Smartphones have changed the world.
Smartphones have changed the world.

In 2010, we still relied on a bag full of gadgets—camera, camcorder, GPS and even alarm clocks and flashlights. Today, we only need one.

THE SMARTPHONE CHANGED. THEN IT CHANGED US.

THE WALL STREET JOURNAL.

JOANNA STERN
The Trillion-Dollar Smartphone Economy
Estimated sales of smartphones and related hardware, content and services in 2020

$484b
Smartphones

$176b
Mobile advertising

$77b
Accessories

$25b
Wearables

$18b
Insurance

$118b
Apps

$12b
Repairs

$9b
Smart speakers

$10b
Music

$8b
Video streaming subscriptions

$3b
Storage; $4b=Others

Deloitte estimates the combined smartphone and smartphone multiplier market to be worth $944 billion in 2020*

* Deloitte defines the "smartphone multiplier" as total sales of products and services depending on smartphone ownership.

Source: Deloitte analysis of data from App Annie, IFPI, Zenith and others
Smartphones Cause Photography Boom

Number of digital photos taken worldwide*

<table>
<thead>
<tr>
<th>Year</th>
<th>Photos Taken</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>660b</td>
</tr>
<tr>
<td>2014</td>
<td>810b</td>
</tr>
<tr>
<td>2015</td>
<td>1,000b</td>
</tr>
<tr>
<td>2016</td>
<td>1,100b</td>
</tr>
<tr>
<td>2017</td>
<td>1,200b</td>
</tr>
</tbody>
</table>

Devices used in 2017

- 4.7% Tablets
- 10.3% Digital cameras
- 85.0% Smartphones

* estimates
Source: InfoTrends via Bitkom
More than 2 billion photos shared on social media per day

Over 100 million are “selfies”
What Smartphones Have Done to the Camera Industry

Digital Camera Sales Dropped 84% Since 2010
Worldwide digital camera shipments by CIPA members

Camera & Imaging Products Association (CIPA) is an international industry association. Members include Olympus, Casio, Canon, Kodak, Sony and Nikon among others.

Source: CIPA
Analog Film: 1935-1985

- Introduced in 1935, and dominant for about 50 years.
- Largely discontinued around 2005.
DIGITAL PHOTOGRAPHY
First Digital Camera Prototype
First Digital Camera 1975

E-cam (Electronic Still Camera)
100x100 resolution (0.01Mpix)
Took 20 seconds to shoot a picture
Patented in 1978

“[Kodak executives] were convinced that no one would ever want to look at their pictures on a screen.” — Steven Sasson
35 years later, Sasson got his due...

“[Kodak executives] were convinced that no one would ever want to look at their pictures on a screen.” — Steven Sasson

National Medal of Technology in 2009
Instant Gratification
First Digital Camera Prototype

First Commercial Digital Cameras
First Commercial Digital Camera 1990

Logitech Fotoman, 1990
376x284 resolution;
Black/white w/ 256 gray levels;
1Mb internal RAM;
Cost: $1000

Nikon bodies, Kodak sensors, 1992
First DSLR
1.5 Mpix resolution;
Tethered External Hard Disk
Cost: up to $20,000
Sold < 1000 units
Invention of CMOS/Camera on a Chip

+ Cheaper, power efficient
- Noisier, rolling shutter readout

It would take another 10 years before CMOS systems would enable mass production of affordable (mobile) cameras

Digital SLRs and Compacts (CCD)

Canon Powershot, 2000
1.5 Mpix resolution;
Cost: $500

Nikon D1, 2000
2-3 Mpix resolution;
Cost: $3 - 5K
Fast Forward to Today (CMOS)

Sony RX100, 2019
20 Mpix resolution;
Cost: $500

Nikon D810, 2019
36 Mpix resolution;
Cost: $3-5K
MOBILE PHOTOGRAPHY
The timeline illustrates the evolution of digital cameras from 1975 to 2019. Key milestones include:

- **1975**: First Digital Camera Prototype
- **1980**: First Commercial Digital Cameras
- **1985**: Electronic Camera with Programmable Transmission Capability
- **1990**: Digital SLRs, Compacts

- 1975: First Digital Camera Prototype
- 1980: First Commercial Digital Cameras
- 1985: Digital SLRs, Compacts
- 1990: 1st Commercial Camera Phone
- 1995: Digital SLRs, Compacts
- 2000: Digital SLRs, Compacts
- 2005: Digital SLRs, Compacts
- 2010: Digital SLRs, Compacts
- 2015: Digital SLRs, Compacts
- 2019: Digital SLRs, Compacts
J-Phone (Sharp), sold in Japan ‘00

0.1 Mpix, CCD
256 color disp.
$500

First camera (flip) phone in the US two years later in 2002

First phone with front camera a year later in 2003

“Video Calls”
1975: First Digital Camera Prototype
1980: First Digital Camera Prototype
1985: First Commercial Digital Cameras
1990: Digital SLRs, Compacts
1995: 1st Commercial Camera Phone
2000: Digital SLRs, Compacts
2005: CMOS
2010: iPhone
2015: iPhone
2019: iPhone
“Apple reinvents the phone”
(but not the camera)

Display and UI were king.

“On the back, the biggest thing of note is we’ve got a two megapixel camera built right in.”

- Steve Jobs

Competition: Compact Cameras
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975</td>
<td>First Digital Camera Prototype</td>
</tr>
<tr>
<td>1980</td>
<td>First Commercial Digital Cameras</td>
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<tr>
<td>1985</td>
<td>1st Commercial Camera Phone</td>
</tr>
<tr>
<td>1990</td>
<td>Digital SLRs, Compacts</td>
</tr>
<tr>
<td>2000</td>
<td>CMOS</td>
</tr>
<tr>
<td>2005</td>
<td>300 dpi displays &amp; 4G Networks</td>
</tr>
<tr>
<td>2010</td>
<td>iPhone</td>
</tr>
</tbody>
</table>
Wireless Network Speed

Transmit a 2 Mpix image

- 0.01 seconds
- 0.5 seconds
- 30 seconds

Source: Silika
2010 -

COMPUTATIONAL PHOTOGRAPHY

“The best camera is the one that’s with you.”
Computation + Photography
How the mobile phone became a camera

Part 2: Modern Technology

Peyman Milanfar
“The best camera is the one that’s with you.”
A Recent History at Google

2012  2014  2016  2018  2019
Can one be as good as the other?
Can one be as good as the other?
Less light gets recorded

5.76 mm

35 mm
Compete with hardware!

Yet most of the improvements are due to software.
Want: More light, dynamic range, resolution

Use a flash

Longer / bracketed exposures

Capture a burst ✔️
Modern Mobile Imaging: Burst Photography

Exposure control

Align: Reliable Optical Flow – Scene is never stationary

Merge: Artifact-free Fusion – Alignment failures, occlusion, ...

Enhance: Denoise, Sharpen, Contrast enhancement, Dynamic Range
Classic Camera Image Processing Pipeline

Sensor with color filter array (CCD/CMOS) → Gain Control A/D Converter Possible LUT → White Balance

“Enhance”

Tone Reproduction → Color Space Transform + Color Preferences → Noise Reduction/Sharpening → Demosaic

“Merge”

JPEG Compression

Michael Brown
Demosaicing: 12MP sensor ≠ 12 million RGB pixels

Missing information

Two-thirds of your picture is made-up!
Demosaicng
Demosaicing … Kills Details and Produces Artifacts
Instead ..... Replace demosaicing with multiple frames
How: “Pixel-shifting”

Shift sensor right 1 pixel

Shift sensor down 1 pixel

Shift sensor down and right 1 pixel
Some Mirrorless Cameras do “Pixel Shift Mode”
Life is not so simple.
Multi-dimensional, non-uniform, interpolation
Source of motion in mobile imaging?
Handheld burst capture
After alignment: what’s still moving?
(Natural) Physiological Tremor

PHYSIOLOGICAL TREMOR

BY

JOHN MARSHALL AND E. GEOFFREY WALSH

From the Neurological Unit, Northern General Hospital, and Department of Physiology, University of Edinburgh

Rhythmicity during muscular contraction has long been studied. The earliest observations dealt with the sounds that can be heard on listening to a contracting muscle and were naturally limited by the poor sensitivity of the ear at low frequencies. When, in the second half of the nineteenth century, graphic recording techniques became readily available a number of papers were published dealing with the periodicity that can be recorded in myograms. Of outstanding interest were the findings of Schäfer (1886) who observed that the rate of excitation employed, provided it was not allowed to fall below a certain limit, the frequency of muscular response to stimulation of the cortex, as indicated by the undulations described by the myograph lever, does not vary with the rate of excitation, but maintains a nearly uniform rate of about 10 per second."

They concluded that the rhythmicity was determined at a spinal rather than at a cortical level.

With the discovery of the alpha waves of the electro-encephalogram the view has sometimes been

Measured in 100s of bursts
What if phone/camera is immobilized?

Simulated “tremor”
Motion : Phase Diversity

Aliasing + Phase diversity $\rightarrow$ Multi-frame Super-Res
The visual system appears to do super-resolution (via micro-saccades)

Minature eye movements enhance fine spatial detail

Michele Rucci, Ramon Iovin, Martina Poletti & Fabrizio Santini

Our eyes are constantly in motion. Even during visual fixation, small eye movements continually jitter the location of gaze. It is known that visual percepts tend to fade when retinal image motion is eliminated in the laboratory. However, it has long been debated whether, during natural viewing, fixational eye movements have functions in addition to preventing the visual scene from fading. In this study, we analysed the influence in humans of fixational eye movements on the discrimination of gratings masked by noise that has a power spectrum similar to that of natural images. Using a new method of retinal image stabilization, we selectively eliminated the motion of the retinal image that normally occurs during the intersaccadic intervals of visual fixation. Here we show that fixational eye movements improve discrimination of high spatial frequency stimuli, but not of low spatial frequency stimuli. This improvement originates from the temporal modulations introduced by fixational eye movements in the visual input to the retina, which emphasize the high spatial frequency harmonics of the stimulus. In a natural visual world dominated by low spatial frequencies, fixational eye movements appear to constitute an effective sampling strategy by which the visual system enhances the processing of spatial detail.
Non-uniform coverage

Dense coverage

Sparse coverage
Merge: Nonlinear Kernel Regression
We can also merge onto higher-res grid

• This has its limits
  • depends on pixel/lens spot size tradeoff
  • for typical mobile sensors, limit is 2x
Robustness model
Gather → Parallel Process

Align → Estimate contribution → Sample → Accumulation

...
"The Pixel 3 is the first smartphone camera to rival cameras with Micro 4/3 sensors."
6 mm < M4/3 17 mm < APS-C 21 mm < 35 mm
M4/3 17 mm < 6 mm + Super-Resolution < APS-C 21 mm < 35 mm
Handheld Multi-Frame Super-Resolution

BARTLOMIEJ WRONSKI, IGNACIO GARCIA-DORADO, MANFRED ERNST, DAMIEN KELLY, MICHAEL KRAININ, CHIA-KAI LIANG, MARC LEVOY, and PEYMAN MILANFAR, Google Inc.
Use Cases: Night Sight, Super-res Zoom
Zoom Use Case

Enhance! RAISR Sharp Images with Machine Learning
Monday, November 14, 2016
Posted by Peyman Milanfar, Research Scientist

[Romano, Milanfar, Isidoro, Transactions on Computational Imaging, 2017]
Filter Learning

Low res images → patches → least-squares solver → filter → High res images

\[
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\]
We can do even better

• Bucket similar patches together and train within buckets

LR images → cheap upscaling → hashing to buckets → Learning per bucket → hash=0 patches (filter learning) → hash=1 pixels (hash=0 pixels)

hash=1 patches (filter learning) → hash=2 pixels (hash=1 pixels)

hash=2 patches (filter learning) → hash=n pixels (hash=2 pixels)

hash=n patches (filter learning) → hash=n pixels (hash=n pixels)

HR images → hashing to buckets
Learned 2x Upscaling Filters

Coherence

Strength

Gradient Angle

0°

180°
No zoom
(2x zoom)
(2x zoom crop) Standard Digital Zoom
(2x zoom crop) Single-frame Super-res
(2x zoom crop) Multi-frame Super-res
“Best hybrid (optical/digital) zoom on the market”
OTHER CHALLENGES IN COMPUTATIONAL IMAGING
**NIMA: Neural Image Assessment**

**Image** $X_i$ → **CNN** → **SPP** → **Dense** → **Softmax** → **Score Probabilities**

**Image classifier CNN** → **Spatial pyramid pooling** → **Fully connected**

**EMD (Earth Mover’s Distance)**

Loss

NIMA for Aesthetic Quality
NIMA For **Technical Quality**
peyman.milanfar@gmail.com

http://www.milanfar.org