Noise and ISO

CS 178, Spring 2010

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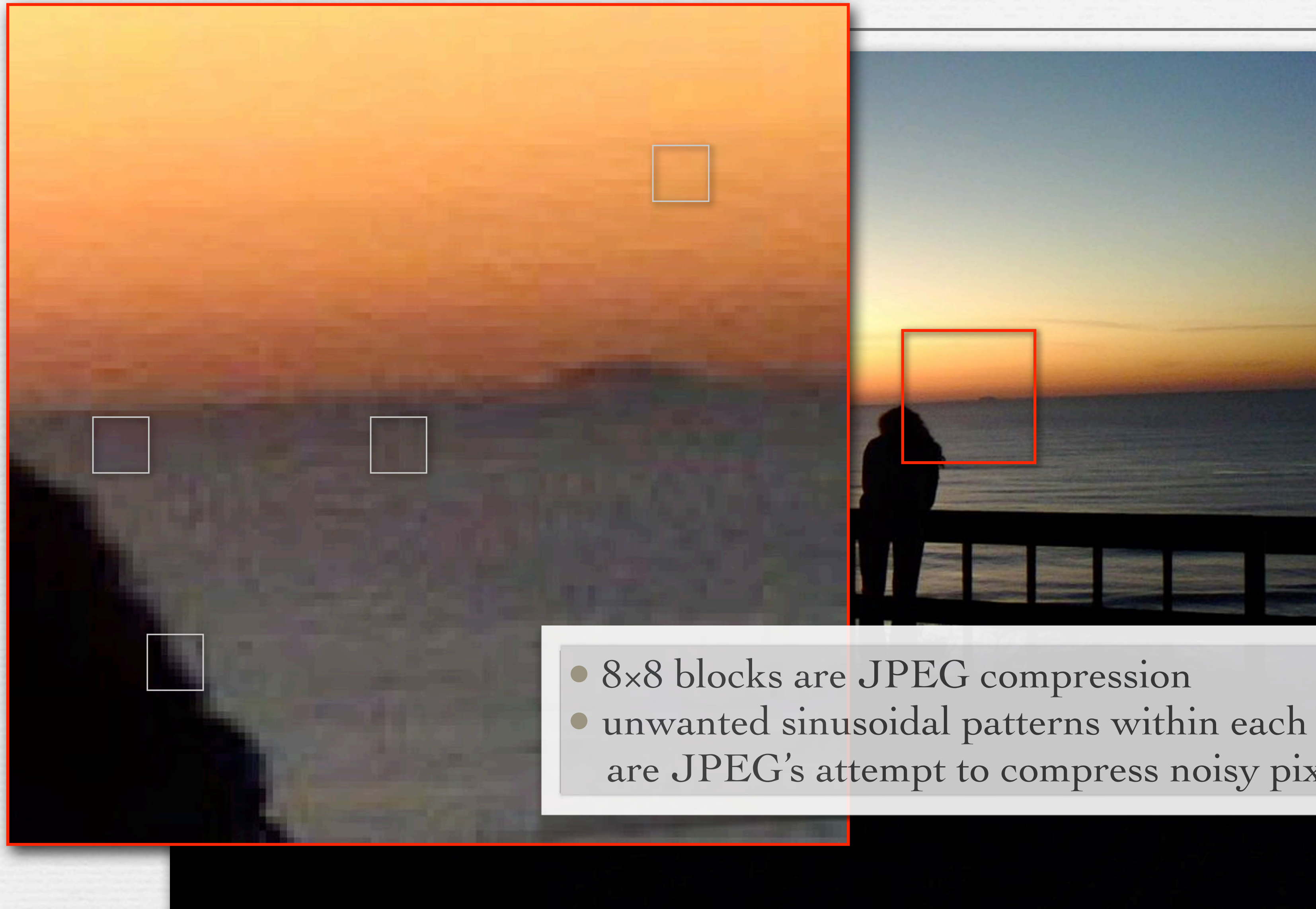
Outline

- examples of camera sensor noise
  - don't confuse it with JPEG compression artifacts
- probability, mean, variance, signal-to-noise ratio (SNR)
- laundry list of noise sources
  - photon shot noise, dark current,
    hot pixels, fixed pattern noise, read noise
- SNR (again), dynamic range (DR), bits per pixel
- ISO
- denoising
  - by aligning and averaging multiple shots
  - by image processing will be covered in a later lecture

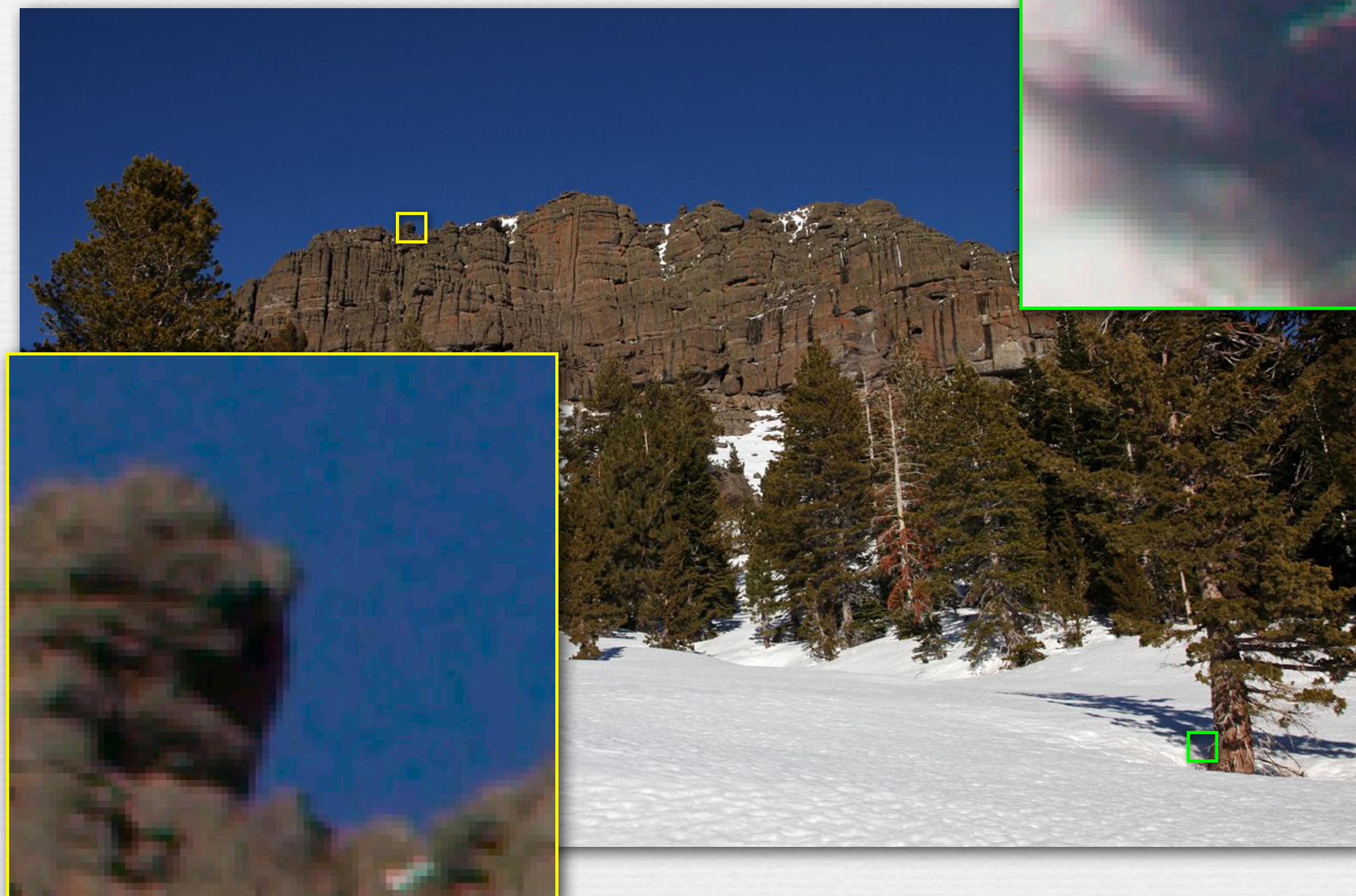
Nokia N95 cell phone at dusk



- 8×8 blocks are JPEG compression
- unwanted sinusoidal patterns within each block are JPEG's attempt to compress noisy pixels

Canon 5D II at noon

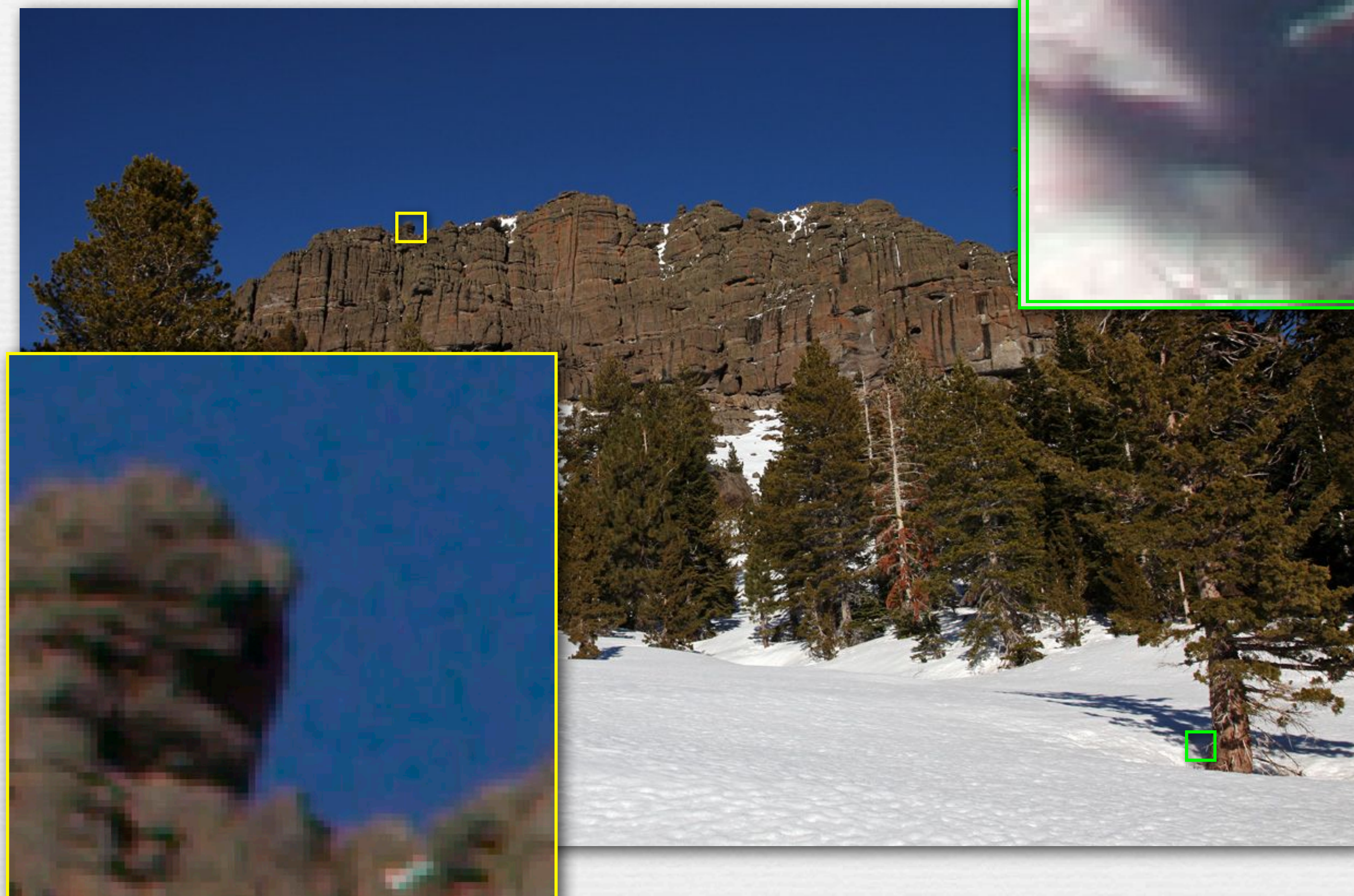
chromatic aberration!



- ISO 200
- f/13.0
- 1/320 sec
- RAW w/o denoising

Canon 5D II at noon

post-processed

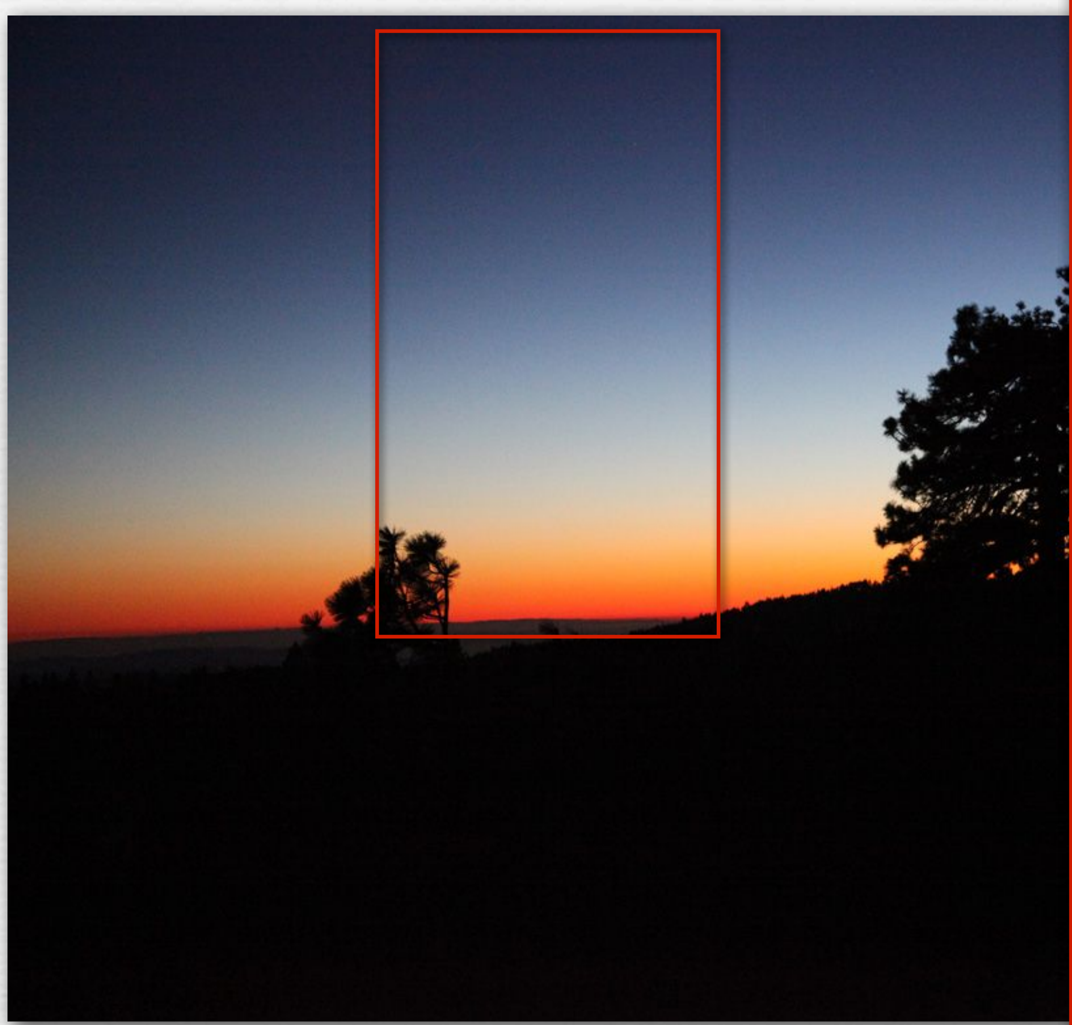


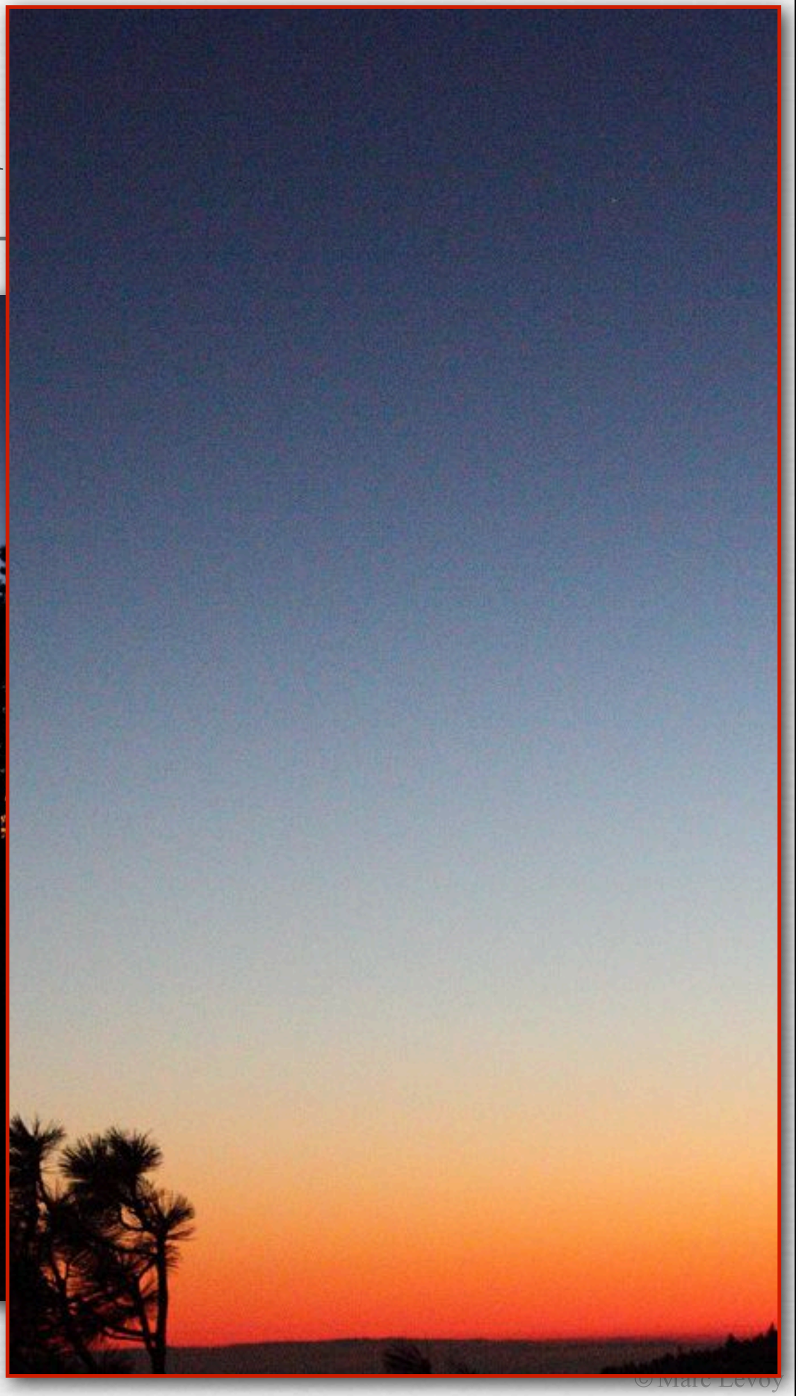
- ISO 200
- f/13.0
- 1/320 sec
- RAW w/o denoising

Canon 5D II at dusk

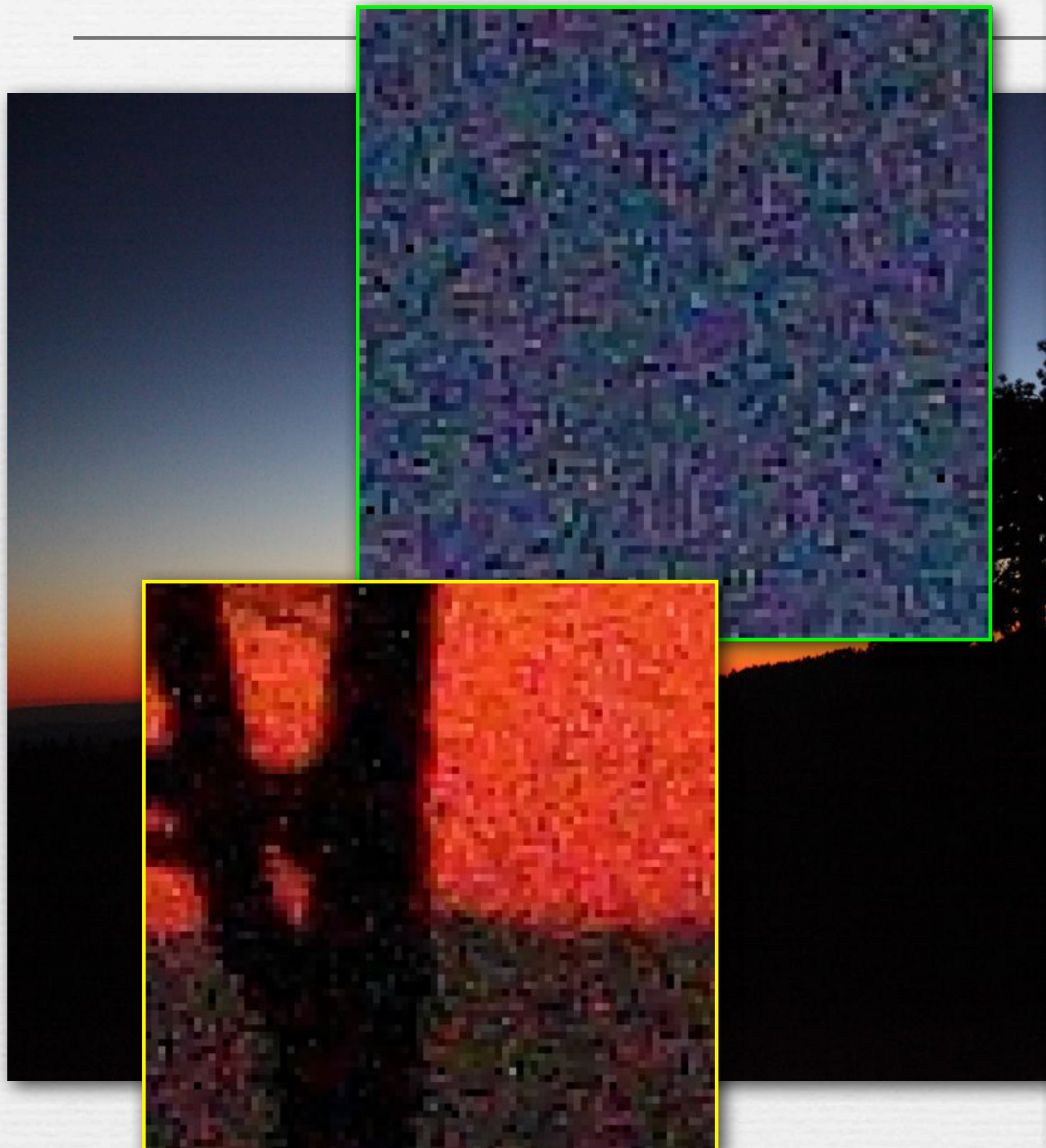
- ISO 6400
- f/4.0
- 1/13 sec
- RAW w/o denoising

Canon 5D II at dusk





Canon 5D II at dusk



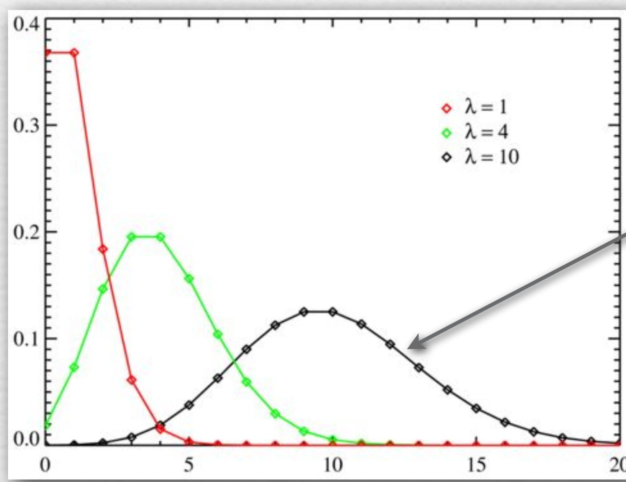
Photon shot noise

- the number of photons arriving during an exposure varies from exposure to exposure and from pixel to pixel
- this number is governed by the Poisson distribution

Poisson distribution

- expresses the probability that a certain number of events will occur during an interval of time
- applicable to rare events that occur
  - with a known average rate, and
  - independently of the time since the last event
- if on average λ events occur in an interval of time, the probability p that k events occur instead is

$$p(k;\lambda) = \frac{\lambda^k e^{-\lambda}}{k!}$$



probability density function

Mean and variance

- the mean of probability density function *p(x)* is

$$\mu = \int x\, p(x)\, dx$$

- the variance of probability density function *p(x)* is

$$\sigma^2 = \int (x-\mu)^2\, p(x)\, dx$$

- the mean and variance of the Poisson distribution are

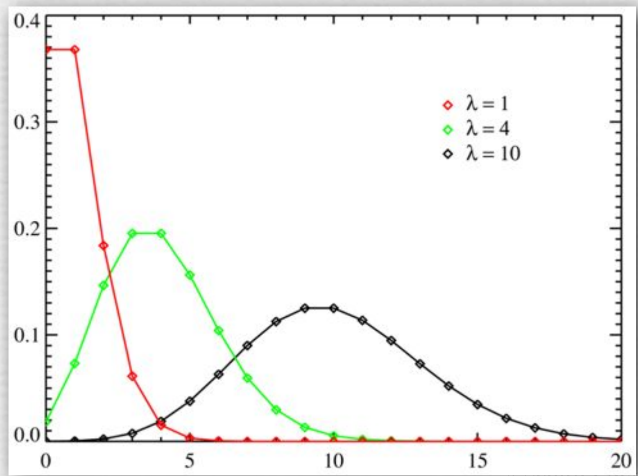
$$\mu = \lambda$$

$$\sigma^2 = \lambda$$

- the standard deviation is

$$\sigma = \sqrt{\lambda}$$

Deviation grows slower than the average.



Signal-to-noise ratio (SNR)

$$SNR = \frac{\text{mean pixel value}}{\text{standard deviation of pixel value}} = \frac{\mu}{\sigma}$$

$$SNR\ (\text{dB}) = 20 \log_{10}\left(\frac{\mu}{\sigma}\right)$$

- example
  - if SNR improves from 100:1 to 200:1,
    it improves $20 \log_{10}(200) - 20 \log_{10}(100) = +6$ dB

Photon shot noise (again)

- photons arrive in a Poisson distribution

$$\mu = \lambda$$

$$\sigma = \sqrt{\lambda}$$

- so

$$SNR = \frac{\mu}{\sigma} = \sqrt{\lambda}$$

- shot noise scales as square root of number of photons
- examples
  - doubling the width and height of a pixel increases its area by 4×, hence # of photons by 4×, hence SNR by 2× or +6 dB
  - opening the aperture by 1 f/stop increases the # of photons by 2×, hence SNR by √2 or +3 dB

Empirical example

- Kodak Q14 test chart

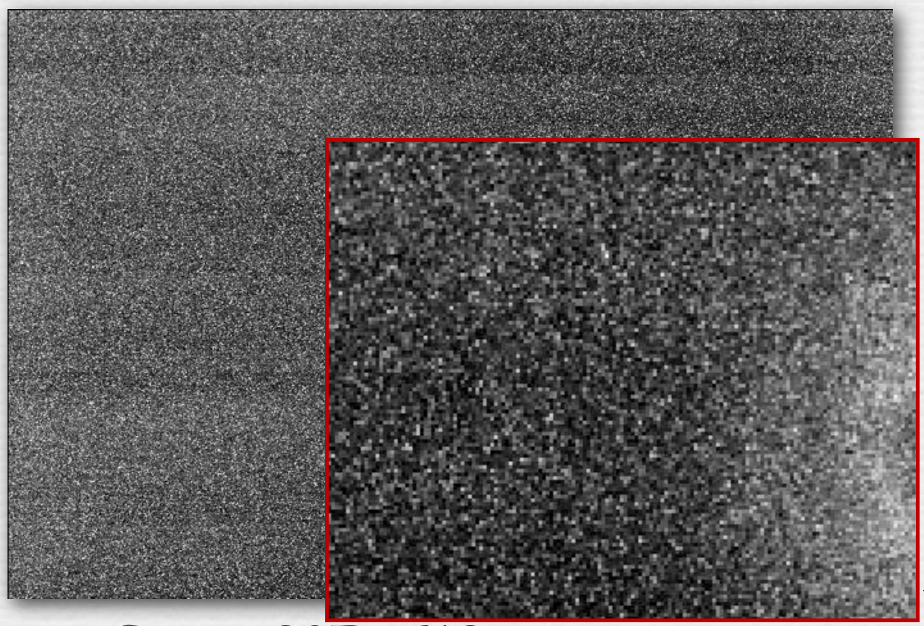
- Canon 10D, ISO 1600, crop from recorded image

- noise grows as sqrt(signal)
- more noise in bright tile than in dark tile, but <u>much</u> more signal
- SNR improves with increasing signal

Dark current

- electrons dislodged by random thermal activity
- increases linearly with exposure time
- increases exponentially with temperature
- varies across sensor, and includes its own shot noise

don't confuse with photon shot noise

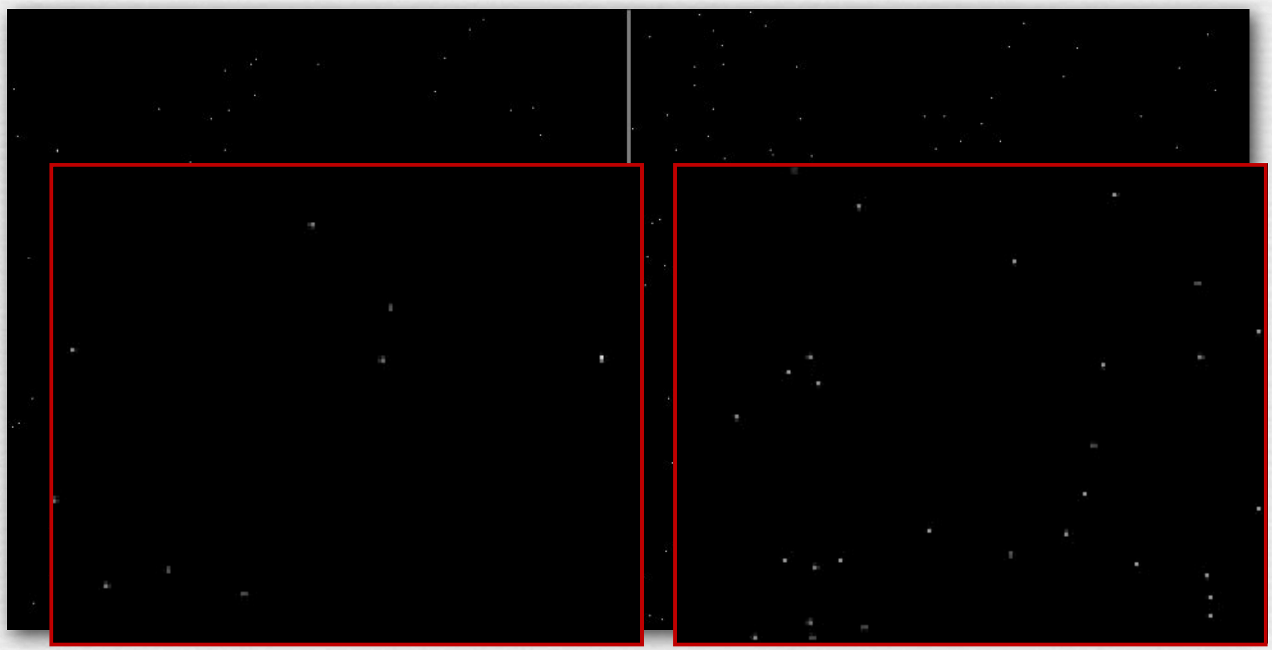


(http://theory.uchicago.edu/~ejm/pix/20d/tests/noise/)

Canon 20D, 612 sec exposure

Hot pixels

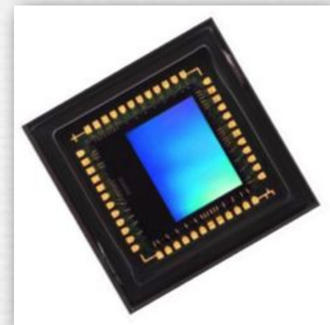
- electrons leaking into well due to manufacturing defects
- increases linearly with exposure time
- increases with temperature, but hard to model
- changes over time, and every camera has them



Canon 20D, 15 sec and 30 sec exposures

Fixing dark current and hot pixels

- example
  - Aptina MT9P031 (in Nokia N95 cell phone)
  - full well capacity = ~8500 electrons
  - dark current = 25 electrons/pix/sec at 55°C

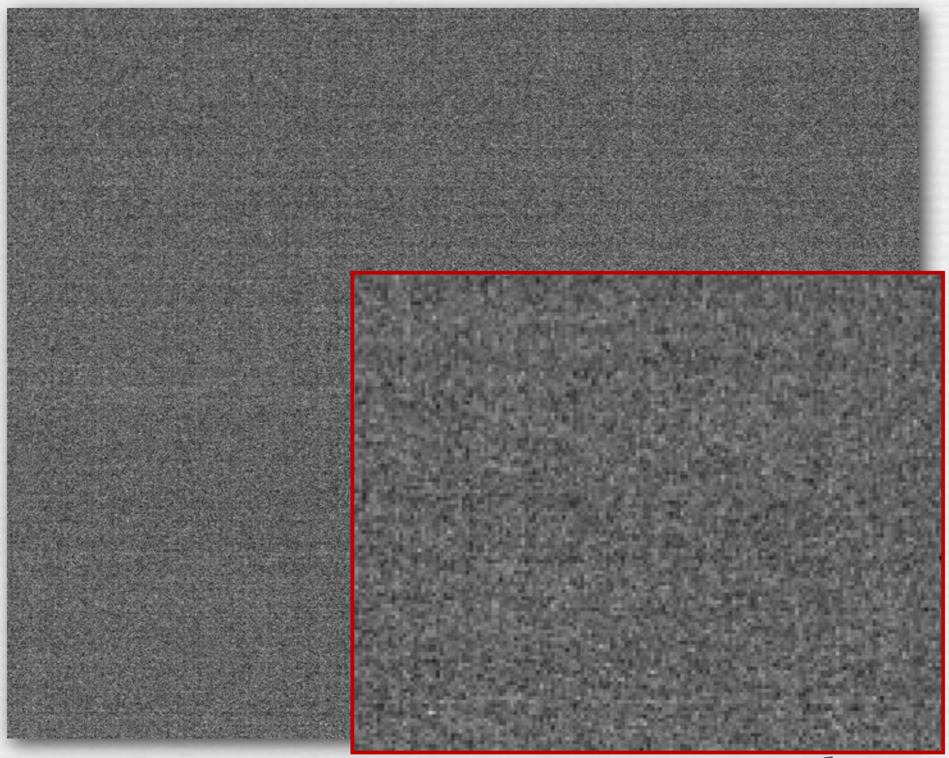


- solution #1: chill the sensor
  - Retiga 4000R bioimaging camera
  - Peltier cooled 25°C below ambient
  - full well capacity = 40,000 electrons
  - dark current = 1.64 electrons/pix/sec

- solution #2: dark frame subtraction
  - available on high-end SLRs
  - compensates for average dark current
  - compensates for hot pixels

Fixed pattern noise (FPN)

- manufacturing variations across pixels, columns, blocks
- mainly in CMOS sensors
- doesn't change over time, so read once and subtract



Canon 20D, ISO 800, cropped

Read noise

- thermal noise in readout circuitry
- again, mainly in CMOS sensors
- not fixed pattern, so only solution is cooling

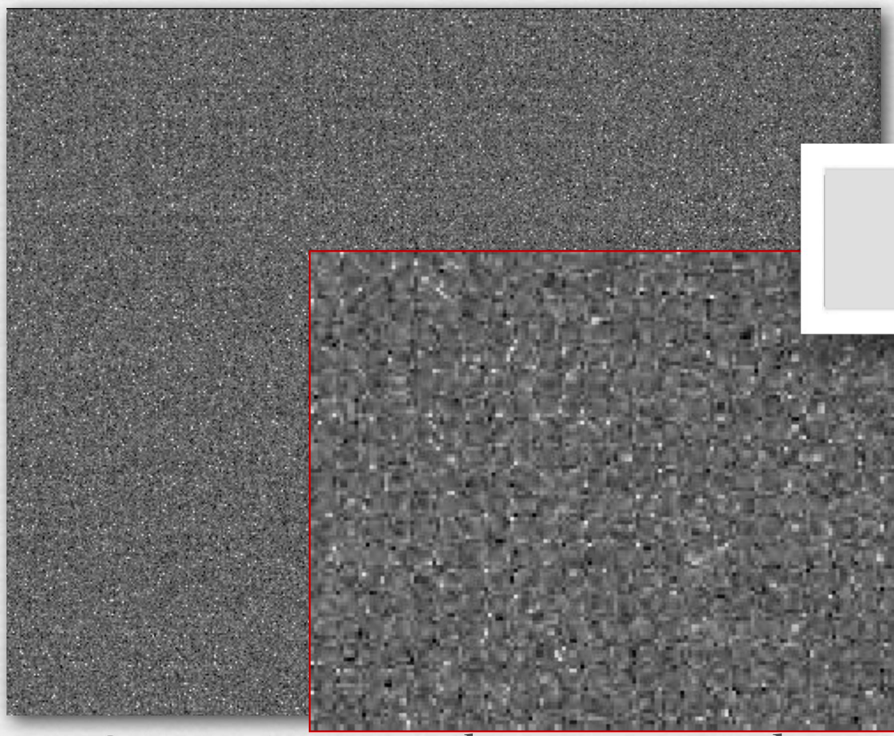


image tainted by JPEG artifacts?

Canon 1Ds Mark III, cropped

Recap

- photon shot noise
  - unavoidable randomness in number of photons arriving
  - grows as the square root of the number of photons, so brighter lighting and longer exposures will be less noisy
- dark current noise
  - grows with exposure time and sensor temperature
  - minimal for most exposure times used in photography
  - correct by subtraction, but only corrects for average dark current
- hot pixels, fixed pattern noise
  - caused by manufacturing defects, correct by subtraction
- read noise
  - electronic noise when reading pixels, unavoidable

Questions?

Signal-to-noise ratio
(with more detailed noise model)

$$SNR = \frac{\text{mean pixel value}}{\text{standard deviation of pixel value}} = \frac{\mu}{\sigma}$$

$$= \frac{P\,Q_e\,t}{\sqrt{P\,Q_e\,t + D\,t + N_r^2}}$$

- where

P = incident photon flux (photons/pixel/sec)

Q_e = quantum efficiency

t = exposure time (sec)

D = dark current (electrons/pixel/sec), including hot pixels

N_r = read noise (rms electrons/pixel), including fixed pattern noise

(formula from http://learn.hamamatsu.com/articles/ccdsnr.html)

Signal-to-noise ratio

(with more detailed noise model)

$$SNR = \frac{\text{mean pixel value}}{\text{standard deviation of pixel value}} = \frac{\mu}{\sigma}$$

$$= \frac{P\,Q_e\,t}{\sqrt{P\,Q_e\,t + D\,t + N_r^2}}$$

pixels are 1/11 as large in area

- examples
  - Retiga 4000R = (1000 × 55%) / √(1000 × 55% + 1.64 + 12^2) = 20.8:1 assuming 1000 photons/pixel/sec for 1 second
  - Aptina MT9P031 = (1000÷11×69%) / √(1000÷11×69% + 25 + 2.6^2) = 6.5:1 assuming pixels are 1/11 as large as Retiga's
- for 10 photons/pixel/sec for 100 seconds
  - Retiga = 18.7:1
  - Aptina = 1.2:1

Don't use your cell phone for astrophotography!

Dynamic range

$$DR = \frac{\text{max output swing}}{\text{noise in the dark}} = \frac{\text{saturation level} - D\,t}{\sqrt{D\,t + N_r^2}}$$

full well capacity

- examples
  - Retiga 4000R = (40,000 - 1.64) / √(1.64 + 12^2) = 3,313:1 (11.7 bits) for a 1 second exposure
  - Aptina MT9P031 = (8500 - 25) / √(25 + 2.6^2) = 1500:1 (10.5 bits) for a 1 second exposure

Don't use your cell phone for fluorescence microscopy!

- determines precision required in ADC, and useful # of bits in RAW image
- any less than ~10 bits would be < 8 bits after gamma transform for JPEG encoding, and you would see quantization artifacts

Low-light cameras

$$DR = \frac{\text{max output swing}}{\text{noise in the dark}} = \frac{\text{saturation level} - D\,t}{\sqrt{D\,t + N_r^2}}$$

- ✦ Andor iXon+888 back-illuminated CCD
  - $40,000
- ✦ performance
  - DR = (80,000 - 0.001) / √(0.001 + 6^2)
    = 13,333:1 (13.7 bits) for a 1 second exposure

if cooled to -75° C

- ✦ "electron multiplication" mode
  - DR = (80,000 - 0.001) / √(0.001 + <1^2)
    = 80,000:1 (16.2 bits)
  - "can see a black cat in a coal mine"

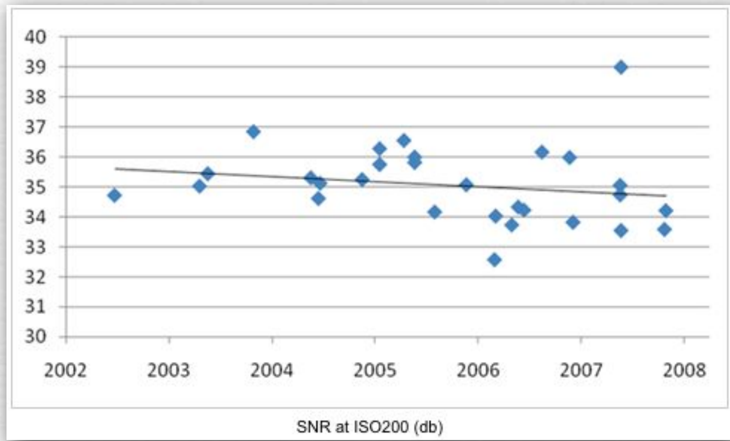
can reliably detect a single photon

ISO

I didn't do a great job of explaining this in class, so I've reorganized this slide to make the argument clearer. Basically, if your aperture is as wide as you want it, and your exposure is as long as you dare make it, then you should raise the ISO to ensure an image that fills the range of numbers representable in the RAW or JPEG file. If you don't raise the ISO, you'll produce a dark image. You could fix this by brightening the image in Photoshop, but if you expand an image having numbers 0..7 (for example) to the range 0..255, you'll see contouring. Even if you don't see contouring, you'll see more noise, because amplification occurs early in the electronic path, thereby reducing read noise.

- amplifies signal before quantization by ADC
  - if you quantize a low signal, then brighten it in Photoshop, you may see quantization artifacts (contouring)
  - amplification also reduces the impact of read noise, since amplification occurs early in the reading process
- doubling ISO doubles the signal, which is linear with light
  - so effect on signal is the same as 2× exposure time, or –1 f/stop
  - maximum ISO on Canon 5D II is 6400; higher ISOs implemented using multiplication after ADC?
- conclusion: raising ISO improves SNR
  - but raising exposure time improves SNR faster, so
  - maximize exposure time to the limits imposed by object motion, camera shake, or sensor saturation, then maximize ISO to the limit imposed by ADC saturation

SNR and ISO over the years



(http://www.dxomark.com/index.php/eng/Insights/SNR-evolution-over-time)

- SNR has been improving with better sensor designs
- but total # of megapixels has risen to offset these improvements, making pixels smaller, so SNR in a pixel has remained static
- display resolutions have not risen as fast as megapixels, so we're increasingly downsizing our images for display
- if you average 4 camera pixels to produce 1 for display, SNR doubles, so for the same display area, SNR has been improving
- this allows higher ISOs to be used in everyday photography

Nikon D3S, ISO 3200, photograph by Michael Kass

Nikon D3S, ISO 6400, photograph by Michael Kass

Nikon D3S, ISO 25,600, denoised in Lightroom 3, photograph by Fredo Durand

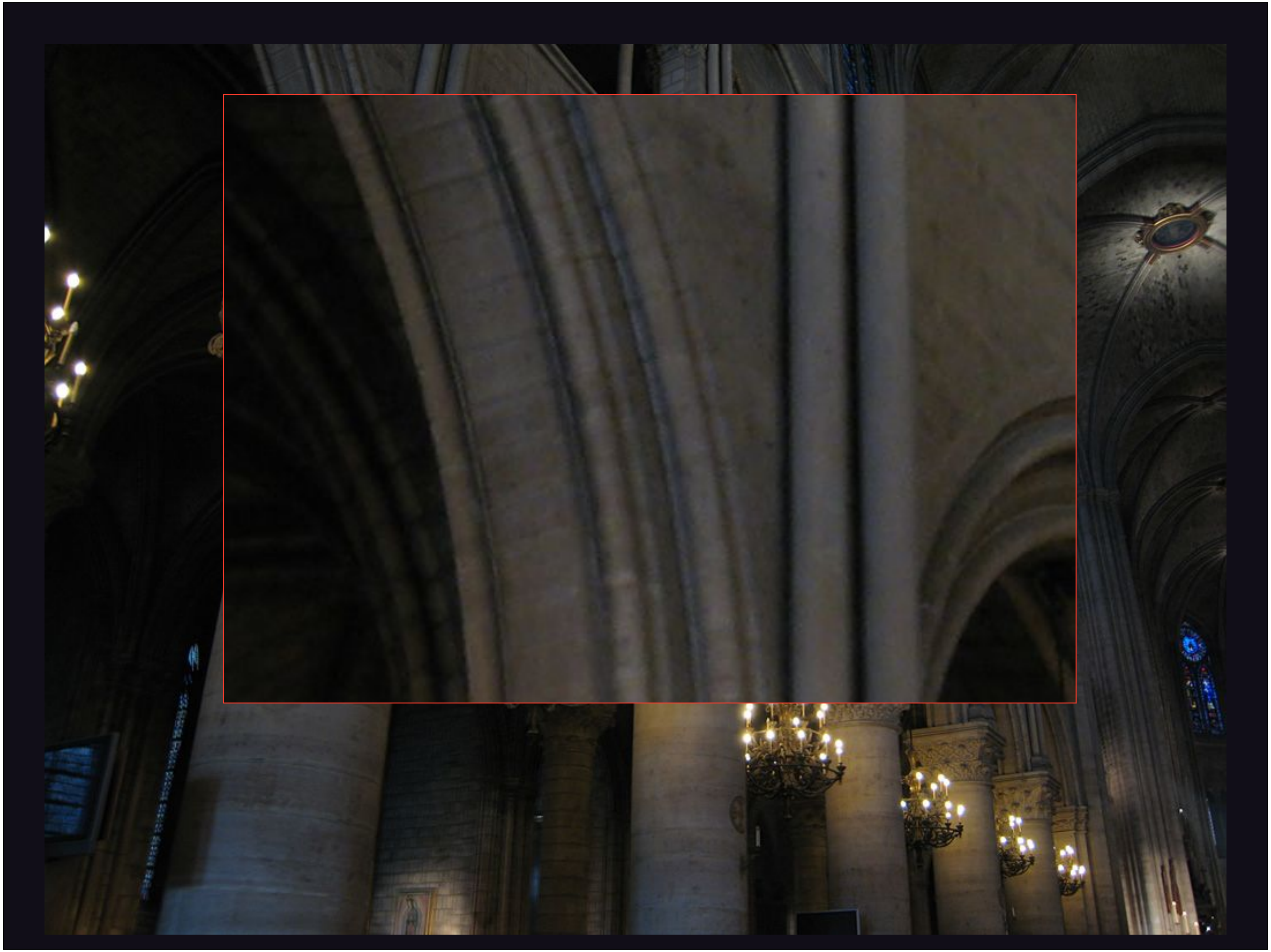
Nikon D3S, ISO 25,600, denoised in Lightroom 3, photograph by Fredo Durand

RAW image from camera, before denoising in Lightroom

Fredo says it was nearly too dark to read the menu, so it really looked like this (darkened)

or maybe it looked like this? (tone mapped to approximate human dark adaptation)

Averaging several short-exposure, high-ISO shots to avoid camera shake & reduce noise



Aligning a burst of short-exposure, high-ISO shots using the Casio EX-F1

1/3 sec

burst at 60fps

Recap

- *signal-to-noise ratio* (SNR) is mean/stddev of pixel value
  - rises with sqrt(brightness and/or exposure time)
  - depends also on dark current and read noise
  - poor for short exposures and very long exposures
- *dynamic range* (DR) is max swing / noise in the dark
  - fixed for a particular sensor and exposure time
  - determines # of useful bits in RAW image
- *ISO* is amplification of signal before conversion to digital
  - maximize exposure time until camera or object blurs, then maximize ISO, making sure not to saturate
  - can combine multiple short-exposure high-ISO pictures

Questions?

Slide credits

- Eddy Talvala

- Filippov, A., *How many bits are really needed in the image pixels?* (sic), http://www.linuxdevices.com/articles/AT9913651997.html