

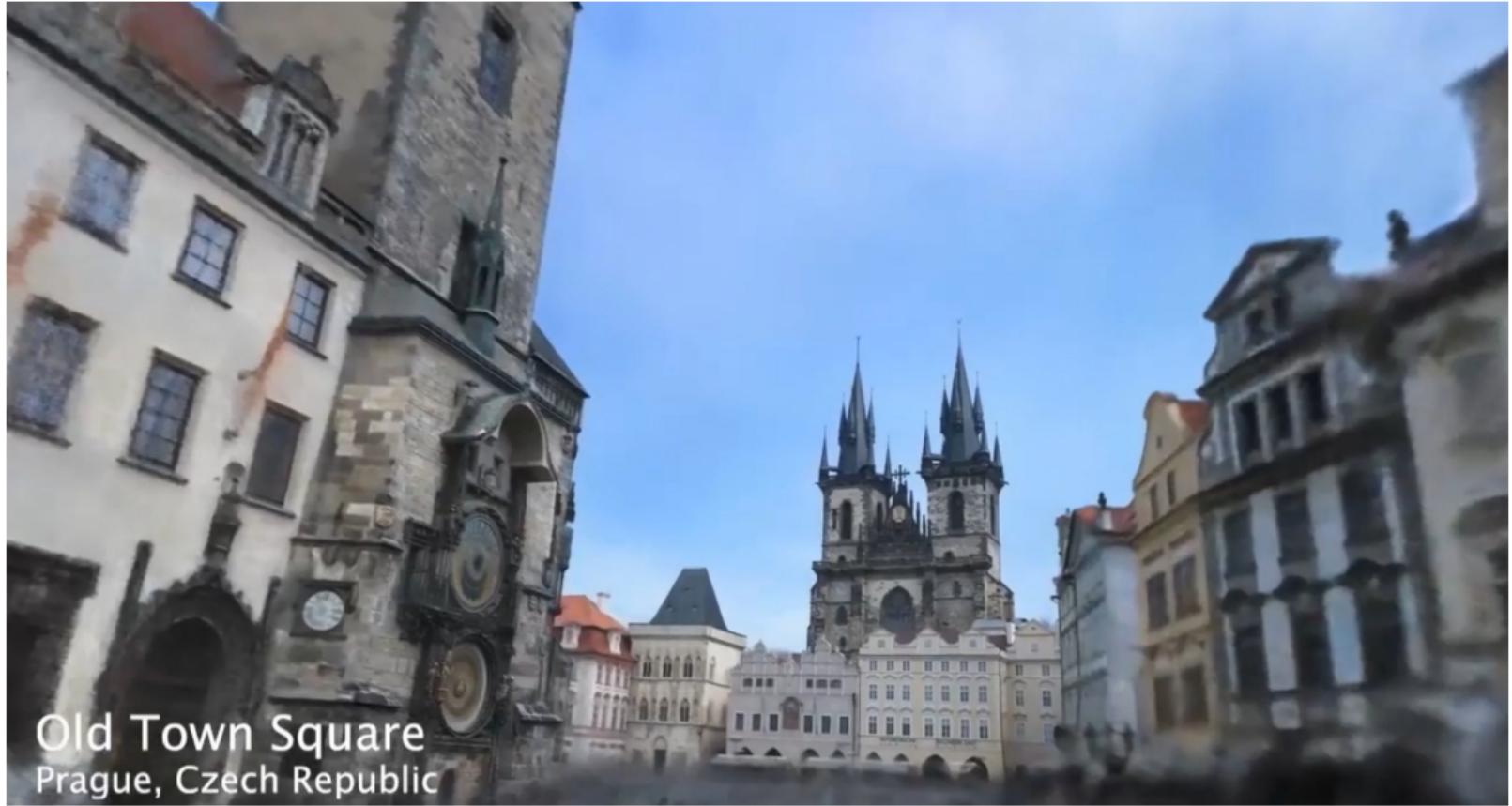
Computer Vision

Lecture 1 – Introduction

Prof. Dr.-Ing. Andreas Geiger
Autonomous Vision Group
University of Tübingen / MPI-IS



e l l i s
European Laboratory for Learning and Intelligent Systems



Old Town Square
Prague, Czech Republic

Agenda

1.1 Organization

1.2 Introduction

1.3 History of Computer Vision

1.1

Organization

Team



Prof. Dr.-Ing.
Andreas Geiger



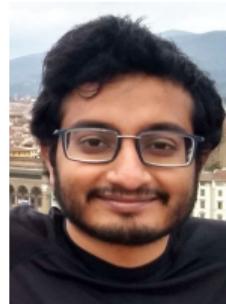
Carolin
Schmitt



Katja
Schwarz



Stefan
Baur



Kashyap
Chitta



Niklas
Hanselmann



Michael
Niemeyer

Contents

Goal: Students gain an understanding of the theoretical and practical concepts of computer vision using deep neural networks and graphical models. A strong focus is put on 3D vision. After this course, students should be able to develop and train computer vision models, reproduce research results and conduct original research.

- ▶ History of computer vision
- ▶ Image formation
- ▶ Structure-from-Motion
- ▶ Stereo Reconstruction
- ▶ Probabilistic Graphical Models
- ▶ Applications of Graphical Models
- ▶ Learning in Graphical Models
- ▶ Shape-from-X
- ▶ Coordinate-based Networks
- ▶ Recognition
- ▶ Compositional Models
- ▶ Self-Supervision and Ethics

Organization

- ▶ SWS: 2V + 2Ü, 6 ECTS, Total Workload: 180h
- ▶ Lectures held via YouTube (provided ~1 week before Lecture Q&A)
- ▶ Plenary lecture and exercise Q&A via Zoom: Thursdays 16:00-18:00
- ▶ Individual exercise Q&A sessions in small groups every other week
 - ▶ **Register now on ILIAS**, max. 20 students per group, first come first serve
- ▶ Exam
 - ▶ Written (date and time will be announced on the course website)
 - ▶ To qualify for the exam, a student must have registered to the course on ILIAS
 - ▶ A 0.3 bonus can be obtained upon submission of Latex notes for 1 lecture
- ▶ Course Website with YouTube, Zoom and ILIAS links:

<https://uni-tuebingen.de/fakultaeten/mathematisch-naturwissenschaftliche-fakultaet/fachbereiche/informatik/lehrstuhle/autonomous-vision/lectures/computer-vision/>

Exercises

- ▶ Exercises are offered every 2 weeks with 6 assignments in total
- ▶ Exercises deepen the understanding with pen & paper and coding tasks
- ▶ Handed out on Thursday via the website and introduced via Zoom
- ▶ Can be conducted in groups
 - ▶ **Find a group partner** via ILIAS forum "Group Partner for Exercises"
- ▶ Individual Q&A sessions offered every other Thursday via Zoom
- ▶ The exercises will not be graded
- ▶ Instead, solutions will be handed out and discussed at the final Q&A
- ▶ All lectures and exercises are relevant for the exam

Lecture Notes

- ▶ We will collaboratively create lecture notes for this new lecture
- ▶ Every student may write a summary for one lecture (yielding a 0.3 bonus)
- ▶ Summaries shall be lightweight, comprehensive and mathematically concise
- ▶ Summaries shall be using the same notation/symbols as used in the slides
- ▶ Only the most important illustrations/graphics shall be included
- ▶ The compiled pdf should not exceed ~5 MB per lecture
- ▶ TAs consolidate materials and integrate into one large document
- ▶ Link to Latex / Overleaf template provided on course website
- ▶ Assignments of students to lectures announced via ILIAS on 30.4.
 - ▶ **Deadline for submission:** 7 days after the corresponding lecture
 - ▶ See assignments on ILIAS for your personal deadline

Course Materials

Books:

- ▶ Szeliski: Computer Vision: Algorithms and Applications
<https://szeliski.org/Book/>
- ▶ Hartley and Zisserman: Multiple View Geometry in Computer Vision
<https://www.robots.ox.ac.uk/~vgg/hzbook/>
- ▶ Nowozin and Lampert: Structured Learning and Prediction in Computer Vision
<https://pub.ist.ac.at/~chl/papers/nowozin-fnt2011.pdf>
- ▶ Goodfellow, Bengio, Courville: Deep Learning
<http://www.deeplearningbook.org>
- ▶ Deisenroth, Faisal, Ong: Mathematics for Machine Learning
<https://mml-book.github.io>
- ▶ Petersen, Pedersen: The Matrix Cookbook
http://cs.toronto.edu/~bonner/courses/2018s/csc338/matrix_cookbook.pdf

Course Materials

Tutorials:

- ▶ The Python Tutorial
<https://docs.python.org/3/tutorial/>
- ▶ NumPy Quickstart
<https://numpy.org/devdocs/user/quickstart.html>
- ▶ PyTorch Tutorial
<https://pytorch.org/tutorials/>
- ▶ Latex / Overleaf Tutorial
<https://www.overleaf.com/learn>

Frameworks / IDEs:

- ▶ Visual Studio Code
<https://code.visualstudio.com/>
- ▶ Google Colab
<https://colab.research.google.com>

Course Materials

Courses:

- ▶ Gkioulekas (CMU): Computer Vision
<http://www.cs.cmu.edu/~16385/>
- ▶ Owens (University of Michigan): Foundations of Computer Vision
<https://web.eecs.umich.edu/~ahowens/eecs504/w20/>
- ▶ Lazebnik (UIUC): Computer Vision
<https://slazebni.cs.illinois.edu/spring19/>
- ▶ Freeman and Isola (MIT): Advances in Computer Vision
<http://6.869.csail.mit.edu/sp21/>
- ▶ Seitz (University of Washington): Computer Vision
<https://courses.cs.washington.edu/courses/cse576/20sp/>
- ▶ Slide Decks covering Szeliski Book
<http://szeliski.org/Book/>

Prerequisites

- ▶ Basic math skills
 - ▶ Linear algebra, probability and information theory. If unsure, have a look at:
Goodfellow et al.: [Deep Learning \(Book\)](#), Chapters 1-4
Luxburg: [Mathematics for Machine Learning \(Lecture\)](#)
Deisenroth et al.: [Mathematics for Machine Learning \(Book\)](#)
- ▶ Basic computer science skills
 - ▶ Variables, functions, loops, classes, algorithms
- ▶ Basic Python and PyTorch coding skills
 - ▶ <https://docs.python.org/3/tutorial/> <https://pytorch.org/tutorials/>
- ▶ Experience with deep learning. If unsure, have a look at:
 - ▶ Geiger: [Deep Learning \(Lecture\)](#)

Prerequisites

Linear Algebra:

- ▶ Vectors: $\mathbf{x}, \mathbf{y} \in \mathbb{R}^n$
- ▶ Matrices: $\mathbf{A}, \mathbf{B} \in \mathbb{R}^{m \times n}$
- ▶ Operations: $\mathbf{A}^T, \mathbf{A}^{-1}, \text{Tr}(\mathbf{A}), \det(\mathbf{A}), \mathbf{A} + \mathbf{B}, \mathbf{AB}, \mathbf{Ax}, \mathbf{x}^\top \mathbf{y}$
- ▶ Norms: $\|\mathbf{x}\|_1, \|\mathbf{x}\|_2, \|\mathbf{x}\|_\infty, \|\mathbf{A}\|_F$
- ▶ SVD: $\mathbf{A} = \mathbf{UDV}^\top$

Prerequisites

Probability and Information Theory:

- ▶ Probability distributions: $P(X = x)$
- ▶ Marginal/conditional: $p(x) = \int p(x, y)dy$, $p(x, y) = p(x|y)p(y)$
- ▶ Bayes rule: $p(x|y) = p(y|x)p(x)/p(y)$
- ▶ Conditional independence: $x \perp\!\!\!\perp y | z \Leftrightarrow p(x, y|z) = p(x|z)p(y|z)$
- ▶ Expectation: $\mathbb{E}_{x \sim p} [f(x)] = \int_x p(x)f(x)dx$
- ▶ Variance: $\text{Var}(f(x)) = \mathbb{E} [(f(x) - \mathbb{E}[f(x)])^2]$
- ▶ Distributions: Bernoulli, Categorical, Gaussian, Laplace
- ▶ Entropy: $H(x)$, KL Divergence: $D_{KL}(p||q)$

Prerequisites

Deep Learning:

- ▶ Machine learning basics, linear and logistic regression
- ▶ Computation graphs, backpropagation algorithm
- ▶ Activation and loss functions, initialization
- ▶ Regularization and optimization of deep neural networks
- ▶ Convolutional neural networks
- ▶ Recurrent neural networks
- ▶ Graph neural networks
- ▶ Autoencoders and generative adversarial networks

Time Management

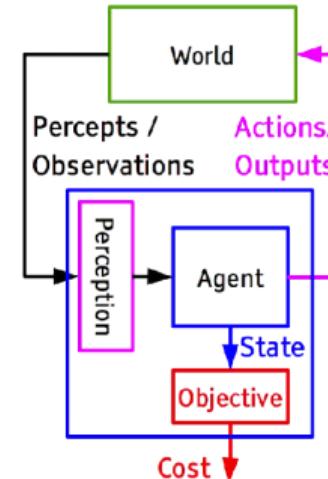
Activity	Time	Total
Watching video lectures	2h / week	24h
Self-study of lecture materials	2h / week	24h
Participation in exercise Q&A sessions	2h / week	24h
Solving the assignments	10h / exercise	60h
Preparation for final exam	48h	48h
Total workload		180h

Artificial Intelligence

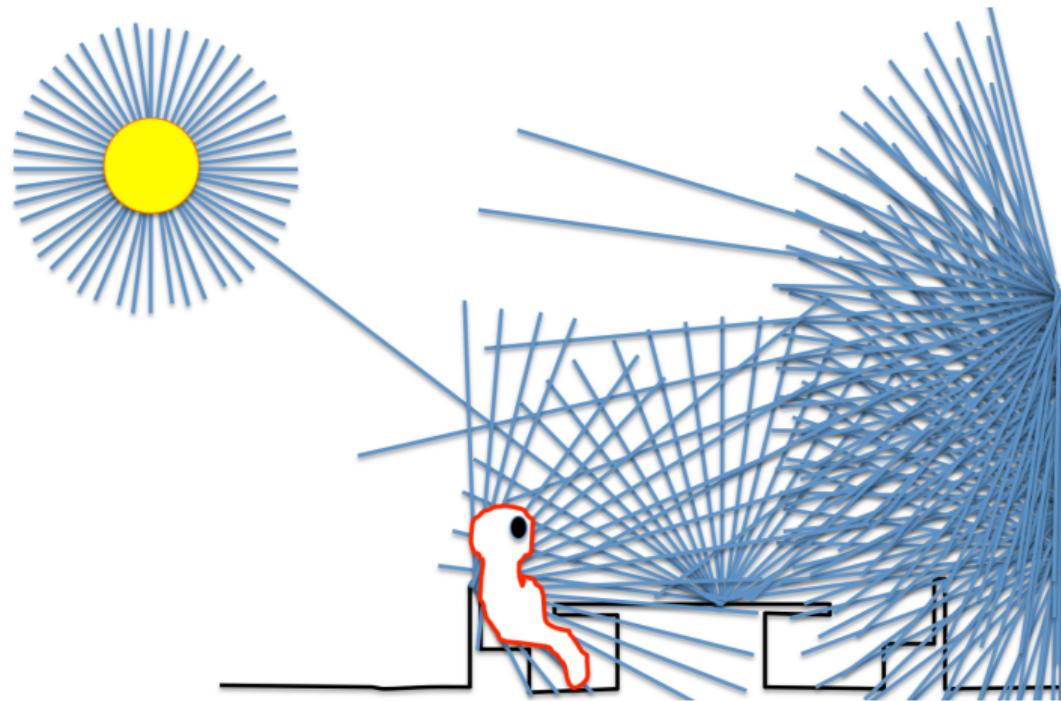
"An attempt will be made to find how to make machines use language, form abstractions and concepts, solve kinds of problems now reserved for humans, and improve themselves."

[John McCarthy]

- ▶ Machine Learning
- ▶ Computer Vision
- ▶ Computer Graphics
- ▶ Natural Language Processing
- ▶ Robotics & Control
- ▶ Art, Industry 4.0, Education ...



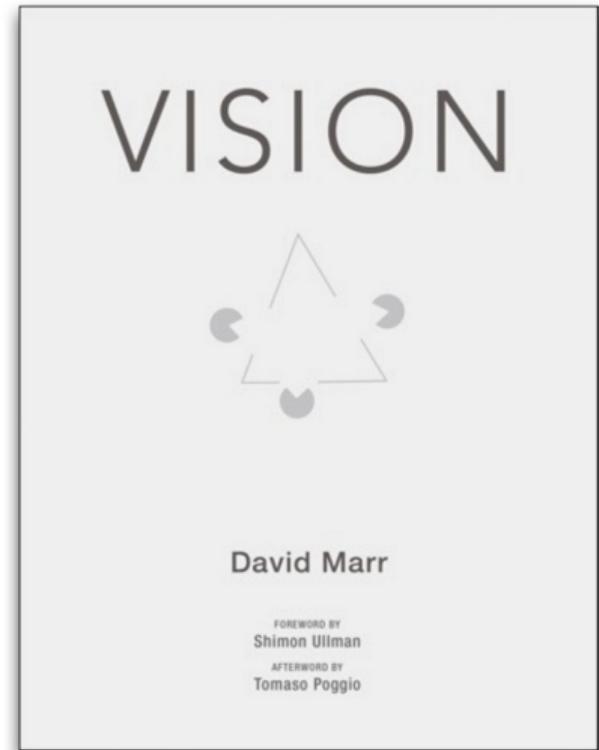
Computer Vision



Goal of Computer Vision is to **convert light into meaning** (geometric, semantic, ...)

Computer Vision

- ▶ What does it mean, to see? The plain man's answer (and Aristotle's, too) would be, to know what is where by looking.
- ▶ 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.

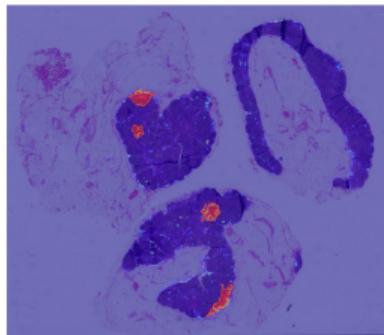


Computer Vision Applications

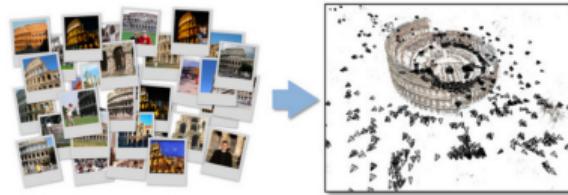
Robotics



Medical applications



3D modeling



Driving



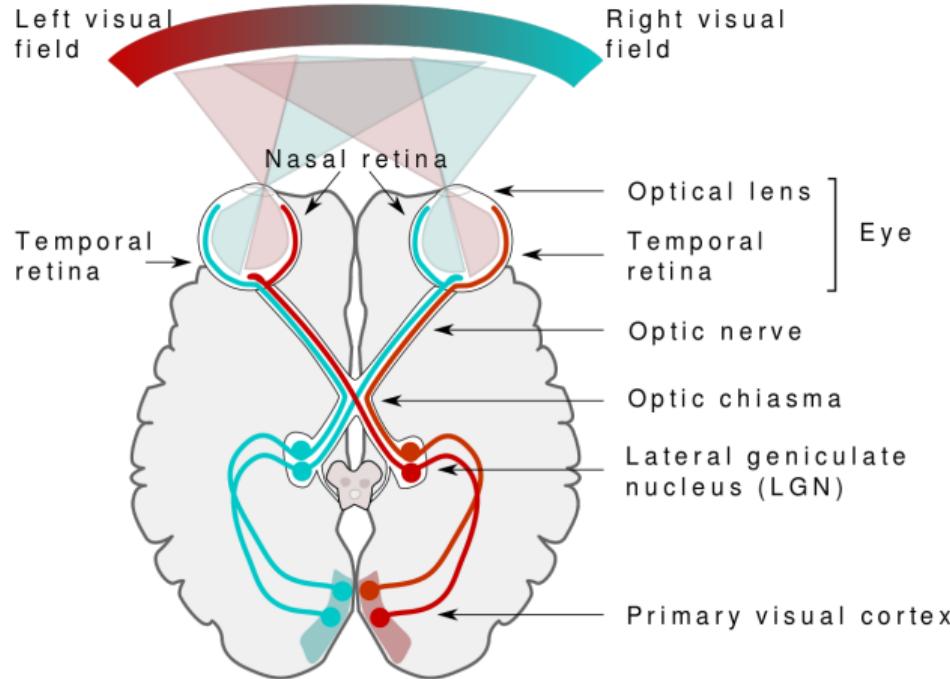
Mobile devices



Accessibility

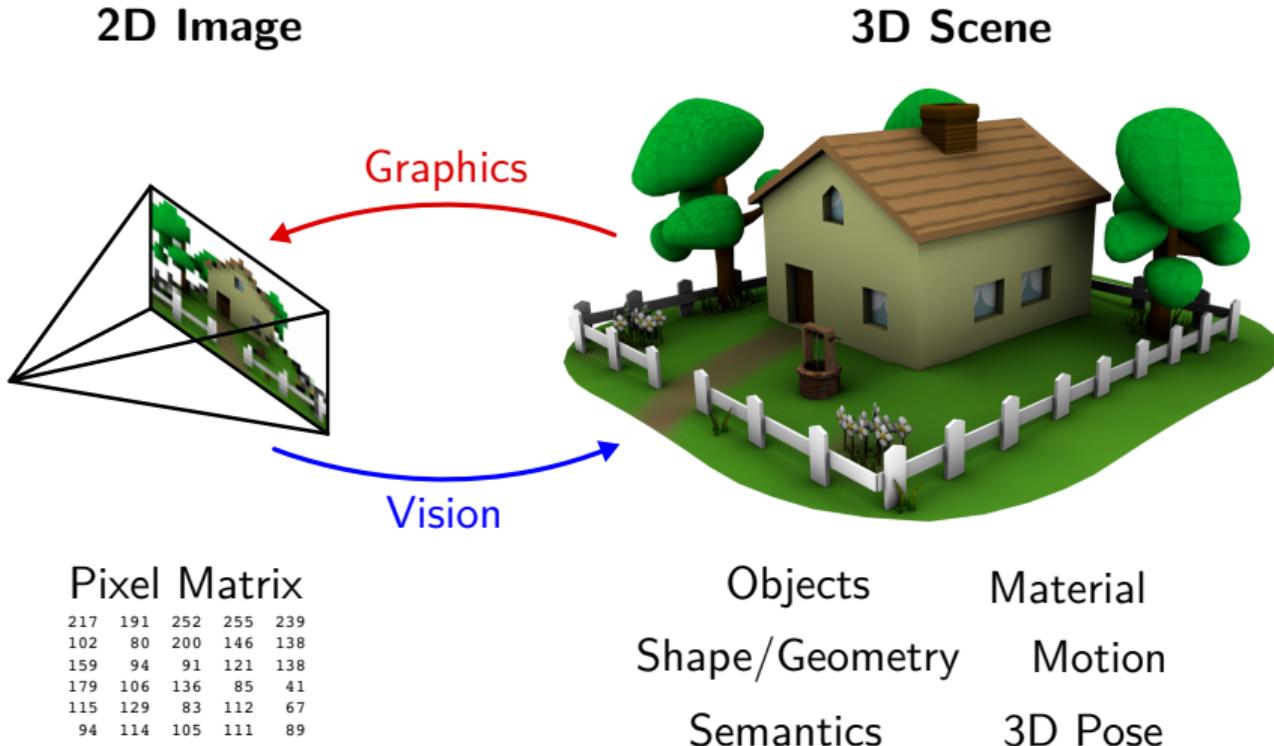


Computer Vision vs. Biological Vision

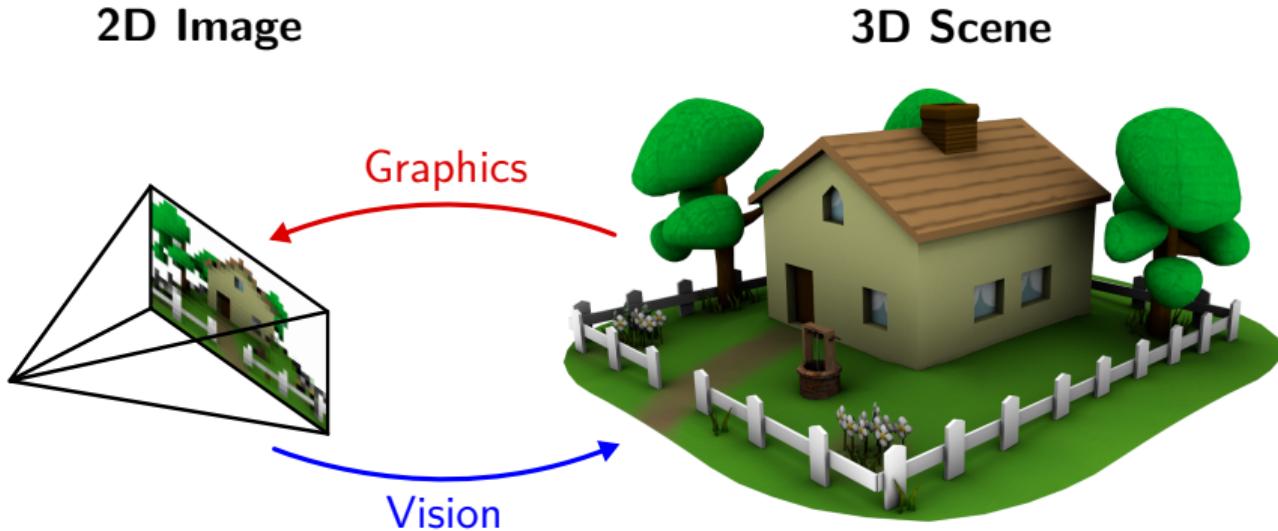


Over **50%** of the processing in the **human brain** is dedicated to **visual information**.

Computer Vision vs. Computer Graphics



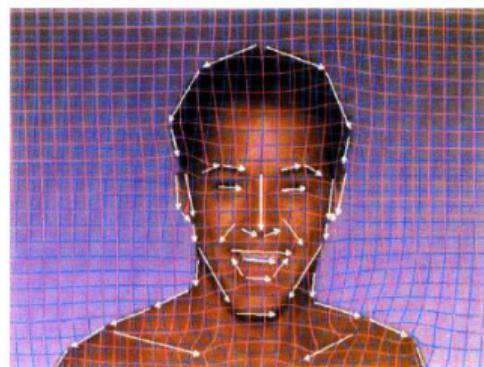
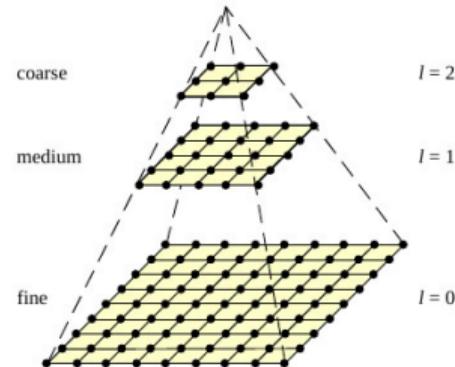
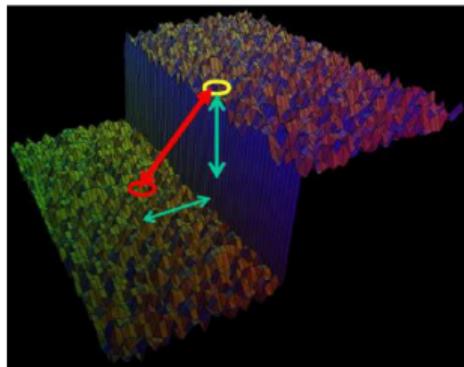
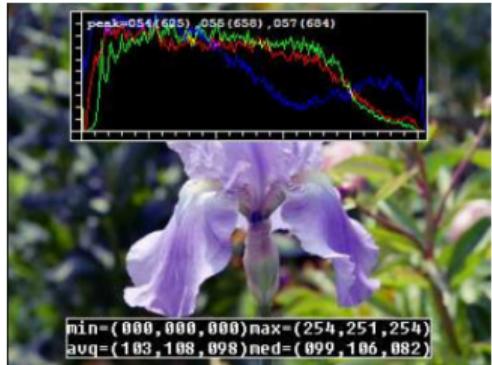
Computer Vision vs. Computer Graphics



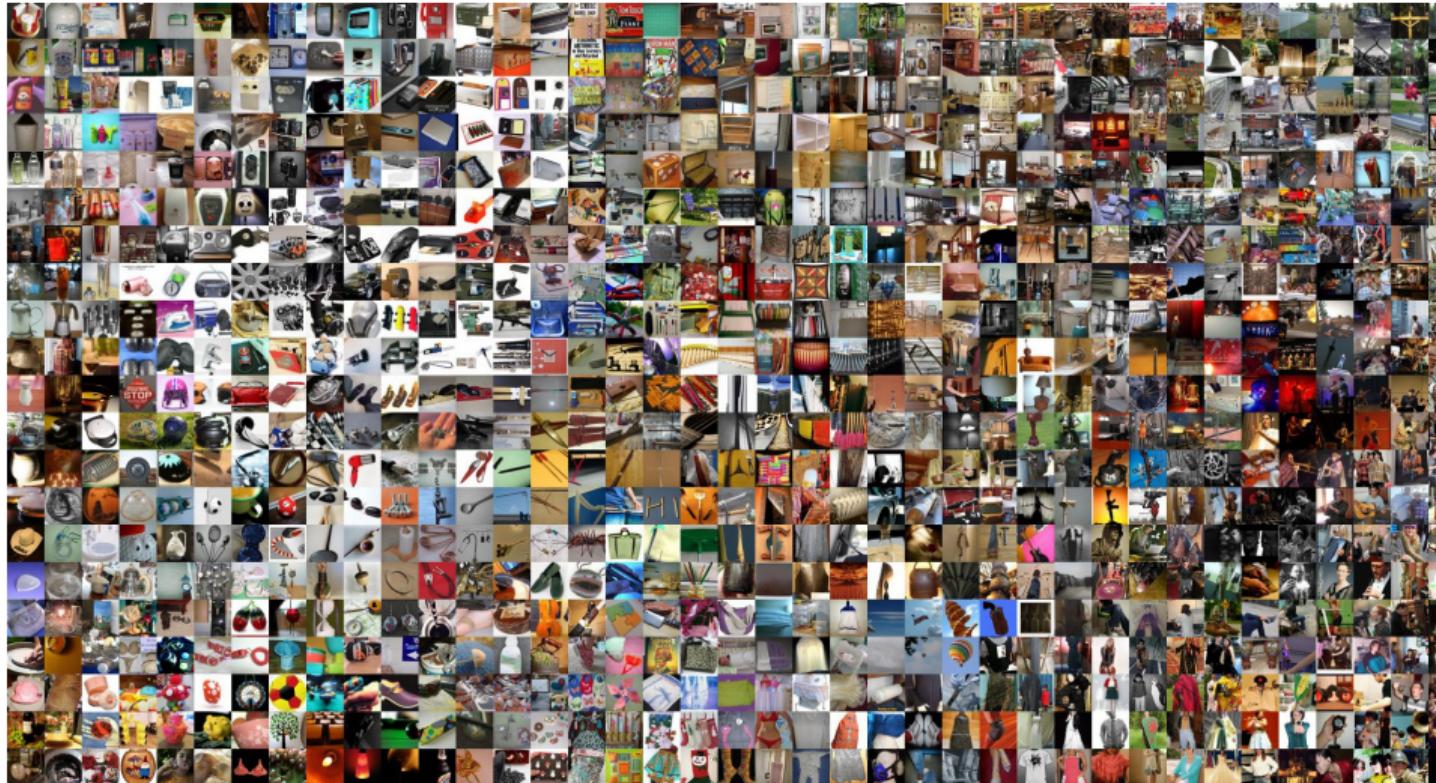
Computer Vision is an ill-posed inverse problem:

- ▶ Many 3D scenes yield the same 2D image
- ▶ Additional constraints (knowledge about world) required

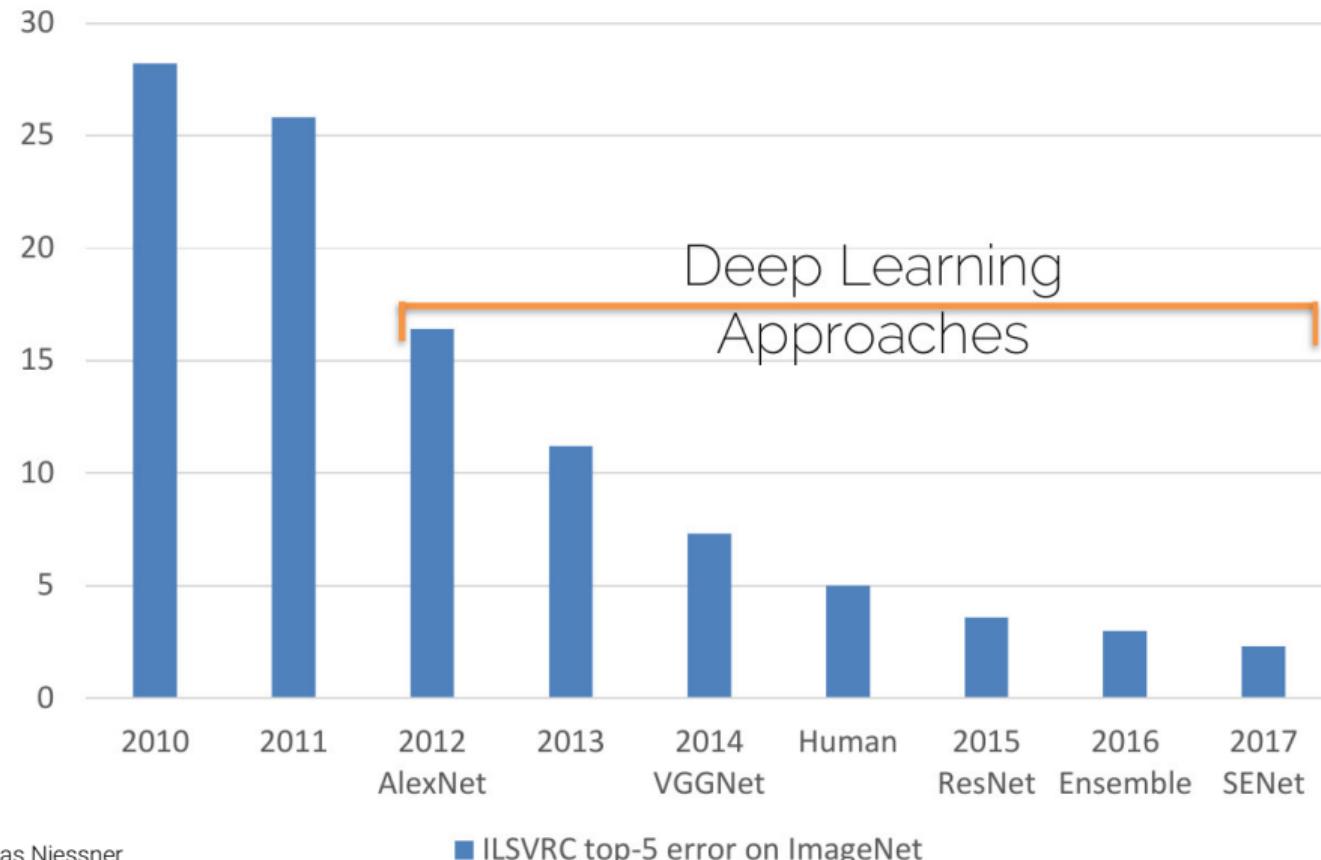
Computer Vision vs. Image Processing



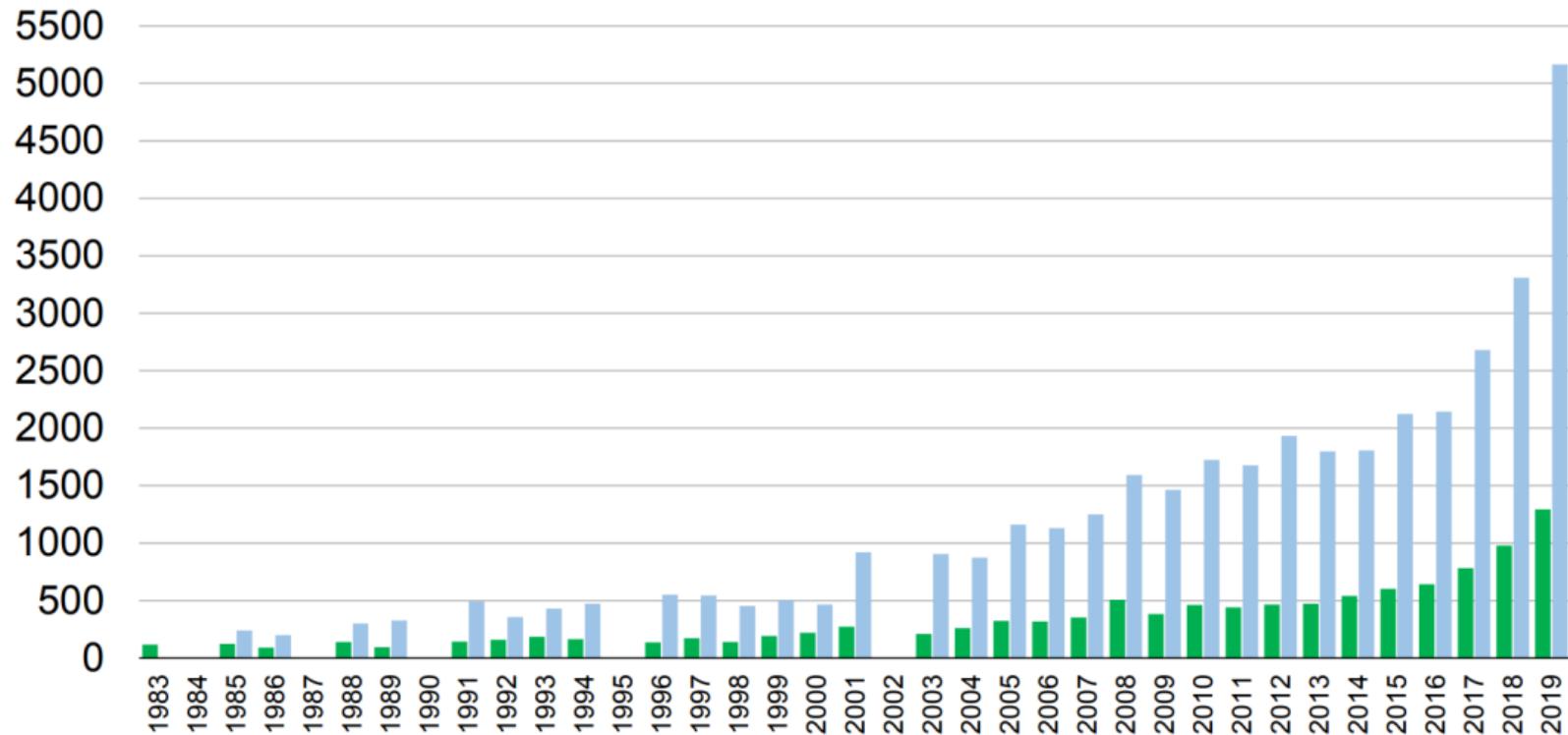
Computer Vision vs. Machine Learning



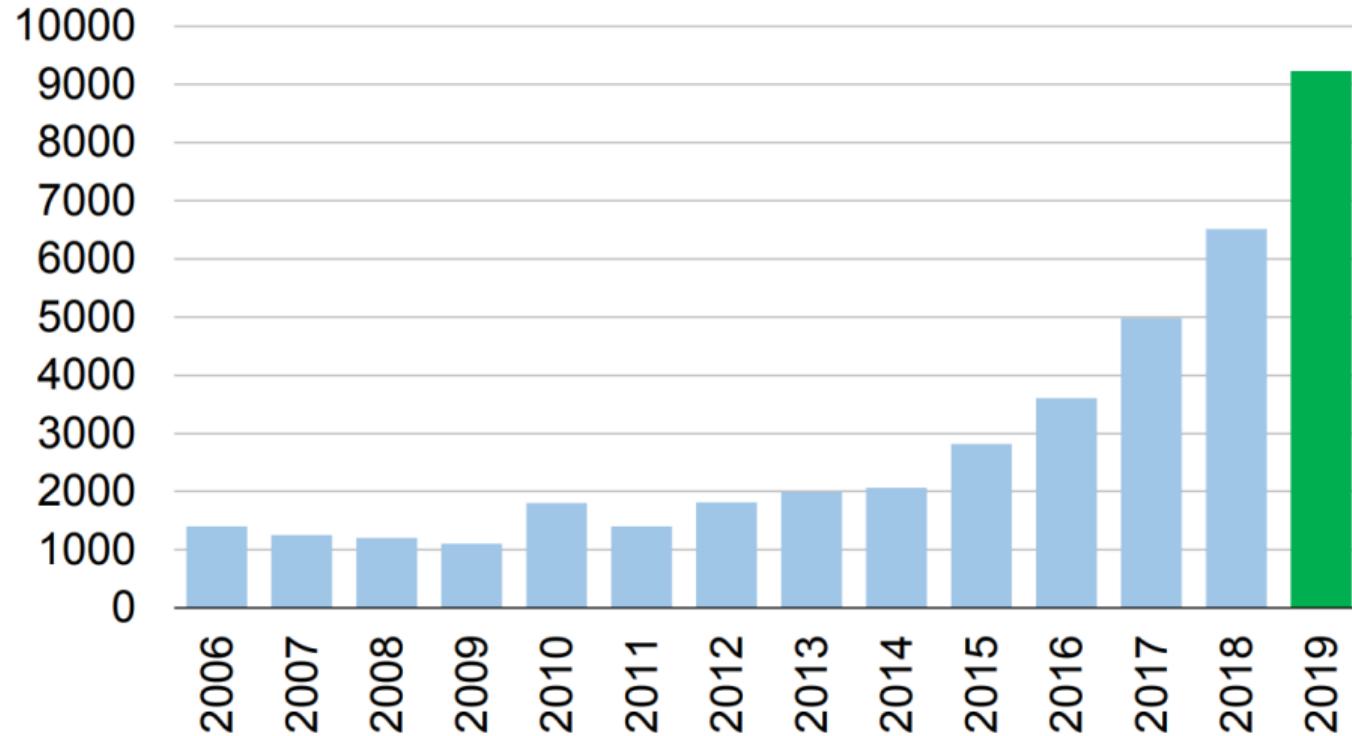
The Deep Learning Revolution



CVPR Submitted and Accepted Papers



CVPR Attendance



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Why is Visual Perception hard?

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
PROJECT MAC

Artificial Intelligence Group
Vision Memo. No. 100.

July 7, 1966

THE SUMMER VISION PROJECT

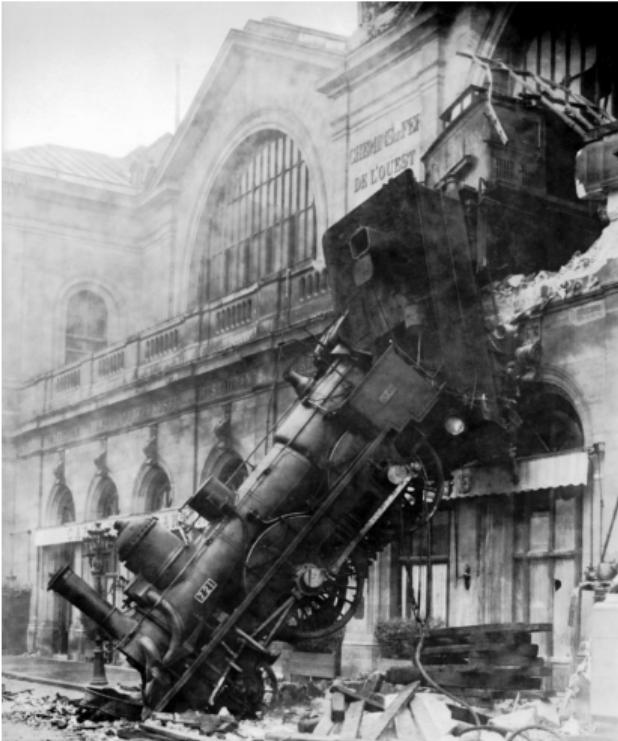
Seymour Papert

The summer vision project is an attempt to use our summer workers effectively in the construction of a significant part of a visual system. The particular task was chosen partly because it can be segmented into sub-problems which will allow individuals to work independently and yet participate in the construction of a system complex enough to be a real landmark in the development of "pattern recognition".

Why is Visual Perception hard?



Why is Visual Perception hard?

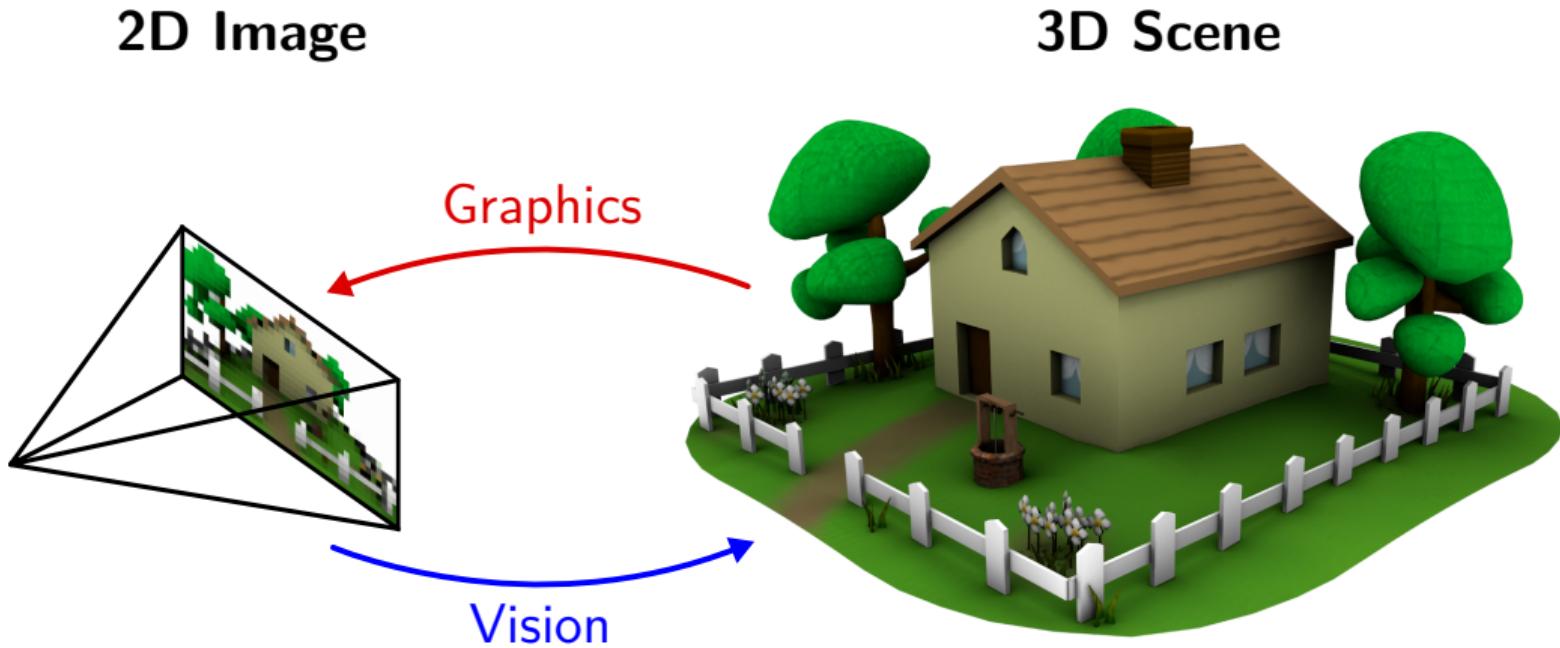


What we see

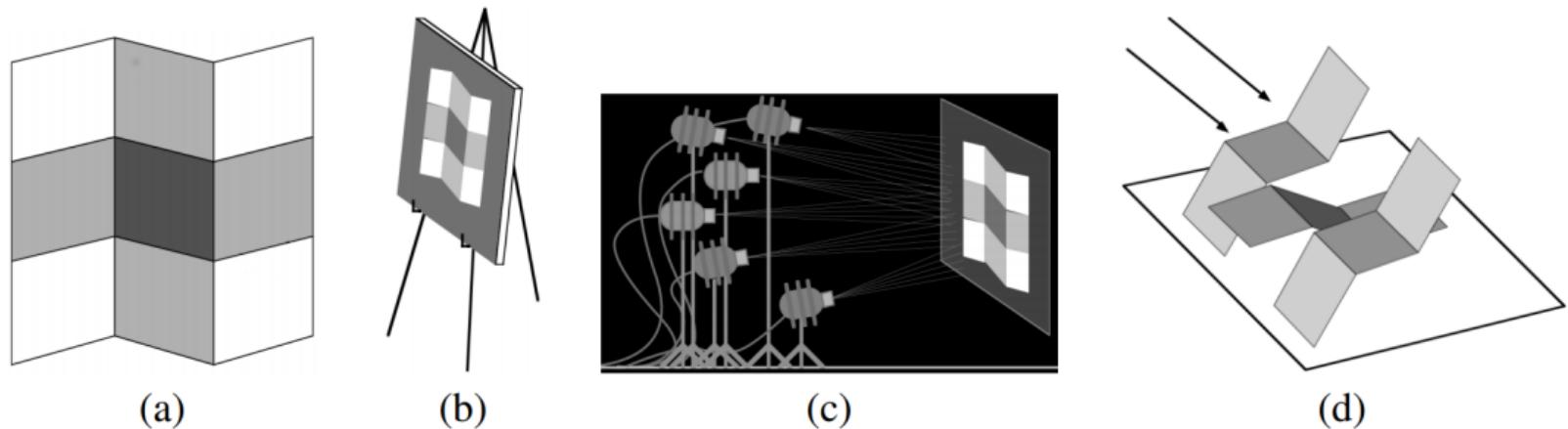
200	133	110	103	117	90	47	30	32	79	66	65
197	122	123	138	98	100	46	45	22	11	43	55
140	116	165	159	90	56	58	47	26	13	54	102
132	148	119	108	123	57	64	46	21	22	79	94
125	121	80	143	101	55	61	38	20	21	81	65
50	71	74	63	52	39	41	39	32	26	97	66
51	59	62	44	40	40	36	28	27	31	29	44
59	62	70	50	48	35	34	35	26	21	24	32
49	59	65	64	58	34	40	28	26	21	23	124
39	45	47	64	54	34	40	24	19	47	133	207
37	42	39	38	39	50	75	74	105	170	197	167
37	47	33	35	50	108	162	184	184	157	125	112
45	48	35	37	75	148	183	156	83	91	91	116
49	48	54	50	75	158	110	66	74	128	155	149
48	51	57	50	65	91	79	92	101	105	132	132
51	58	66	55	58	52	91	91	68	115	158	174
57	60	61	52	56	61	60	55	92	146	188	190
65	50	54	56	57	51	54	56	80	115	177	187
67	40	40	61	65	48	39	30	36	75	151	181
53	32	36	35	61	43	37	26	29	35	126	189
29	42	107	20	28	41	40	26	30	36	113	200
30	21	32	24	34	37	33	23	25	39	105	171
32	28	19	23	29	36	47	69	132	169	183	128
31	25	62	54	47	44	81	190	227	231	206	155
44	66	99	72	67	63	89	128	127	115	109	157
53	47	47	41	29	32	25	20	41	81	89	175
38	44	61	73	54	48	37	87	90	111	126	189
39	41	83	97	86	91	74	134	131	153	143	185
42	56	98	102	112	111	94	137	121	141	146	181
94	114	114	114	122	113	77	117	117	154	149	169
157	176	116	121	130	139	103	161	148	180	145	125
143	178	182	178	139	153	129	168	175	187	170	152
127	163	203	197	153	164	143	160	195	182	165	211
68	107	127	125	101	107	100	123	149	186	167	215

What the computer sees

Challenges: Images are 2D Projections of the 3D World



Challenges: Images are 2D Projections of the 3D World



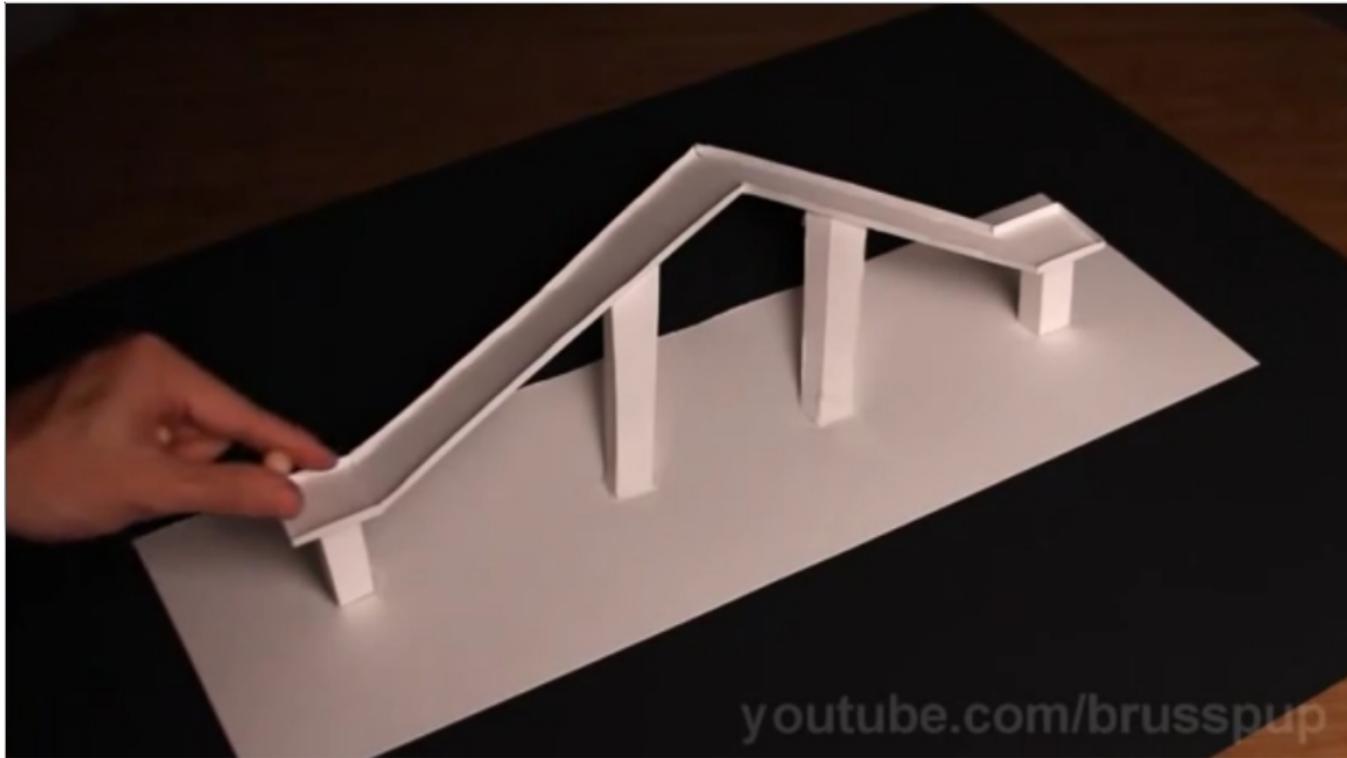
Adelson and Pentland's workshop metaphor:

To explain an image (a) in terms of reflectance, lighting and shape, (b) a painter, (c) a light designer and (d) a sculptor will design three different, but plausible, solutions.

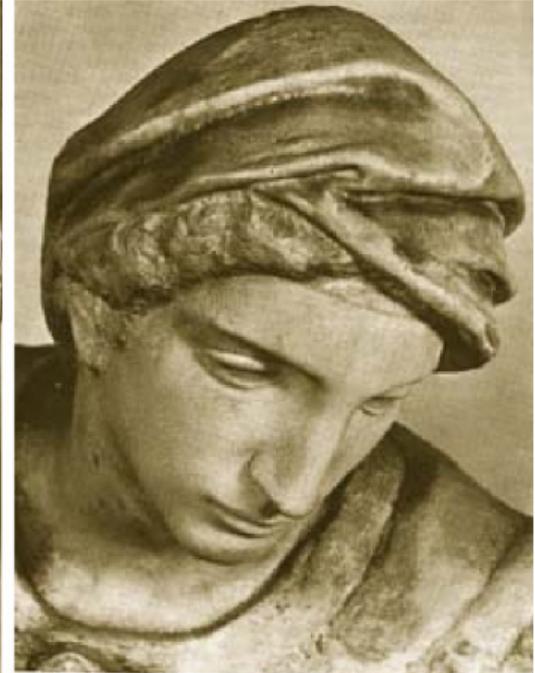
Ames Room Illusion



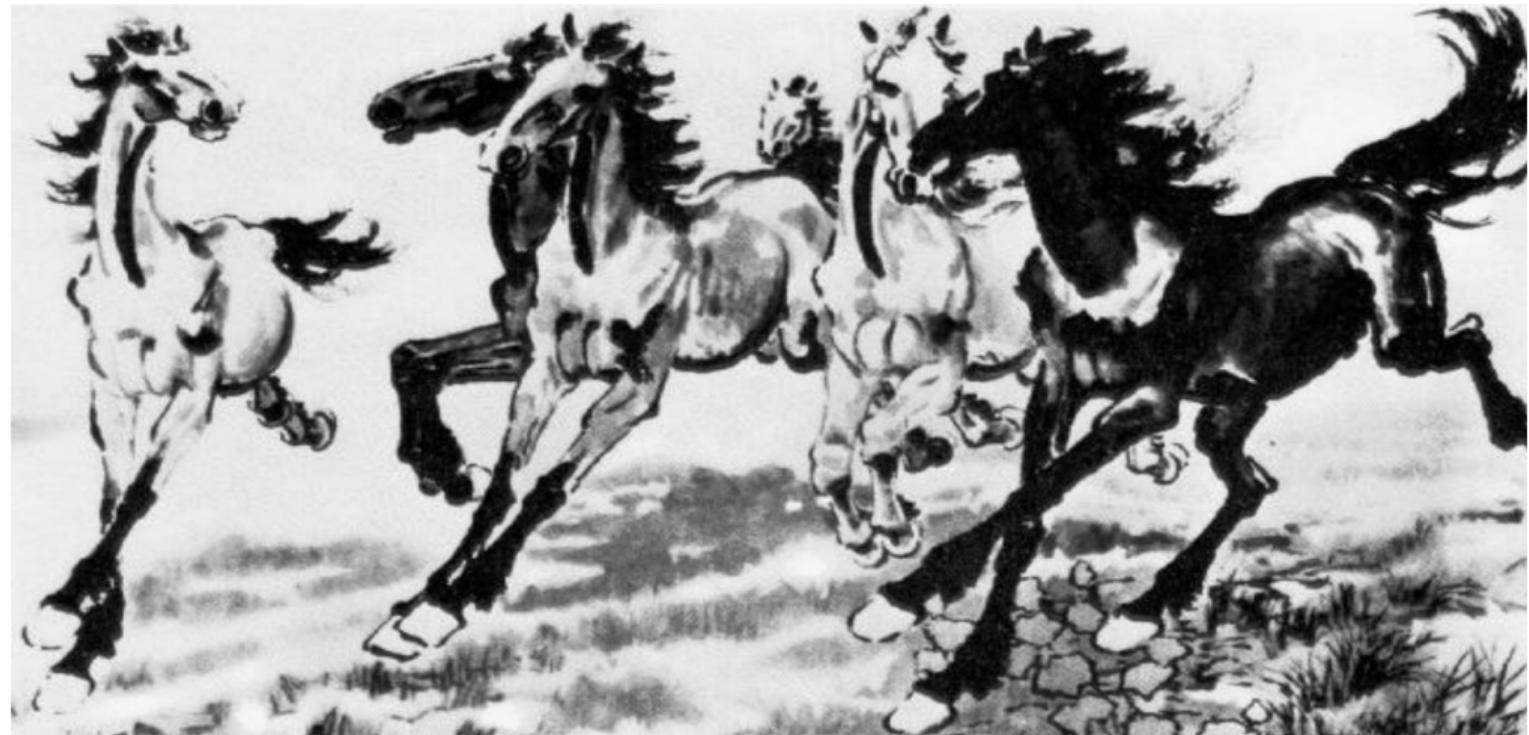
Perspective Illusion



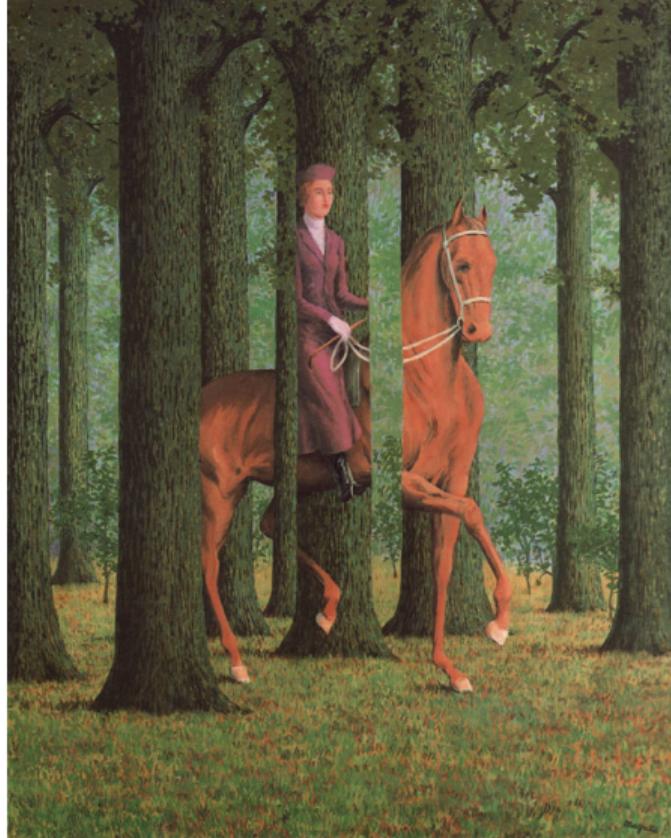
Challenges: Viewpoint Variation



Challenges: Deformation



Challenges: Occlusion



René Magritte (1957)

Challenges: Illumination



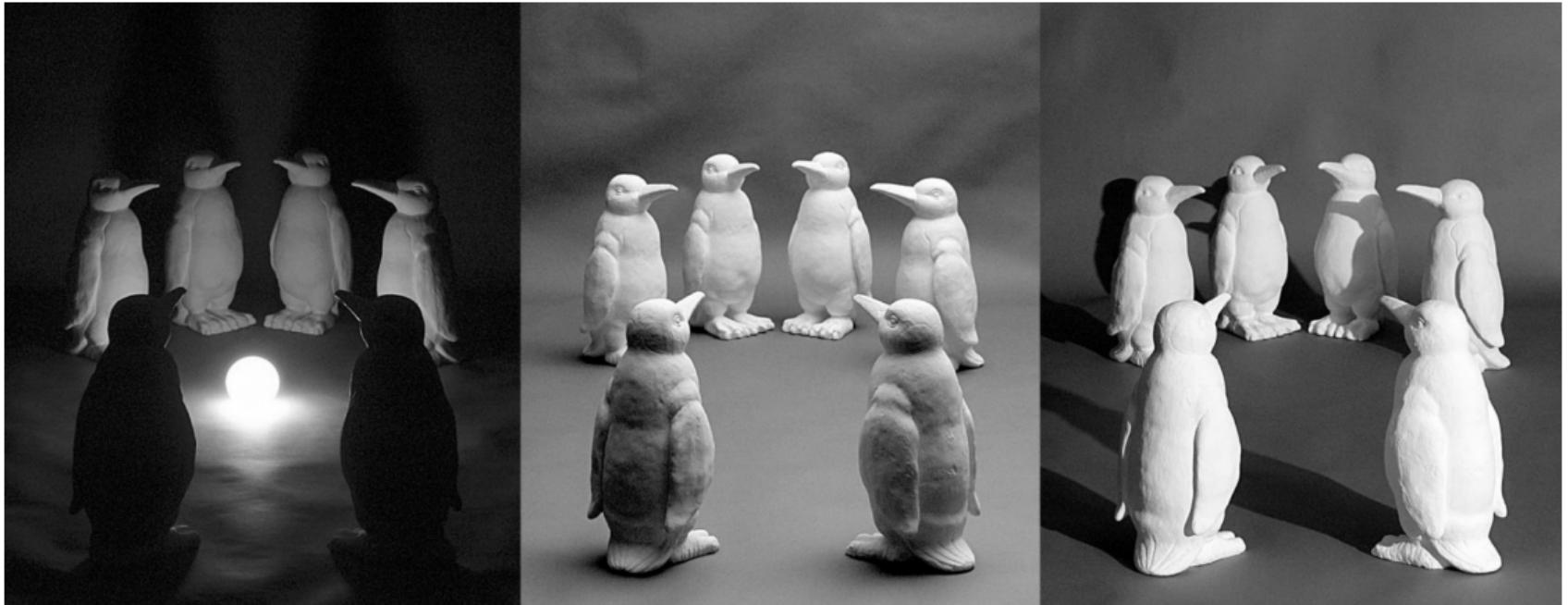
Challenges: Illumination



Challenges: Illumination



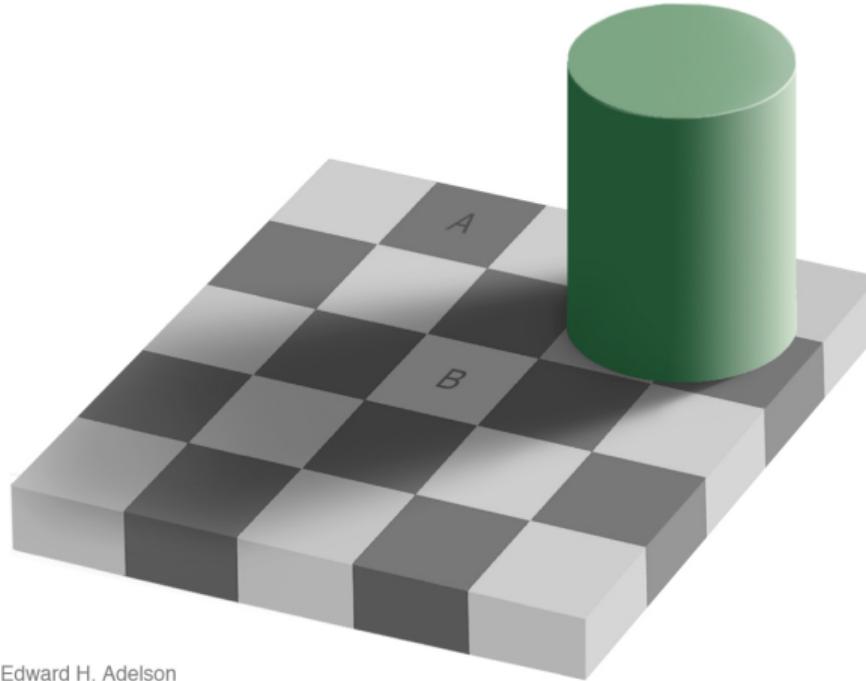
Challenges: Illumination



Challenges: Motion

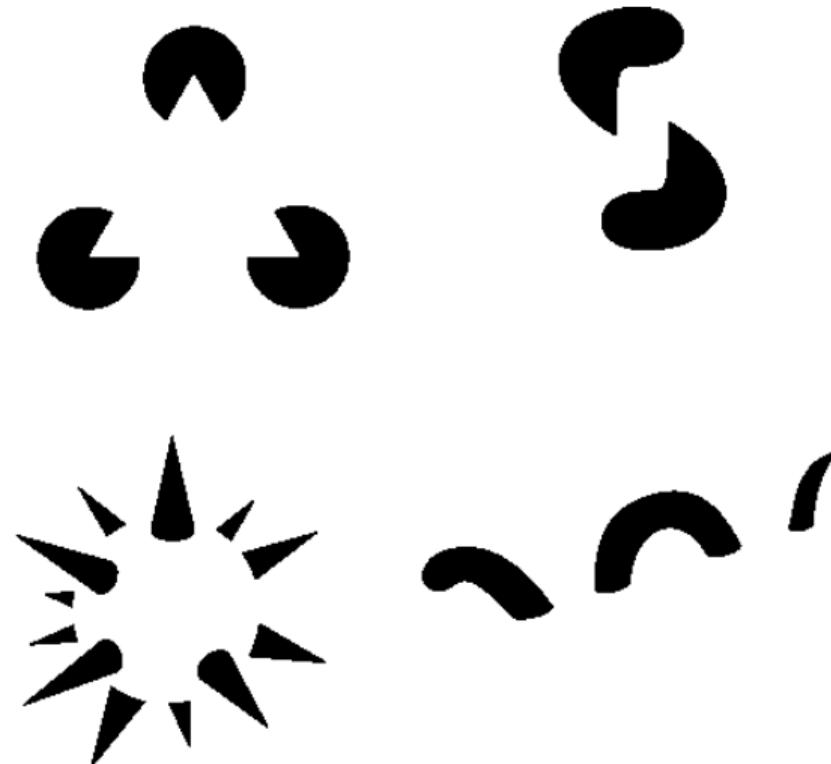


Challenges: Perception vs. Measurement



<http://persci.mit.edu/gallery/checkershadow>

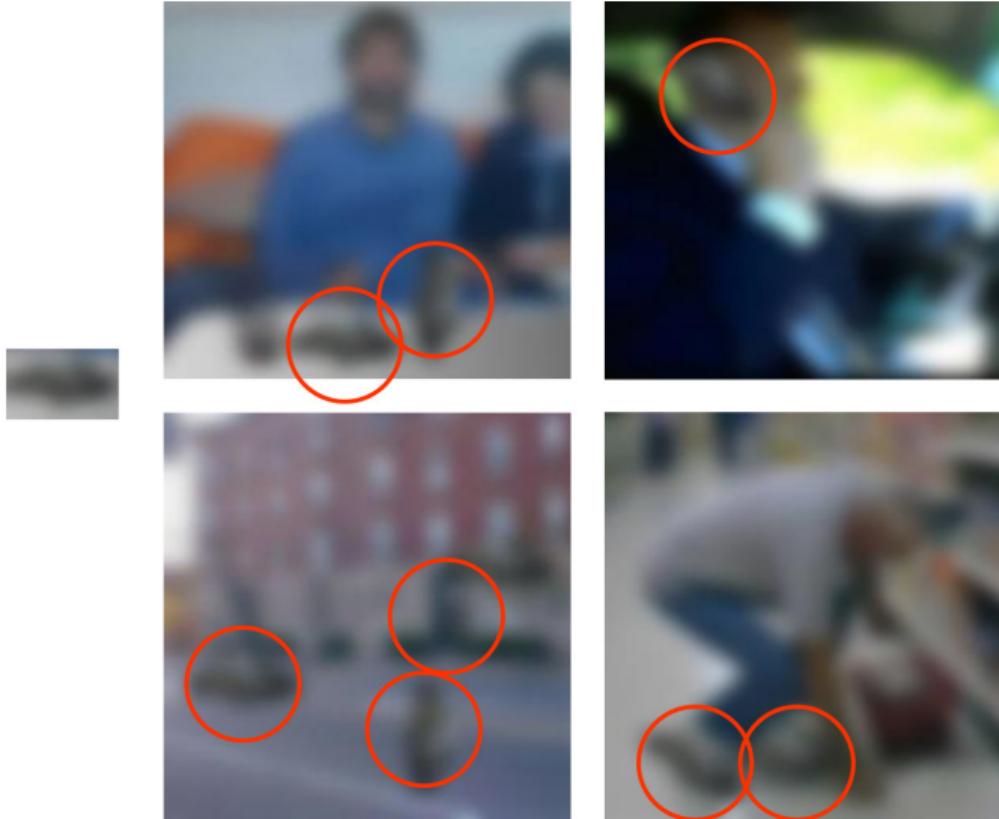
Challenges: Perception vs. Measurement



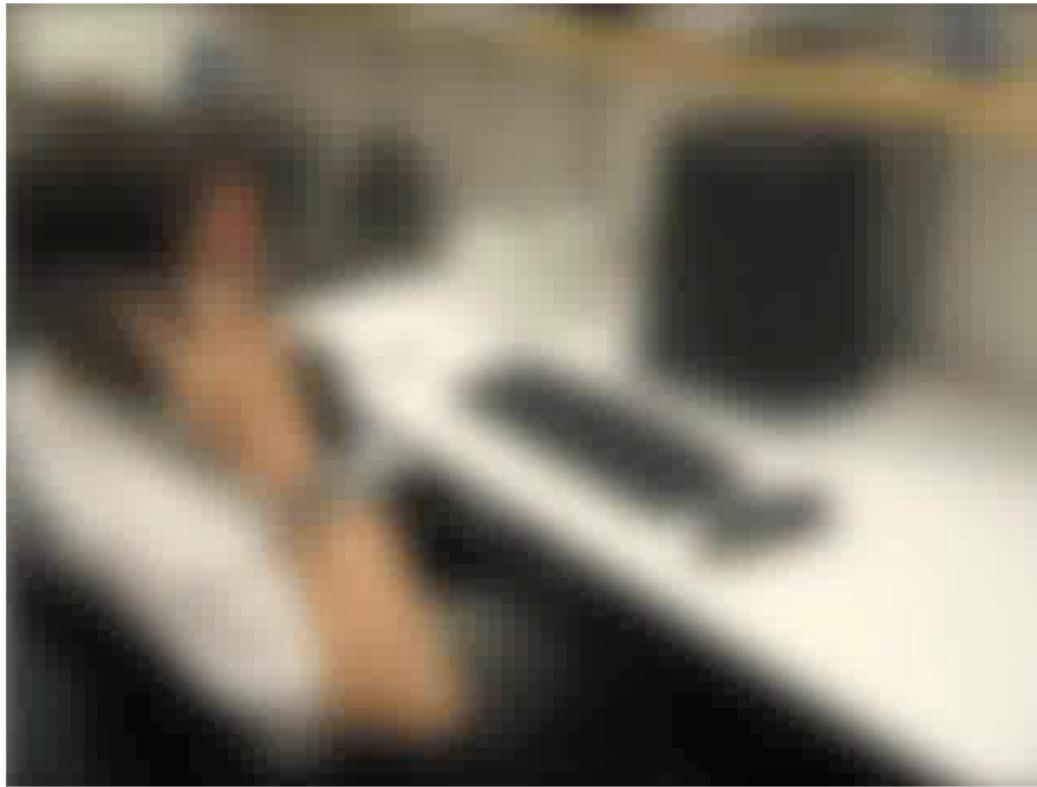
Challenges: Perception vs. Measurement



Challenges: Local Ambiguities



Challenges: Local Ambiguities



Challenges: Local Ambiguities



Challenges: Intra Class Variation



<http://www.homeworkshop.com/>

Challenges: Number of Object Categories



1.3

History of Computer Vision

Credits

Svetlana Lazebnik (UIUC): Computer Vision: Looking Back to Look Forward

- ▶ <https://slazebni.cs.illinois.edu/spring20/>

Steven Seitz (Univ. of Washington): 3D Computer Vision: Past, Present, and Future

- ▶ <http://www.youtube.com/watch?v=kyIzMr917Rc>
- ▶ <http://www.cs.washington.edu/homes/seitz/talks/3Dhistory.pdf>

Pre-History



Perspective
Leonardo da Vinci
(1452–1519)



Photometry
Johann Heinrich Lambert
(1728–1777)



Least Squares
Carl Friedrich Gauss
(1777–1855)



Stereopsis
Charles Wheatstone
(1802–1875)

1510: Perspectograph



"Perspective is nothing else than the seeing of an object behind a sheet of glass, smooth and quite transparent, on the surface of which all the things may be marked that are behind this glass. All things transmit their images to the eye by pyramidal lines, and these pyramids are cut by the said glass. The nearer to the eye these are intersected, the smaller the image of their cause will appear."

– Leonardo da Vinci

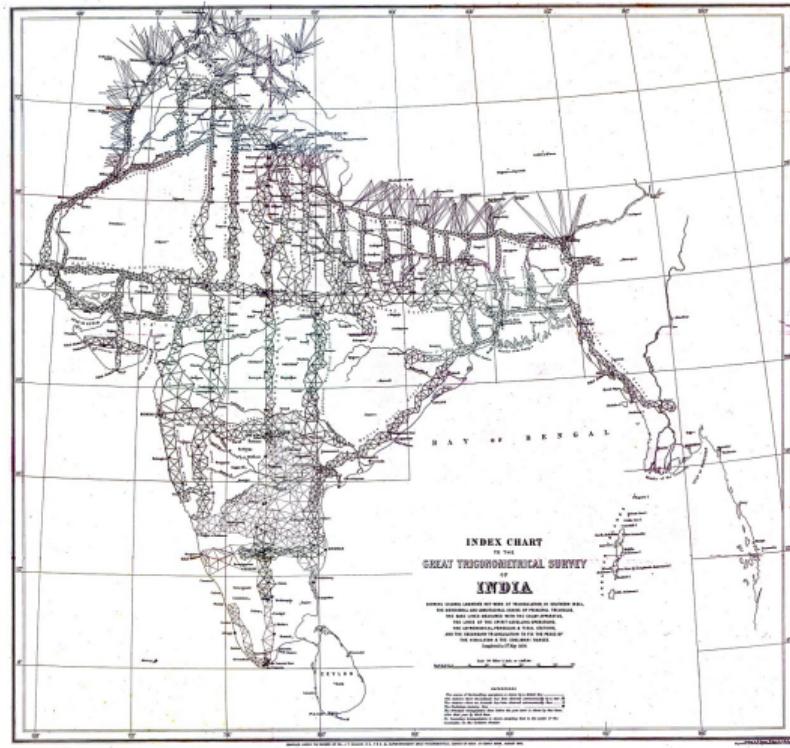
1839: Daguerreotype

- ▶ First publicly available photographic process invented by Louis Daguerre
- ▶ Widely used during the 1840s and 1850s
- ▶ Polish a sheet of silver-plated copper and treat with fumes to make light sensitive
- ▶ Make resulting latent image visible by fuming it with mercury vapor and remove its sensitivity to light by chemical treatment
- ▶ Rinse, dry and seal behind glass



1802-1871: Great Trigonometrical Survey

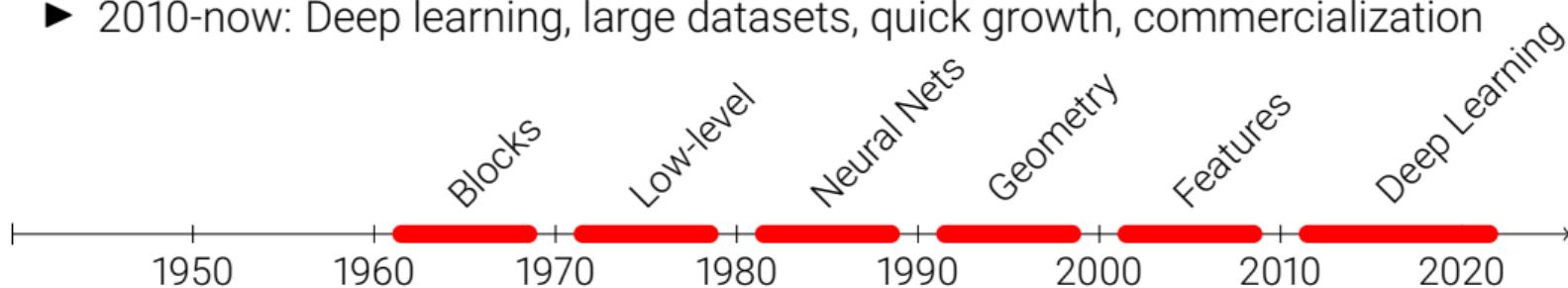
- ▶ Multi-decade project to measure the entire Indian subcontinent with scientific precision
- ▶ Under the leadership of George Everest, the project was made responsible of the Survey of India
- ▶ Manual bundle adjustment proves Mt. Everest highest mountain on earth mountain on earth



Overview

Waves of development:

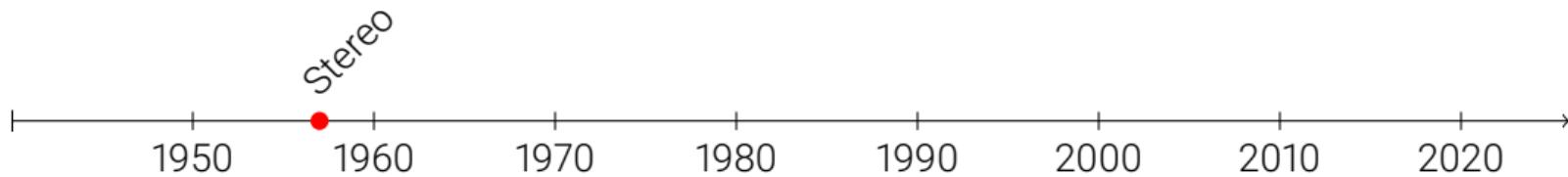
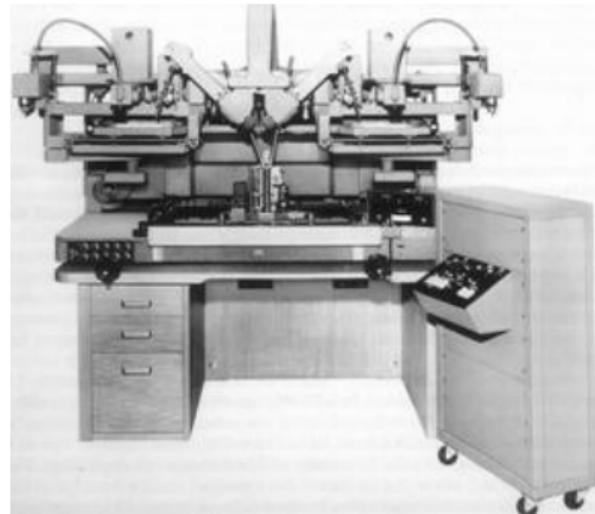
- ▶ 1960-1970: Blocks Worlds, Edges and Model Fitting
- ▶ 1970-1981: Low-level vision: stereo, flow, shape-from-shading
- ▶ 1985-1988: Neural networks, backpropagation, self-driving
- ▶ 1990-2000: Dense stereo and multi-view stereo, MRFs
- ▶ 2000-2010: Features, descriptors, large-scale structure-from-motion
- ▶ 2010-now: Deep learning, large datasets, quick growth, commercialization



A Brief History of Computer Vision

1957: Stereo

- ▶ Gilbert Hobrough demonstrated an analog implementation of stereo image correlation
- ▶ This led to the creation of the Raytheon-Wild B8 Stereomat
- ▶ Used to create Elevation Maps (Photogrammetry, since 1840)



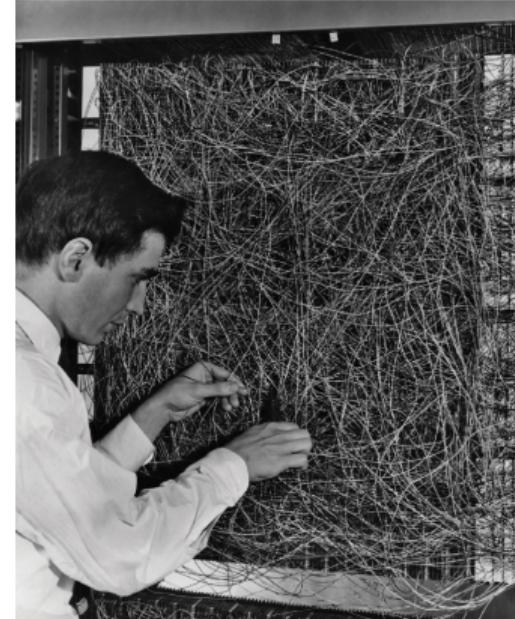
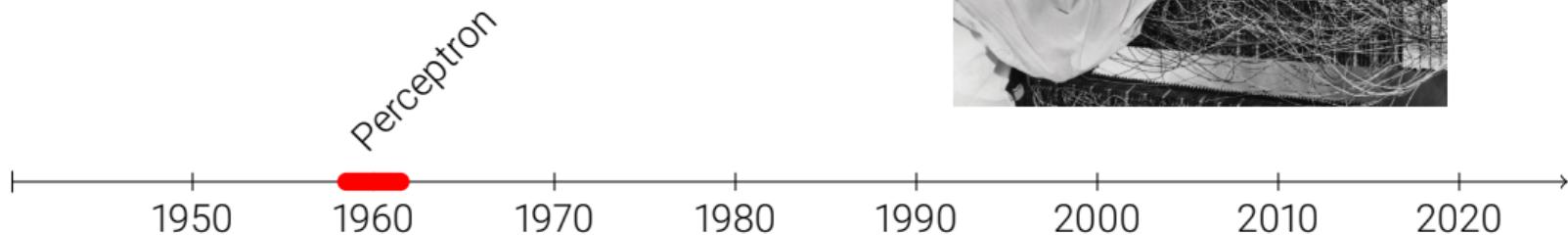
A Brief History of Computer Vision

1958-1962: Rosenblatt's Perceptron

- ▶ First algorithm and implementation to train single linear threshold neuron
- ▶ Optimization of perceptron criterion:

$$\mathcal{L}(\mathbf{w}) = - \sum_{n \in \mathcal{M}} \mathbf{w}^T \mathbf{x}_n y_n$$

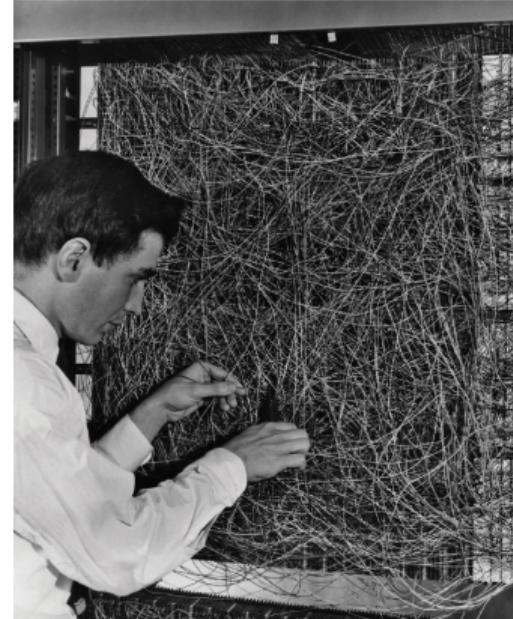
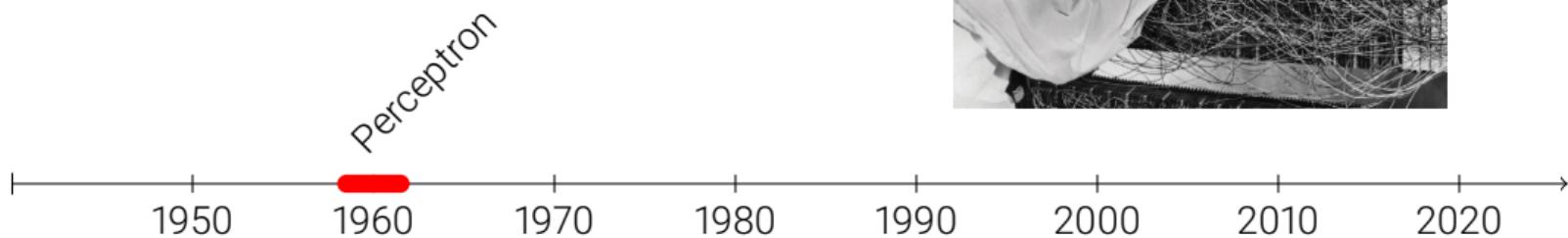
- ▶ Novikoff proved convergence



A Brief History of Computer Vision

1958-1962: Rosenblatt's Perceptron

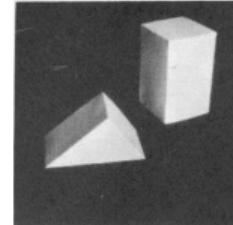
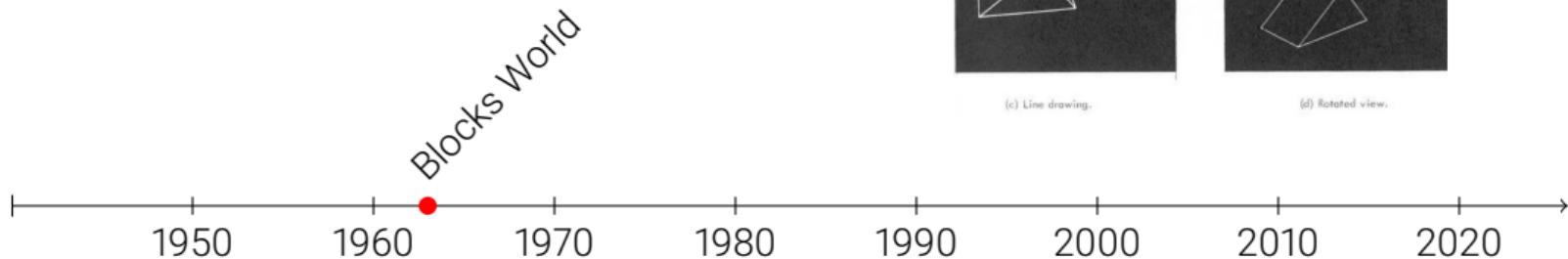
- ▶ First algorithm and implementation to train single linear threshold neuron
- ▶ Overhyped: Rosenblatt claimed that the perceptron will lead to computers that walk, talk, see, write, reproduce and are conscious of their existence



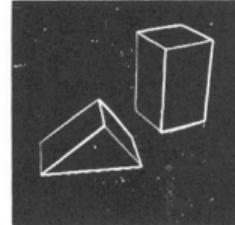
A Brief History of Computer Vision

1963: Larry Robert's Blocks World

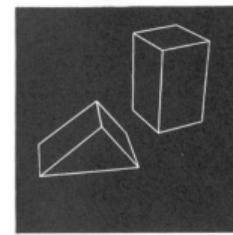
- ▶ Scene understanding for robotics
- ▶ Extracts edges as primitives
- ▶ Infers 3D structure of an object from topological structure of the 2D lines
- ▶ Interpret images as projections of 3D scenes, not 2D pattern recognition



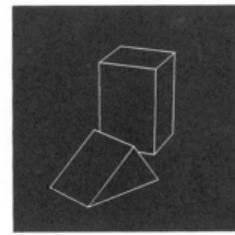
(a) Original picture.



(b) Differentiated picture.



(c) Line drawing.

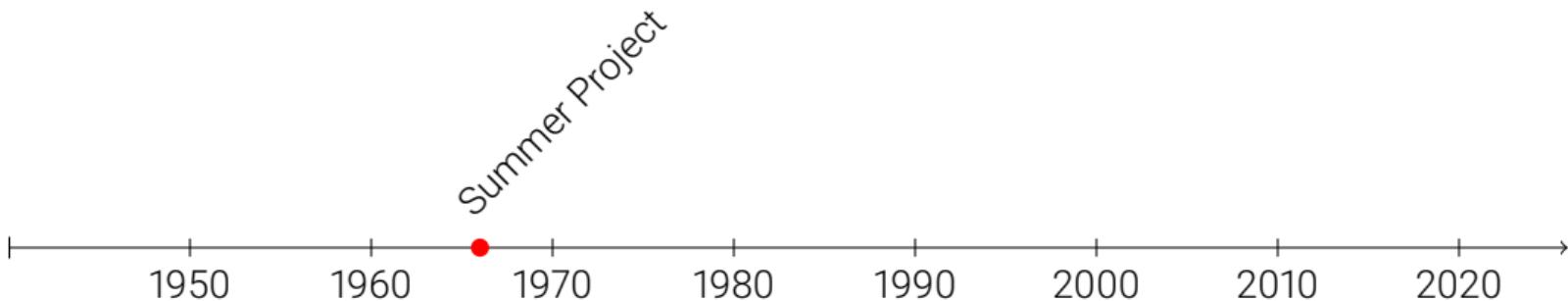


(d) Rotated view.

A Brief History of Computer Vision

1966: MIT Summer Vision Project

- Underestimated the challenge of computer vision, committed to “blocks world”



MASSACHUSETTS INSTITUTE OF TECHNOLOGY
PROJECT MAC

Artificial Intelligence Group
Vision Memo. No. 100.

July 7, 1966

THE SUMMER VISION PROJECT
Seymour Papert

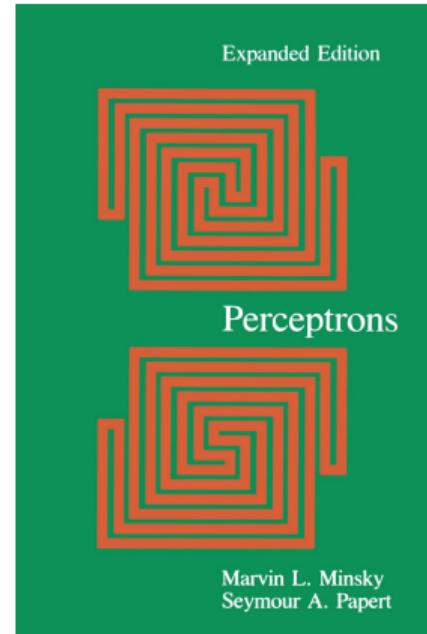
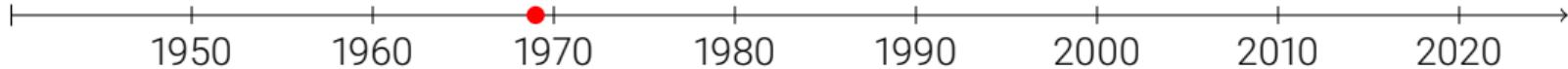
The summer vision project is an attempt to use our summer workers effectively in the construction of a significant part of a visual system. The particular task was chosen partly because it can be segmented into sub-problems which will allow individuals to work independently and yet participate in the construction of a system complex enough to be a real landmark in the development of "pattern recognition".

A Brief History of Computer Vision

1969: Minsky and Papert publish book

- ▶ Several discouraging results
- ▶ Showed that single-layer perceptrons cannot solve some very simple problems (XOR problem, counting)
- ▶ Symbolic AI research dominates 70s

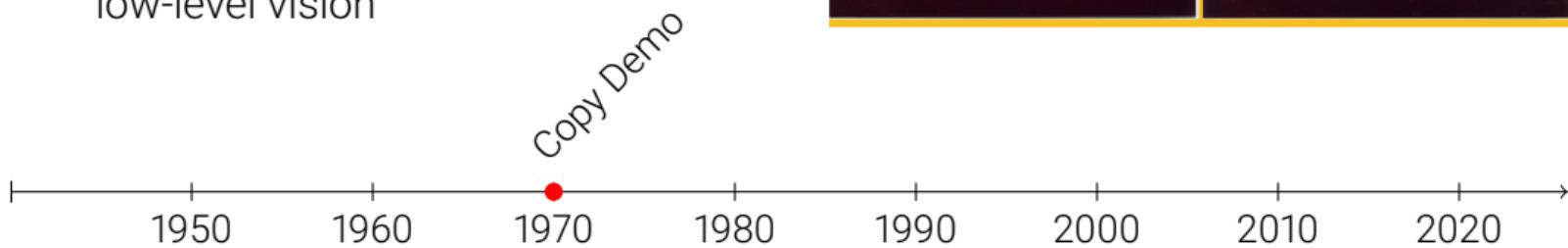
Minsky/Papert



A Brief History of Computer Vision

1970: MIT Copy Demo

- ▶ Vision system recovers structure of a blocks scene, robot plans and builds copy from another set of blocks
- ▶ Vision, planning and manipulation
- ▶ But low-level edge finding not robust enough for task, led to attention on low-level vision



A Brief History of Computer Vision

1970: Shape from Shading

- ▶ Recover 3D from single 2D image
- ▶ Assumes Lambertian surface and constant albedo
- ▶ Applies smoothness regularization to constrain the ill-posed problem

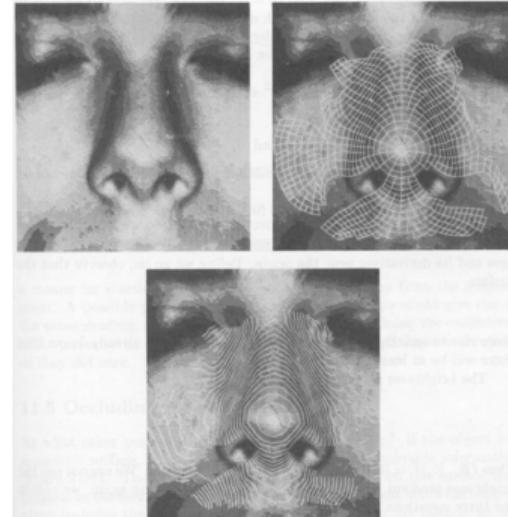


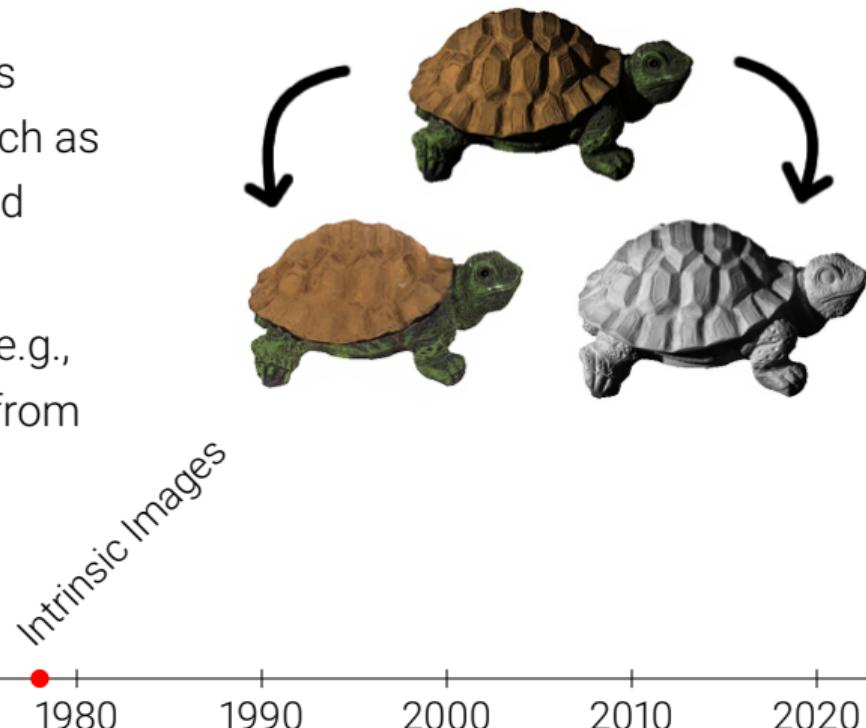
Figure 11-7. The shape-from-shading method is applied here to the recovery of the shape of a nose. The first picture shows the (crudely quantized) gray-level image available to the program. The second picture shows the base characteristics superimposed, while the third shows a contour map computed from the elevations found along the characteristic curves.



A Brief History of Computer Vision

1978: Intrinsic Images

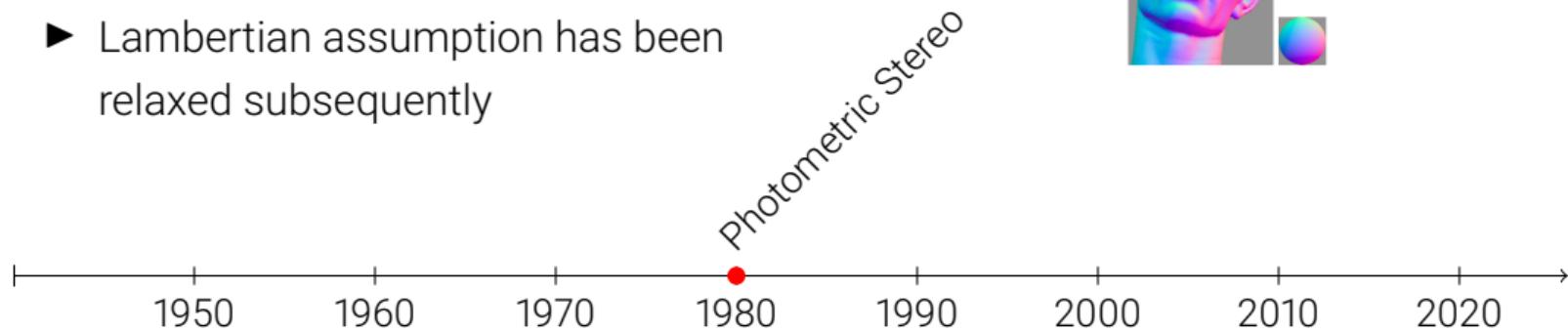
- Decomposing an image into its different intrinsic 2D layers, such as reflectance, shading, shape and motion components
- Useful for downstream tasks, e.g., object detection independent from shadows and lighting



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1980: Photometric Stereo

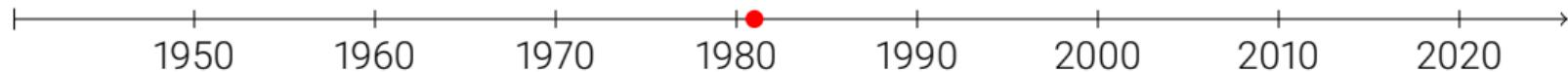
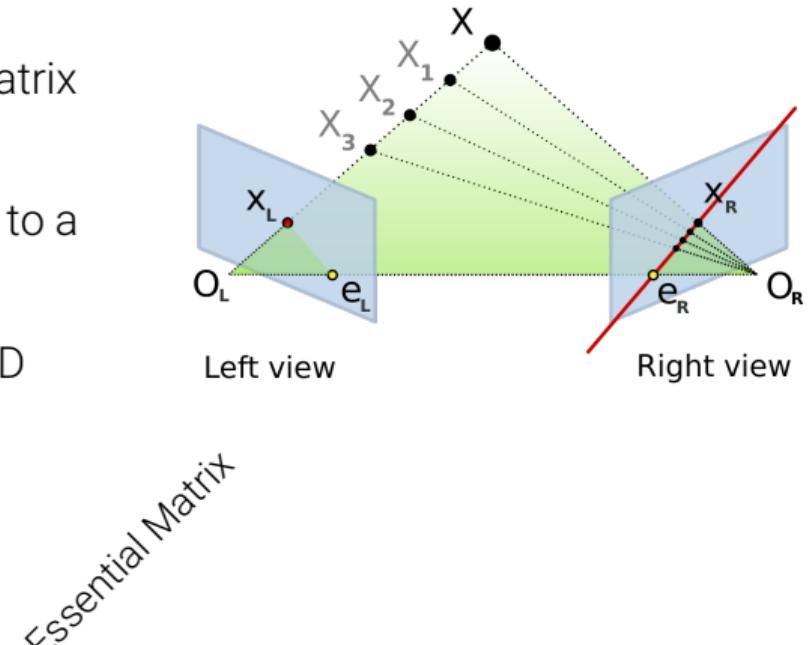
- ▶ Recover 3D from multiple 2D images, taken from the same viewpoint with different lighting conditions
- ▶ Requires at least 3 images
- ▶ Unprecedented detail and accuracy
- ▶ Lambertian assumption has been relaxed subsequently



A Brief History of Computer Vision

1981: Essential Matrix

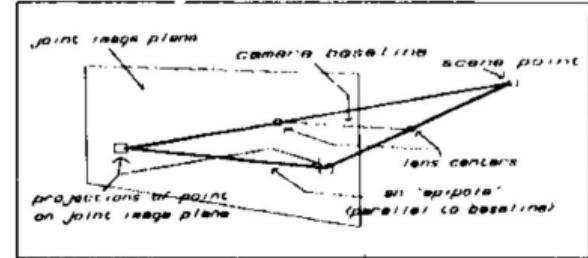
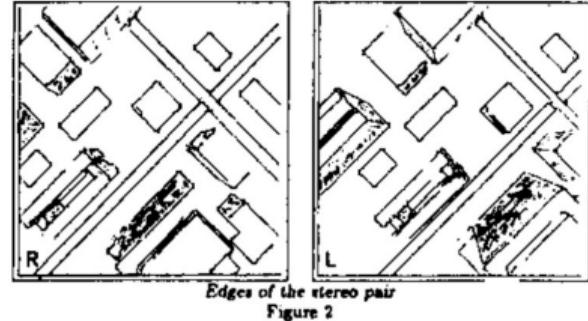
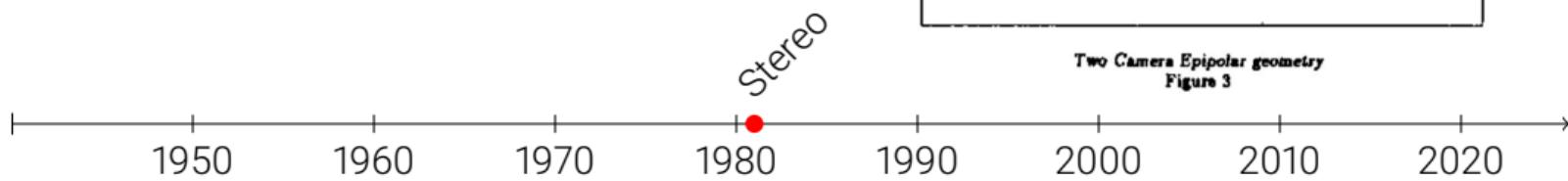
- ▶ Defines two-view geometry as matrix mapping points to epipolar lines
- ▶ Reduces correspondence search to a 1D problem
- ▶ Can be estimated from a set of 2D correspondences
- ▶ Key ideas known for 100 years



A Brief History of Computer Vision

1981: Binocular Scanline Stereo

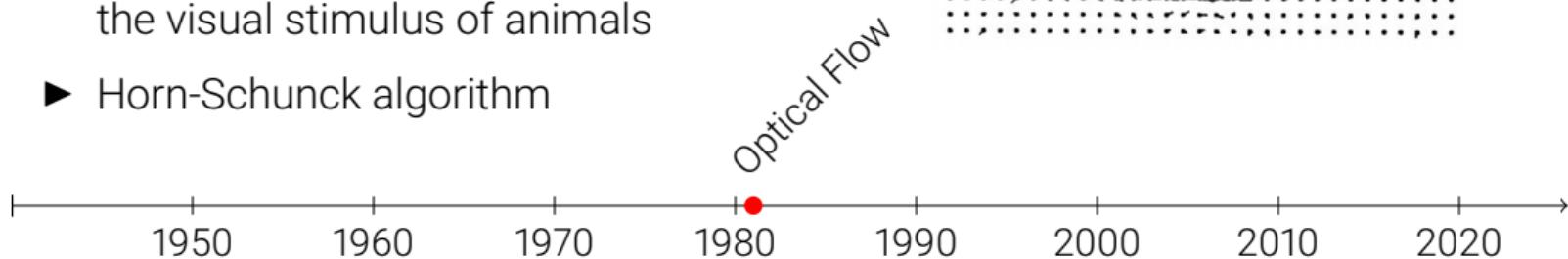
- ▶ Correlate points along epipolar lines
- ▶ Use dynamic programming to introduce constraints along scanlines (image rows)
- ▶ Allows for overcoming ambiguities, but streaking artifacts between rows



A Brief History of Computer Vision

1981: Dense Optical Flow

- ▶ Pattern of apparent motion of objects, surfaces, and edges in a visual scene
- ▶ Measured by (densely) tracking pixels between two frames
- ▶ Investigated by Gibson to describe the visual stimulus of animals
- ▶ Horn-Schunck algorithm

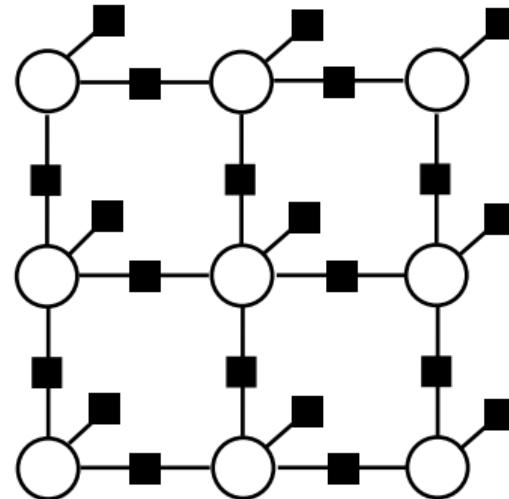
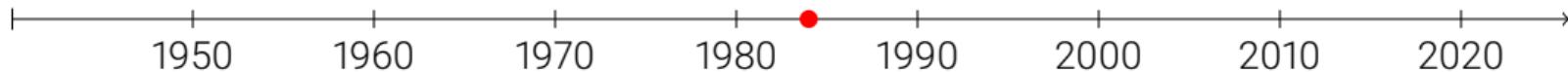


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1984: Markov Random Fields

- ▶ MRFs for encoding prior knowledge (e.g., about smoothness)
- ▶ Resolves ambiguities in many ill-posed vision problems (e.g., stereo, flow, denoising)
- ▶ Global optimization (e.g., variational inference, sampling, belief propagation, graph cuts)

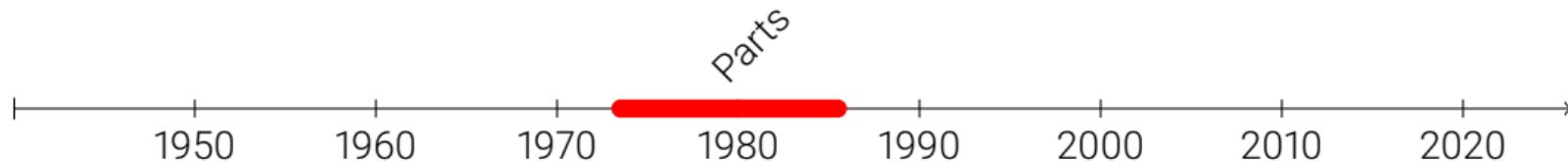
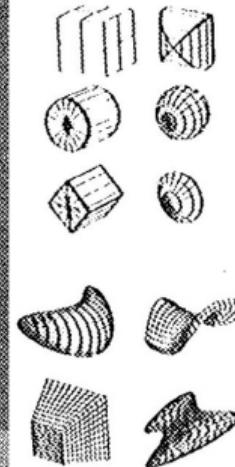
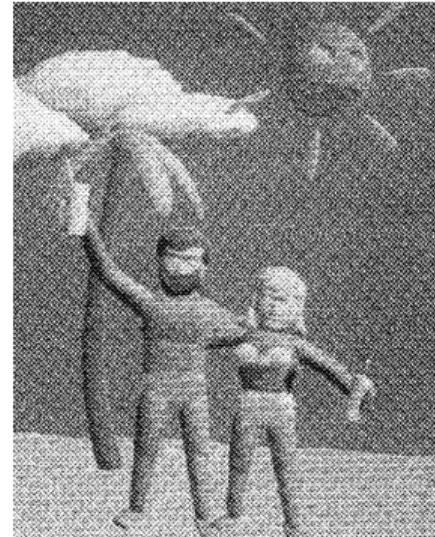
MRFs



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1980s: Part-based Models

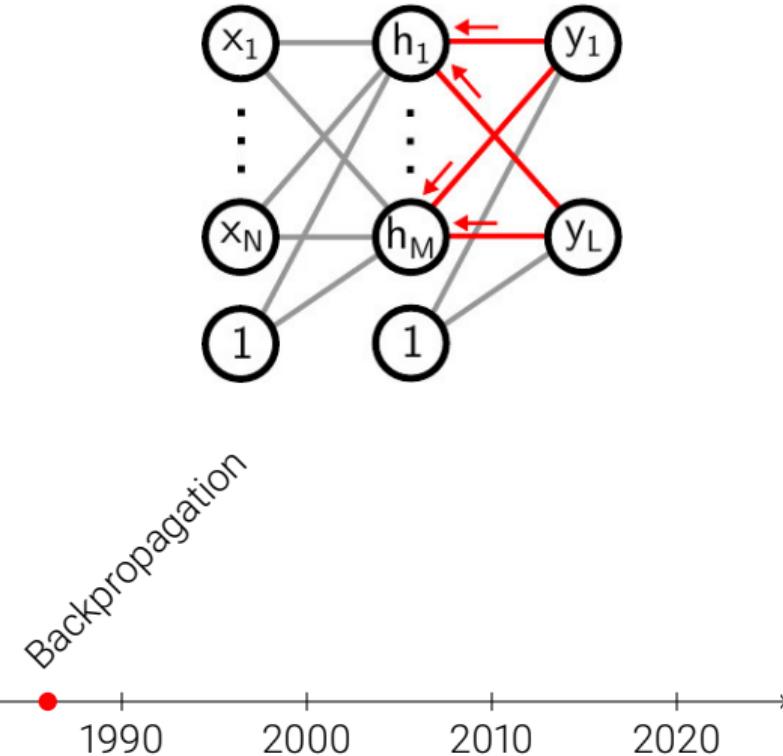
- ▶ 1973: Pictorial Structures
- ▶ 1976: Generalized Cylinders
(solids of revolution, swept curves)
- ▶ 1986: Superquadrics
(generalization of quadric surfaces)
- ▶ Express complex relationships
- ▶ Compact representation



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1986: Backpropagation Algorithm

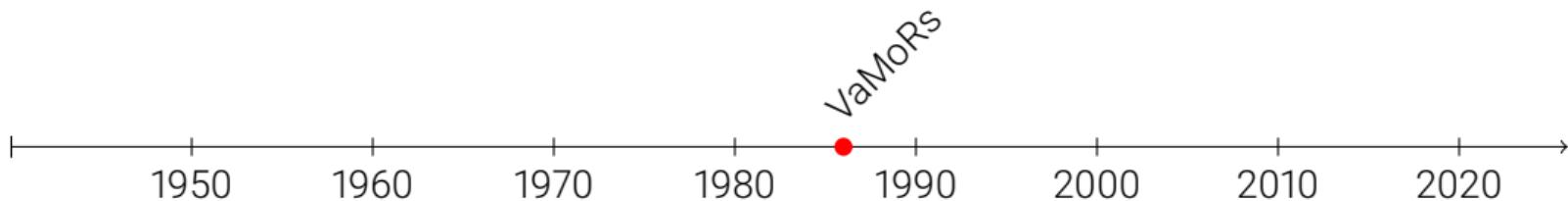
- ▶ Efficient calculation of gradients in a deep network wrt. network weights
- ▶ Enables application of gradient based learning to deep networks
- ▶ Known since 1961, but first empirical success in 1986
- ▶ Remains main workhorse today



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1986: Self-Driving Car VaMoRs

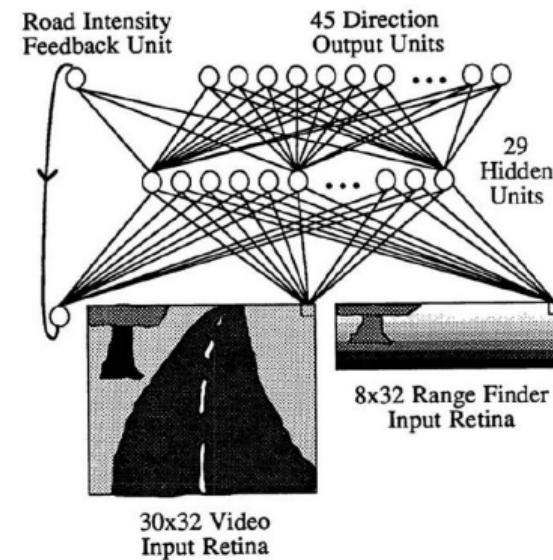
- ▶ Developed by Ernst Dickmanns in context of EUREKA-Prometheus
- ▶ Demonstration to Daimler-Benz Research 1986 in Stuttgart
- ▶ Longitudinal & lateral guidance with lateral acceleration feedback
- ▶ Speed: 0 to 36 km/h



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1988: Self-Driving Car ALVINN

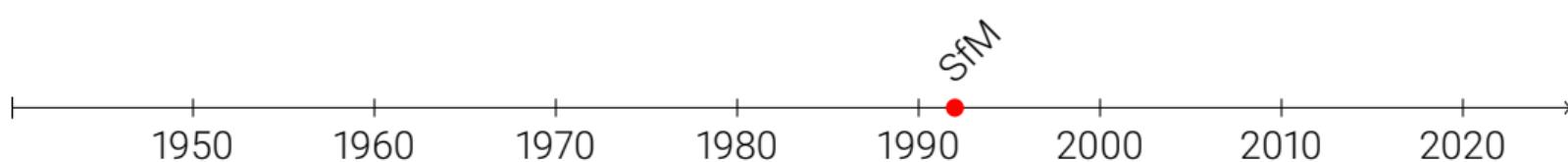
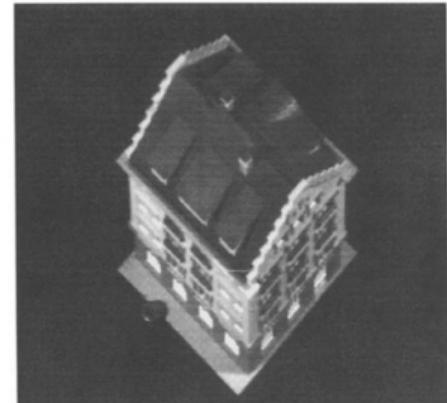
- ▶ Forward-looking, vision based driving
- ▶ Fully connected neural network maps road images to vehicle turn radius
- ▶ Trained on simulated road images
- ▶ Tested on unlined paths, lined city streets and interstate highways
- ▶ 90 consecutive miles at up to 70 mph



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1992: Structure-from-Motion

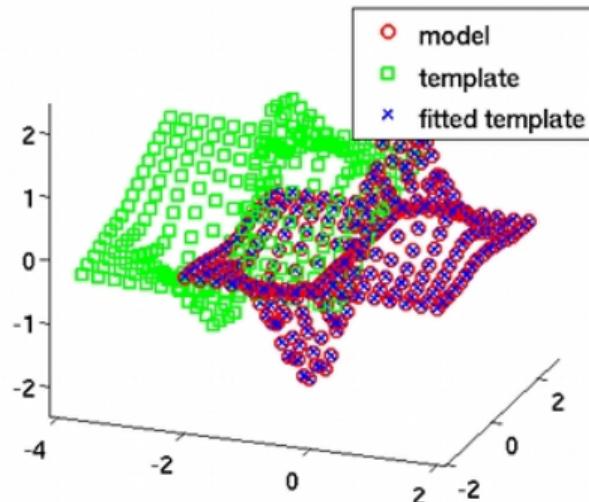
- ▶ Estimating 3D structures from 2D image sequences of static scenes
- ▶ Requires only a single camera
- ▶ Tomasi-Kanade factorization provides closed-form (SVD-based) solution for orthographic case
- ▶ Today: non-linear least squares



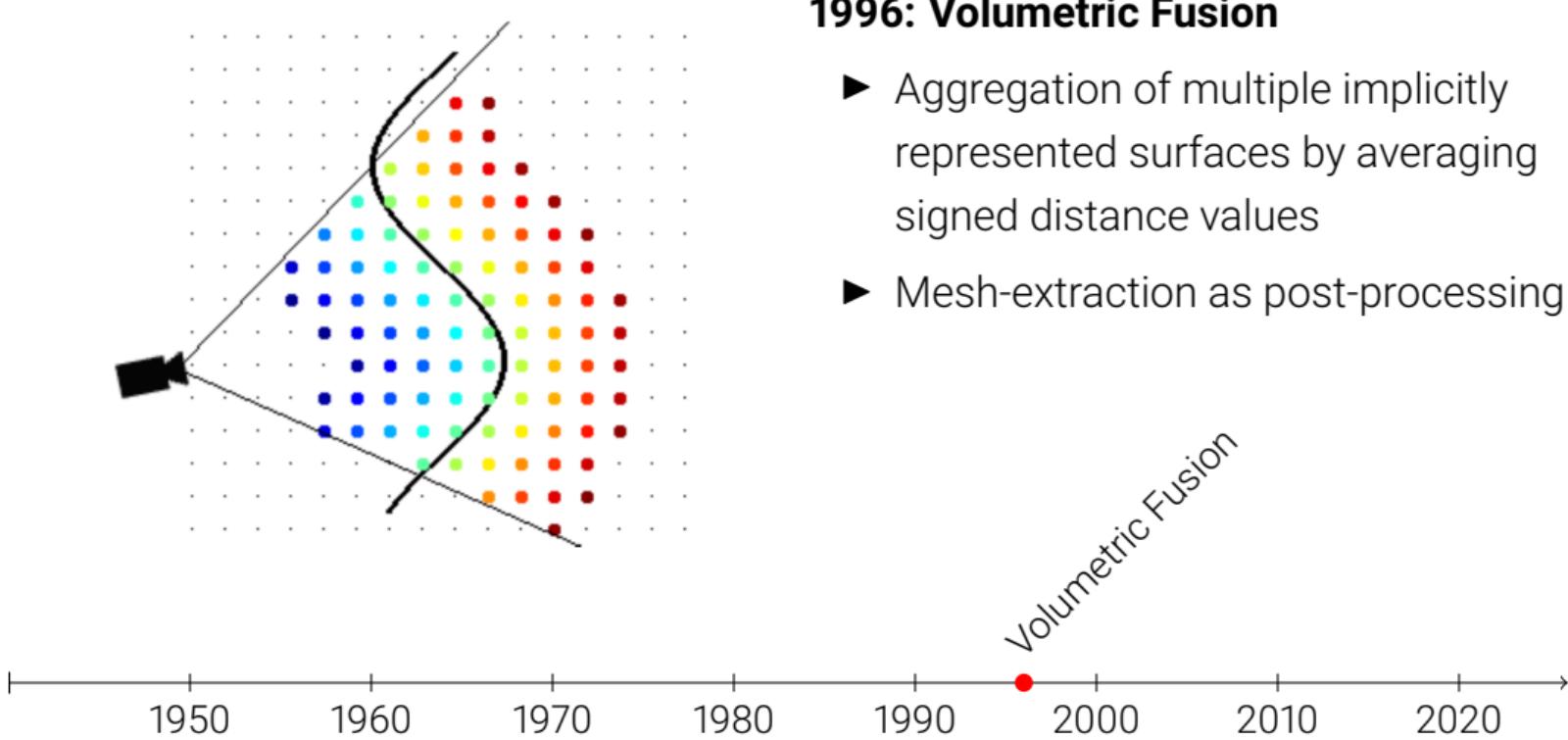
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1992: Iterative Closest Points

- ▶ Registering two point clouds by iteratively optimizing a (rigid or non-rigid) transformation
- ▶ Used to aggregate partial 2D or 3D surfaces from different scans, to estimate relative camera poses from point clouds or to localize wrt. a map



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A Brief History of Computer Vision

1998: Multi-View Stereo

- ▶ 3D reconstruction from multiple input images using level-set methods
- ▶ Reconstruction vs. image matching
- ▶ Proper model of visibility
- ▶ Flexible topology
- ▶ Provable convergence
- ▶ Other approaches (dead-ends):
Voxel-coloring, space carving

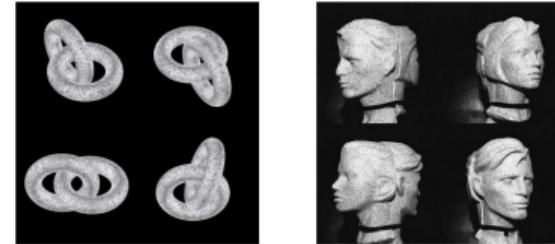


Fig. 3. Multicamera images of 3D objets. On the left hand side, two crossing synthetic tori (24 images). On the right hand side, real images: two human heads (18 images).

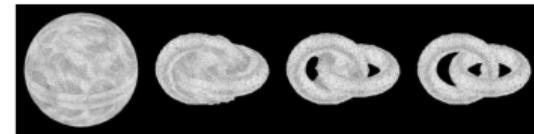
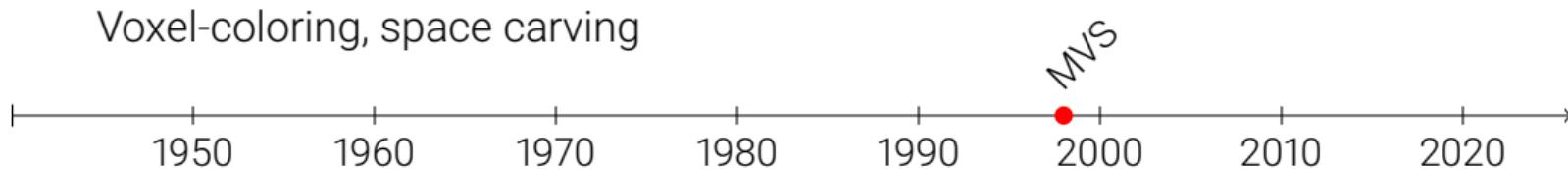


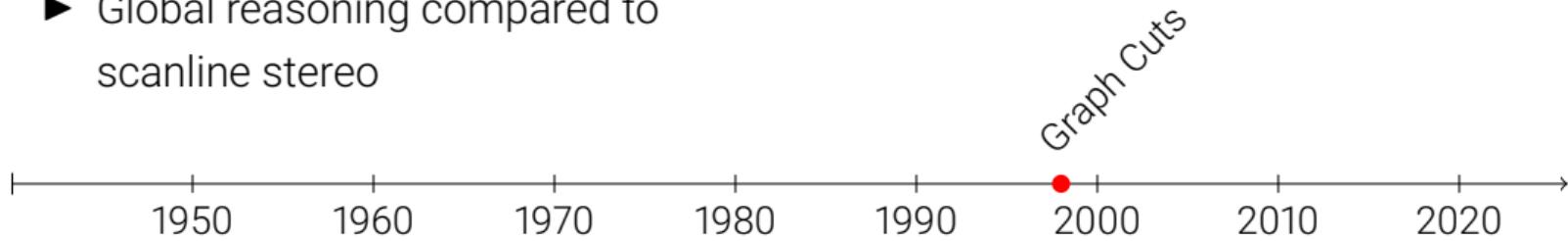
Fig. 4. Evolution of the surface for the two tori.



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1998: Stereo with Graph Cuts

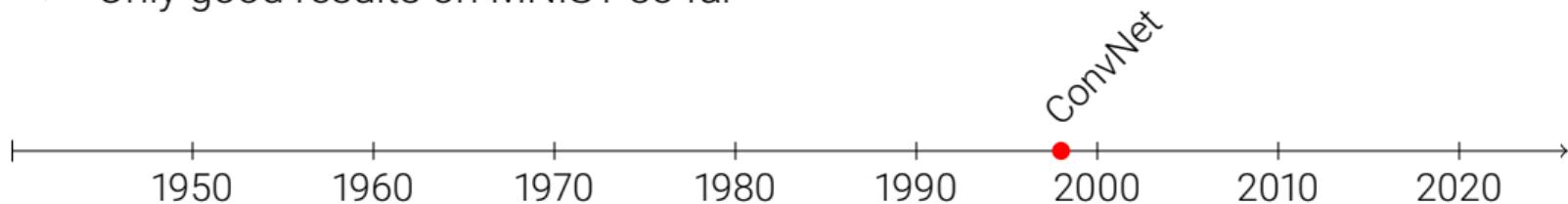
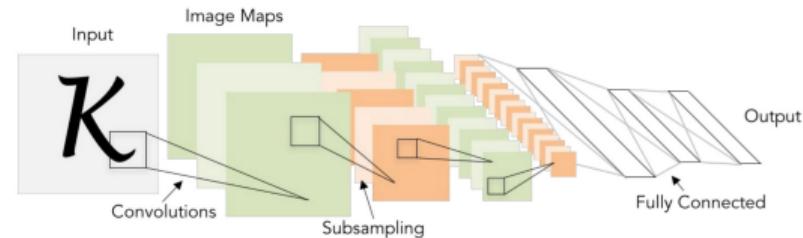
- ▶ Popular discrete MAP inference algorithm for Markov Random Fields
- ▶ First versions included unary and pairwise terms
- ▶ Later versions also included specific forms of higher-order potentials
- ▶ Global reasoning compared to scanline stereo



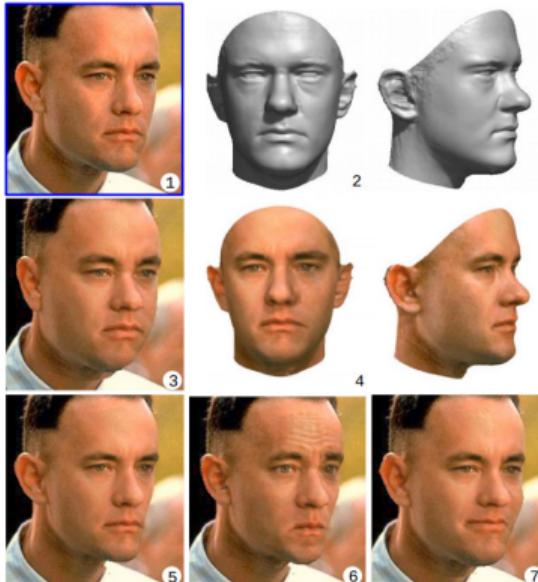
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1998: Convolutional Neural Networks

- ▶ Similar to Neocognitron, but trained end-to-end using backpropagation
- ▶ Implements spatial invariance via convolutions and max-pooling
- ▶ Weight sharing reduces parameters
- ▶ Tanh/Softmax activations
- ▶ Only good results on MNIST so far

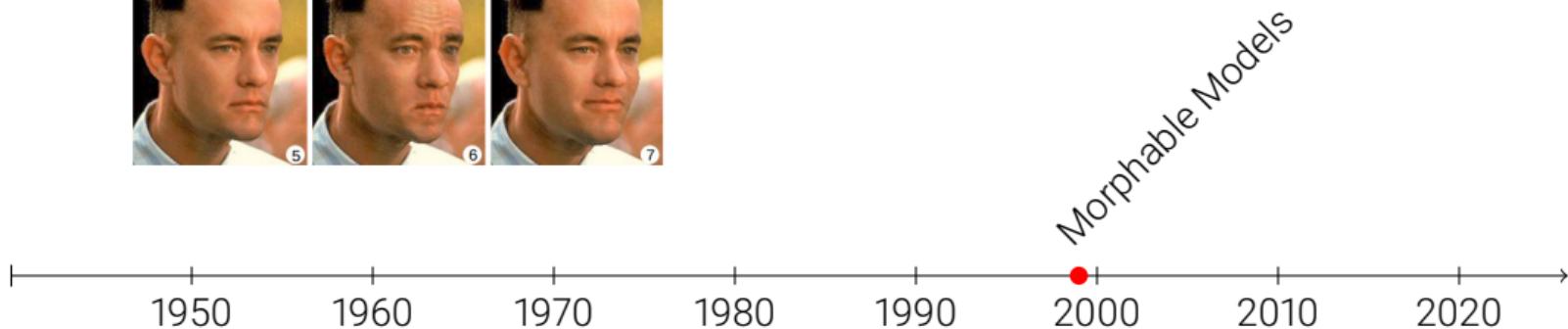


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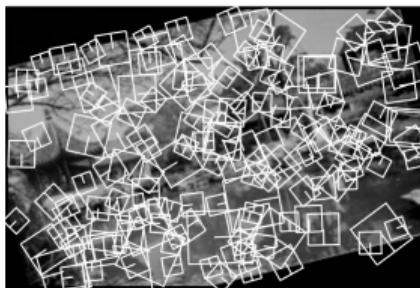
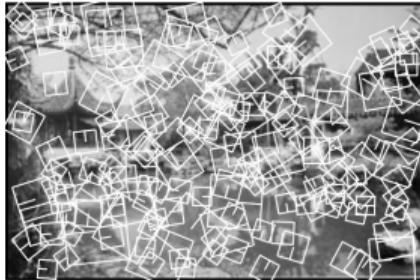


1999: Morphable Models

- ▶ Single-view 3D face reconstruction
- ▶ Linear combination of 200 laser scans of faces
- ▶ Stunning results at the time

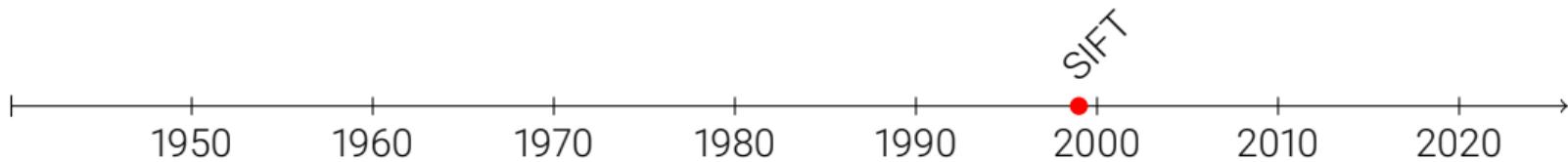


A Brief History of Computer Vision



1999: SIFT

- ▶ Scale Invariant Feature Transform
- ▶ Detection and description of salient local features in an image
- ▶ Enabled many applications
(e.g., image stitching, reconstruction, motion estimation, ...)

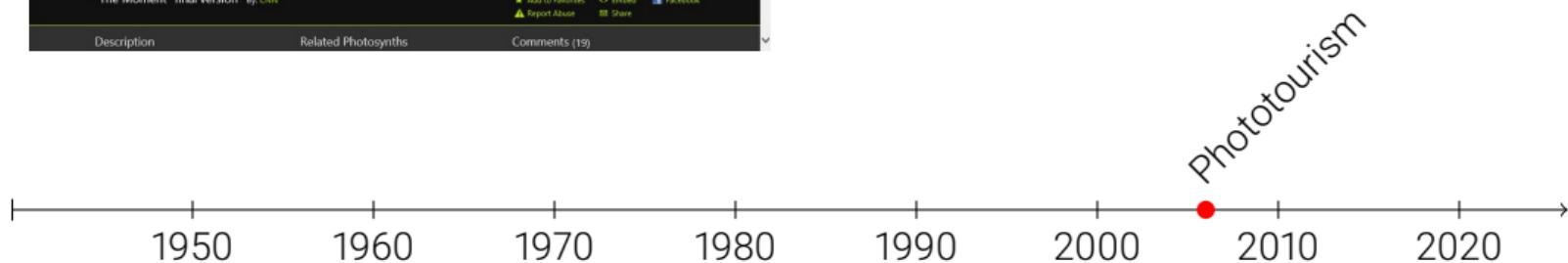


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2006: Photo Tourism

- ▶ Large-scale 3D reconstruction from internet photos
- ▶ Key ingredients: SIFT feature matching, bundle adjustment
- ▶ Microsoft Photosynth (discont.)

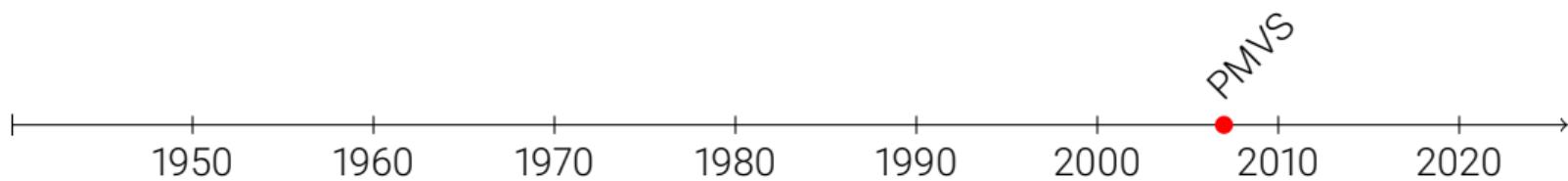


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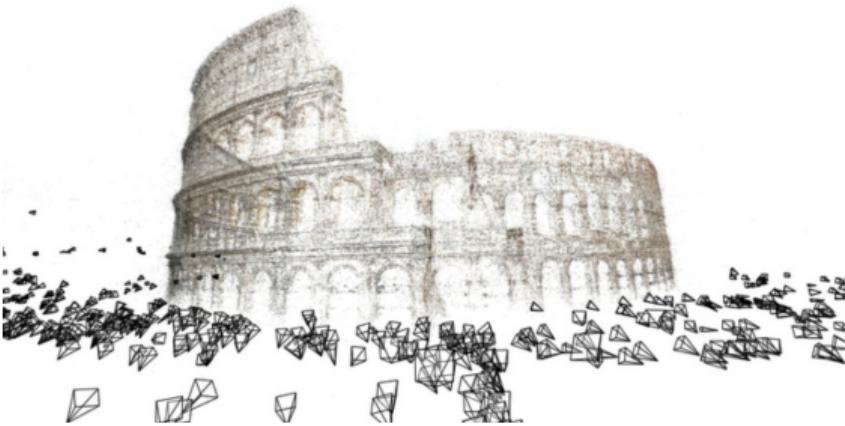


2007: PMVS

- ▶ Patch-based Multi View Stereo
- ▶ Robust reconstruction of various small and large objects
- ▶ Performance of 3D reconstruction techniques continues to increase

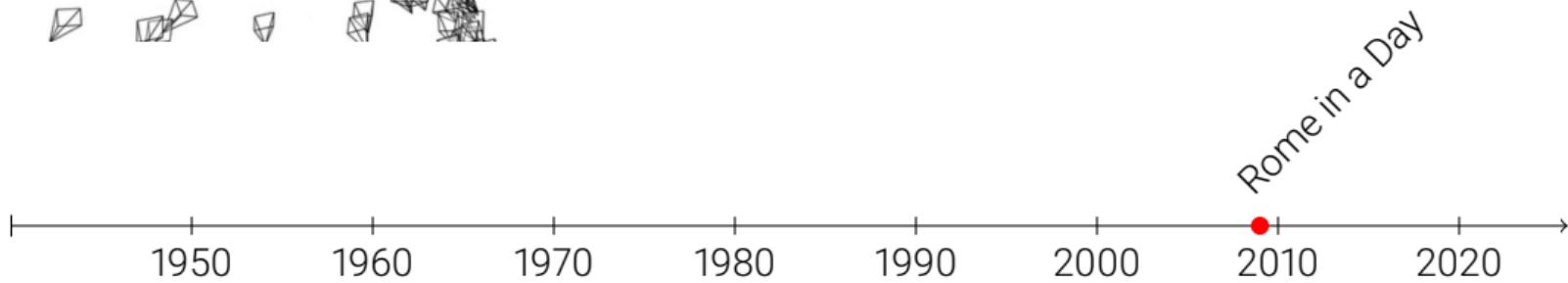


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2009: Building Rome in a Day

- ▶ 3D reconstruction of landmarks and cities from unstructured Internet photo-collections
- ▶ Follow-up: Rome on a Cloudless Day

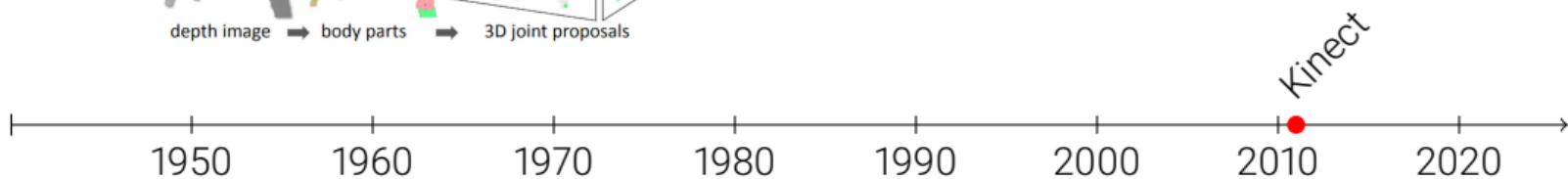


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2011: Kinect

- ▶ Active light 3D sensing
- ▶ ML for 3D pose estimation
- ▶ Multiple hardware generations
- ▶ Early versions failed to commercialize but heavily used for robotics and vision research



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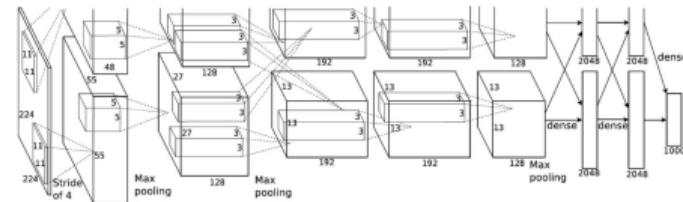
2009-2012: ImageNet and AlexNet

ImageNet

- ▶ Recognition benchmark (ILSVRC)
- ▶ 10 million annotated images
- ▶ 1000 categories

AlexNet

- ▶ First neural network to win ILSVRC
via **GPU training, deep models, data**



Image/AlexNet



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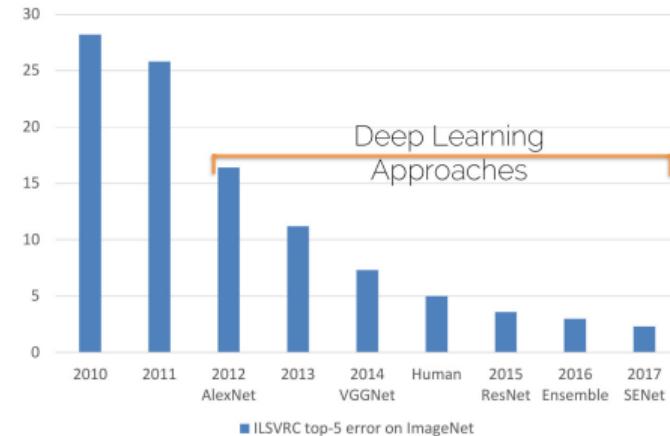
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AlexNet

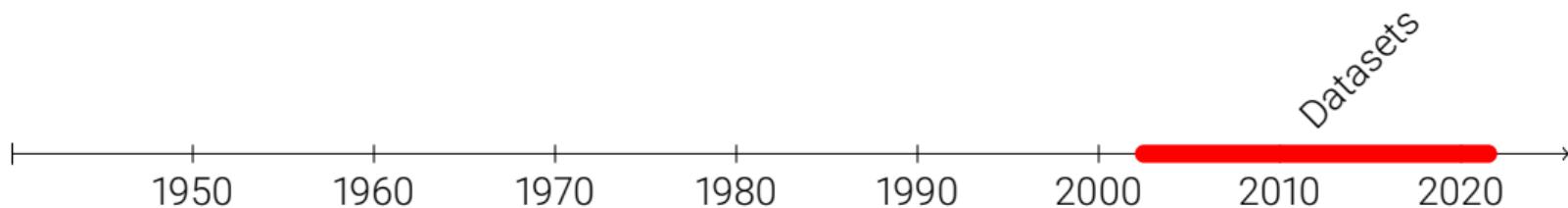
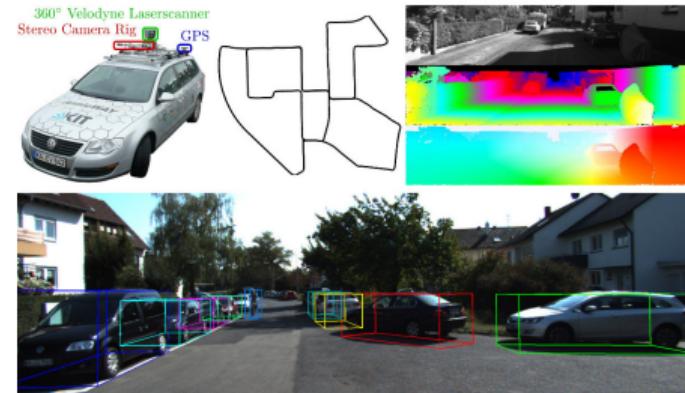
- ▶ First neural network to win ILSVRC via **GPU training, deep models, data**
- ▶ Sparked deep learning revolution



A Brief History of Computer Vision

2002-now: Golden Age of Datasets

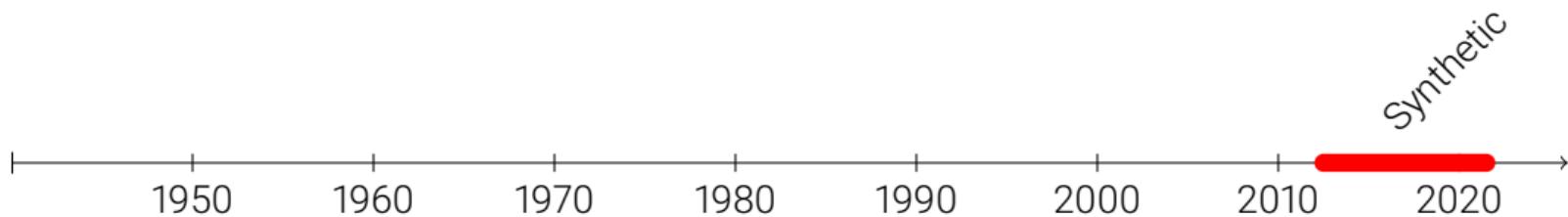
- ▶ Middlebury Stereo and Flow
- ▶ KITTI, Cityscapes: Self-driving
- ▶ PASCAL, MS COCO: Recognition
- ▶ ShapeNet, ScanNet: 3D DL
- ▶ Visual Genome: Vision/Language
- ▶ MITOS: Breast cancer



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2012-now: Synthetic Data

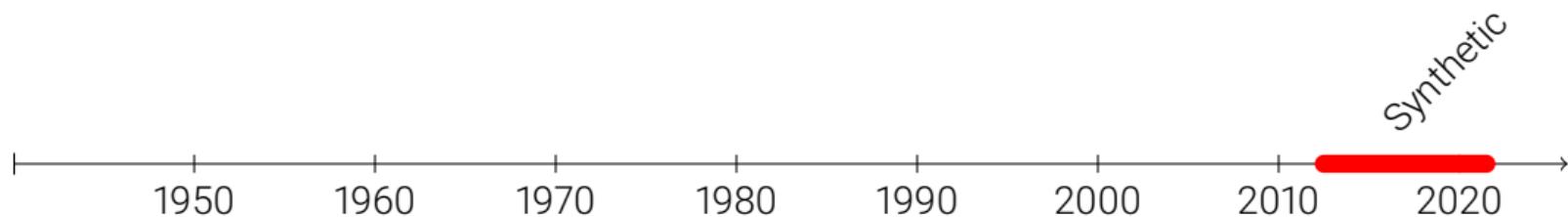
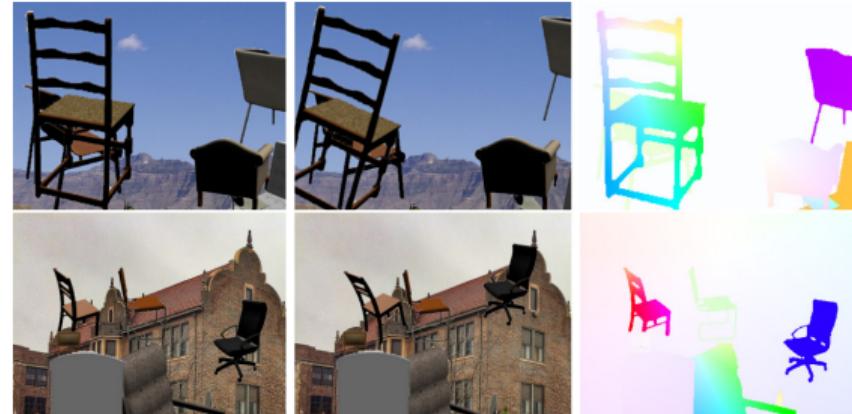
- ▶ Annotating real data is expensive
- ▶ Led to surge of synthetic datasets
- ▶ Creating 3D assets is also costly



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2012-now: Synthetic Data

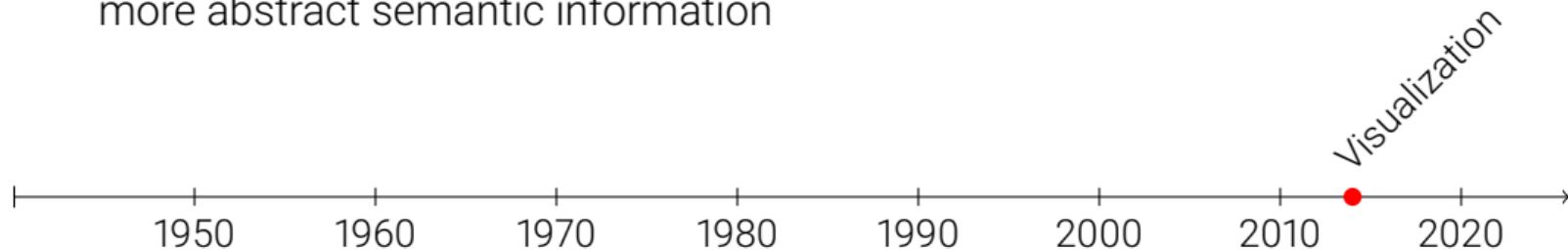
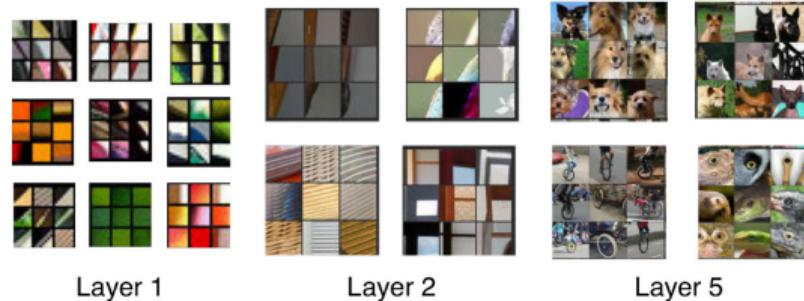
- ▶ Annotating real data is expensive
- ▶ Led to surge of synthetic datasets
- ▶ Creating 3D assets is also costly
- ▶ But even very simple 3D datasets proved tremendously useful for pre-training (e.g., in optical flow)



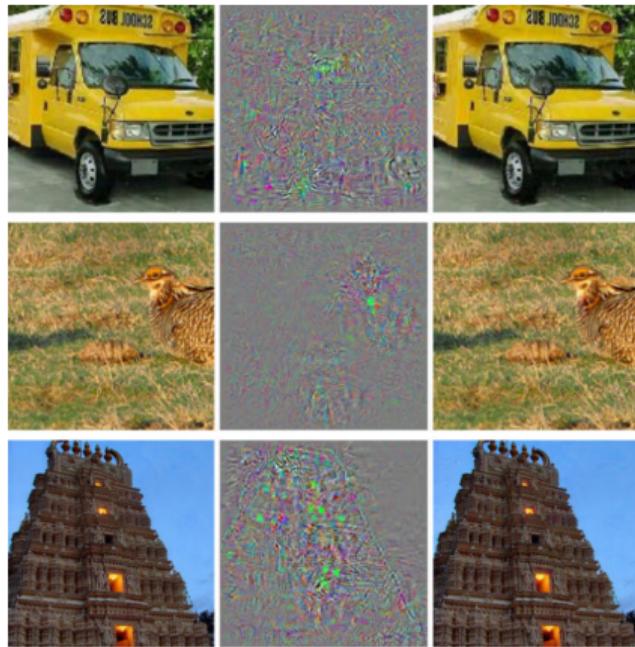
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2014: Visualization

- ▶ Goal: provide insights into what the network (black box) has learned
- ▶ Visualized image regions that most strongly activate various neurons at different layers of the network
- ▶ Found that higher levels capture more abstract semantic information

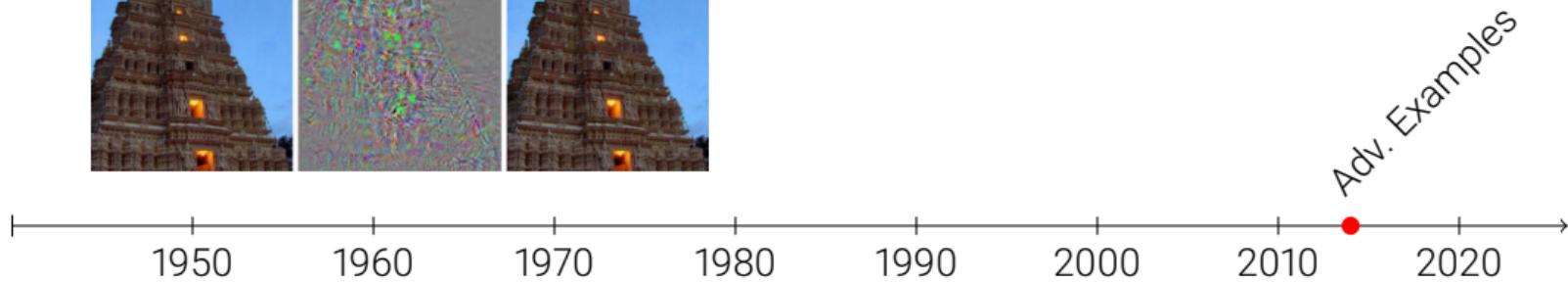


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2014: Adversarial Examples

- ▶ Accurate image classifiers can be fooled by imperceptible changes (here magnified for visibility)
- ▶ All images in the right column are classified as “ostrich”

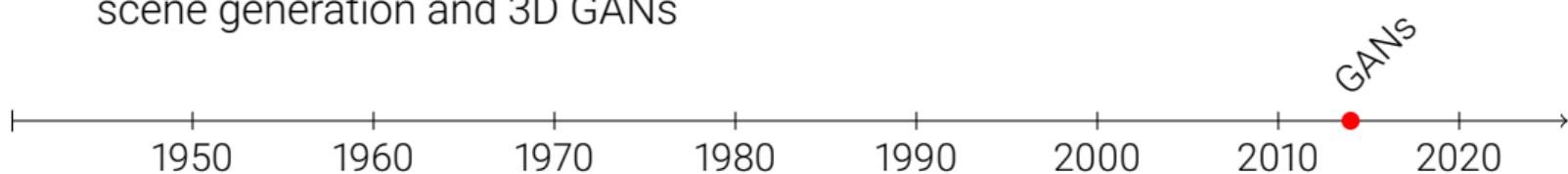


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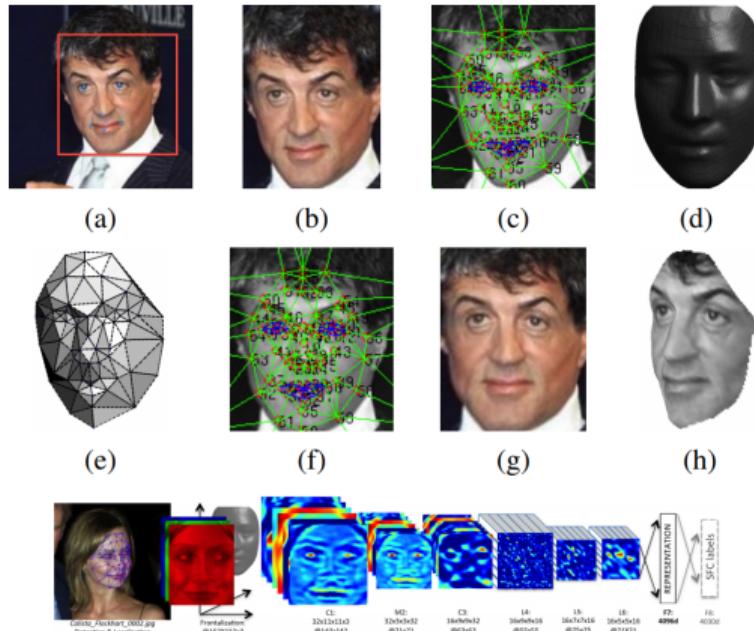
2014: Generative Adversarial Networks

- Deep generative models (VAEs, GANs) produce compelling images
- StyleGAN2 is state-of-the-art
- Results on faces hard to distinguish from real images
- Active research on image translation, domain adaptation, content and scene generation and 3D GANs

Moore's Law of AI
4.5 years of progress on faces

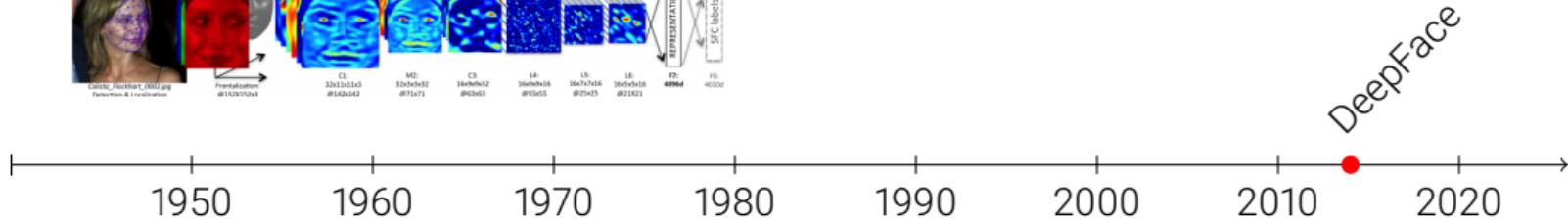


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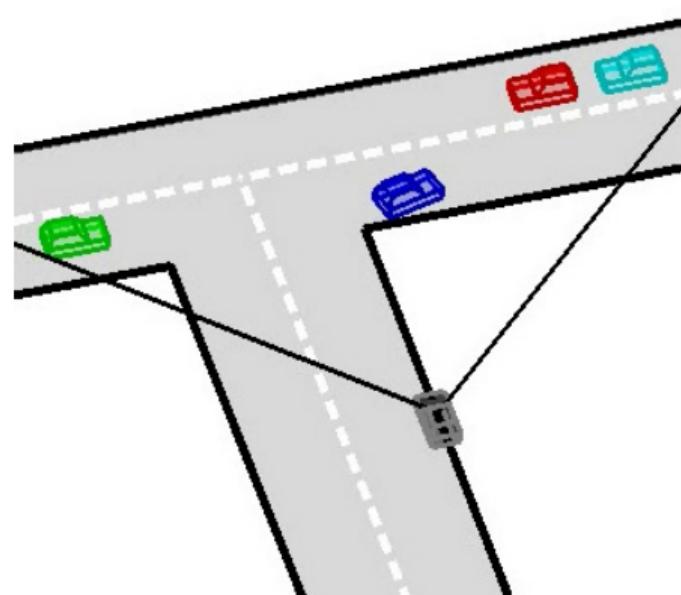


2014: DeepFace

- ▶ Combination of model-based alignment with deep learning for face recognition
- ▶ First model to reach human-level face recognition performance



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2014: 3D Scene Understanding

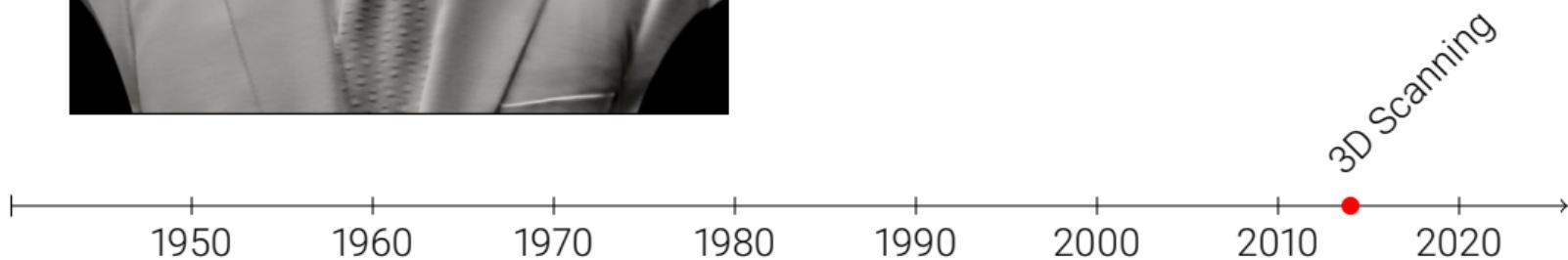
- ▶ Parsing RGB and RGB-D images into holistic 3D scene representations
- ▶ Methods for indoors and outdoors

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2014: 3D Scanning

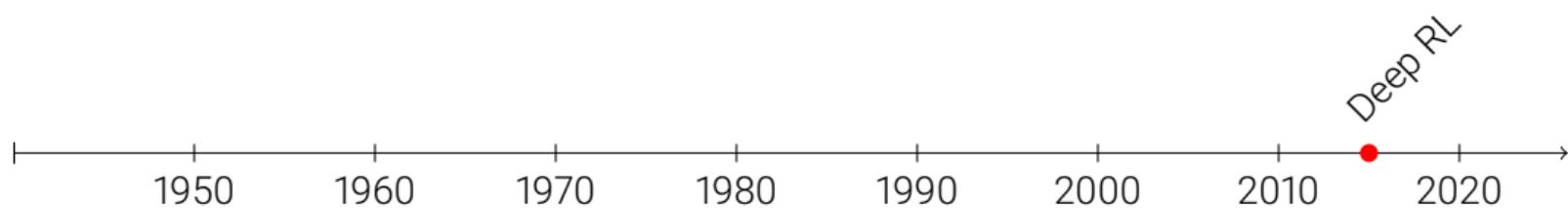
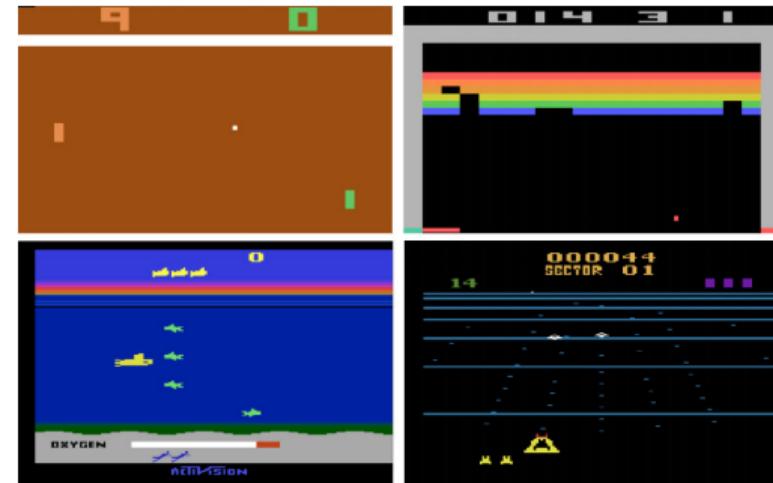
- ▶ 3D scanning techniques allow for creating accurate replicas
- ▶ Debevec's team scans Obama
- ▶ Exhibition in Smithsonian
- ▶ <https://dpo.si.edu/blog/>



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2015: Deep Reinforcement Learning

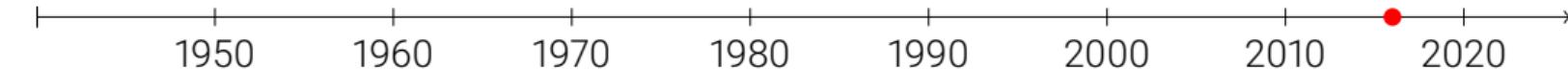
- ▶ Learning a policy (state→action) through random exploration and reward signals (e.g., game score)
- ▶ No other supervision
- ▶ Success on many Atari games
- ▶ But some games remain hard



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2016: Style Transfer

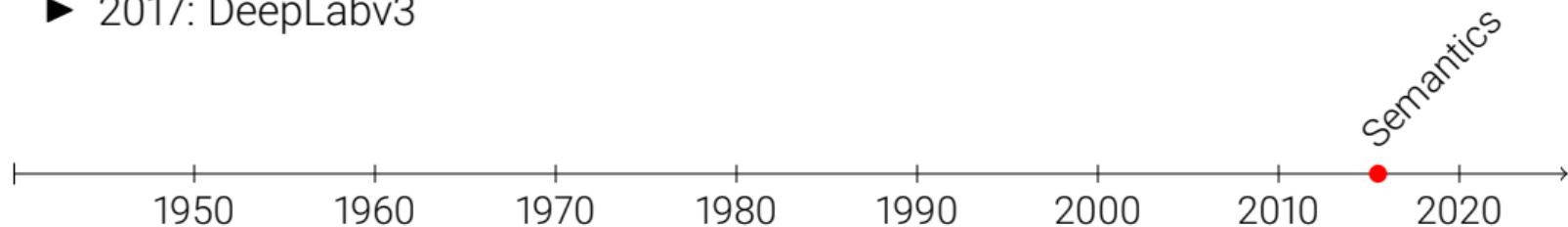
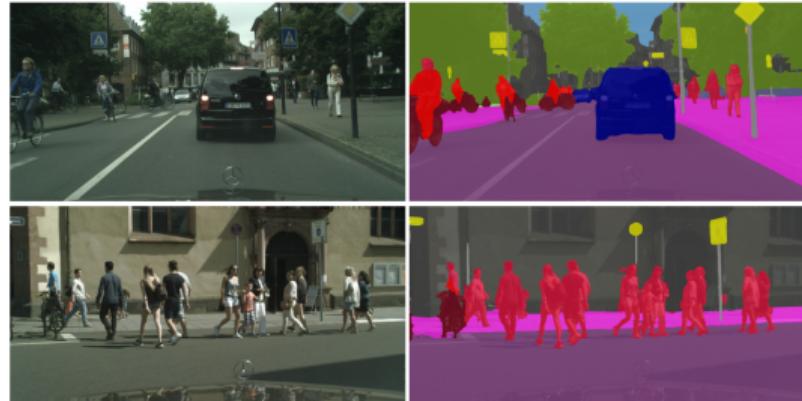
- ▶ Manipulate photograph to adopt style of another image (painting)
- ▶ Uses deep network pre-trained on ImageNet for disentangling content from style
- ▶ It is fun! Try yourself:
<https://deepart.io/>



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2015-2017: Semantic Segmentation

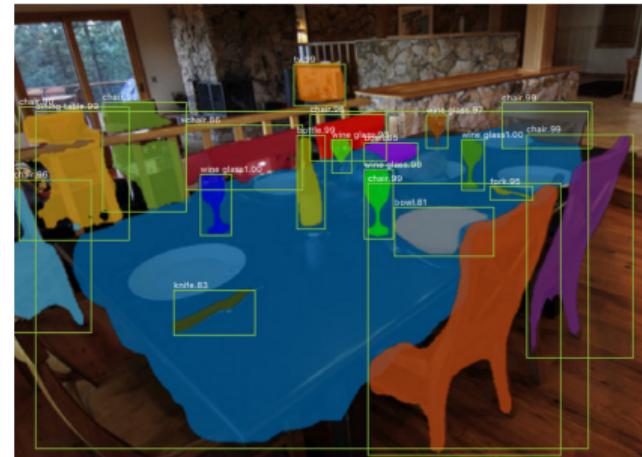
- ▶ Assign semantic class to every pixel
- ▶ Semantic segmentation starts to work on challenging real-world datasets (e.g., CityScapes)
- ▶ 2015: FCN, SegNet
- ▶ 2016: DeepLab, FSO
- ▶ 2017: DeepLabv3



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2017: Mask R-CNN

- Deep neural network for joint object detection and instance segmentation
- Outputs “structured object”, not only a single number (class label)
- State-of-the-art on MS-COCO



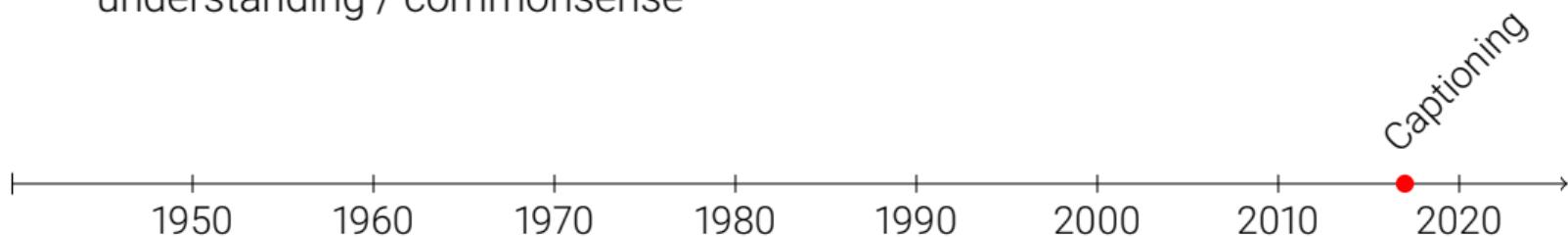
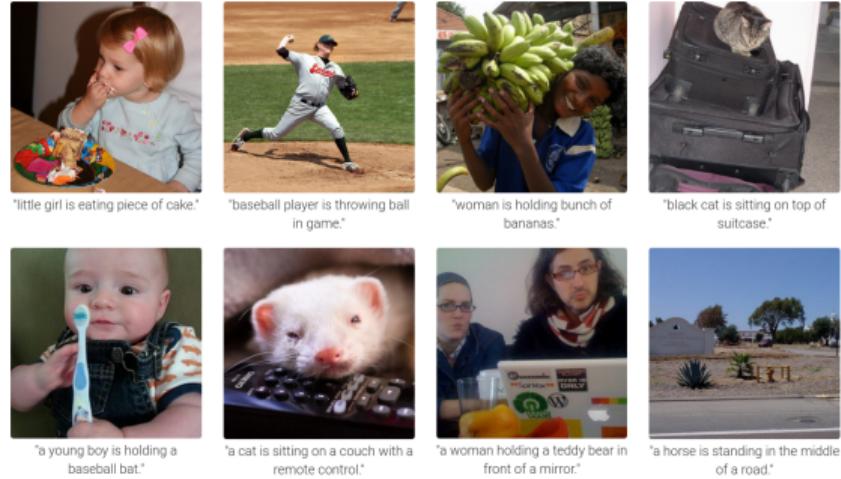
Mask R-CNN



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2017: Image Captioning

- Growing interest in combining vision with language
- Several new tasks emerged including image captioning and visual question answering
- However, models still lack understanding / commonsense

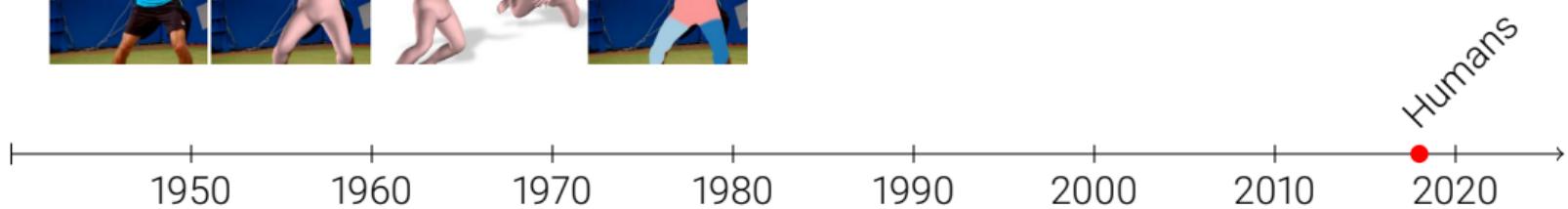


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2018: Human Shape and Pose

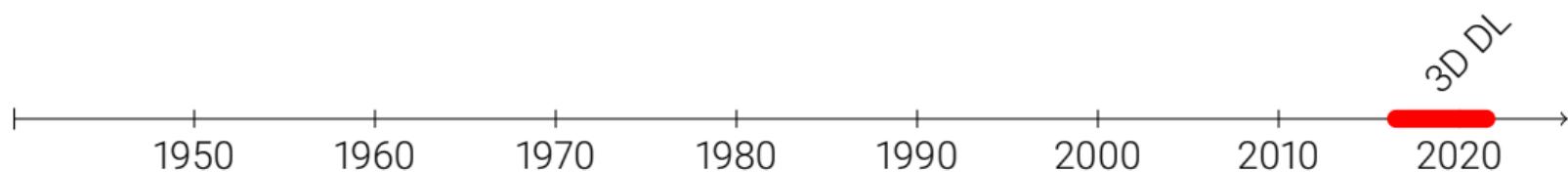
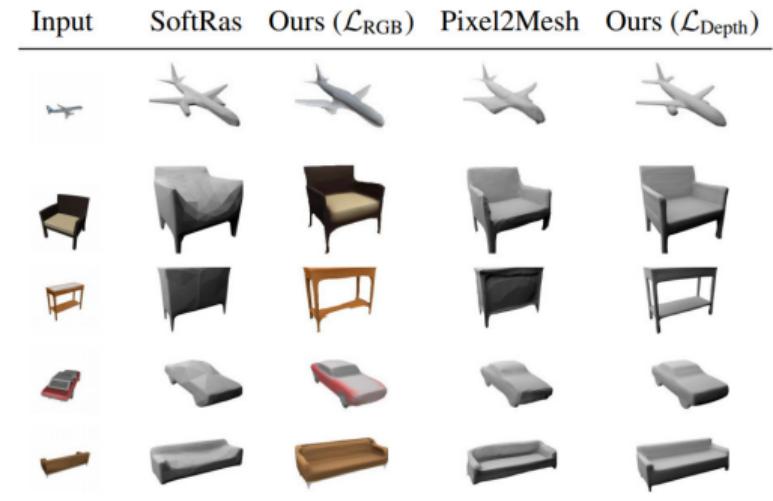
- ▶ Human pose/shape models mature
- ▶ Rich parametric models (e.g., SMPL, STAR)
- ▶ Regression from RGB images only
- ▶ Models of pose-dependent deformation and clothing



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2016-2020: 3D Deep Learning

- ▶ First deep models to output 3D representations
- ▶ Voxels, point clouds, meshes, implicit representations
- ▶ Prediction of 3D models even from a single image
- ▶ Geometry, materials, light, motion



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Applications and Commercial Products



Google Portrait Mode



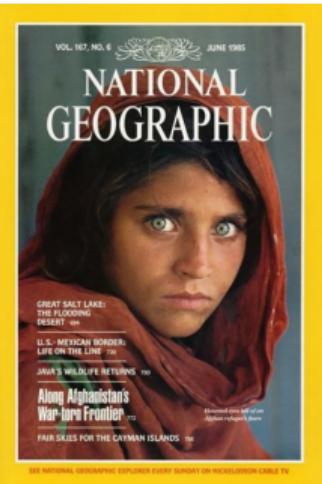
it flies itself.



Self-Driving Cars



Microsoft HoloLens



Iris Recognition



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Current Challenges

- ▶ Un-/Self-Supervised Learning
- ▶ Interactive learning
- ▶ Accuracy (e.g., self-driving)
- ▶ Robustness and generalization
- ▶ Inductive biases
- ▶ Understanding and mathematics
- ▶ Memory and compute
- ▶ Ethics and legal questions

