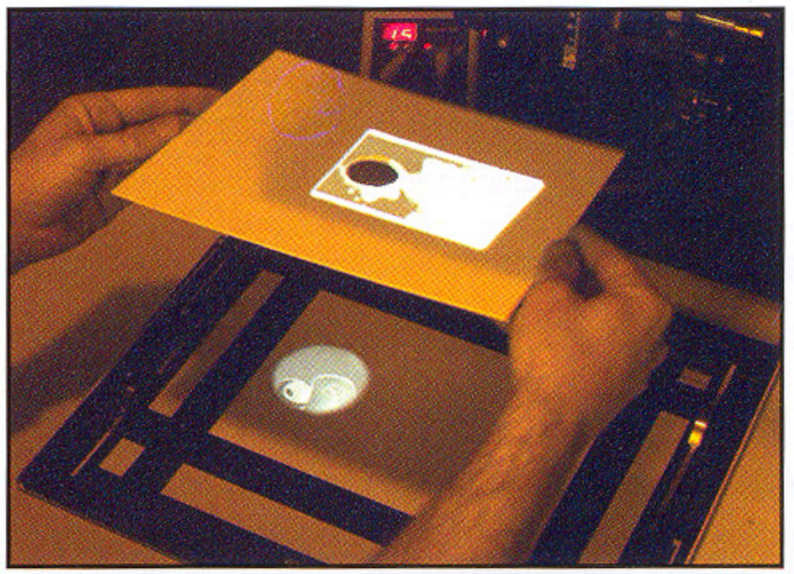


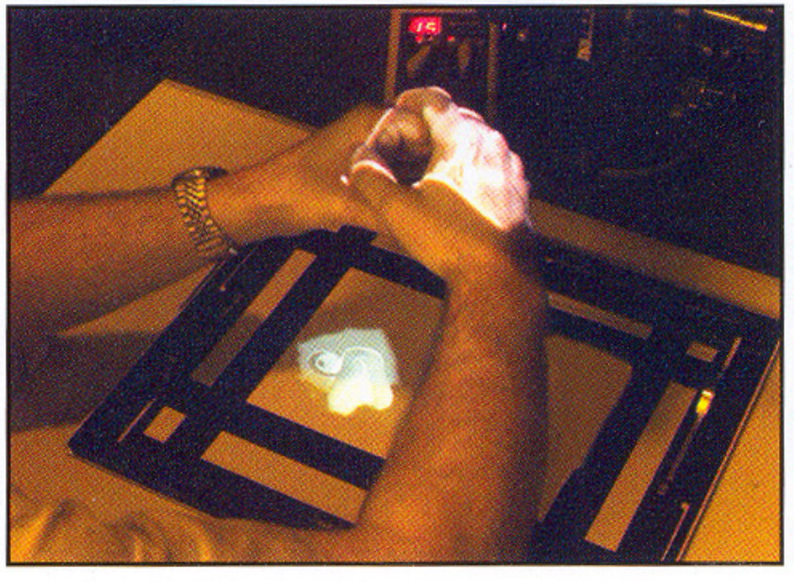
From The Master Printing Course, Rudman

Dodging and burning



Dodging *holds back light during the basic printing exposure to lighten an area.*



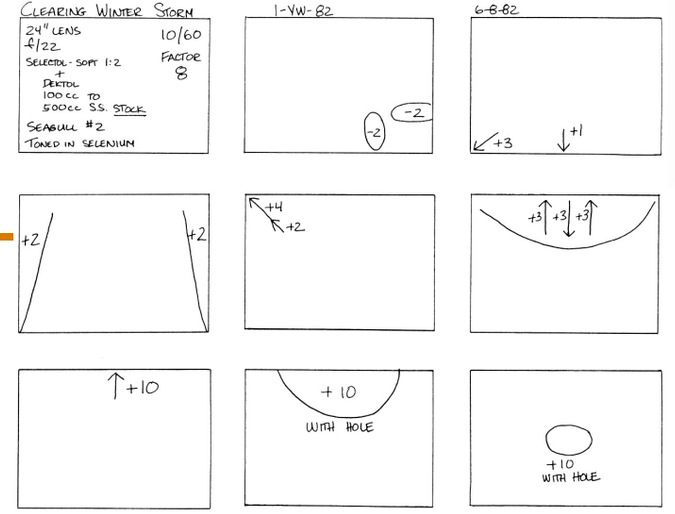


Burning *adds light after the basic exposure to darken an area.*

From Photography by London et al.

Dodging and burning

- **Must be done for every single print!**



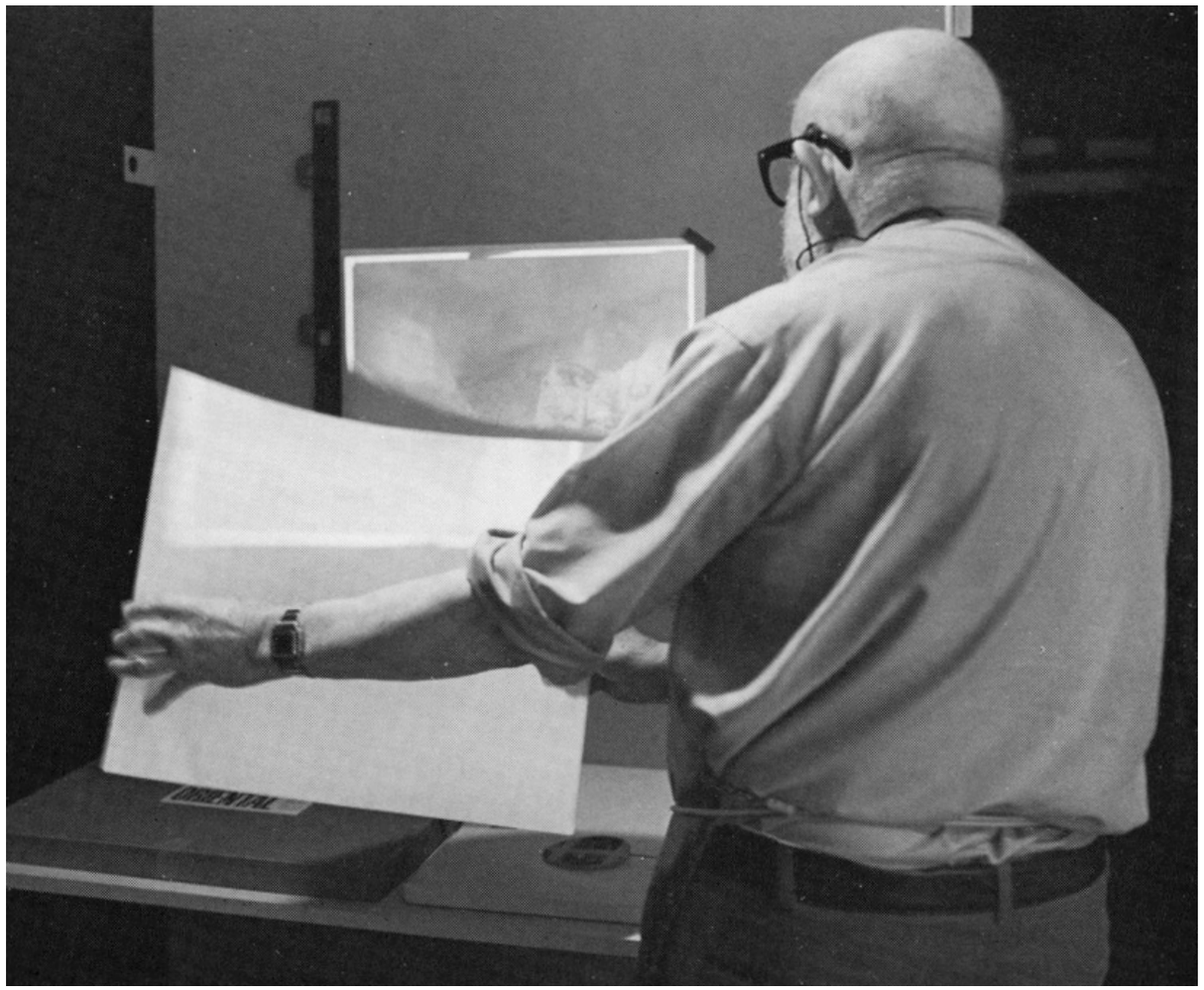


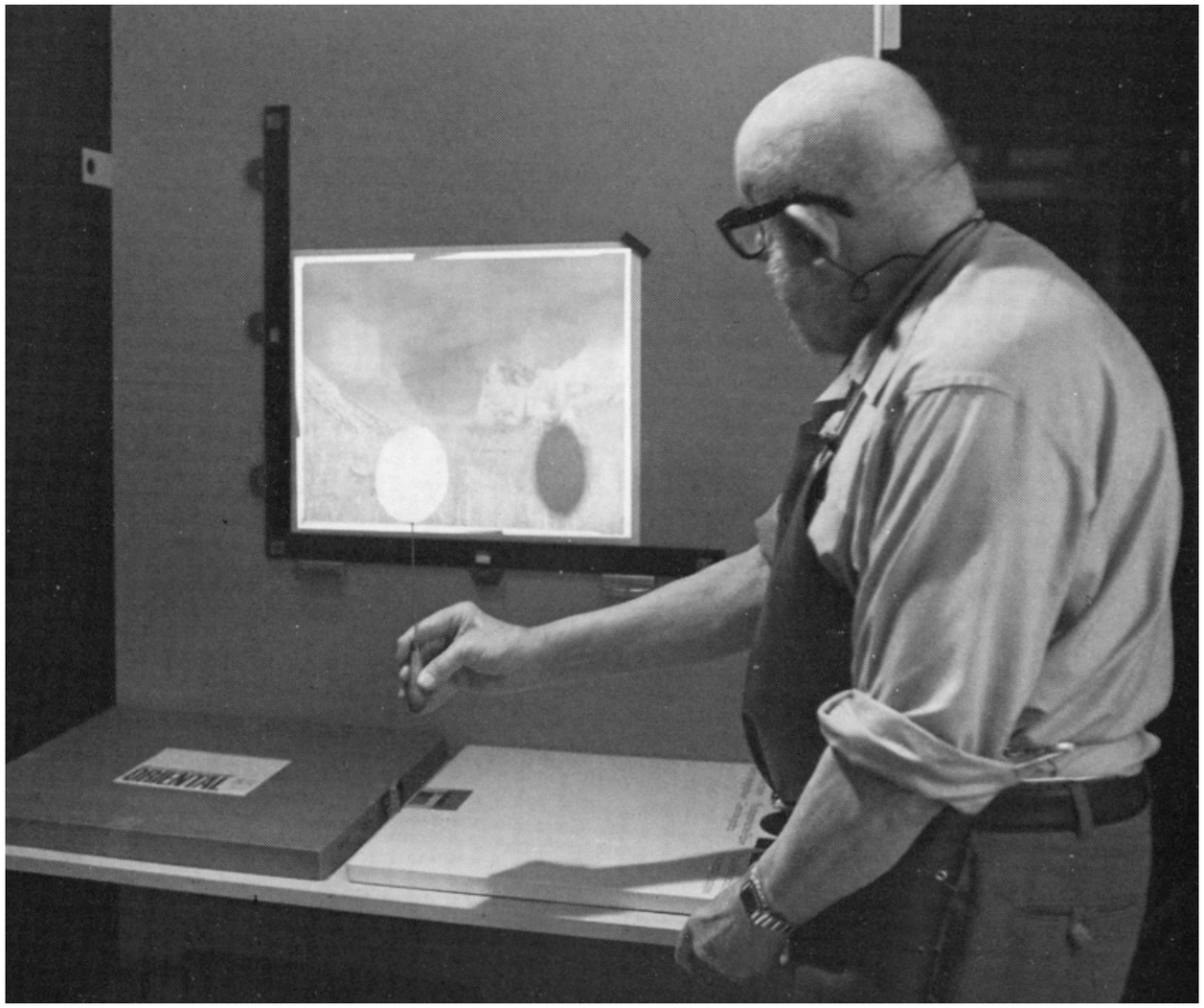
Straight print



After dodging and burning

Dodging and burning



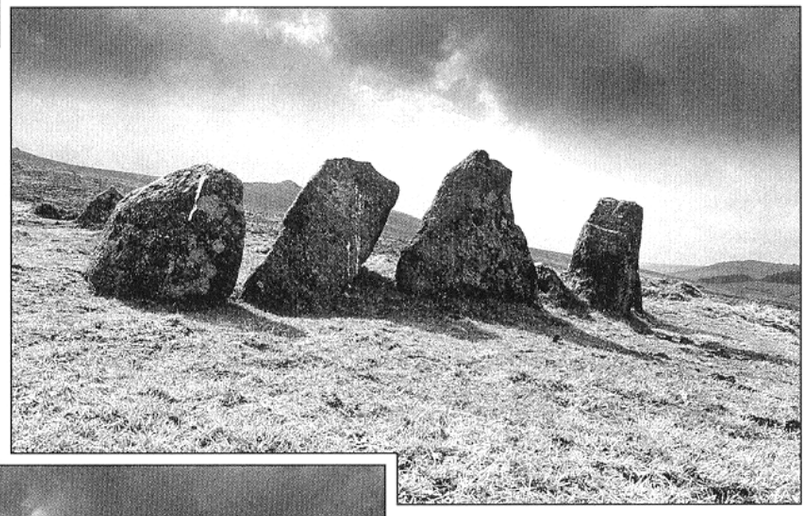


Source: Ansel Adams

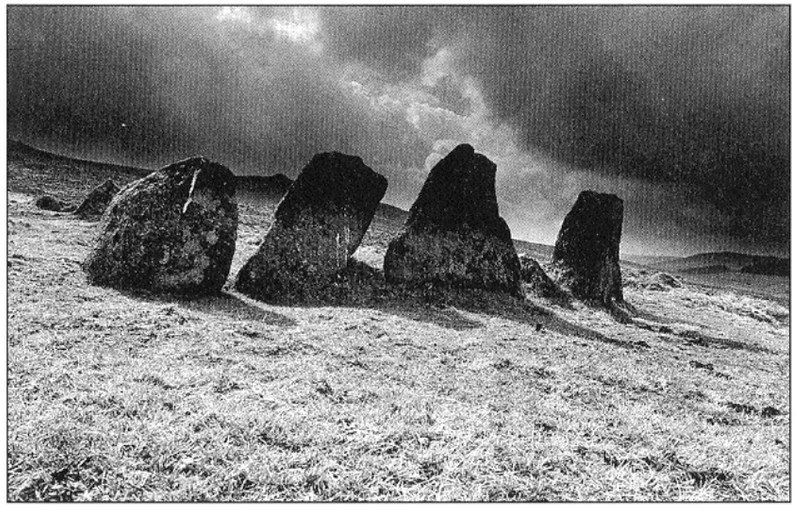
Dodging & burning is difficult!



A *The straight work print without additional burning-in.*

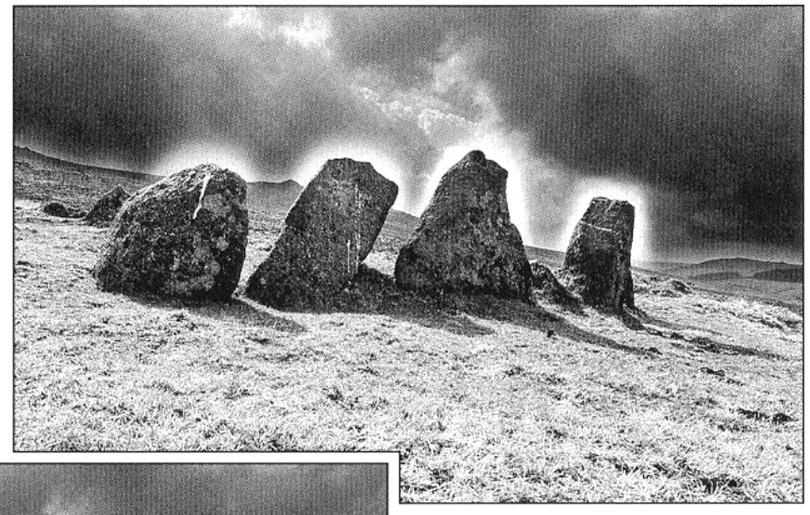


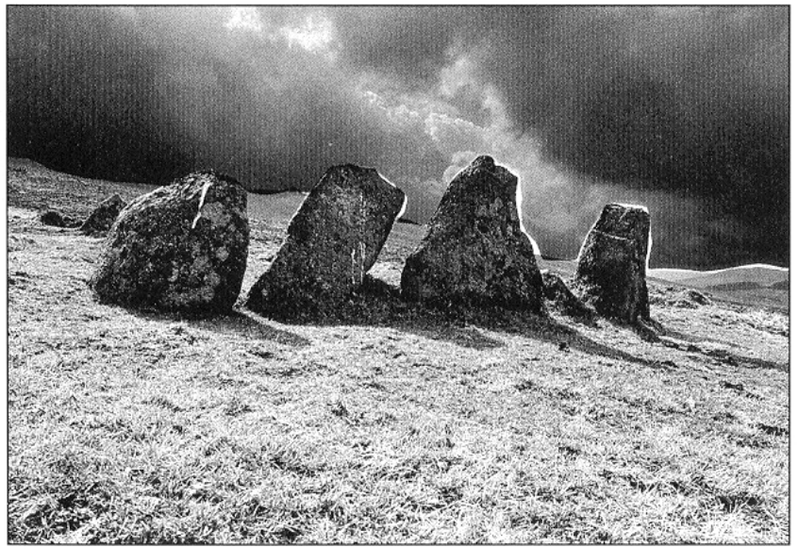
B *This print shows the result of trying to mask off the foreground by using a moving card. An even more obvious light band will appear in the sky if the card is not kept moving.*



C *In order to remove the light band in fig B, the mask has been lowered. This, however, has caused parts of the horizon to become black.*

D *The halo effect, here deliberately exaggerated, resulted from dodging the stones during the second exposure while burning-in the sky.*





E *It is very difficult to cut a dodging card with precision, especially for a relatively small print like this. As a result, parts of the sky at the horizon are white, although careful spotting can disguise this problem when it is small. But parts of the mid-grey hill tops have gone jet black, which is less easy to rectify.*

Source: Rudman

Questions?

- **Gordon Parks**



Digital dodge-burn and graduated ND

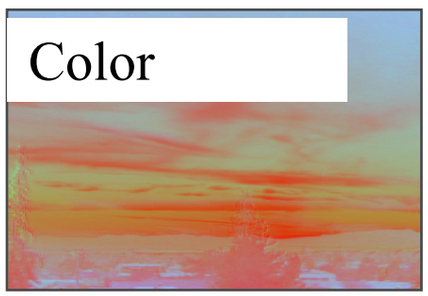
- **Use adjustment layer and gradient tool**
  - Use curve adjustment layer
  - Modulate its effect using the layer mask
- **Just paint in black**
  - On a separate layer
  - With a low opacity
- **Multiple exposure photography**
  - Use a tripod
  - “Bracket” your exposure
  - Stack exposures as layers in photoshop
  - Use layer masks to select which region comes from which exposure

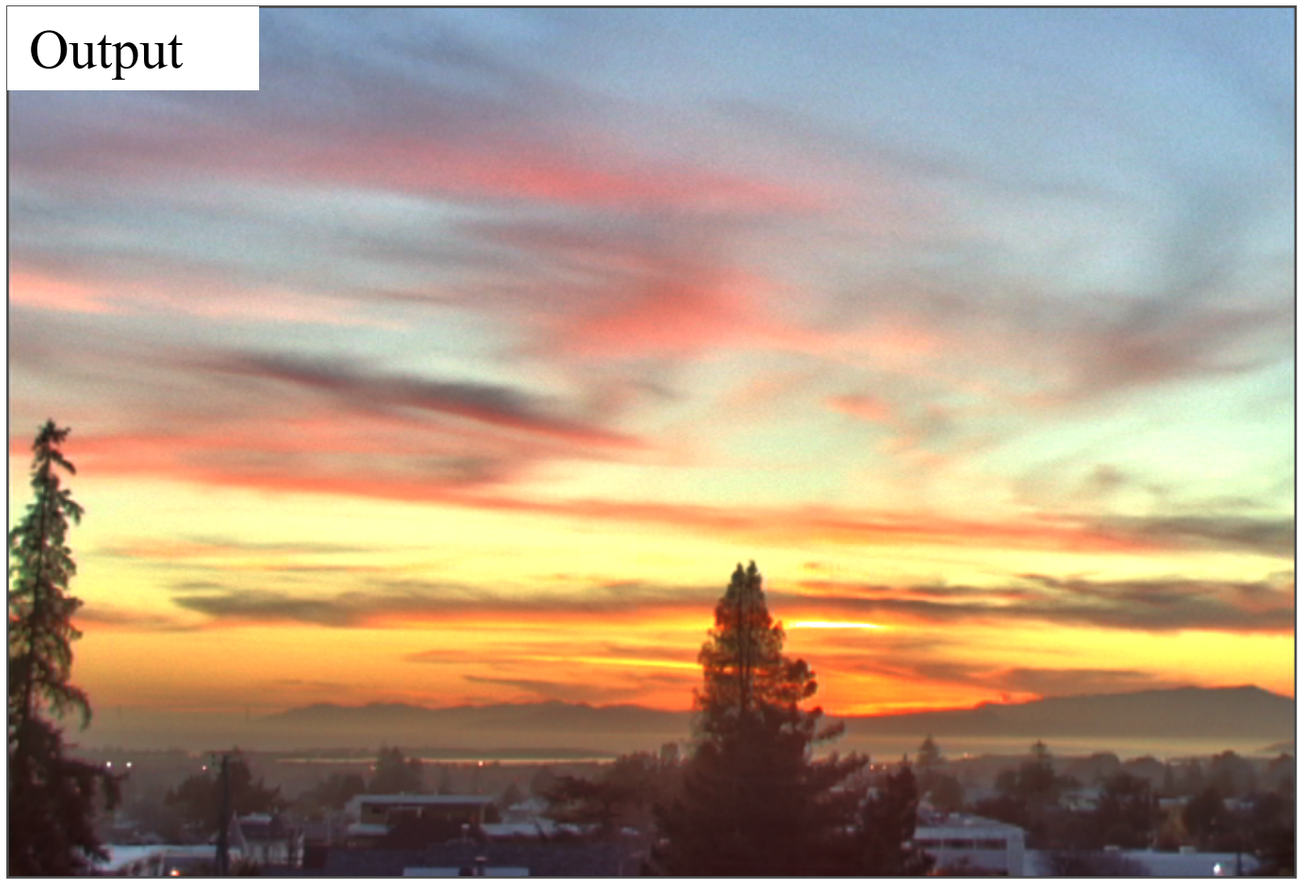
What have we learnt?

- **Log is good**
- **Luminance is different from chrominance**
- **Separate components:**
  - Low and high frequencies
- **Strong edges are important**

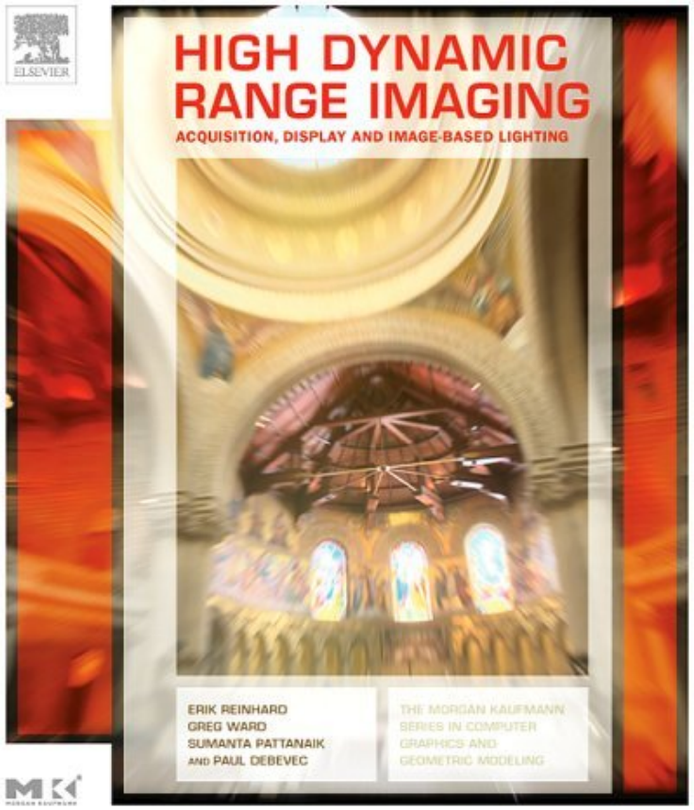


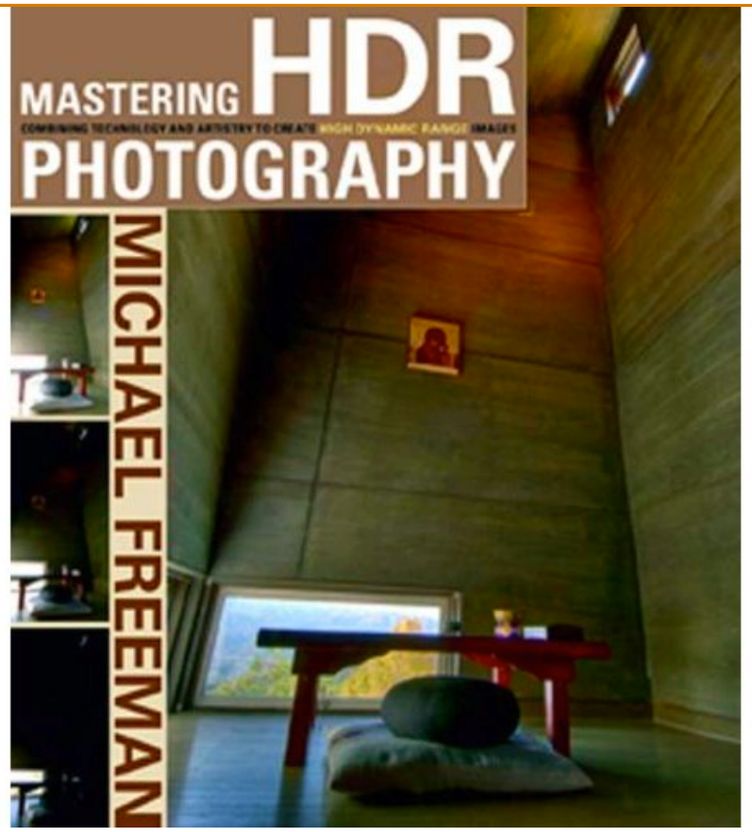


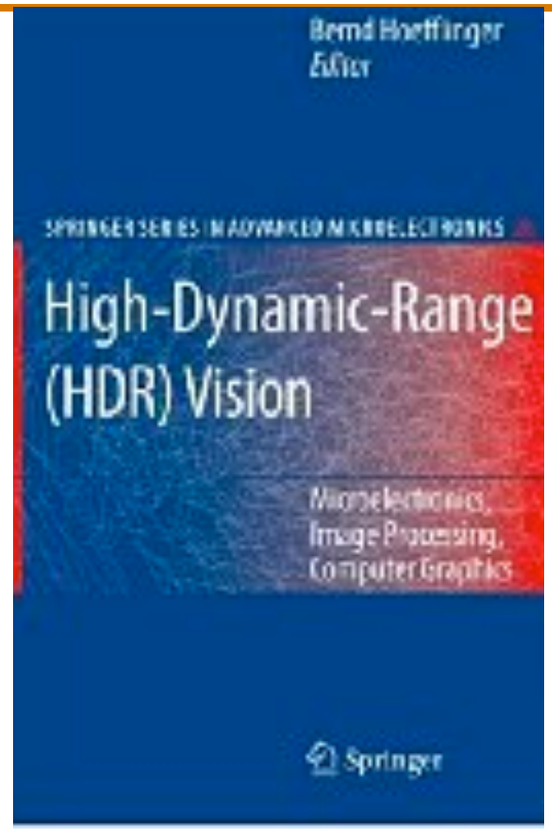


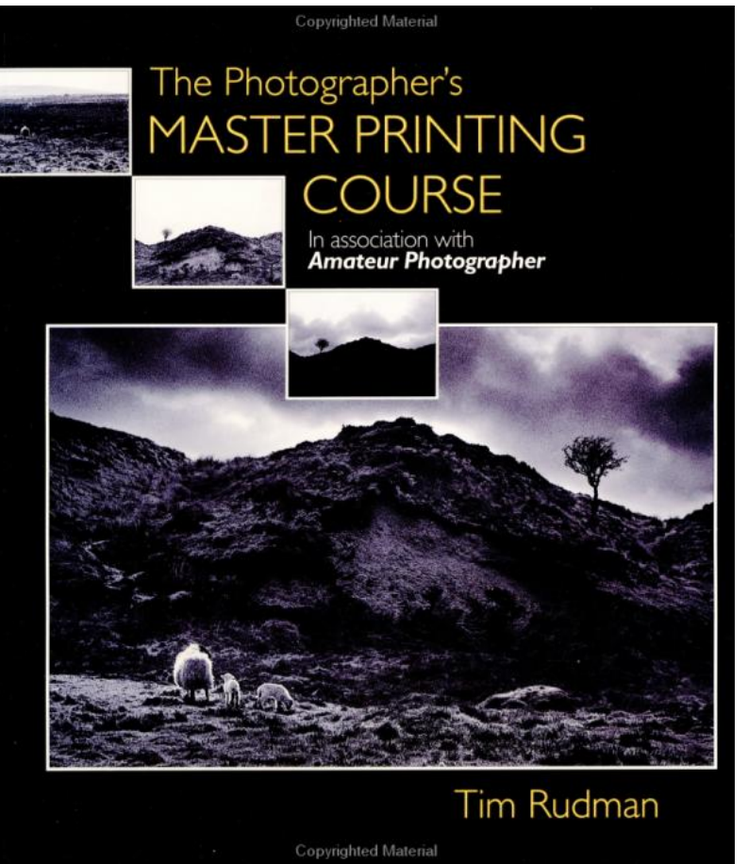


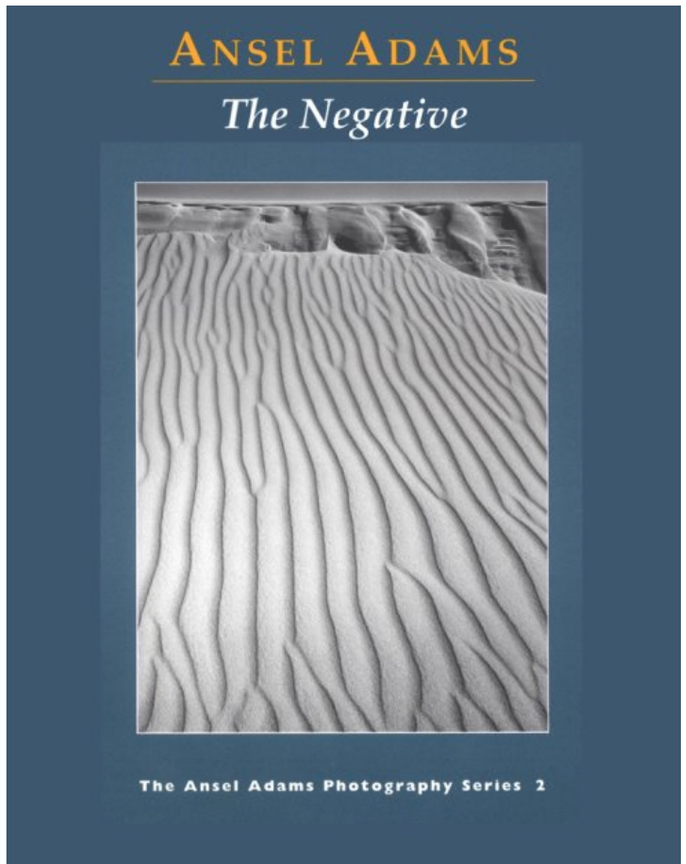
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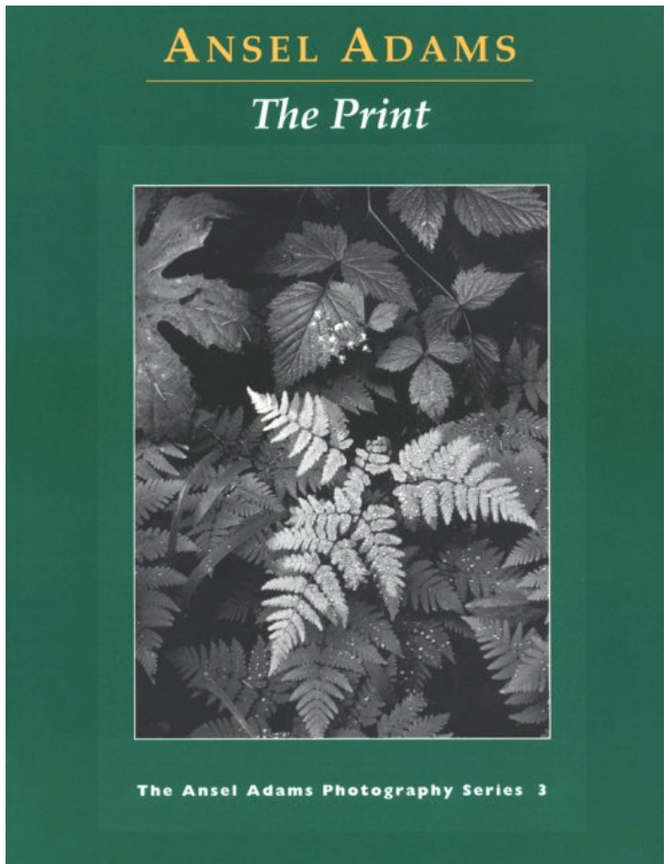

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Other tone mapping references

- **J. DiCarlo and B. Wandell, Rendering High Dynamic Range Images** http://www-isl.stanford.edu/%7Eabbas/group/papers_and_pub/spie00_jeff.pdf
- **Choudhury, P., Tumblin, J., "The Trilateral Filter for High Contrast Images and Meshes". http://www.cs.northwestern.edu/~jet/publications.html**
- **Tumblin, J., Turk, G., "Low Curvature Image Simplifiers (LCIS): A Boundary Hierarchy for Detail-Preserving Contrast Reduction."** http://www.cs.northwestern.edu/~jet/publications.html
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- **Photographic Tone Reproduction for Digital Images Erik Reinhard, Mike Stark, Peter Shirley and Jim Ferwerda** http://www.cs.utah.edu/%7Ereinhard/cdrom/
- **Ashikhmin, M. ``A Tone Mapping Algorithm for High Contrast Images''** http://www.cs.sunysb.edu/~ash/tm.pdf
- **Retinex at Nasa** http://dragon.larc.nasa.gov/retinex/background/retpubs.html
- **Gradient Domain High Dynamic Range Compression Raanan Fattal, Dani Lischinski, Michael Werman** http://www.cs.huji.ac.il/~danix/hdr/
- **Li et al. : Wavelets and activity maps** http://web.mit.edu/yzli/www/hdr_companding.htm

Tone mapping code

- http://www.mpi-sb.mpg.de/resources/pfstools/
- http://scanline.ca/exrtools/
- http://www.cs.utah.edu/~reinhard/cdrom/source.html
- http://www.cis.rit.edu/mcsl/icam/hdr/

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http://people.csail.mit.edu/sparis/bf_course/

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http://gl.ict.usc.edu/HDRShop/

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http://www.anyhere.com/

http://www.cybergrain.com/tech/hdr/

Available in HDRShop



Slide from Siggraph 2005 course on HDR

Questions?