UNIVERSITY OF DELAWARE

ELEG404/604

IMAGING & DEEP LEARNING

From Sensing to Inference

DIGITAL IMAGING • REMOTE SENSING • COMPUTATIONAL IMAGING • AI

Gonzalo R. Arce | Department of Electrical and Computer Engineering

UNIVERSITY OF DELAWARE

ELEG404/604

ASSESSMENT & GRADING

Homework	10%
Quizzes	20%
2 Midterms	30%
Project	20%
Final	20%

COURSE OVERVIEW

Structure, grading, and expectations

INSTRUCTOR
Gonzalo R. Arce
Department of Electrical and Computer Engineering

TOPICS: DIGITAL IMAGING • REMOTE SENSING • COMPUTATIONAL IMAGING • AI

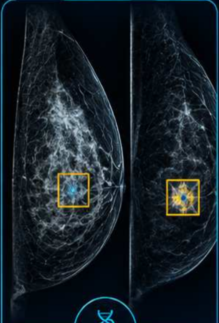
UNIVERSITY OF DELAWARE

To discover from images what is present in the world, where things are, what actions are taking place, to predict and anticipate events in the world

The rise and impact of computer vision

Robotics

Accessibility

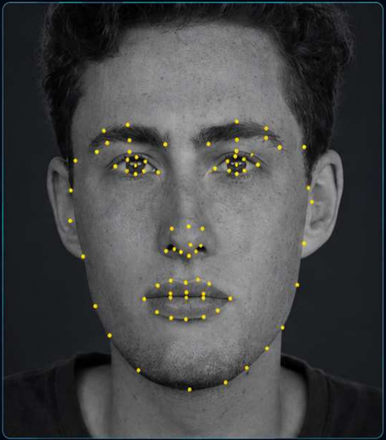


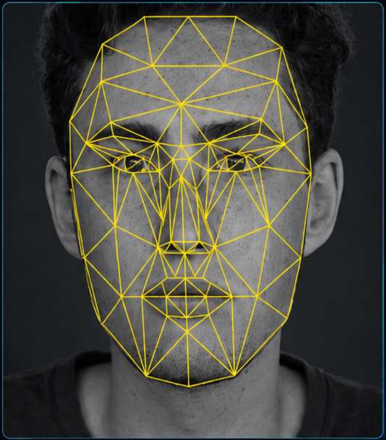
Biology & Medicine

Mobile computing

Autonomous driving

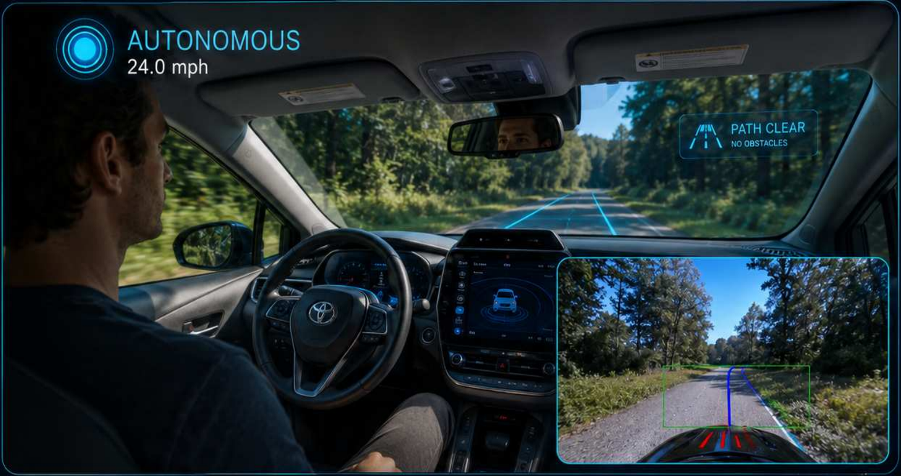
IMPACT: FACIAL DETECTION & RECOGNITION





IMPACT: SELF-DRIVING CARS

VISUAL SENSING
↓
FEATURE PROCESSING
↓
AUTONOMOUS DECISION



IMPACT: MEDICINE, BIOLOGY, HEALTHCARE

VISUAL SENSING
/ CAPTURE

↓

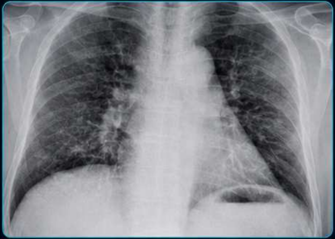
FEATURE EXTRACTION
/ AI ANALYSIS

↓

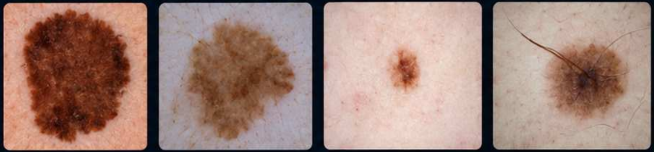
HEALTHCARE
/ DIAGNOSIS

Breast cancer

COVID-19



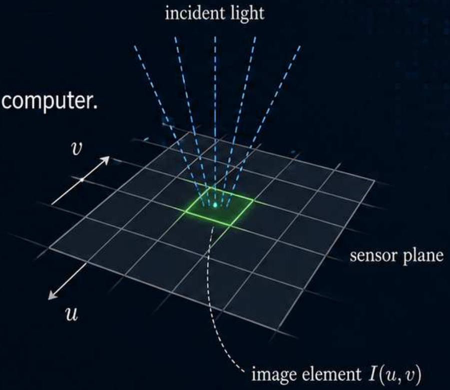
Skin cancer



INTRODUCTION

Digital imaging refers to processing of digital images by means of a computer.

- An image may be defined as a function $f(x, y)$, where (x, y) are spatial coordinates and $f(x, y)$ is the intensity.
- When x, y, and f are all finite, discrete quantities, the image is called a digital image.
- Each value $f(x, y)$ is referred to as a picture element, image element, pel, or pixel.



IMPACT: ACCESSIBILITY

Computer vision enables **real-time understanding** of surroundings to assist people with navigation, mobility, and safety.

Navigate with confidence
Guidance on paths, obstacles, and safe routes.

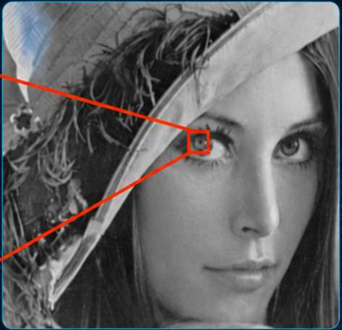
See what matters
Visual assistance for detecting lanes, crossings, and surroundings.

More independence
Technology that empowers everyday movement.

WHAT IS AN IMAGE?

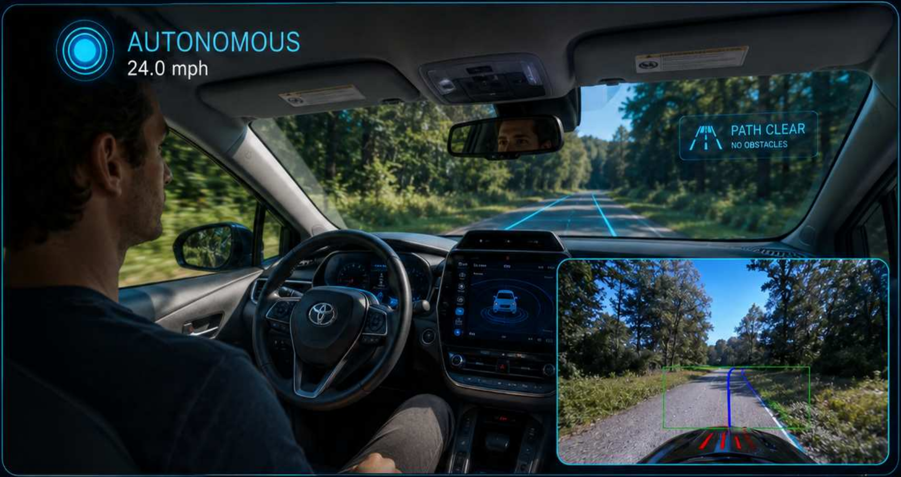
An image is a **matrix of numbers.**

12	12	11	13	12
12	13	10	12	11
13	12	11	14	10
11	14	12	13	12
12	13	13	14	10



Each individual number in this matrix is a picture element or **PIXEL.**

IMPACT: SELF-DRIVING CARS



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VISUAL SENSING / CAPTURE

↓

FEATURE EXTRACTION / AI ANALYSIS

↓

HEALTHCARE / DIAGNOSIS

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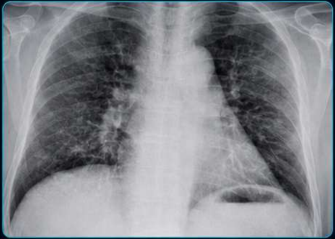
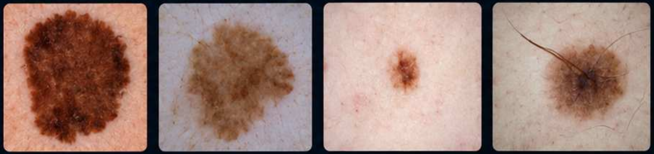
COVID-19



Skin cancer



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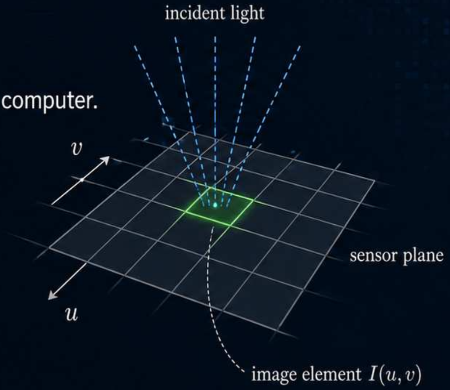

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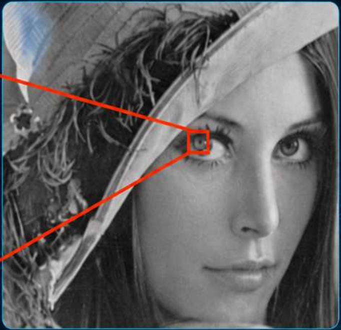
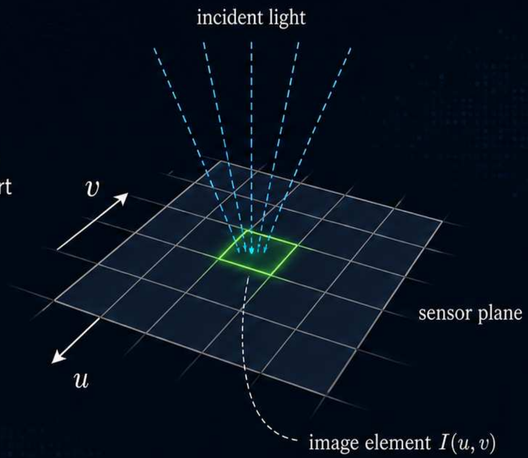


Each individual number in this matrix is a picture element or **PIXEL.**

GOING DIGITAL

Projection on the image plane of a camera is a two-dimensional, time-dependent, continuous distribution of light energy. To convert this image into a digital image, 3 steps are necessary:

- Spatial sampling
- Temporal sampling
- Quantization of pixel values



GOING DIGITAL

- **Spatial sampling:** Conversion of the continuous signal to its discrete representation.
- **Temporal sampling:** Integrates at regular intervals the amount of light incident on each individual sensor element.
- **Quantization of pixel values:** Image values on the computer they are commonly converted to an integer scale.

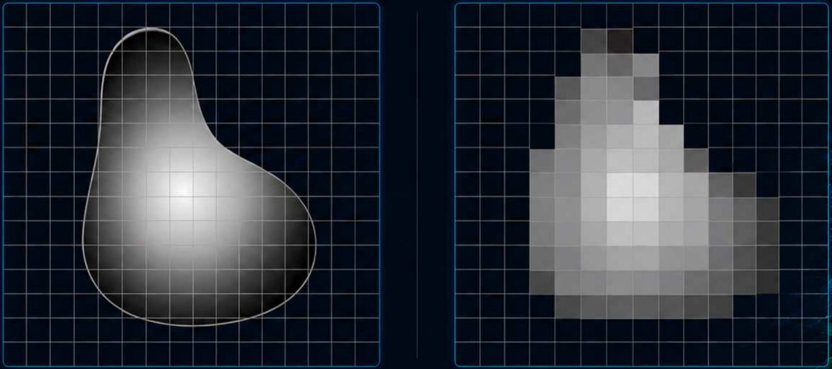
$\downarrow F(x,y)$

148	123	52	107	123	162	172	123	64	89	…
147	130	92	95	98	130	171	155	169	163	…
141	118	121	146	117	107	144	137	136	134	…
82	106	93	172	149	131	138	114	113	129	…
57	101	72	54	109	111	104	135	106	125	…
138	135	114	82	121	110	34	76	101	111	…
138	102	128	159	168	147	116	129	124	117	…
113	89	89	109	106	126	114	150	164	145	…
120	121	123	87	85	70	119	64	79	127	…
145	141	143	134	111	124	117	113	64	112	…
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	…

SAMPLING AND QUANTIZATION

(a) CONTINUOUS IMAGE
PROJECTED ONTO A SENSOR ARRAY

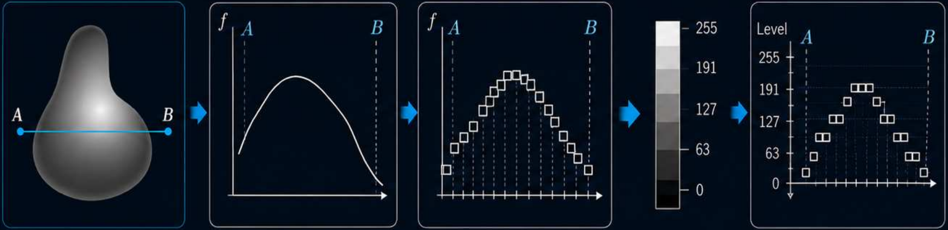
(b) SAMPLED AND QUANTIZED IMAGE
RESULT OF IMAGE SAMPLING AND QUANTIZATION



Continuous image projected onto a sensor array → result of image sampling and quantization.

GENERATING A DIGITAL IMAGE

(a) CONTINUOUS IMAGE | (b) SCAN LINE (CONTINUOUS) | (c1) SAMPLING | (c2) QUANTIZATION | (d) DIGITAL SCAN LINE



A continuous intensity image $f(x,y)$.

Intensity profile along the scan line from A to B.

Sample the continuous profile at regular intervals.

Map each sample to the nearest discrete intensity level.

The quantized samples form the digital scan line (a row of pixels).

(a) Continuous image: A 2-D scene described by a continuous intensity function $f(x,y)$.

(b) Scan line: A horizontal line from A to B and its continuous intensity profile.

(c) Sampling & quantization: Sample the profile at discrete positions and map each sample to a discrete intensity level.

(d) Digital scan line: The resulting sequence of quantized values—the building blocks (pixels) of a digital image.

TEMPORAL SAMPLING IN FAST-MOVING IMAGERY

Temporal sampling means measuring or capturing image information at discrete time instants.

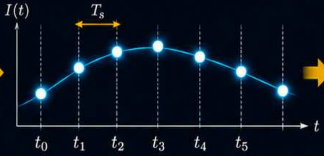
① CONTINUOUS MOTION IN TIME

The scene evolves continuously.

Continuous motion in time

② TEMPORAL SAMPLING

Measure at discrete, equally spaced instants.



Sampling period: T_s (seconds per sample)

$$I[n] = I(nT_s)$$

The discrete-time sequence $I[n]$ contains one value (one frame) at each sample instant nT_s.

③ SAMPLED IMAGE FRAMES

The continuous motion becomes a discrete sequence of images.

Each frame is the amount of light measured during Δt around t_n.

HIGHER TEMPORAL SAMPLING RATE

Smaller T_s (more frames per second)

Smooth motion representation; less temporal blur.

VS.

LOWER TEMPORAL SAMPLING RATE

Larger T_s (fewer frames per second)

Jerkier motion; more temporal blur and aliasing.

KEY TAKEAWAY

Temporal sampling captures a dynamic scene at discrete times; **higher sampling rates represent fast motion more faithfully.**

EXPOSURE TIME AND SNAPSHOT IMAGING

① SHORT EXPOSURE

Very short integration window Δt_s

Fewer photons

Sharp motion, fewer photons

Measurement is noisier (lower photon count).

$$g_s(x, y; t_0) = \int_{t_0}^{t_0+\Delta t_s} I(x, y, t)\, dt$$

② LONGER EXPOSURE

Longer integration window Δt_ℓ

More photons

More photons, more blur

Scene motion during integration causes blur.

$$g_\ell(x, y; t_0) = \int_{t_0}^{t_0+\Delta t_\ell} I(x, y, t)\, dt$$

③ TRADEOFF

Exposure time controls the snapshot outcome.

	SHORT EXPOSURE (Δt_s)	LONG EXPOSURE (Δt_ℓ)
Motion	Freezes motion (high temporal fidelity)	Motion blur (low temporal fidelity)
Photon Count	Lower photon count fewer photons	Higher photon count more photons
Noise	Noisier measurement (lower SNR)	Less noise (higher SNR)
Result	Sharper snapshot (less blur)	Blurrier snapshot (more blur)

Exposure time sets how long photons are integrated while the scene moves.

A snapshot is the time-integrated photon measurement of a dynamic scene.

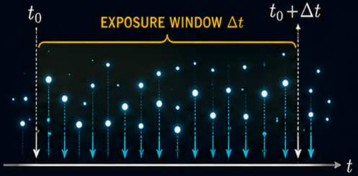
$$\bar{g}(x, y; t_0) = \frac{1}{\Delta t} \int_{t_0}^{t_0+\Delta t} I(x, y, t)\, dt$$

TEMPORAL INTEGRATION OF PHOTONS

① MOVING SCENE

The scene evolves continuously while light arrives at the sensor.

② EXPOSURE / PHOTON INTEGRATION



$$\bar{g}(x,y;t_0) = \int_{t_0}^{t_0+\Delta t} I(x,y,t)\,dt$$

Snapshot intensity equals the photons integrated during the exposure window.

③ SNAPSHOT FRAME

One frame stores the accumulated light from the moving scene.

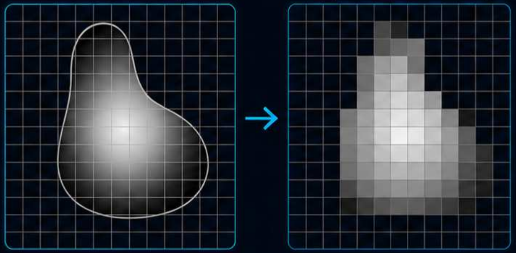
A camera snapshot is not an instantaneous point measurement;
it is the temporal integration of photons over a finite exposure interval Δt.

$$\bar{g}(x,y;t_0) = \frac{1}{\Delta t}\int_{t_0}^{t_0+\Delta t} I(x,y,t)\,dt$$

SAMPLING, QUANTIZATION & INTENSITY

1 SAMPLING & QUANTIZATION

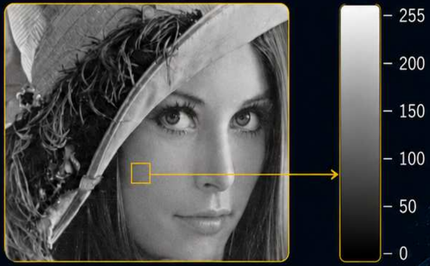
Continuous image | Sampled & quantized image



Sampling selects discrete spatial locations; **quantization** maps each sample to a finite gray level.

2 INTENSITY IMAGE

Grayscale intensity image | Gray level



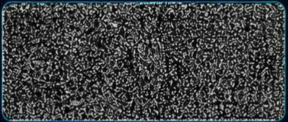
Each pixel value represents a **shade of gray**.

> A digital grayscale image is a **matrix** of **quantized intensity values**.

BIT PLANES IN PRACTICE

Original (8-bit grayscale)

Bit plane 1 (LSB)



Bit plane 2

Bit plane 3

Bit plane 4

Bit plane 5

Bit plane 6

Bit plane 7

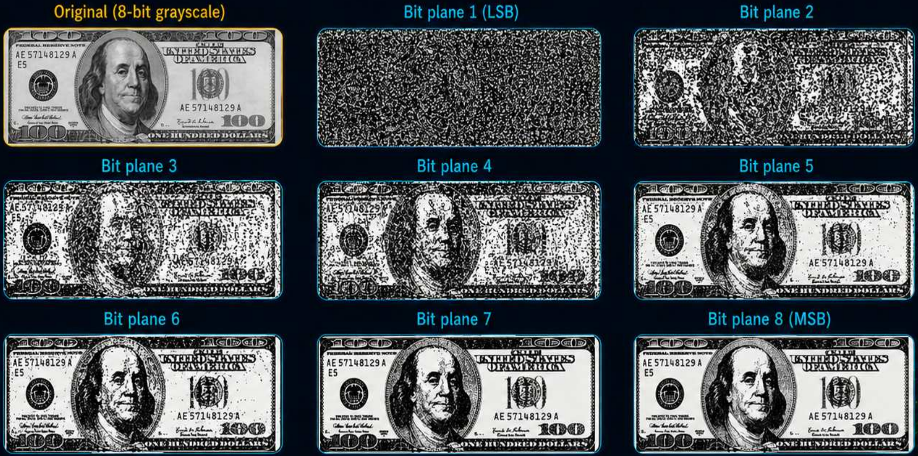
Bit plane 8 (MSB)

Each bit plane is a binary image; higher-order planes retain more visual information.

BIT-PLANE REPRESENTATION

An 8-bit image can be decomposed into 8 binary bit planes from least to most significant.

BIT PLANES IN PRACTICE



Each bit plane is a binary image; higher-order planes retain more visual information.

QUANTIZATION

How many different colors are needed to represent a particular image?

8 bits/pixel

4 bits/pixel

2 bits/pixel

Fewer bits per pixel result in fewer distinct tonal levels (colors).

Number of levels per color channel (approx.)

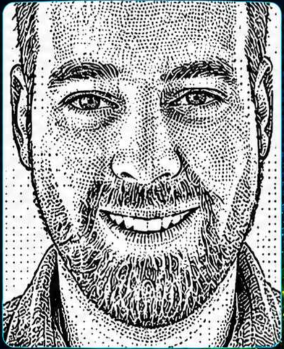
- 8 bits → 256 levels
- 4 bits → 16 levels
- 2 bits → 4 levels

BINARY IMAGES

- Binary image pixels can take on one of two values: black or white.
- These values are encoded using a single bit (0/1) per pixel.
- Binary images are used for line graphics, document archiving, fax transmission, and many printing systems.

PRINTING EXAMPLE

BINARY PORTRAIT



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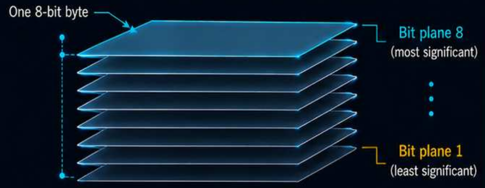
BIT PLANES & PIXEL VALUES

CONCEPT: 8-BIT BIT-PLANE REPRESENTATION

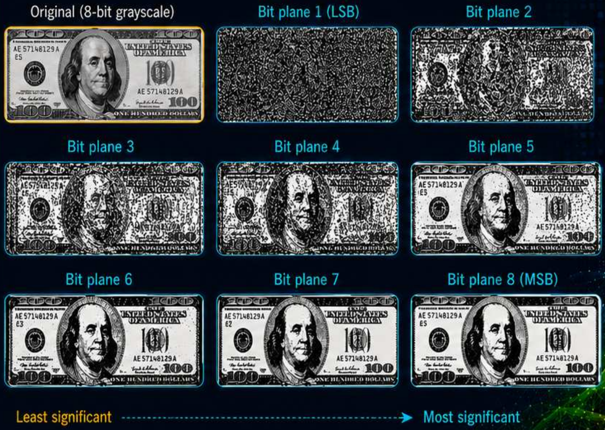


PIXEL VALUES (GRAYSCALE INTENSITY)

Bit Depth (k)	Values per Pixel (2^k)	Range	Typical Use
1-bit	2	0..1	Binary images: documents, fax
8-bit	256	0..255	Universal: photo, scan, print
12-bit	4096	0..4095	High quality: photo, scan, print
16-bit	65536	0..65535	Highest quality: medicine, astronomy

Information within an image element depends on the data type used to represent it. A pixel can be represented by any of 2^k different values.

PRACTICE: $100 BILL (8-BIT GRAYSCALE) DECOMPOSED INTO BIT PLANES



An 8-bit grayscale image can be decomposed into binary bit planes, while each pixel stores one of 2^k intensity values.

QUANTIZATION & BINARY IMAGES

QUANTIZATION

How many different colors are needed to represent a particular image?

8 bits/pixel

→

4 bits/pixel

→

2 bits/pixel

Fewer bits per pixel result in **fewer distinct tonal levels (colors).**

Number of levels per color channel (approx.)

8 bits → 256 levels | 4 bits → 16 levels | 2 bits → 4 levels

BINARY IMAGES

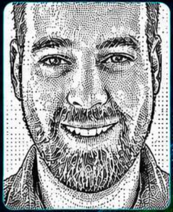
Binary image pixels can take on one of two values: **black** or **white.**

0	1
black	white

- These values are encoded using a single bit (0/1) per pixel.
- Binary images are used for **line graphics, document archiving, fax transmission,** and many **printing systems.**

Printing Example

Binary Portrait



★ Binary images are the **1-bit extreme** of quantization.

PIXEL VALUES

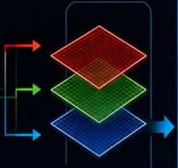
Information within an image element depends on the data type used to represent it.
A pixel can be represented by any of 2^k different values.

Grayscale (Intensity Images)

Channels	Bits/Pixel	Range	Typical Use	Example
1	1	0…1	Binary image: document, illustration, fax	
1	8	0…255	Universal: photo, scan, print	
1	12	0…4095	High quality: photo, scan, print	
1	14	0…16383	Professional: photo, scan, print	
1	16	0…65535	Highest quality: medicine, astronomy	 

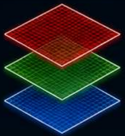
RGB IMAGE

CHANNEL DECOMPOSITION



COMBINE
the three intensity images to form a color image.

FINAL RGB IMAGE

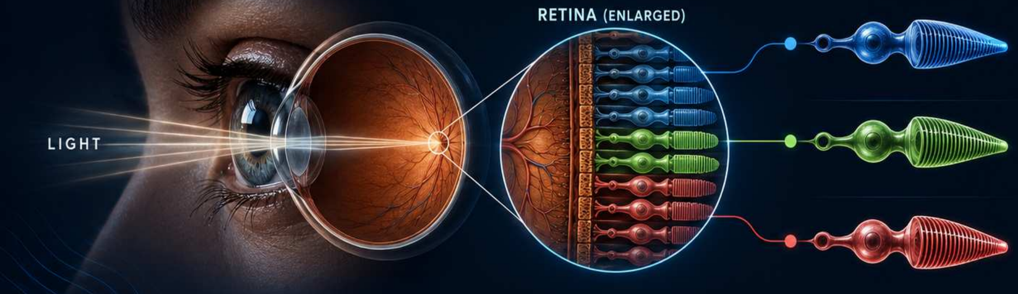


A color image is formed by combining three intensity images, one for each primary color channel: Red, Green, and Blue.

$$I_{RGB}(x,y) = [\ R(x,y),\ G(x,y),\ B(x,y)\ ]$$

WHY RED, GREEN, AND BLUE?

Human vision samples color with *three cone families*.



S-cones
Short wavelength
(blue)

M-cones
Medium wavelength
(green)

L-cones
Long wavelength
(red)

RGB imaging approximates the trichromatic response of the human visual system.

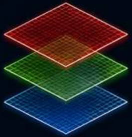
RGB IMAGE

RED CHANNEL

GREEN CHANNEL

BLUE CHANNEL

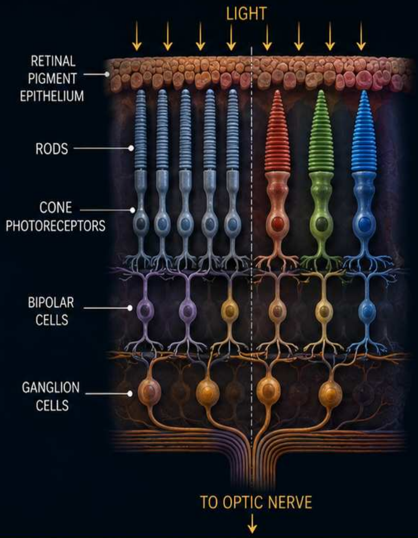
FINAL RGB IMAGE

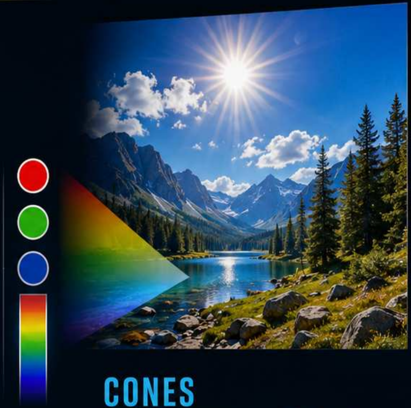


A color image is formed by stacking three intensity images: $R(x,y)$, $G(x,y)$, $B(x,y)$.

$$I_{RGB}(x,y) = [\, R(x,y),\, G(x,y),\, B(x,y) \,]$$

RODS AND CONES





RODS

- high sensitivity
- low-light vision
- grayscale intensity

CONES

- color vision
- red / green / blue sensitivity
- high spatial detail

IMAGE SENSING ACROSS THE ELECTROMAGNETIC SPECTRUM

Imaging machines extend vision beyond the visible band.

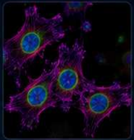
GAMMA RAYS

Medical gamma imaging

X-RAYS

Radiography / CT imaging

ULTRAVIOLET



Fluorescence microscopy

VISIBLE

Photography / human vision

INFRARED

Thermal imaging / remote sensing

MICROWAVES

SAR / radar imaging

RADIO WAVES

Radio astronomy / communication

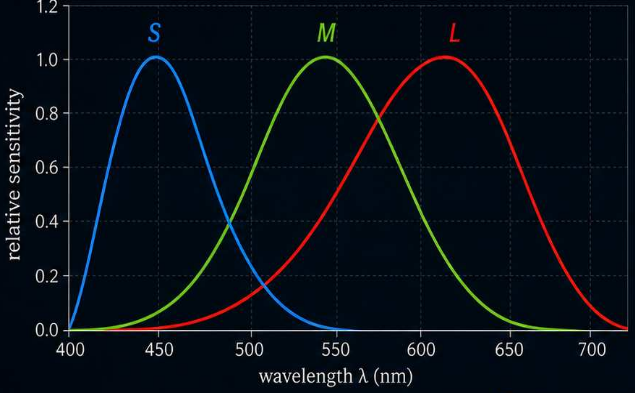
HIGHER FREQUENCY → LOWER FREQUENCY

GAMMA RAYS	X-RAYS	ULTRAVIOLET	VISIBLE	INFRARED	MICROWAVES	RADIO WAVES
10^{-12} m	10^{-10} m	10^{-8} m	10^{-6} m (400–700 nm)	10^{-4} m	10^{-2} m	10^{0} – 10^{6} m

High-energy, short-wavelength radiation probes matter and internal structure.

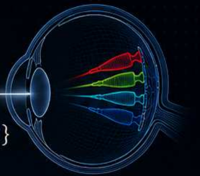
Infrared and **microwave** bands are crucial for remote sensing of Earth and beyond.

SPECTRAL SENSITIVITY OF COLOR VISION



S = short wavelength
M = medium wavelength
L = long wavelength

FROM SPECTRAL ENERGY TO COLOR SIGNALS



$$c_k = \int s_k(\lambda)\, E(\lambda)\, d\lambda, \quad k \in \{R, G, B\}$$

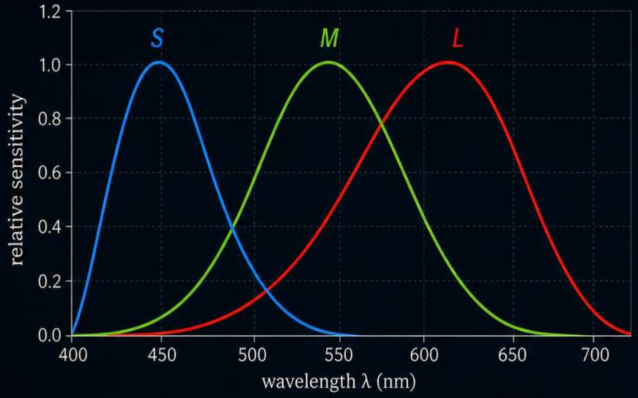
$s_k(\lambda)$: cone spectral sensitivity | $E(\lambda)$: spectral power distribution
c_k: cone response (linear signal)

Cone responses weight incoming spectral energy.
Each cone type (S, M, L) has a distinct sensitivity curve.

Color channels are formed by integrating $E(\lambda)$ against sensitivity curves.
This converts a spectrum into three cone responses.

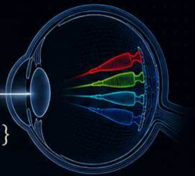
RGB imaging approximates human trichromatic sensing.
Modern cameras map spectra to device RGB channels.

SPECTRAL SENSITIVITY OF COLOR VISION



S = short wavelength
M = medium wavelength
L = long wavelength

FROM SPECTRAL ENERGY TO COLOR SIGNALS



$$c_k = \int s_k(\lambda)\, E(\lambda)\, d\lambda, \quad k \in \{R, G, B\}$$

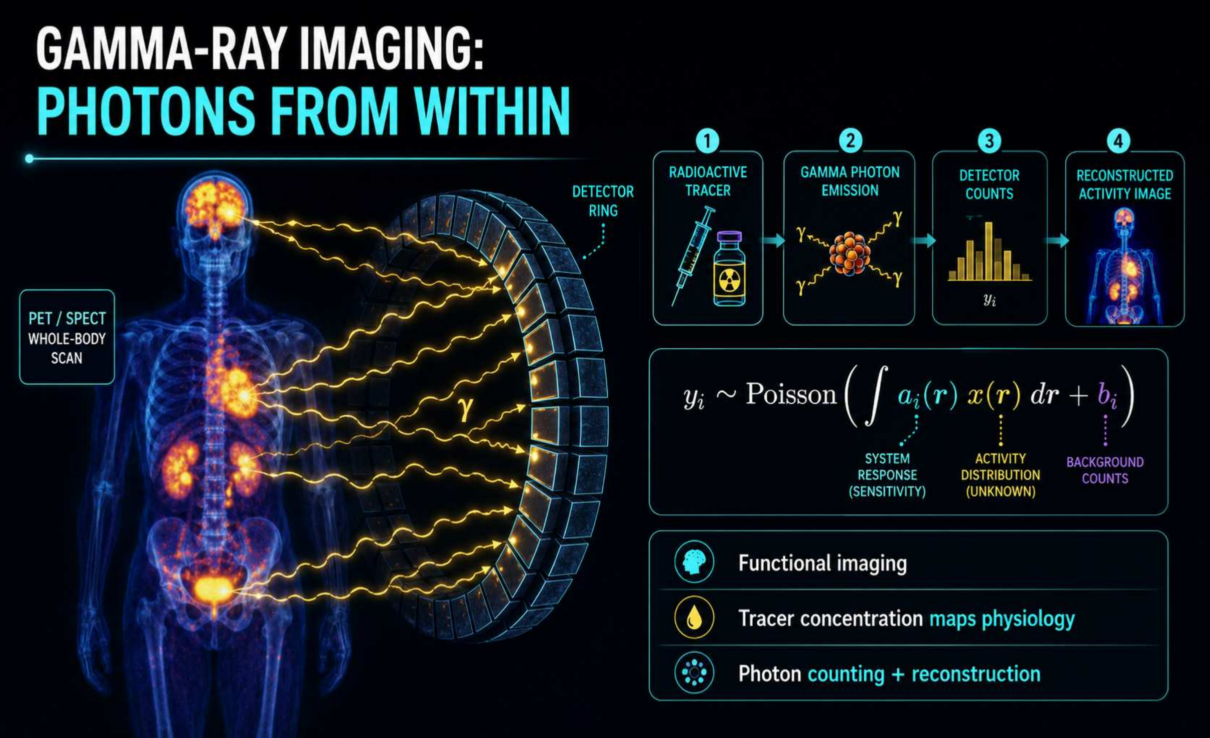
$s_k(\lambda)$: cone spectral sensitivity | $E(\lambda)$: spectral power distribution

c_k: cone response (linear signal)

Cone responses weight incoming spectral energy.
Each cone type (S, M, L) has a distinct sensitivity curve.

Color channels are formed by integrating $E(\lambda)$ against sensitivity curves.
This converts a spectrum into three cone responses.

RGB imaging approximates human trichromatic sensing.
Modern cameras map spectra to device RGB channels.

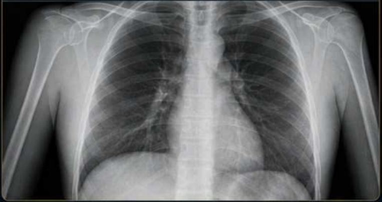

GAMMA-RAY IMAGING:
PHOTONS FROM WITHIN
DETECTOR RING
PET / SPECT WHOLE-BODY SCAN
γ
1 RADIOACTIVE TRACER
2 GAMMA PHOTON EMISSION
γ γ γ γ
3 DETECTOR COUNTS
y_i
4 RECONSTRUCTED ACTIVITY IMAGE
$y_i \sim \mathrm{Poisson}\left(\int a_i(r)\, x(r)\, dr + b_i \right)$
SYSTEM RESPONSE (SENSITIVITY)
ACTIVITY DISTRIBUTION (UNKNOWN)
BACKGROUND COUNTS
Functional imaging
Tracer concentration maps physiology
Photon counting + reconstruction

ELEG404/604

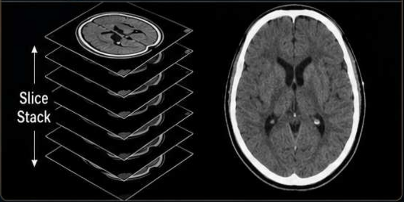
MEDICAL IMAGING & IMAGE ANALYSIS

X-RAY IMAGING AND COMPUTED TOMOGRAPHY

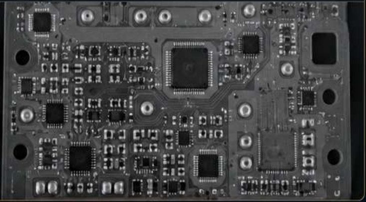
1. MEDICAL RADIOGRAPHY
Chest Projection



2. COMPUTED TOMOGRAPHY (CT)
Brain Slice (Axial)



3. INDUSTRIAL INSPECTION
Circuit Board



FORWARD MODELS

Projection Radiography

$$I = I_0 \exp\left(-\int \mu(s)\, ds\right)$$

Computed Tomography (CT)

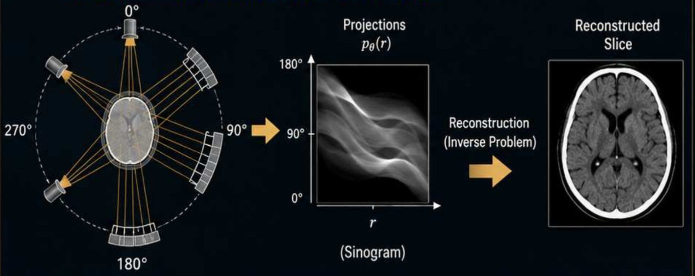
$$p_\theta(r) = \int_{L(\theta,r)} \mu(x,y)\, ds$$

I_0: incident intensity I: detected intensity

μ: linear attenuation coefficient

$L(\theta, r)$: line at angle θ and detector offset r

CT ACQUISITION: ROTATING SOURCE & DETECTORS



HISTORICAL MILESTONE

CT:
from
minutes
to
seconds

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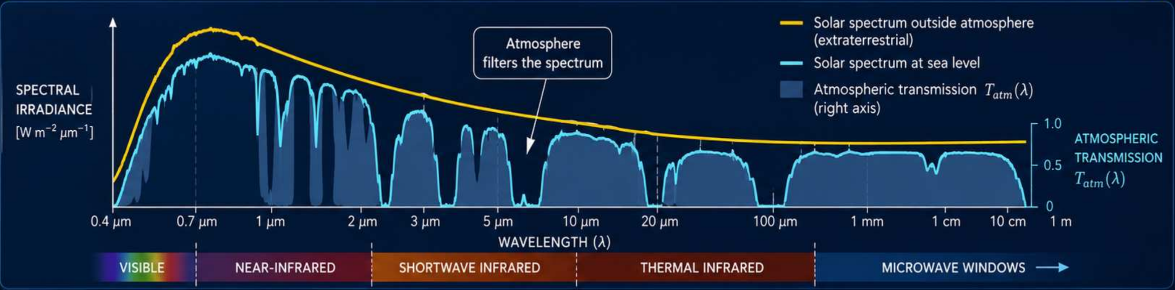
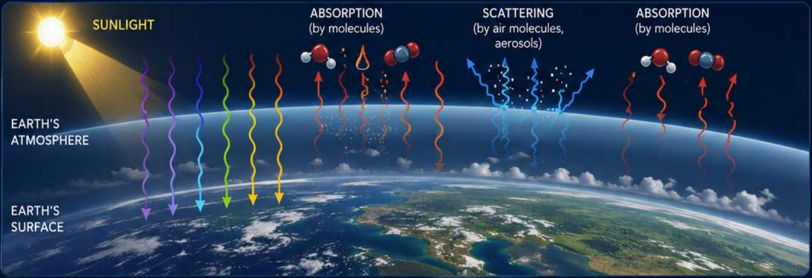
ATMOSPHERIC WINDOWS AND REMOTE SENSING





Usable windows enable satellite imaging

CO_2 O_3 Water vapor, CO_2, and ozone create **absorption bands**

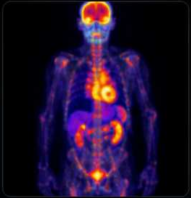
$$L_{sensor}(\lambda) = T_{atm}(\lambda)\, L_{surface}(\lambda) + L_{path}(\lambda)$$

Measured radiance = transmitted surface radiance + path radiance (scattering/emission)

Key idea: The atmosphere does not block all wavelengths—windows of high transmission allow energy to reach the surface and the sensor. Remote sensing uses these natural windows to observe Earth.

IMAGING BEYOND THE VISIBLE BAND

GAMMA IMAGING / NUCLEAR MEDICINE

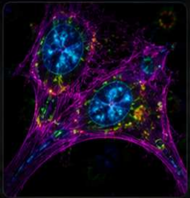


Senses **EMISSION** from radioactive tracers inside the body.

X-RAY CT / RADIOGRAPHY

Senses **ATTENUATION** as X-rays pass through matter.

UV FLUORESCENCE MICROSCOPY



Senses **FLUORESCENCE** emitted by molecules excited by UV light.

VISIBLE PHOTOGRAPHY

Senses **REFLECTANCE** of visible light from surfaces.

INFRARED THERMAL IMAGING

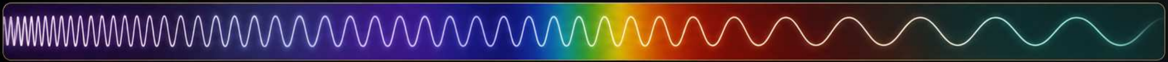
Senses **HEAT** emitted as thermal (IR) radiation from objects.

MICROWAVE SAR / RADAR

Senses **COHERENT SCATTERING** of microwaves from structures.

FREQUENCY (Hz) DECREASING →

WAVELENGTH (m) INCREASING →



GAMMA	X-RAYS	ULTRAVIOLET	VISIBLE	INFRARED	MICROWAVES
$10^{22} - 10^{20}$	$10^{20} - 10^{16}$	$10^{16} - 10^{15}$	$10^{15} - 10^{14}$	$10^{14} - 10^{11}$	$10^{11} - 10^{8}$

Different wavelengths interact with matter differently—
revealing structure, composition, temperature, and motion.

THE ELECTROMAGNETIC SPECTRUM

Gamma rays | X-rays | Ultraviolet | **Visible** | Infrared | Microwaves | Radio waves

WAVELENGTH (λ)	10^{-12} m	10^{-10} m	10^{-8} m	400–700 nm (10^{-7} m)	10^{-6} m	10^{-3} m	10^{-1} m	10^{3} m	→ **LONGER WAVELENGTH**
FREQUENCY (f)	10^{20} Hz	10^{18} Hz	10^{16} Hz	$\sim 5 \times 10^{14}$ Hz	10^{14} Hz	10^{11} Hz	10^{9} Hz	10^{6} Hz	→ **LOWER FREQUENCY**
PHOTON ENERGY (E) $E = hf$	10^{8} eV	10^{6} eV	10^{4} eV	2.8–1.8 eV	1 eV	10^{-3} eV	10^{-6} eV	10^{-9} eV	→ **LOWER ENERGY**

Imaging systems extend human vision across wavelength, energy, and scale.

Spectral Bands: What Each Wavelength Reveals

SPECTRAL BAND	WAVELENGTH (μm)	WHAT IT REVEALS
Visible Blue	0.45–0.52 μm	water penetration
Visible Green	0.52–0.60 μm	plant vigor
Visible Red	0.63–0.69 μm	vegetation discrimination
Near Infrared	0.76–0.90 μm	biomass and shoreline mapping
Shortwave Infrared	1.55–1.75 μm	soil and vegetation moisture
Thermal Infrared	10.4–12.5 μm	temperature / thermal mapping

Spectral band selection turns wavelength into information.

Remote Sensing and Spectral Imaging

1. VISIBLE (RGB)

True-color view

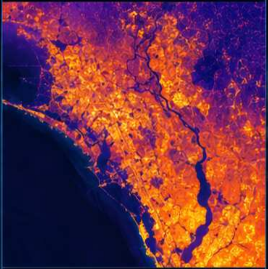
2. NEAR-INFRARED (NIR)

Vegetation vigor (high NIR reflectance)

3. SHORTWAVE INFRARED (SWIR)

Geology & soils, moisture content

4. THERMAL INFRARED (TIR)



Surface temperature (heat)

$$y_b(x, y) = \int S_b(\lambda)\, L(x, y, \lambda)\, d\lambda$$

Bandpass sensing

Each band b measures radiance weighted by its spectral response $S_b(\lambda)$.

Material signatures

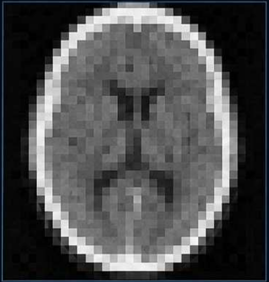
Different materials have distinct spectral reflectance $L(x, y, \lambda)$.

Land cover + vegetation + water

Spectral imaging reveals and quantifies Earth's surfaces.

CT Imaging: From Minutes to Seconds

1972: first-generation CT

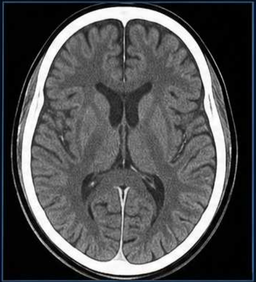


~5 minutes per slice

1972 → today

Rotating source & detector
collect projections from many angles

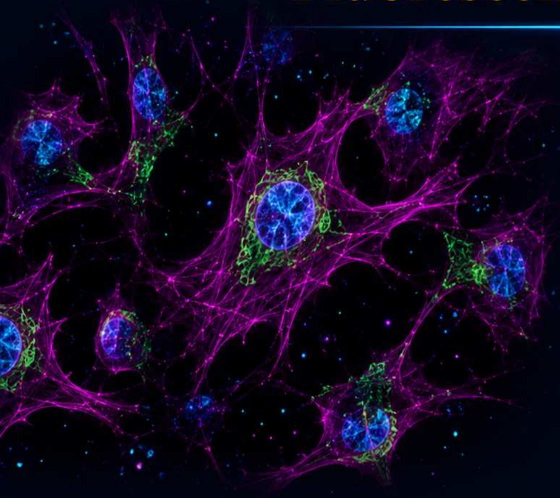
Modern helical CT

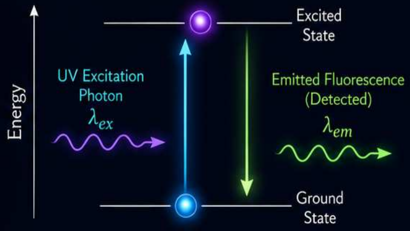


seconds per volume

More projections + faster acquisition + reconstruction algorithms transformed tomography.

Ultraviolet Imaging:
Fluorescence Microscopy





$$\lambda_{ex} < \lambda_{em}$$

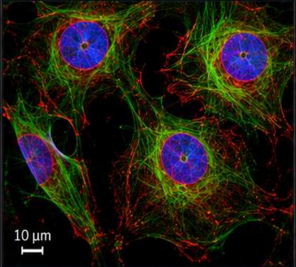
$$E = \frac{hc}{\lambda}$$

E = energy
h = Planck's constant (6.626×10^{-34} J·s)
c = speed of light (2.998×10^{8} m/s)
λ = wavelength

- Molecular specificity
- High contrast
- Biology and medicine

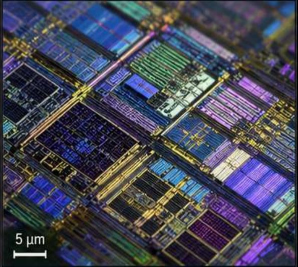
Visible and Infrared Imaging Across Scales

OPTICAL MICROSCOPY
Cells



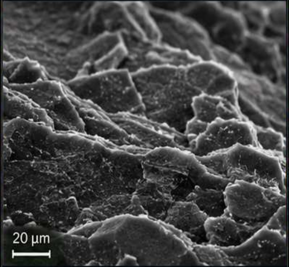
Biological structure and function

SEMICONDUCTOR IMAGING
Microchip Detail



Layers, features, and doping

MATERIAL SURFACE IMAGING
Surface Texture



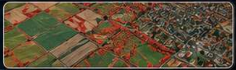
Topography, defects, roughness

INFRARED THERMAL IMAGING
Building Heat Loss

Heat, energy, and emissivity

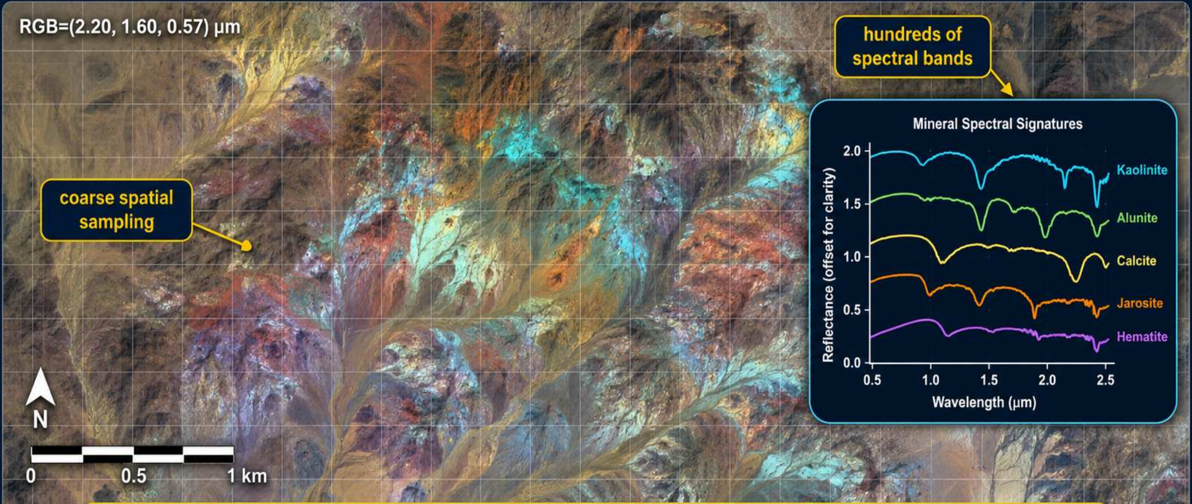
Changing wavelength *changes what physical contrast* we see.

Spectral Bands: What Each Wavelength Reveals

SPECTRAL BAND	WAVELENGTH (µm)	WHAT IT REVEALS	EXAMPLE IMAGE
Visible Blue	0.45–0.52 µm	water penetration	
Visible Green	0.52–0.60 µm	plant vigor	
Visible Red	0.63–0.69 µm	vegetation discrimination	
Near Infrared	0.76–0.90 µm	biomass and shoreline mapping	
Shortwave Infrared	1.55–1.75 µm	soil and vegetation moisture	
Thermal Infrared	10.4–12.5 µm	temperature / thermal mapping	

Spectral band selection turns wavelength into information.

Hyperion: Rich Spectra, Coarse Spatial Detail



Takeaway: Hyperspectral data identifies materials, but **spatial detail can be limited.**

Visible vs. Shortwave Infrared Imaging

VISIBLE | **NEAR / SHORTWAVE INFRARED (NIR / SWIR)**

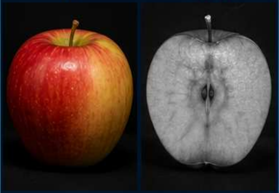
WAVELENGTH

400 nm — 700 nm — 0.7 µm — 1.4 µm

increasing penetration / material contrast →

1. FRUIT / APPLE

VIS | SWIR



SWIR reveals subsurface defects, bruising, and internal structure.

2. HIDDEN LIQUID IN PLASTIC BOTTLE

VIS | SWIR

SWIR penetrates plastic to reveal liquid level and contents.

3. PAINTING / UNDERDRAWING

VIS | SWIR

SWIR reveals underdrawings and changes invisible in visible light.

4. BANKNOTE / SECURITY INK

VIS | SWIR

SWIR reveals security features and inks invisible to the eye.

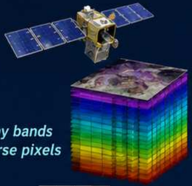
TAKEAWAY: SWIR imaging sees beyond color: **subsurface structure, moisture,** and **material composition.**

University of Delaware

Hyperion and WorldView-3 Fusion

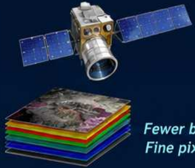
High spectral detail + high spatial detail

HYPERION
Hyperspectral



Many bands
Coarse pixels

WORLDVIEW-3
Multispectral

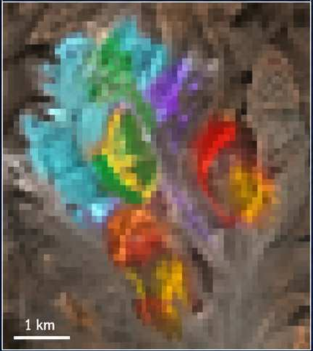


Fewer bands
Fine pixels

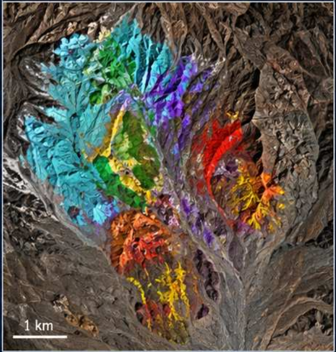
Parameter	Hyperion	WorldView-3
VNIR Bands	50	8
SWIR Bands	117	8
GSD (Ground Sample Distance)	30 m	1.24 m (VNIR) 7.5 m / 3.7 m (SWIR)
Swath Width	7.7 km	13.1 km

Cuprite, Nevada – Mineral Mapping

Hyperion (30 m) – Hyperspectral Map



Fused (Hyperion + WV-3) – Sharpened Map



Alunite | Kaolinite | Buddingtonite | Jarosite | Hematite | Chalcopyrite | Other / Unclassified

$$X_{fused} \approx \text{spatial detail (WV3)} + \text{spectral richness (Hyperion)}$$

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Hyperion–WV3 Fusion: *Sharper Spectral Maps*

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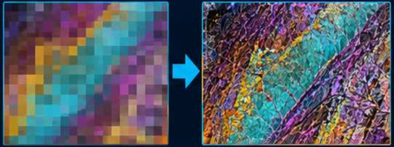
BEFORE / AFTER

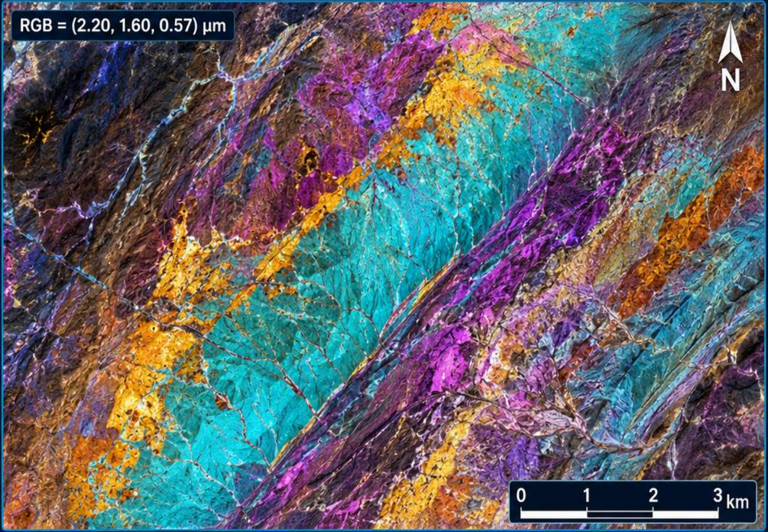
Hyperion (coarse) | Hyperion–WV3 (fused sharp)



- spectral fidelity
- spatial sharpening
- mineral discrimination

$$\hat{X} = \arg\min_{X} \|Y_H - H_s X\|^2 + \|Y_W - H_W X\|^2 + \lambda\, \mathcal{R}(X)$$

Fusion aims to preserve spectral signatures while recovering fine spatial structure.



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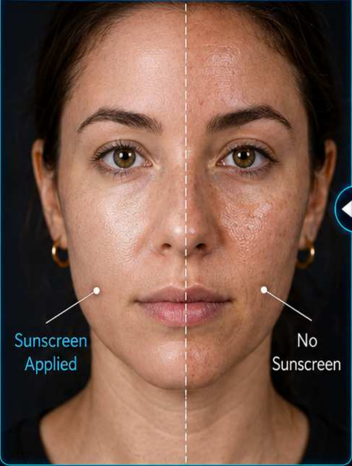
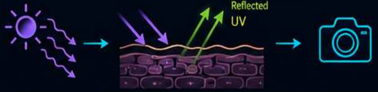
Ultraviolet Imaging: Sunscreen Made Visible

VISIBLE LIGHT



ULTRAVIOLET (UV) IMAGE

HOW IT WORKS



IMAGING MODEL

$$I_{UV}(x,y) = \int_{\lambda_1}^{\lambda_2} S_{UV}(\lambda)\, E(\lambda)\, R(x,y,\lambda)\, d\lambda$$

Sunscreen changes UV reflectance / absorption $R(x,y,\lambda)$.

- UV reveals sunscreen coverage
- Protected regions appear darker
- Useful for skin-care education and dermatology

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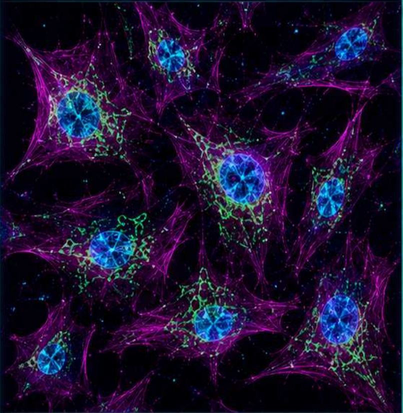
Ultraviolet Imaging: Fluorescence and Surface Effects

UV FLUORESCENCE MICROSCOPY



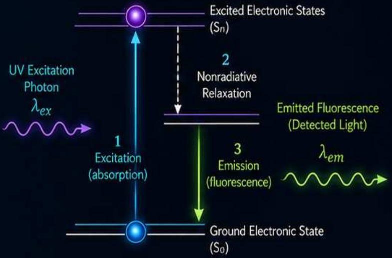
Actin (Alexa Fluor 647) Nuclei (DAPI) Mitochondria (MitoTracker Green)

UV SURFACE EFFECT: FORENSIC FINGERPRINT

Latent fingerprint visualized with fluorescence powder under 365 nm UV light.

Ridges fluoresce; background remains dark.

UV FLUORESCENCE: CONCEPT AND ENERGY DIAGRAM



$$\lambda_{ex} < \lambda_{em}$$

$$E = \frac{hc}{\lambda}$$

E = energy
h = Planck's constant (6.626×10^{-34} J·s)
c = speed of light (2.998×10^{8} m/s)
λ = wavelength

1 Excitation (UV absorbed) 2 Nonradiative relaxation (heat) 3 Emission (visible fluorescence)

Molecular specificity
Selective to fluorescent molecules and markers.

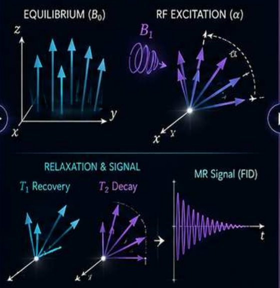
High contrast
Bright signal on dark backgrounds.

Applications in biology, forensics, and authentication
From cellular imaging to security and trace evidence.

Magnetic Resonance Imaging: From Spins to k-Space

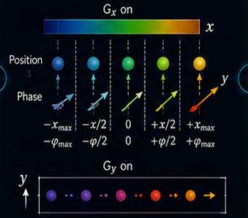
1 THE MRI SYSTEM

2 SPIN EXCITATION & RELAXATION



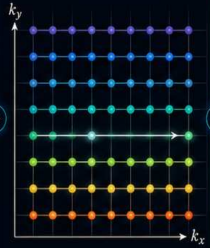
3 GRADIENT ENCODING (Spatial Frequency)

Gradients turn position into phase.
Different locations precess at different rates.



Gradients map spatial position (x,y) to spatial frequency (k_x, k_y).

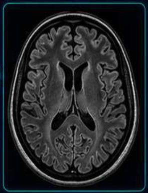
4 k-SPACE ACQUISITION (Line-by-Line Sampling)



Each readout samples a line in k-space.
Stacking lines fills k-space.

5 IMAGE RECONSTRUCTION

Inverse Fourier Transform of k-space



High-resolution anatomical image with rich soft-tissue contrast.

WHAT HAPPENS?

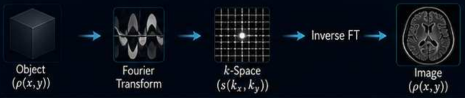
- RF pulse excites spins, creating coherent transverse magnetization.
- Gradients encode position as phase (frequency) during signal readout.
- Measurements fill k-space, which encodes all spatial frequencies.

THE MRI FORWARD MODEL

$$s(k_x, k_y) = \iint \rho(x,y)\, e^{-j2\pi(k_x x + k_y y)}\, dxdy$$

- $s(k_x, k_y)$: Measured signal in k-space
- $\rho(x,y)$: Object spin density (image space)
- $e^{-j2\pi(k_x x + k_y y)}$: Complex sinusoid (spatial frequency)

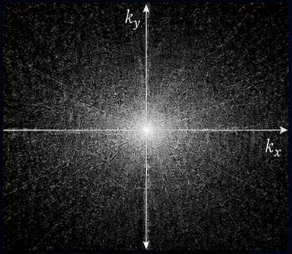
FROM SPATIAL FREQUENCY TO IMAGE



k-space center → image contrast | k-space extent → resolution

MRI Reconstruction: *k*-Space to Image

k-SPACE (Magnitude)

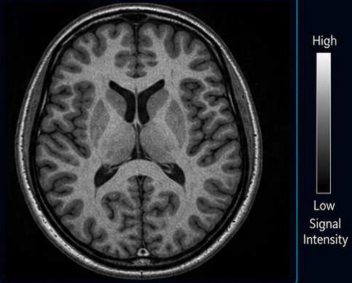


Low — Signal Magnitude (log scale) — High

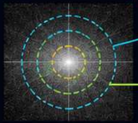
inverse Fourier transform →

$$\rho(x, y) = \iint s(k_x, k_y) e^{j2\pi(k_x x + k_y y)}\, dk_x dk_y$$

RECONSTRUCTED IMAGE (Magnitude)



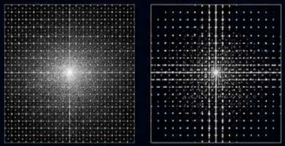
WHAT *k*-SPACE ENCODES



- **Center** (low k) → Contrast / Overall intensity
- **Outer** (high k) → Edges / Fine detail

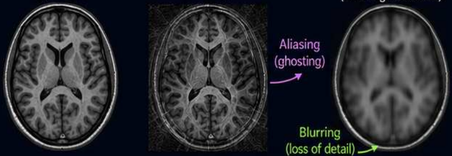
SAMPLING IN *k*-SPACE

Fully Sampled | Undersampled



EFFECT ON RECONSTRUCTED IMAGE

Fully Sampled | Undersampled | Undersampled (with regularization)

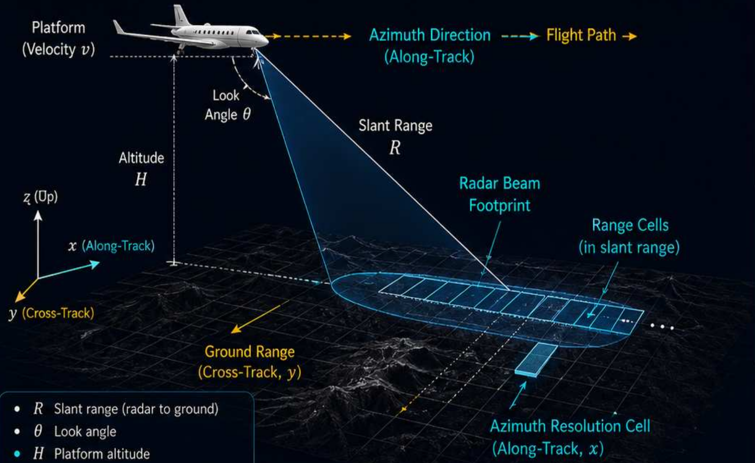


KEY TAKEAWAYS

- **Center** = low spatial frequencies / **contrast**
- Edges of k-space = **fine detail**
- Reconstruction converts spatial frequencies into **anatomy**

Synthetic Aperture Radar: Range and Azimuth Geometry

Side-Looking Geometry



- R Slant range (radar to ground)
- θ Look angle
- H Platform altitude
- x Along-track (azimuth) direction
- y Cross-track (ground range) direction

Focused SAR Image (Example)

RANGE RESOLUTION
(Across-Track)

$$\rho_r \approx \frac{c}{2B}$$

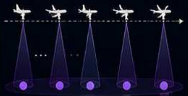
B = transmitted bandwidth
c = speed of light

AZIMUTH RESOLUTION
(Along-Track, Stripmap)

$$\rho_{az} \approx \frac{L}{2}$$

L = synthetic aperture length (projected along track)

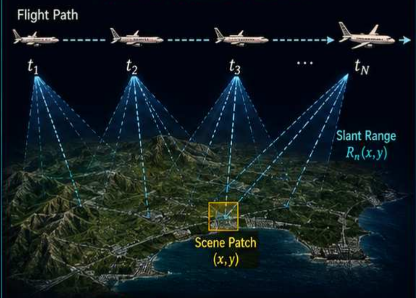
PROCESSING INTUITION



The antenna moves along track and transmits many pulses. Coherent processing synthesizes a long aperture L, focusing energy in azimuth and achieving high resolution ρ_{az}.

SAR Imaging:
From Phase History to Focused Image

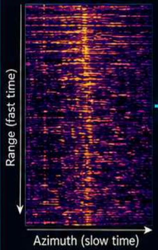
Synthetic Aperture in Azimuth



Many **coherent** looks of the same scene patch build a long **synthetic aperture** in azimuth.

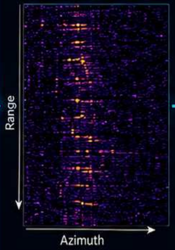
SAR Image Formation Pipeline

1) Raw Echoes (Phase History)



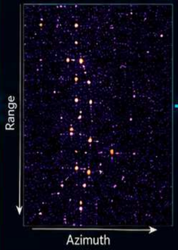
Echoes recorded versus range and azimuth.

2) Range Compression (Matched Filter)



Compress each pulse in range to resolve scatterers.

3) Azimuth Compression (Doppler / Matched Filter)



Coherently sum across the aperture to focus in azimuth.

4) Focused SAR Image

Sharp, high-resolution SAR intensity image.

$$I(x,y) = \left| \sum_{n=1}^{N} p_n(x,y)\, e^{-j\phi_n(x,y)} \right|$$

$p_n(x,y)$ = magnitude (amplitude) of n^{th} look at (x,y)

$\phi_n(x,y)$ = two-way phase for n^{th} look

N = number of aperture positions

- Microwaves provide **all-weather** imaging
- Coherent phase enables **fine azimuth** resolution
- Focusing converts repeated observations into a **sharp image**

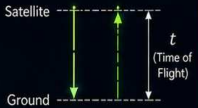
Key Performance

Range Resolution	$\Delta R = \frac{c}{2B}$
Azimuth Resolution	$\Delta x \approx \frac{\lambda R}{2L}$
Contrast	High via coherent gain

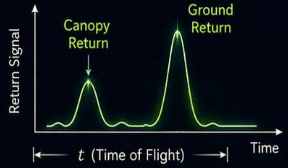
Satellite LiDAR Sensing: Laser Footprints from Orbit

TIME OF FLIGHT (TOF)

Laser pulse travels to the surface and back.



RETURN WAVEFORM



RANGE FROM TIME OF FLIGHT

$$R = \frac{ct}{2}$$

R = slant range
c = speed of light
t = time of flight

ELEVATION (ABOVE REFERENCE)

$$z = H_{sat} - R$$

z = elevation
H_{sat} = satellite altitude
R = slant range

1. ACTIVE SENSING

LiDAR emits its own laser pulses and measures the returned signal.

2. PRECISE ELEVATION FROM TIME OF FLIGHT

Distance is computed from TOF, then converted to elevation.

3. FOOTPRINTS SAMPLE TERRAIN AND CANOPY STRUCTURE

Each footprint captures vertical structure from canopy to ground.

Visible vs. Shortwave Infrared Imaging

VISIBLE | **NEAR / SHORTWAVE INFRARED (NIR / SWIR)**

WAVELENGTH: 400 nm — 700 nm — 0.7 µm — 1.4 µm

increasing penetration / material contrast →

1. FRUIT / APPLE

VIS | SWIR

SWIR reveals subsurface defects, bruising, and internal structure.

2. HIDDEN LIQUID IN PLASTIC BOTTLE

VIS | SWIR

SWIR penetrates plastic to reveal liquid level and contents.

3. PAINTING / UNDERDRAWING

VIS | SWIR

SWIR reveals underdrawings and changes invisible in visible light.

4. BANKNOTE / SECURITY INK

VIS | SWIR

SWIR reveals security features and inks invisible to the eye.

TAKEAWAY: SWIR imaging sees beyond color: **subsurface structure, moisture,** and **material composition.**