Lecture 8: Sampling (continued)

( unless otherwise stated slides are taken or adopted from Bob Woodham, Jim Little and Fred Tung )
Menu for Today (September 25, 2020)

Topics:
- Color Filter Arrays
- Bayer patterns
- Template matching
- Normalized Correlation

Readings:
- Today’s Lecture: Forsyth & Ponce (2nd ed.) 4.5
- Next Lecture: Forsyth & Ponce (2nd ed.) 4.6, 4.7

Reminders:
- Assignment 1: Image Filtering and Hybrid Images due September 30th
- Quiz 1 is out (due by midnight Friday) — chance performance 45%
- Lecture timing
Today’s “fun” Example: Müller-Lyer Illusion
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Lecture 7: Re-cap

In the **continuous** case, images are functions of two spatial variables, $x$ and $y$.

The **discrete** case is obtained from the continuous case via sampling (i.e. spatial tessellation, grayscale quantization).

If a signal is **bandlimited** then it is possible to design a sampling strategy such that the sampled signal captures the underlying continuous signal exactly.
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If we know what we imaging (position and texture of objects, etc.) and how (distance of those object to the camera, lens parameters of the camera, etc.) then we can calculate whether resolution of the sensor is sufficient to produce artifact-free images.
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If we know what we imaging (position and texture of objects, etc.) and how (distance of those object to the camera, lens parameters of the camera, etc.) then we can calculate what resolution sensor we may need to “trust” our imaging.
Lecture 7: Re-cap

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If a signal is **bandlimited** then it is possible to design a sampling strategy such that the sampled signal captures the underlying continuous signal exactly.

Adequate sampling may not always be practical. In such cases there is a trade-off between “things missing” and “artifacts”.
— Different applications make the trade-off differently
Sometimes **undersampling** is unavoidable, and there is a trade-off between “things missing” and “artifacts.”

— **Medical imaging**: usually try to maximize information content, tolerate some artifacts

— **Computer graphics**: usually try to minimize artifacts, tolerate some information missing
Example

Sensor Resolution: 10 x 8

Sensor Resolution: 10 x 8
Example

**Sensor** Resolution: 10 x 8

![Sensor Image Resolution: 10 x 8](image1)

**Sensor** Resolution: 10 x 8

![Sensor Image Resolution: 10 x 8](image2)

**Image** Resolution: 10 x 8

![Image Resolution: 10 x 8](image3)

**Image** Resolution: 5 x 4

![Image Resolution: 5 x 4](image4)
Review: Continuous Case

— Images also can be considered a function of time. Then, we write \( i(x, y, t) \) where \( x \) and \( y \) are spatial variables and \( t \) is a temporal variable.

— To make the dependence of brightness on wavelength explicit, we can instead write \( i(x, y, t, \lambda) \) where \( x, y \) and \( t \) are as above and where \( \lambda \) is a spectral variable.

— More commonly, we think of “color” already as discrete and write

\[
\begin{align*}
    i_R(x, y) \\
    i_G(x, y) \\
    i_B(x, y)
\end{align*}
\]

for specific colour channels, R, G and B.
**Color** is an Artifact of Human Perception

“Color” is **not** an objective physical property of light (electromagnetic radiation). Instead, light is characterized by its wavelength.

What we call “color” is how we subjectively perceive a very small range of these wavelengths.
Color Filter Arrays (CFA)

Slide Credit: Ioannis (Yannis) Gkioulkas (CMU)
**Color Filter Arrays (CFA)**

- **Microlens**
  - Color filter
  - Photodiode
  - Potential well

*Slide Credit: Ioannis (Yannis) Gkioulekas (CMU)*
Color Filters

Two design choices:
- What spectral sensitivity functions $f(\lambda)$ to use for each color filter?
- How to spatially arrange (“mosaic”) different color filters?
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Generally do not match human sensitivity
**Color Filters**

Two **design choices**:

- What spectral sensitivity functions $f(\lambda)$ to use for each color filter?
- How to spatially arrange (“mosaic”) different color filters?

**Bayer mosaic**

Generally do not match human sensitivity

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**Canon 50D**

$\text{Pixel Quantum Efficiency}$

$\lambda$ (nm)

**Slide Credit**: Ioannis (Yannis) Gkioulakas (CMU)
Two design choices:
- What spectral sensitivity functions $f(\lambda)$ to use for each color filter?
- How to spatially arrange ("mosaic") different color filters?

Why more green pixels?

Generally do not match human sensitivity
Different Color Filter Arrays (CFAs)

Finding the “best” CFA mosaic is an active research area.

How would you go about designing your own CFA? What criteria would you consider?

CYGM
Canon IXUS, Powershot

RGBE
Sony Cyber-shot

Slide Credit: Ioannis (Yannis) Gkioulekas (CMU)
Many **Different Spectral Sensitivity** Functions

Each camera has its more or less unique, and most of the time secret, SSF

Same scene captured using 3 different cameras with identical settings

*Slide Credit: Ioannis (Yannis) Gkioullekas (CMU)*
RAW Bayer Image

After all of this, what does an image look like?

- Kind of disappointing
- We call this the RAW image

Lots of noise

Slide Credit: Ioannis (Yannis) Gkioulekas (CMU)
Produce full RGB image from mosaiced sensor output

Any ideas on how to do this?
Produce full RGB image from mosaiced sensor output

Interpolate from neighbors:
- Bilinear interpolation (needs 4 neighbors)
- Bicubic interpolation (needs more neighbors, may overblur)
- Edge-aware interpolation
Demosaicing by Bilinear Interpolation

**Bilinear** interpolation: Simply average your 4 neighbors.

\[
G_? = \frac{G_1 + G_2 + G_3 + G_4}{4}
\]

Neighborhood changes for different channels:

*Slide Credit:* Ioannis (Yannis) Gkioulekas (CMU)
(in camera) **Image Processing Pipeline**

The sequence of image processing operations applied by the camera’s image signal processor (ISP) to convert a RAW image into a “conventional” image.

- **RAW image** (mosaiced, linear, 12-bit)
- **analog front-end**
- **CFA demosaicing**
- **white balance**
- **tone reproduction**
- **compression**
- **final RGB image** (non-linear, 8-bit)

**Slide Credit**: Ioannis (Yannis) Gkioulekas (CMU)
(in camera) **White** balance

- **Tungsten**
- **Fluorescent**
- **Flash**
- **Cloudy**
- **Shade**
- **Daylight**
(in camera) **Tone** reproduction

- **Tone mapped with Li et al. 2005**
- **Corrected saturation reduced**
- **Corrected saturation enhanced**
- **Tone mapped with Reinhard et al. 2012**
“Color” is **not** an objective physical property of light (electromagnetic radiation). Instead, light is characterized by its wavelength.

Color Filter Arrays (CFAs) allow capturing of mosaiced color information; the layout of the mosaic is called **Bayer** pattern.

**Demosaicing** is the process of taking the RAW image and interpolating missing color pixels per channel