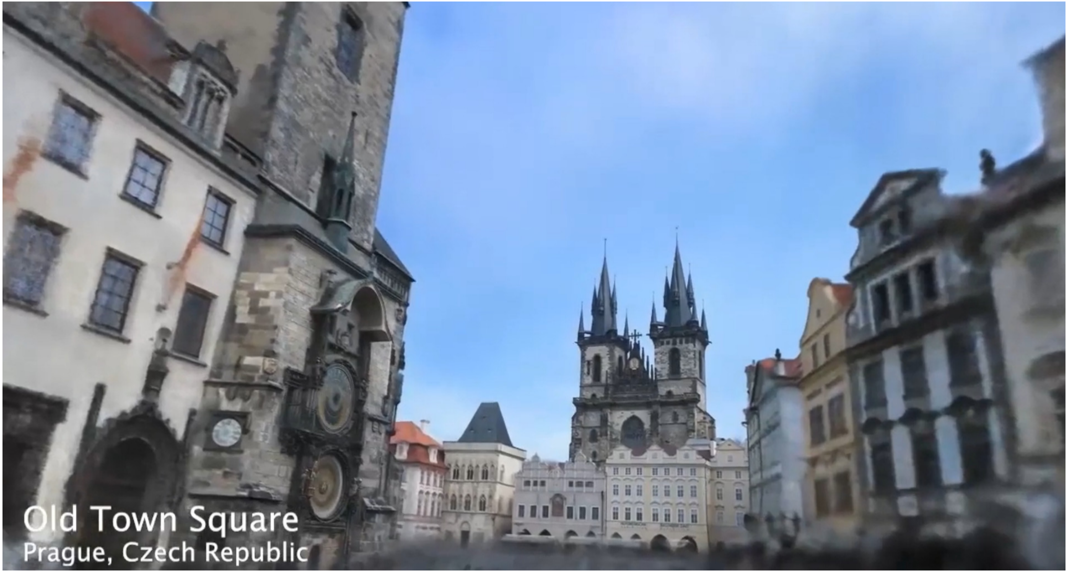
# Computer Vision – Summer 2022

## Lecture 1 – Introduction

Prof. Dr.-Ing. Andreas Geiger

Autonomous Vision Group

University of Tübingen / MPI-IS




Martin-Brualla, Radwan, Sajjadi, Barron, Dosovitskiy and Duckworth: NeRF in the Wild: Neural Radiance Fields for Unconstrained Photo Collections. CVPR, 2021.

# Agenda

**1.1** Organization

**1.2** Introduction

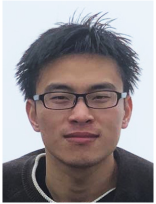
**1.3** History of Computer Vision

# 1.1
# Organization

# Team

Prof. Dr.-Ing.
Andreas Geiger

Michael
Niemeyer



Zehao
Yu

Markus
Flicke

# Agenda

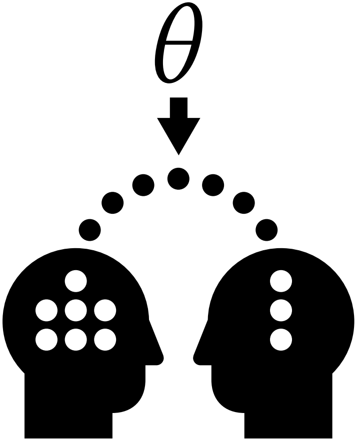
**Goal:** Students gain an understanding of the theoretical and practical concepts of computer vision using deep neural networks and graphical models. A strong focus is put on 3D vision. After this course, students should be able to develop and train computer vision models, reproduce research results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

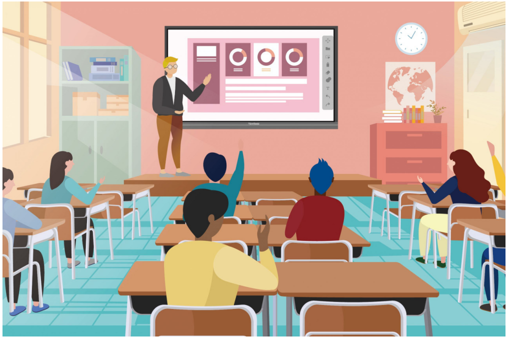
# Teaching Philosophy

# What is Teaching?

- Knowledge transfer (bidirectional)
- Understanding
- Learning to learn
- Critical thinking
- Engaging students
- Fostering discussion
- Apply knowledge in practice
- Having some fun along the way ..



# Flipped Classroom



**Regular Classroom**

- Lecturer “reads” lecture in class
- Students digest content at home
- Little “quality time”, no fun

**Flipped Classroom**

- Students watch lectures at home
- Content discussed during lecture
- Maximize interaction time

# Flipped Classroom

## Schedule

| Date | Lecture Slides and Videos | Interactive Sessions (Zoom \| MvL6+Zoom) | TA Support |
|---|---|---|---|
| 22.04. | **L01 - Introduction \| Slides**<br>1.1 Organization \| Video<br>1.2 Introduction \| Video<br>1.3 History of Computer Vision \| Video | **L01 - Lecture Organization**<br>E01 - Exercise Introduction \| Problems | Michael<br>Niemeyer |
| 29.04. | **L02 - Image Formation \| Slides**<br>2.1 Primitives and Transformations \| Video<br>2.2 Geometric Image Formation \| Video<br>2.3 Photometric Image Formation \| Video<br>2.4 Image Sensing Pipeline \| Video | **L02 - Lecture Q&A**<br>E01 - Exercise Individual Q&A | Michael<br>Niemeyer |
| 06.05. | **L03 - Structure-from-Motion \| Slides**<br>3.1 - Preliminaries\| Video<br>3.2 - Two-frame Structure-from-Motion\| Video<br>3.3 - Factorization \| Video<br>3.4 - Bundle Adjustment \| Video | **L03 - Lecture Q&A**<br>E01 - Exercise Q&A<br>E02 - Exercise Introduction \| Problems | Michael<br>Niemeyer |

### Summer 2022

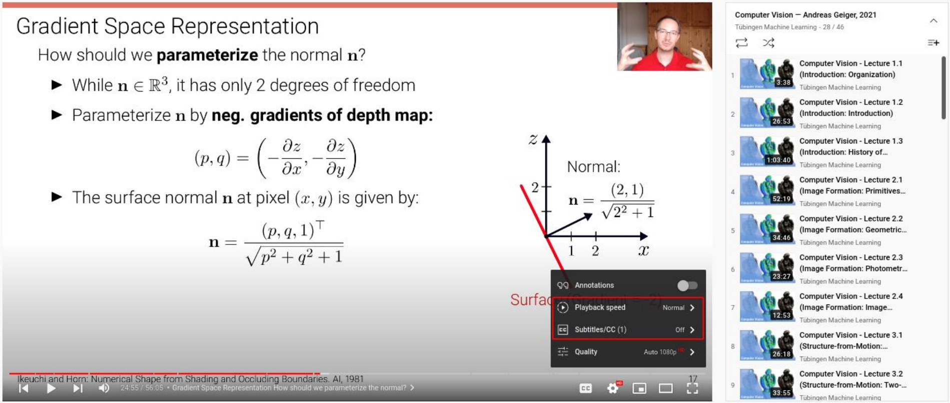
- **Live Sessions:**
  Fri, 10:15-12:00
  (until 27.5. via Zoom, from 3.6. on Hybrid: MvL6 + Zoom)
- **Individual Sessions:**
  Fri, 9:15-10:00
  Fri, 11:15-12:00
  Fri, 12:15-13:00
- **Important Links:**
  YouTube Lectures
  Slides / Exercises
  ILIAS / Zoom / Quiz

# Flipped Classroom

**More time for:**

- Interaction and discussion
- Answering questions on ILIAS
- Improving the materials
- Understanding the learning progress
- Developing new formats
  (e.g., Interactive sessions, quizzes ...)
- Implementing new tools
  (e.g., Lecture quiz server, ...)

# Flipped Classroom




- High quality lecture videos
- Available anytime, anywhere
- Slides available while watching
- Can be watched multiple times
- Adjustable speed, closed captions
- Questions $\Rightarrow$ Forum & live sessions

# Organization

# Organization

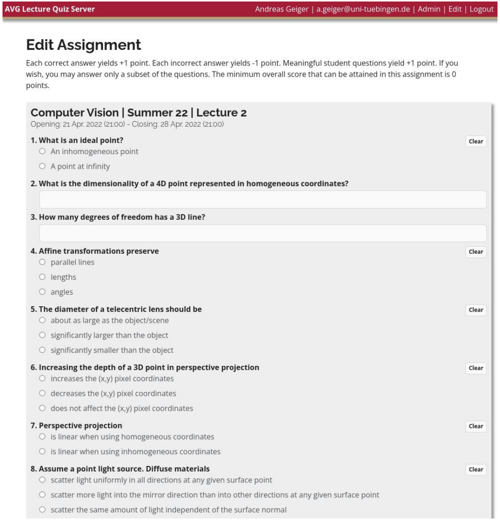
- Lectures provided in advance via YouTube
  - Students need to watch the lecture before joining the interactive live session
  - Students are encouraged to ask questions via the ILIAS forum and lecture quiz
- Interactive sessions (Fridays: 10:15-12:00)
  - Lecture Q&A, Exercise introduction and Q&A
  - Until end of May via Zoom, thereafter hybrid (MvL6+Zoom)
  - No tutorials by student assistants (this is a Master course!), instead we provide:
    - Individual exercise sessions in small groups every other week
    - Fast (<24h) feedback via ILIAS forum (make use of this opportunity!)
- Exam
  - Written (date and time available on course website)
  - A bonus can be obtained upon participation in the lecture quizzes
- Course Website with YouTube, Slides/Exercises, ILIAS, Zoom and Quiz links:
  `https://uni-tuebingen.de/de/203146`
- **Register** to ILIAS and Lecture Quiz Server **today** to participate in this course!

# Exercises

- Exercises are offered every 2 weeks, 6 assignments in total [Slides / Exercises]
- Exercises deepen the understanding with pen & paper and coding tasks
- Completion is voluntary and not a requirement to participate in the exam
- From experience: performance in exercises and exam highly correlated
- Problems handed out on Friday and introduced in the interactive session
- Can be conducted in groups of up to 2 students
- Individual Q&A sessions offered every other Friday (choose one slot)
- Important: You should **only join if you have started working** on them!
- In the past, we graded exercises, but students rather preferred solutions
  $\Rightarrow$ We will not grade exercises, but hand out and discuss the solutions instead
- But how do I stay motivated to watch the lectures and do the exercises?

# AVG Lecture Quiz Server

- We provide quiz questions to students during lectures 2-12 and exercises 1-6
- Students may gain up to 5 bonus points for the exam (out of 50 exam points)
- Answers may not be shared
- Participation is voluntary
- Opening & Deadline: Thursdays, 9pm
  (Questions for L02 and E01 available from 21.4.2022)
- **Register today** ⇒ participation link
- Use student email, validate information
- Please report bugs directly to me



AVG Lecture Quiz Server — Andreas Geiger | a.geiger@uni-tuebingen.de | Admin | Edit | Logout

## Edit Assignment

Each correct answer yields +1 point. Each incorrect answer yields -1 point. Meaningful student questions yield +1 point. If you wish, you may answer only a subset of the questions. The minimum overall score that can be attained in this assignment is 0 points.

### Computer Vision | Summer 22 | Lecture 2

Opening: 21 Apr. 2022 (21:00) - Closing: 28 Apr. 2022 (21:00)

**1. What is an ideal point?** Clear
- An inhomogeneous point
- A point at infinity

**2. What is the dimensionality of a 4D point represented in homogeneous coordinates?**

**3. How many degrees of freedom has a 3D line?**

**4. Affine transformations preserve** Clear
- parallel lines
- lengths
- angles

**5. The diameter of a telecentric lens should be** Clear
- about as large as the object/scene
- significantly larger than the object
- significantly smaller than the object

**6. Increasing the depth of a 3D point in perspective projection** Clear
- increases the (x,y) pixel coordinates
- decreases the (x,y) pixel coordinates
- does not affect the (x,y) pixel coordinates

**7. Perspective projection** Clear
- is linear when using homogeneous coordinates
- is linear when using inhomogeneous coordinates

**8. Assume a point light source. Diffuse materials** Clear
- scatter light uniformly in all directions at any given surface point
- scatter more light into the mirror direction than into other directions at any given surface point
- scatter the same amount of light independent of the surface normal

https://uni-tuebingen.de/de/203146

# AVG Lecture Quiz Server: Student Questions

**10. Do you have a question or comment about this lecture which you like to discuss during the live session?**

Slide number: (required field; enter 0 for a general question)

Hint: Question must comprise between 20 and 200 characters. 0/200

**We appreciate your feedback as well:**

- Questions stipulate thinking and provide valuable feedback to us
- Students are encouraged to ask a question regarding the lecture (1 point)
- Questions will be discussed during the interactive session (only ask if you join)
- All students are encouraged to ask questions, hard and easy ones
- Dare to ask: if you have a question, many others will be wondering as well

# Interactive Sessions

**Fridays, 10:15 – 12:00:**

1. Warmup questions (10 min)
2. Discussion of student questions (45 min)
   - Submitted via quiz server
   - Spontaneous
3. Exercise introduction and Q&A (45 min)

   Every 2 weeks, we offer individual Q&As:
   - Friday, 9:15 – 10:00 (Zoom)
   - Friday, 11:15 – 12:00 (MvL6+Zoom)
   - Friday, 12:15 – 13:00 (Zoom)

   Choose one slot, get individual feedback.

   Start solving assignments before joining!

**http://etc.ch/skoR**

# What will the exam look like?

- Written main and make-up exam
- You may choose freely (but no 3rd exam)
- Registration via Lecture Quiz Server
- Only pen and ruler allowed (no notes)
- Duration: 90 minutes (can be solved in 60)
- 5 Tasks, 10 points each, 25 points will pass
- Bonus added only to passed exams
- Tasks cover both lectures and exercises
- Mix of knowledge, calculation, multiple choice
- Old exams now available on ILIAS

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

Faculty of Science
Department of Computer Science

Prof. Dr. Andreas Geiger
Maria-von-Linden-Straße 6
72076 Tübingen

**Computer Vision**
Exam, Summer 2021

Tübingen, August 10, 2021

Student Number:
Seat Number:
First Name:
Last Name:
Date of Birth:
Program of Study (e.g., "Informatik"):
Master ☐ Bachelor ☐

| Task | 1 | 2 | 3 | 4 | 5 | $\sum$ |
|---|---|---|---|---|---|---|
| Maximal Score | 10 | 10 | 10 | 10 | 10 | 50 |
| Attained Score | | | | | | |
| Correction | | | | | | |

**Remarks:**

- Leave your bag and jacket at the front desk. Only take your **pen, ruler, student ID** with you.
- Notes, books, printouts, smartphones or calculators are not permitted.
- Have your student ID ready for inspection.
- Write your full name at the top of **every** page.
- Use the space provided for your answers. You can use the back side if you need more space.
- Additional paper can be obtained at the front desk.
- Use black or blue pen. Pencil or red pens are not allowed and will lead to a score of 0.
- A total score of **25** is sufficient for passing the exam. The duration of the exam is **90 minutes**.

**Good Luck!**

More information: `https://uni-tuebingen.de/de/171060`

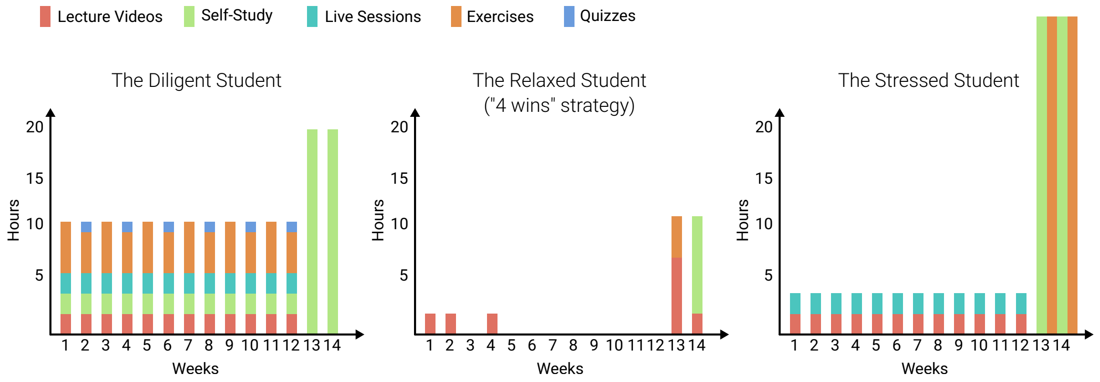
# Bonus Points

- 11 lecture quizzes (10 points per quiz)
- 6 exercise quizzes (10 points per quiz)
- 170 quiz points in total
- Formula: bonus points $= \left\lfloor \frac{\text{quiz points}}{34} \right\rceil$
  - $\geq$ 17 quiz points $\Rightarrow$ 1 bonus point
  - $\geq$ 51 quiz points $\Rightarrow$ 2 bonus points
  - $\geq$ 85 quiz points $\Rightarrow$ 3 bonus points
  - $\geq$ 119 quiz points $\Rightarrow$ 4 bonus points
  - $\geq$ 153 quiz points $\Rightarrow$ 5 bonus points
- 5 bonus points yield up to 2 grade steps
- Bonus added only to passed exams

# Work Ethics

This lecture has 6 ECTS, corresponding to a total workload of ∼180 hours (MHB)

- There are many different study types - we support them all!



# Course Materials and Prerequisites

# 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`
- Inoffical lecture notes written by students in summer 2021
  `https://uni-tuebingen.de/de/203146`

# 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/`

**Frameworks / IDEs:**

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

# Course Materials

**Related 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

**Math:**

- 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)

**Computer Science:**

- Variables, functions, loops, classes, algorithms

**Deep Learning:**

- Geiger: Deep Learning (Lecture)

**Python and PyTorch:**

- `https://docs.python.org/3/tutorial/`
- `https://pytorch.org/tutorials/`

# Prerequisites

**Linear Algebra:**

- Vectors: $\mathbf{x}, \mathbf{y} \in \mathbb{R}^n$
- Matrices: $\mathbf{A}, \mathbf{B} \in \mathbb{R}^{m \times n}$
- Operations: $\mathbf{A}^T$, $\mathbf{A}^{-1}$, $\mathrm{Tr}(\mathbf{A})$, $\det(\mathbf{A})$, $\mathbf{A} + \mathbf{B}$, $\mathbf{AB}$, $\mathbf{Ax}$, $\mathbf{x}^\top \mathbf{y}$
- 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: $x \perp\!\!\!\perp y \mid z \Leftrightarrow p(x,y|z) = p(x|z)p(y|z)$
- Expectation: $\mathbb{E}_{x\sim p}\left[f(x)\right] = \int_x p(x)f(x)dx$
- Variance: $\mathrm{Var}(f(x)) = \mathbb{E}\left[(f(x) - \mathbb{E}[f(x)])^2\right]$
- 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

# Thank You!

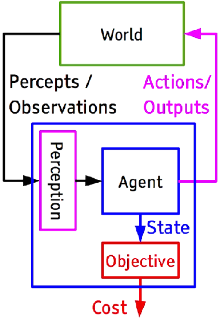
Looking forward to our discussions

# 1.2
# Introduction

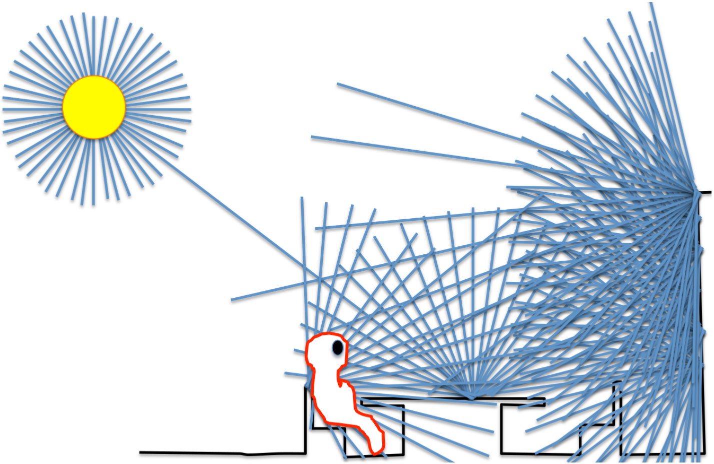
# Artificial Intelligence

"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

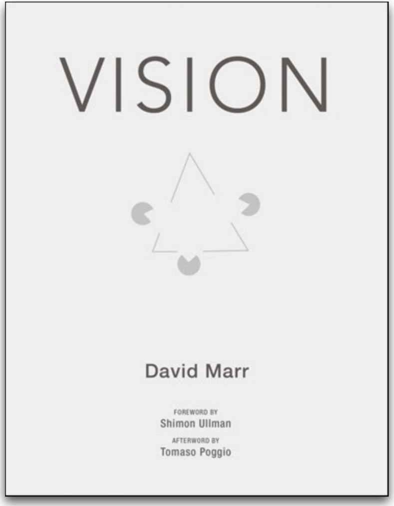


Goal of Computer Vision is to **convert light into meaning** (geometric, semantic, . . . )

Image Credits: Antonio Torralba

# 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.

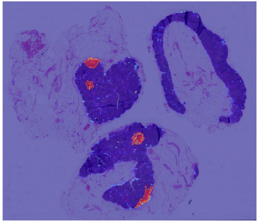



Slide Credit: Torralba, Freeman, Isola

# Computer Vision Applications

Robotics

Medical applications



3D modeling

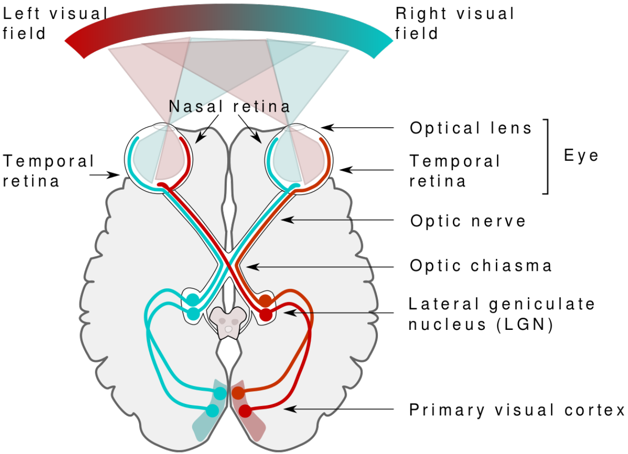
Driving

Mobile devices


Accessibility


Slide Credit: Torralba, Freeman, Isola

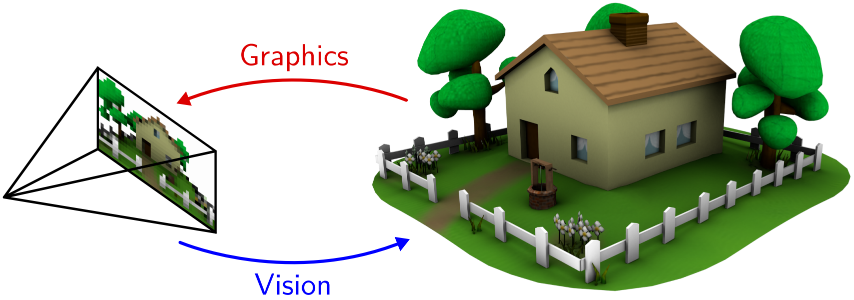
# Computer Vision vs. Biological Vision




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

# Computer Vision vs. Computer Graphics

**2D Image** | **3D Scene**




Pixel Matrix

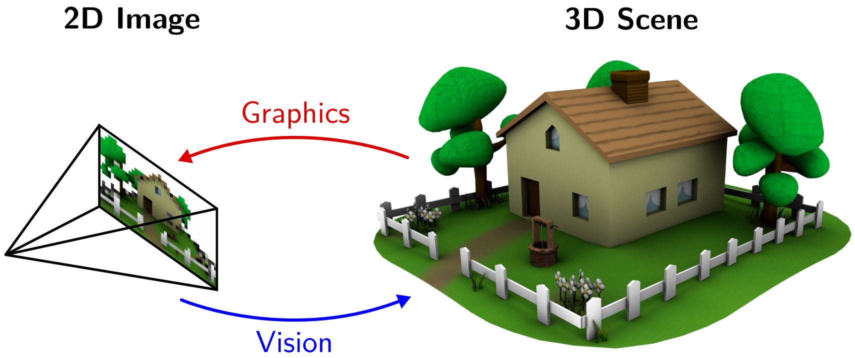
| | | | | |
|---|---|---|---|---|
| 217 | 191 | 252 | 255 | 239 |
| 102 | 80 | 200 | 146 | 138 |
| 159 | 94 | 91 | 121 | 138 |
| 179 | 106 | 136 | 85 | 41 |
| 115 | 129 | 83 | 112 | 67 |
| 94 | 114 | 105 | 111 | 89 |

Objects | Material

Shape/Geometry | Motion

Semantics | 3D Pose

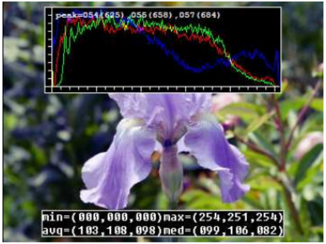
# Computer Vision vs. Computer Graphics

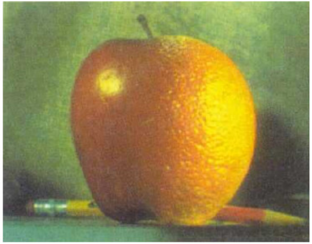


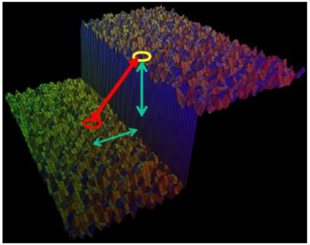

**Computer Vision is an ill-posed inverse problem:**

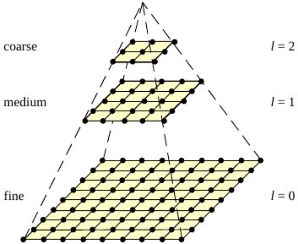
- Many 3D scenes yield the same 2D image
- Additional constraints (knowledge about world) required

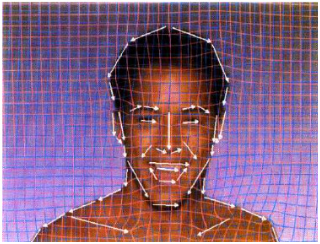
# Computer Vision vs. Image Processing





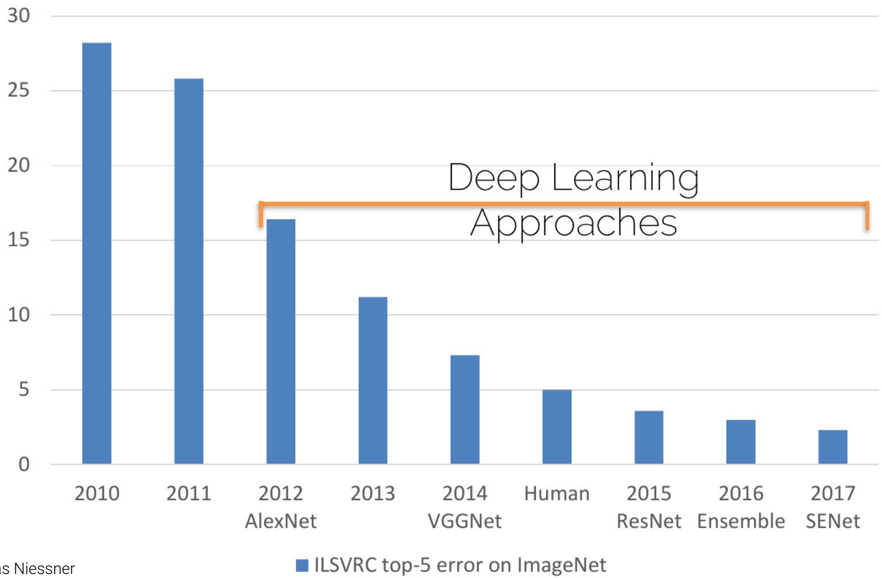


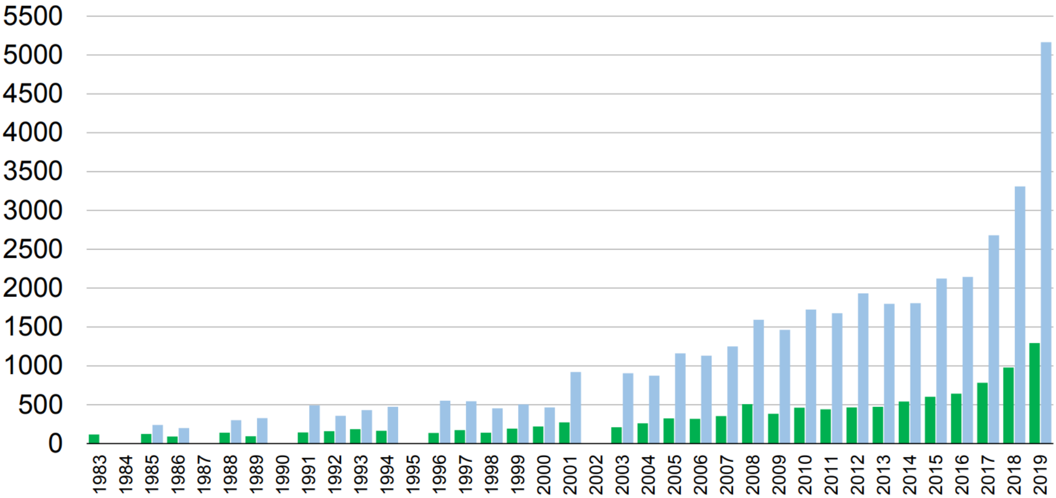
# Computer Vision vs. Machine Learning

Deng, Dong, Socher, Li, Li and Li: ImageNet: A large-scale hierarchical image database. CVPR, 2009.

# The Deep Learning Revolution

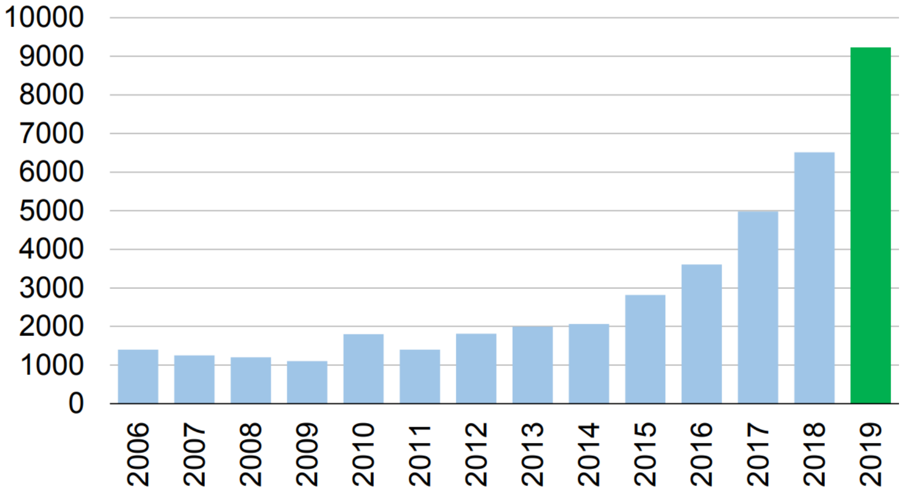


# CVPR Submitted and Accepted Papers




Slide Credit: CVPR 2019 Welcome Slides

# CVPR Attendance

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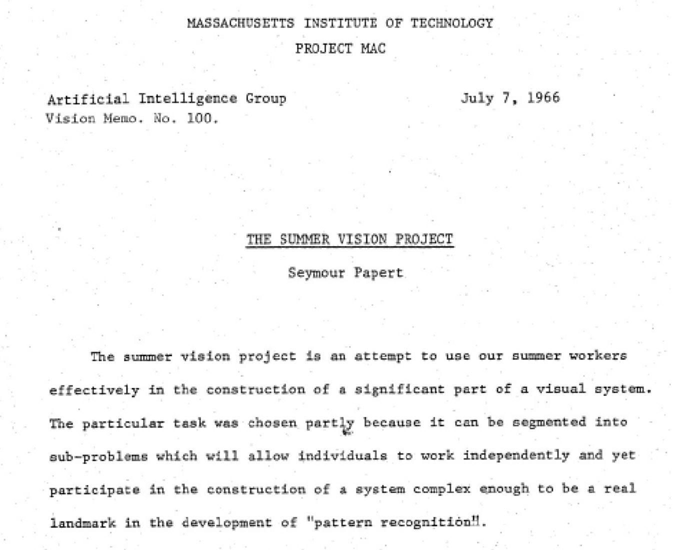
# Why is Visual Perception hard?



MASSACHUSETTS INSTITUTE OF TECHNOLOGY

PROJECT MAC

Artificial Intelligence Group July 7, 1966
Vision Memo. No. 100.

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".

Papert: The Summer Vision Project. MIT AI Memos, 1966.

# Why is Visual Perception hard?

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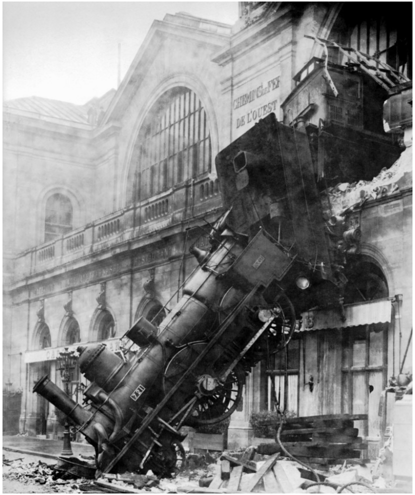


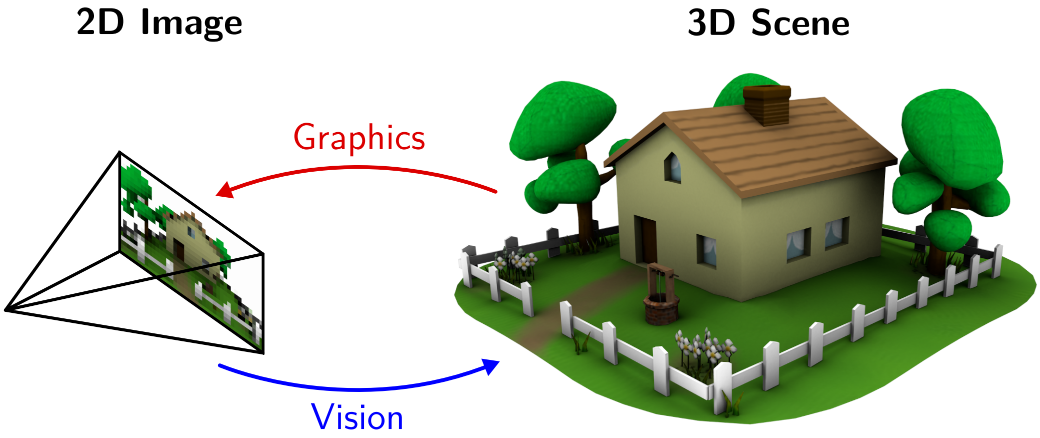

What we see

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 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 | 88 | 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 | 89 | 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 | 183 | 203 | 197 | 153 | 164 | 143 | 180 | 195 | 182 | 165 | 211 |
| 88 | 107 | 127 | 125 | 101 | 107 | 100 | 123 | 149 | 186 | 167 | 215 |

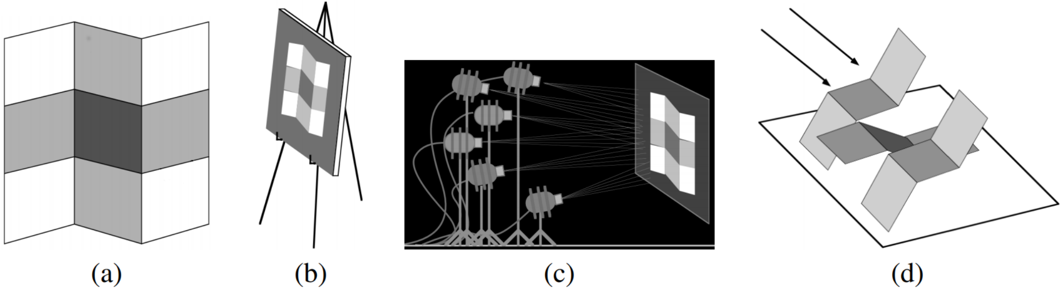
What the computer sees

Slide Credits: Li Fei-Fei

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



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



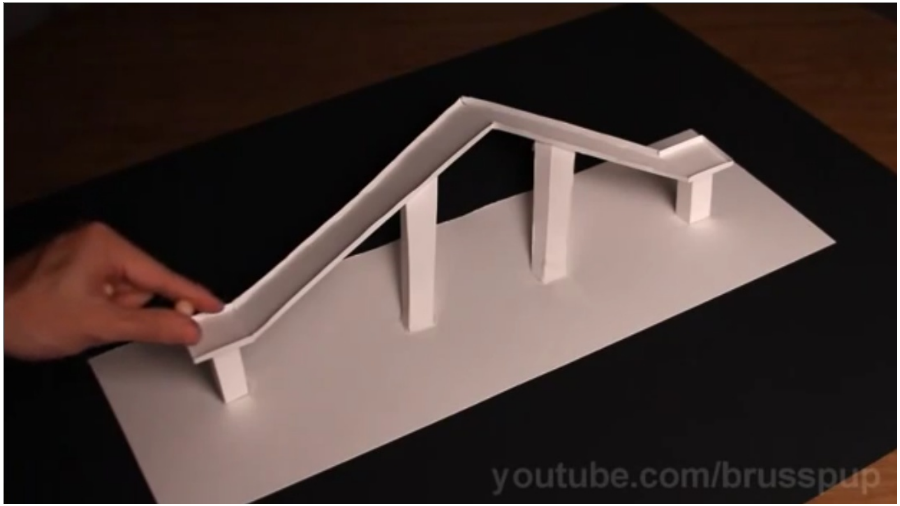
**Adelson and Pentland's workshop metaphor:**

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.

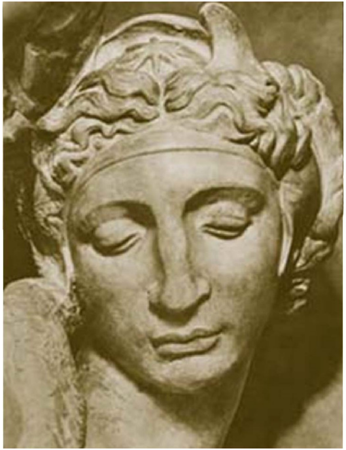
Adelson and Pentland: The perception of shading and reflectance. Perception as Bayesian inference, 1996.

# Ames Room Illusion

# Perspective Illusion

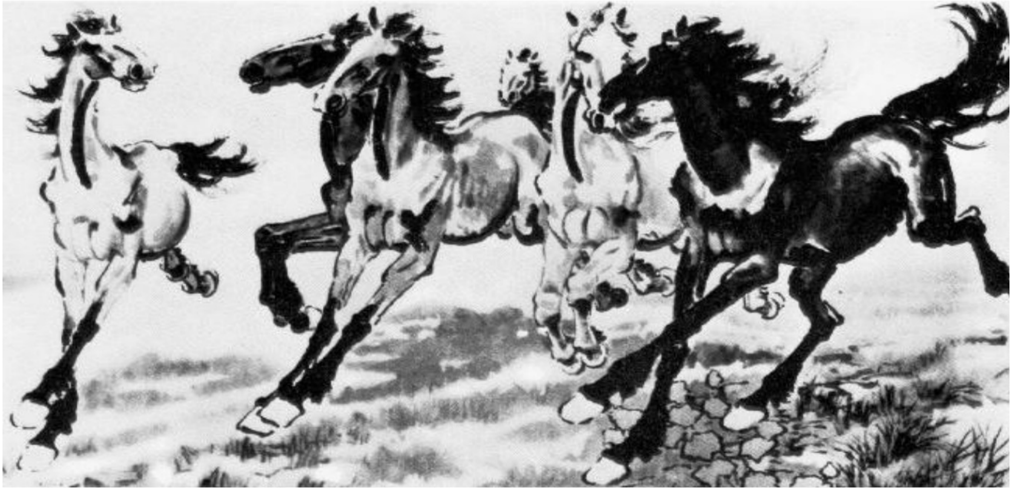


# Challenges: Viewpoint Variation



Michelangelo (1475-1564)

# Challenges: Deformation



Xu Beihong (1943)

# Challenges: Occlusion

René Magritte (1957)

# Challenges: Illumination

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Slide Credits: Antonio Torralba

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# Challenges: Illumination

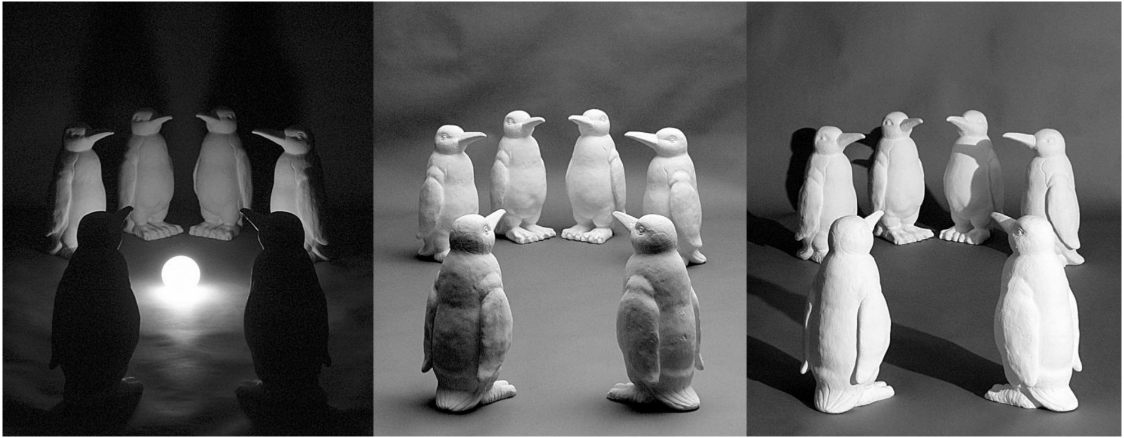
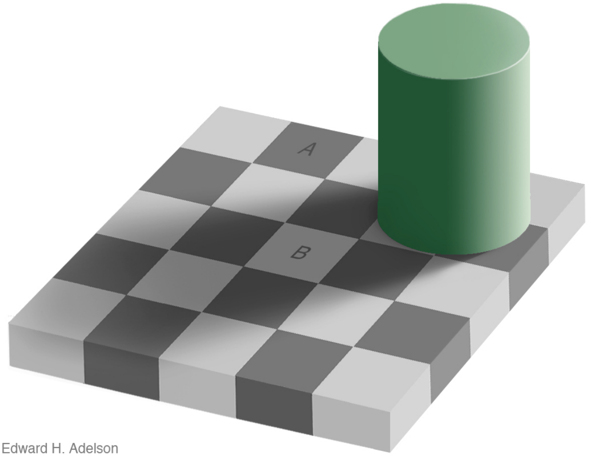


Image Credits: Jan Koenderink

# Challenges: Motion

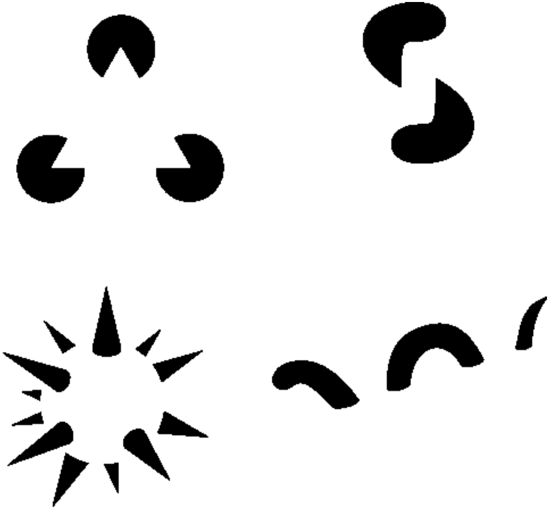
# Challenges: Perception vs. Measurement




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



# Challenges: Perception vs. Measurement



Gaetano Kanizsa (1976)

# Challenges: Perception vs. Measurement

# Challenges: Local Ambiguities

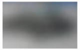


Image Credits: Antonio Torralba

# Challenges: Local Ambiguities

Image Credits: Antonio Torralba

# Challenges: Local Ambiguities

Image Credits: Antonio Torralba

# Challenges: Intra Class Variation

http://www.homeworkshop.com/

Image Credits: Antonio Torralba

# Challenges: Number of Object Categories


Image Credits: Antonio Torralba

# 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."

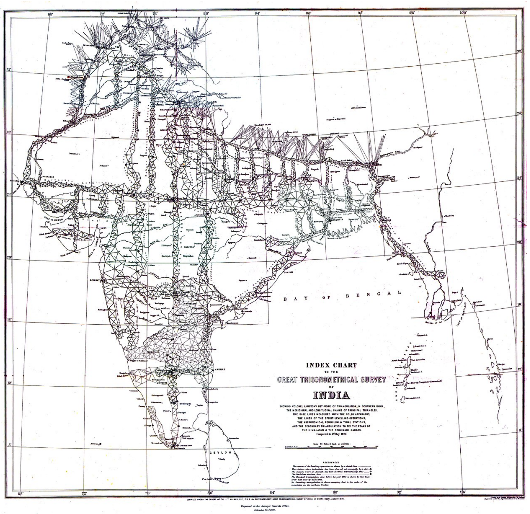
– Leonardo da Vinci

# 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

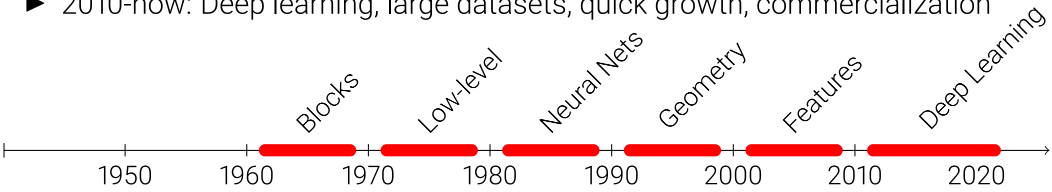
- Multi-decade project to measure the entire Indian subcontinent with scientific precision
- Under the leadership of George Everest, the project was made responsible of the Survey of India
- Manual bundle adjustment proves Mt. Everest highest mountain on earth mountain on earth



# Overview

**Waves of development:**

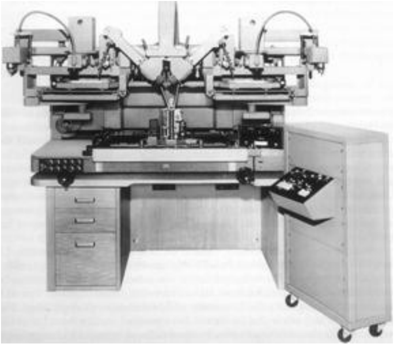
- 1960-1970: Blocks Worlds, Edges and Model Fitting
- 1970-1981: Low-level vision: stereo, flow, shape-from-shading
- 1985-1988: Neural networks, backpropagation, self-driving
- 1990-2000: Dense stereo and multi-view stereo, MRFs
- 2000-2010: Features, descriptors, large-scale structure-from-motion
-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

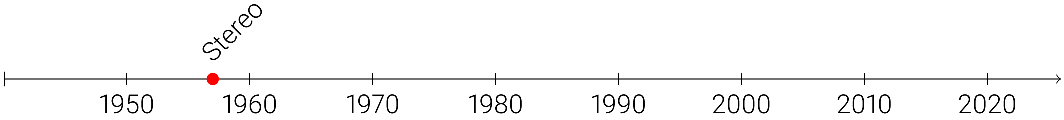


# A Brief History of Computer Vision

**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)






Roberts: Machine perception of 3-d solids. PhD Thesis, 1965.

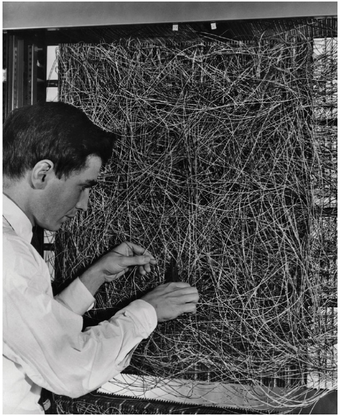
# A Brief History of Computer Vision

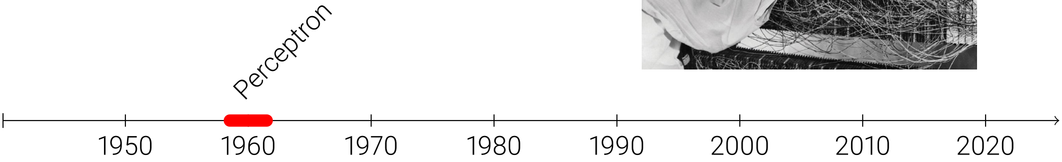
## 1958-1962: Rosenblatt's Perceptron

- 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



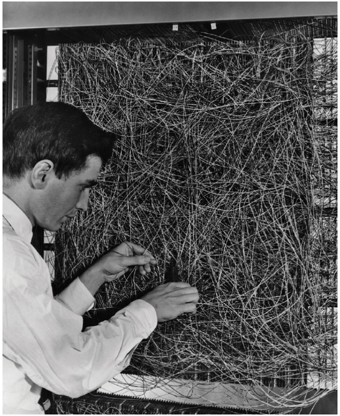


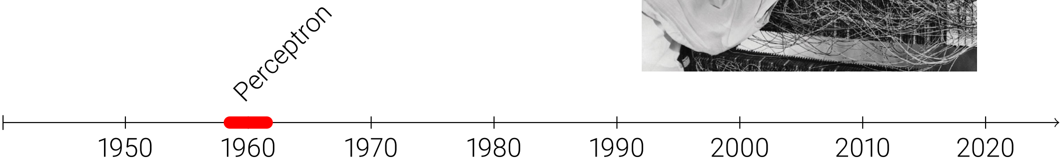

Rosenblatt: The perceptron - a probabilistic model for information storage and organization in the brain. Psychological Review, 1958.

# 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



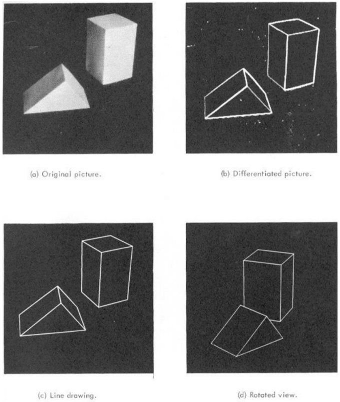


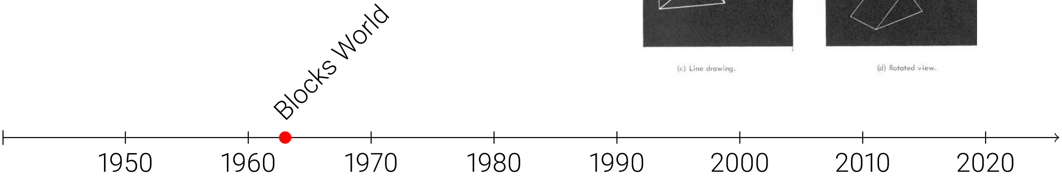

Rosenblatt: The perceptron - a probabilistic model for information storage and organization in the brain. Psychological Review, 1958.

# 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



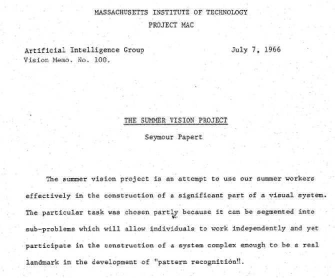




Roberts: Machine Perception of Three-Dimensional Solids. PhD Thesis, 1965.

# A Brief History of Computer Vision

## 1966: MIT Summer Vision Project

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



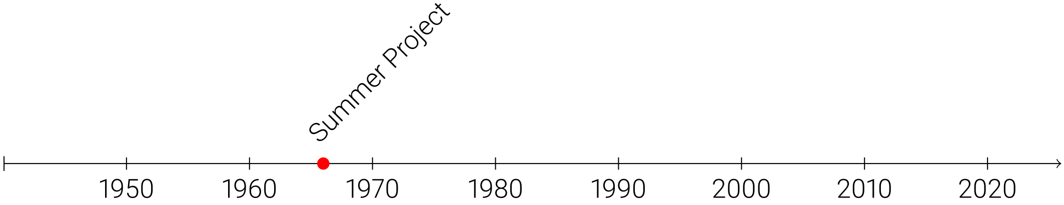
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
PROJECT MAC

Artificial Intelligence Group July 7, 1966
Vision Memo. No. 100.

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".

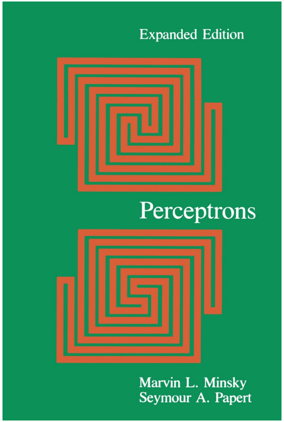


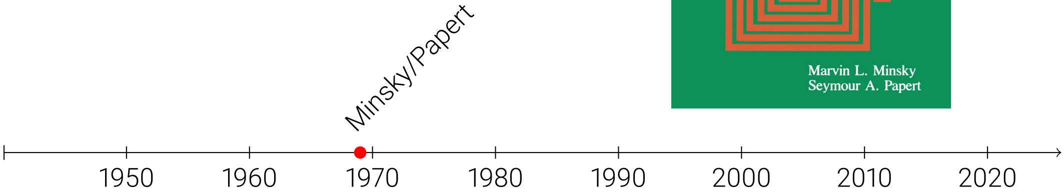

Papert: The Summer Vision Project. MIT AI Memos, 1966.

# 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



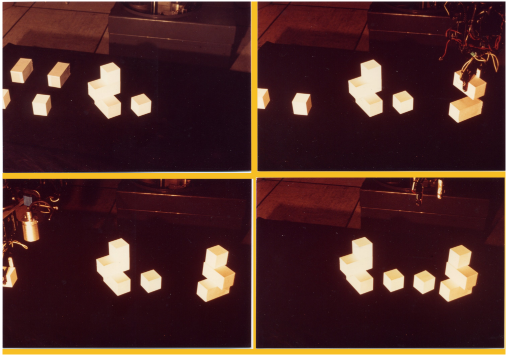



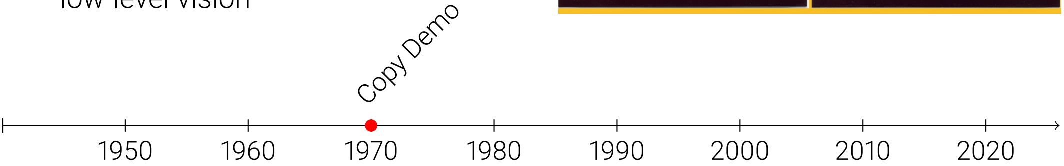

Minsky and Papert: Perceptrons: An introduction to computational geometry. MIT Press, 1969.

# 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






Papert: The Summer Vision Project. MIT AI Memos, 1966.

# A Brief History of Computer Vision

**1970: Shape from Shading**

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

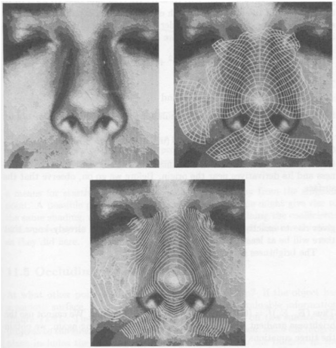
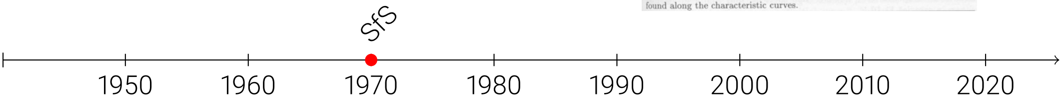


**Figure 11-7.** The shape-from-shading method is applied here to the recovery of the shape of a nose. The first picture shows the (crudely quantized) gray-level image available to the program. The second picture shows the base characteristics superimposed, while the third shows a contour map computed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

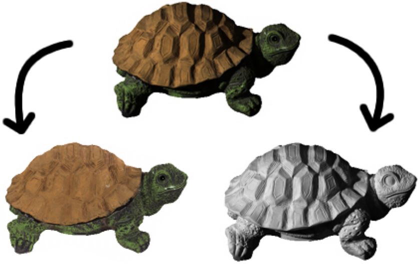


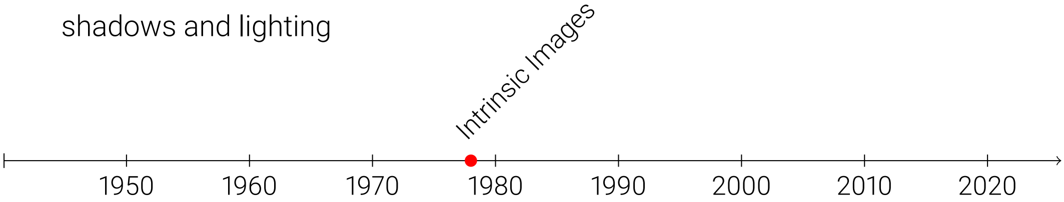

Horn: Shape From Shading: A Method for Obtaining the Shape of a Smooth Opaque Object From One View. MIT TR, 1970.

# 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



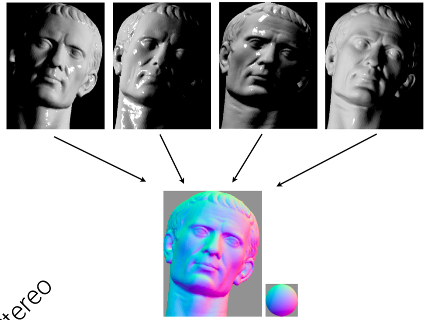


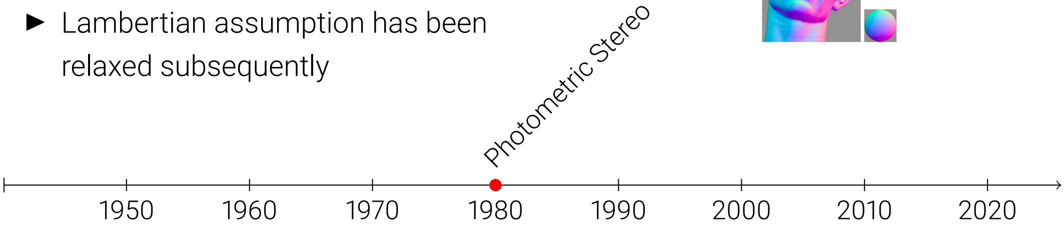

Barrow and Tenenbaum: Recovering intrinsic scene characteristics from images. Computer Vision Systems, 1978.

# A Brief History of Computer Vision

### 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



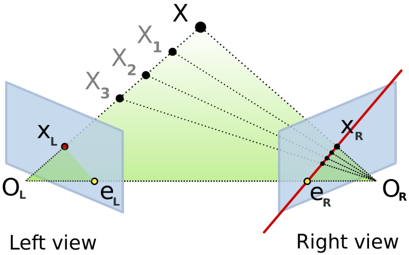


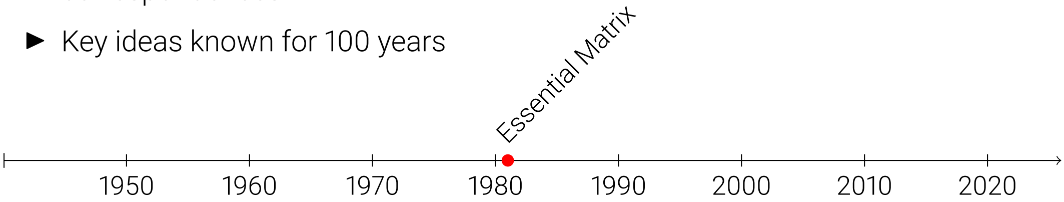

Woodham. Photometric method for determining surface orientation from multiple images. Optical Engineerings, 1980.

# 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



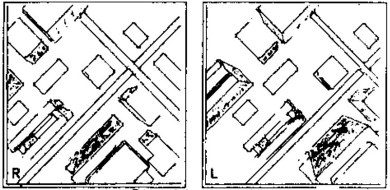




Longuet-Higgins. A computer algorithm for reconstructing a scene from two projections. Nature, 1981.

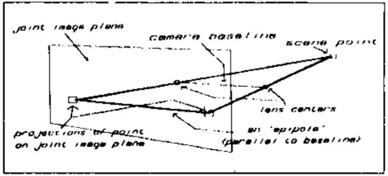
# A Brief History of Computer Vision

## 1981: Binocular Scanline Stereo

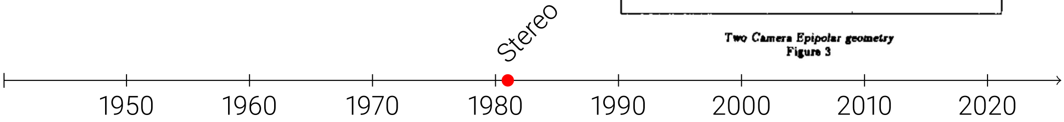
- Correlate points along epipolar lines
- Use dynamic programming to introduce constraints along scanlines (image rows)
- Allows for overcoming abiguities, but streaking artifacts between rows




Edges of the stereo pair
Figure 2




Two Camera Epipolar geometry
Figure 3

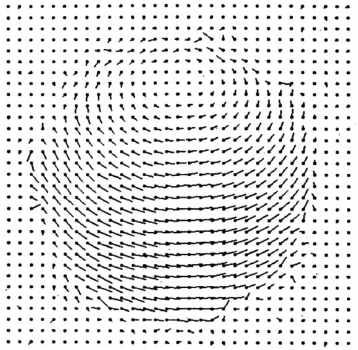


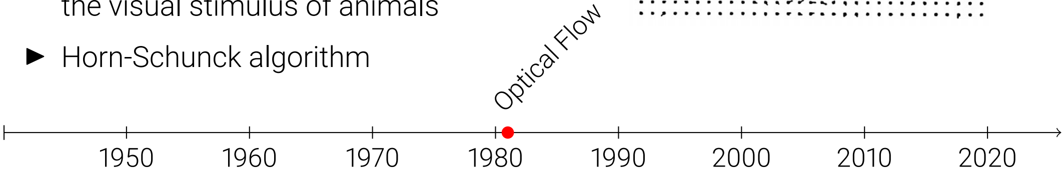

Baker and Binford: Depth from Edge and Intensity Based Stereo. IJCAI, 1981.

# 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



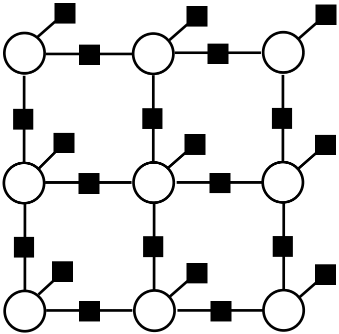


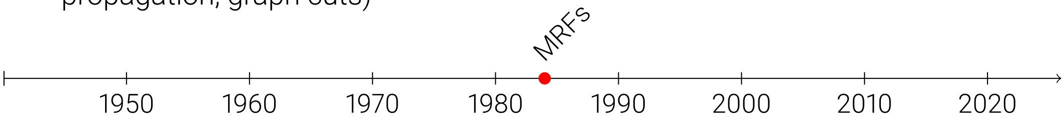

Horn and Schunck: Determining Optical Flow. Artificial Intelligence, 1981.

# A Brief History of Computer Vision

**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)



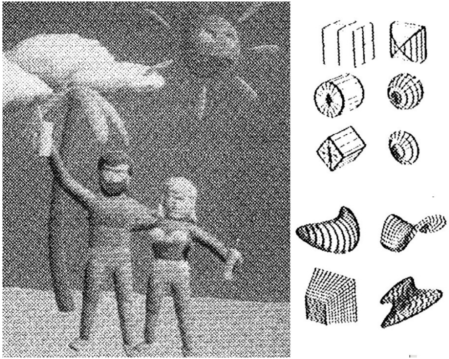


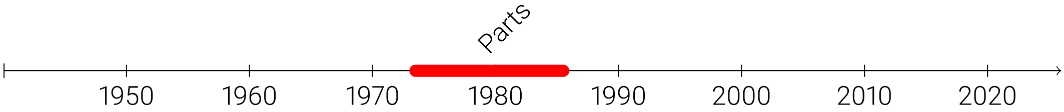

Geman and Geman: Stochastic Relaxation, Gibbs Distributions, and the Bayesian Restoration of Images. TPAMI, 1984.

# A Brief History of Computer Vision

**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



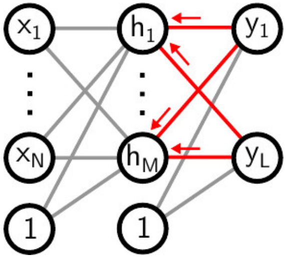


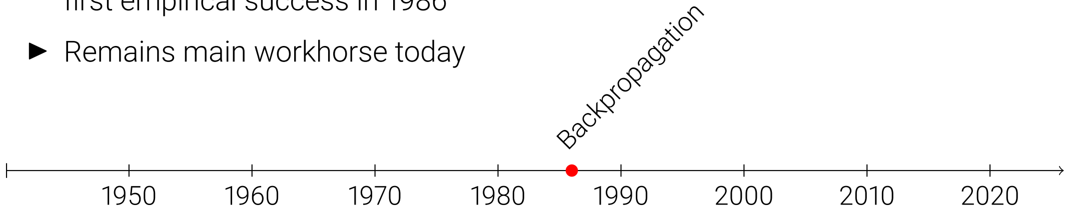

Pentland: Parts: Structured descriptions of shape. AAAI, 1986.

# A Brief History of Computer Vision

**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



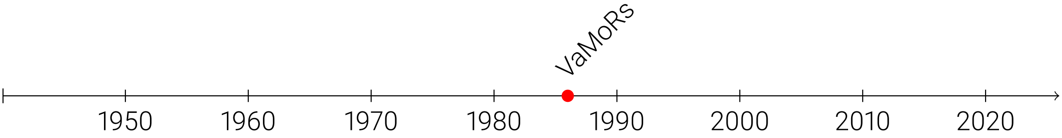




Rumelhart, Hinton and Williams: Learning representations by back-propagating errors. Nature, 1986.

# A Brief History of Computer Vision

**1986: Self-Driving Car VaMoRs**

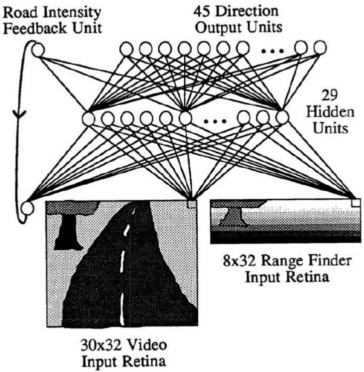
- Developed by Ernst Dickmanns in context of EUREKA-Prometheus
- Demonstration to Daimler-Benz Research 1986 in Stuttgart
- Longitudinal & lateral guidance with lateral acceleration feedback
- Speed: 0 to 36 km/h

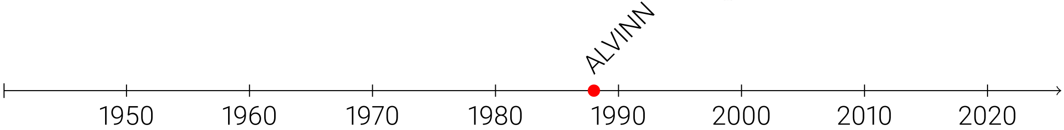


# A Brief History of Computer Vision

**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



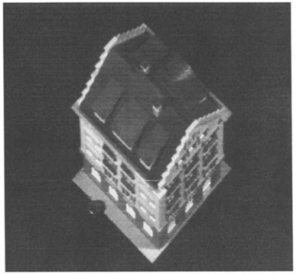



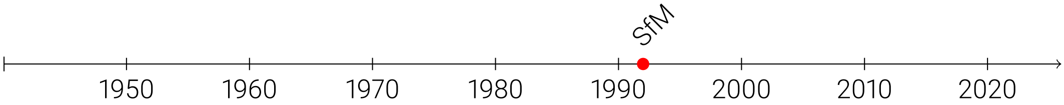

Pomerleau: ALVINN: An Autonomous Land Vehicle in a Neural Network. NIPS, 1988.

# A Brief History of Computer Vision

**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



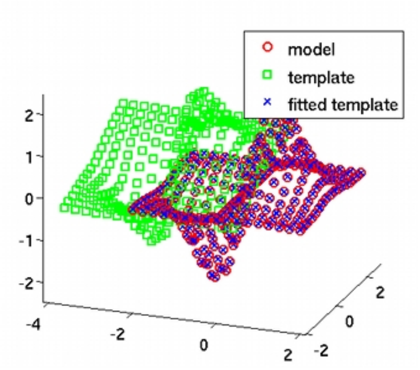


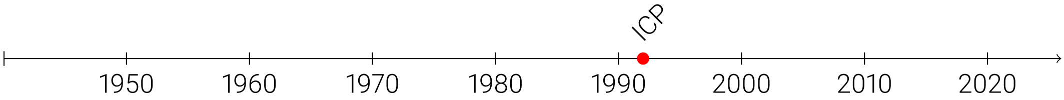

Tomasi and Kanade: Shape and motion from image streams under orthography: a factorization method. IJCV, 1992.

# A Brief History of Computer Vision

## 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




Besl and McKay: A Method for Registration of 3-D Shapes. PAMI, 1992.

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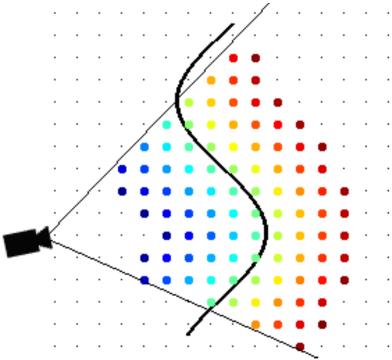
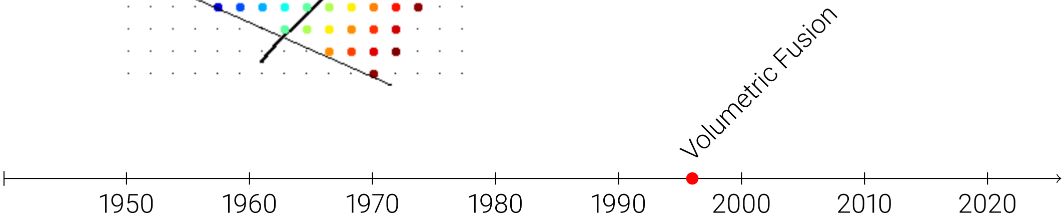


**1996: Volumetric Fusion**

- Aggregation of multiple implicitly represented surfaces by averaging signed distance values
- Mesh-extraction as post-processing




Curless and Levoy: A Volumetric Method for Building Complex Models from Range Images. SIGGRAPH, 1996.

# 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

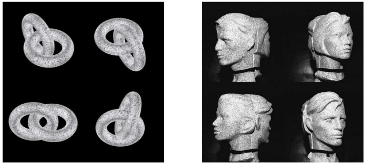


**Fig. 3.** Multicamera images of 3D objets. On the left hand side, two crossing synthetic tori (24 images). On the right hand side, real images: two human heads (18 images).

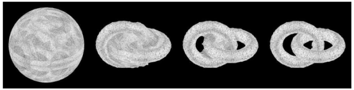
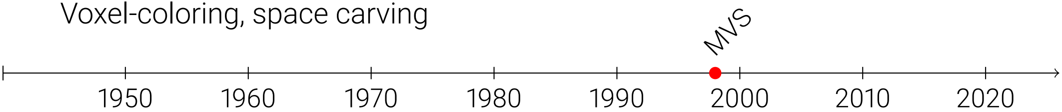


**Fig. 4.** Evolution of the surface for the two tori.

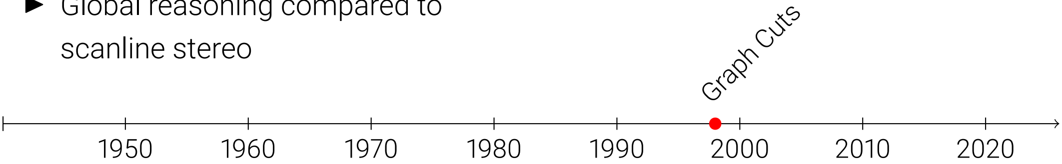



Faugeras and Keriven: Complete Dense Stereovision Using Level Set Methods. ECCV, 1998.

# A Brief History of Computer Vision

**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

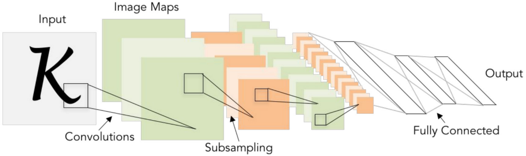


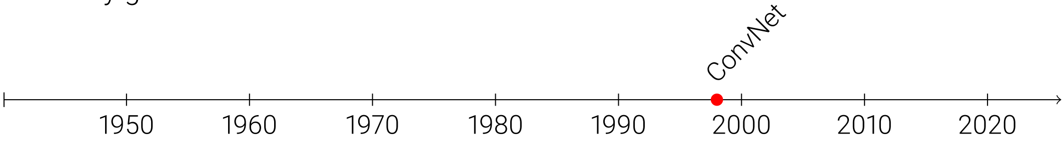

Boykov, Veksler and Zabih: Markov Random Fields with Efficient Approximations. CVPR, 1998.

# A Brief History of Computer Vision

**1998: Convolutional Neural Networks**

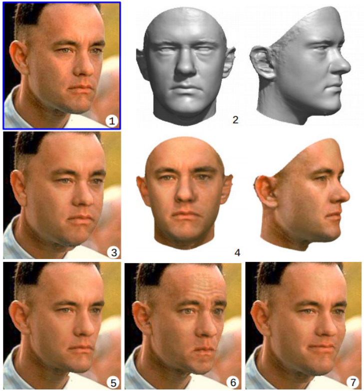
- Similar to Neocognitron, but trained end-to-end using backpropagation
- Implements spatial invariance via convolutions and max-pooling
- Weight sharing reduces parameters
- Tanh/Softmax activations
- Only good results on MNIST so far



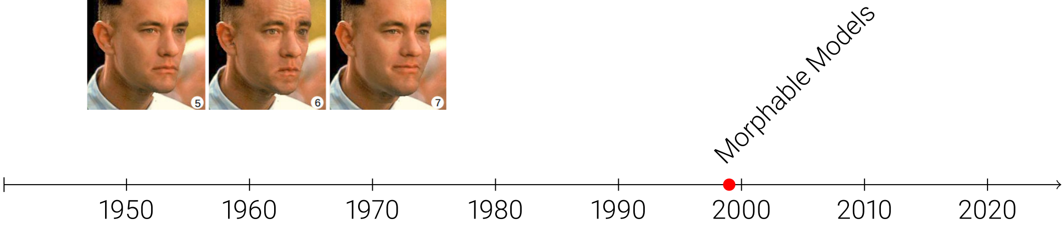

LeCun, Bottou, Bengio and Haffner: Gradient-based learning applied to document recognition. Proceedings of the IEEE, 1998.

# A Brief History of Computer Vision



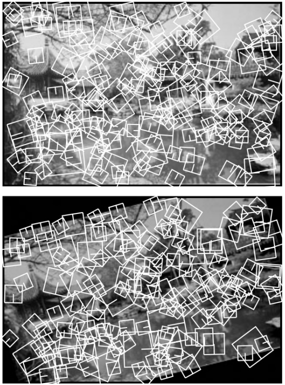

**1999: Morphable Models**

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



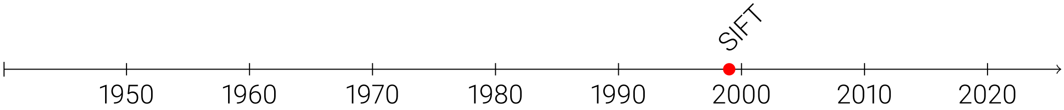

Blanz and Vetter: A Morphable Model for the Synthesis of 3D Faces. SIGGRAPH, 1999.

# A Brief History of Computer Vision



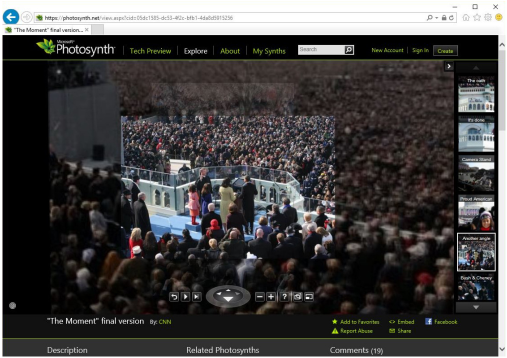
**1999: SIFT**

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



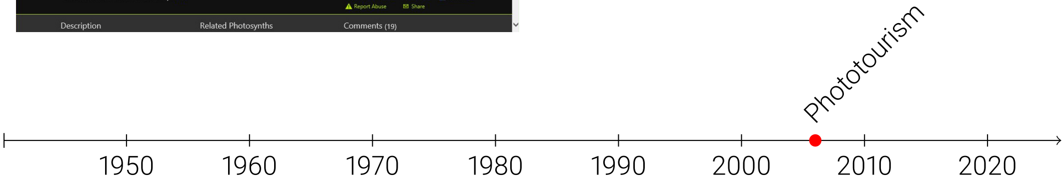

Lowe: Object Recognition from Local Scale-Invariant Features. ICCV, 1999.

# A Brief History of Computer Vision




## 2006: Photo Tourism

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

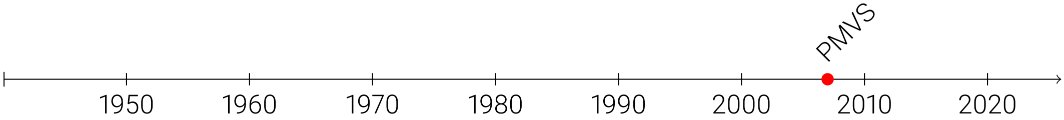



Snavely, Seitz and Szeliski: Photo tourism: exploring photo collections in 3D. SIGGRAPH, 2006.

# A Brief History of Computer Vision

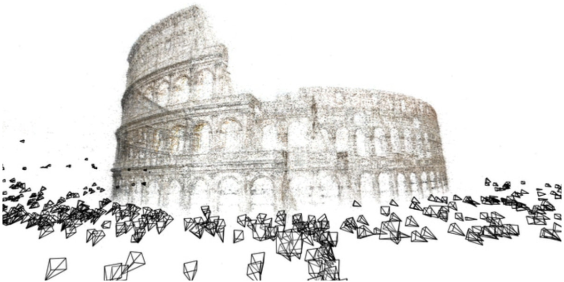
**2007: PMVS**

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



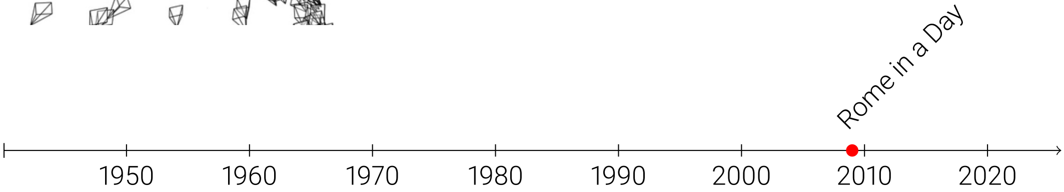

Furukawa and Ponce: Accurate, Dense, and Robust Multi-View Stereopsis. CVPR 2007.

# A Brief History of Computer Vision



**2009: Building Rome in a Day**

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

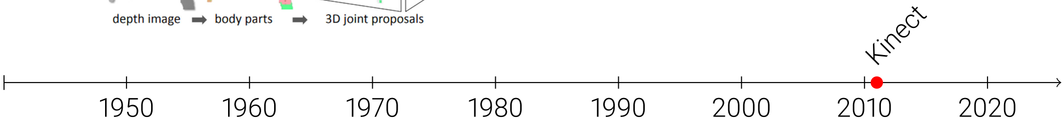



Agarwal, Snavely, Simon, Seitz and Szeliski: Building Rome in a day. ICCV, 2009.

# A Brief History of Computer Vision


**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




Shotton et al.: Real-time human pose recognition in parts from single depth images. CVPR, 2011.

# A Brief History of Computer Vision

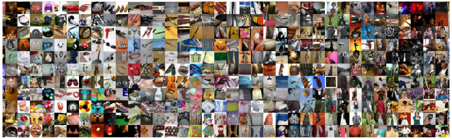
**2009-2012: ImageNet and AlexNet**

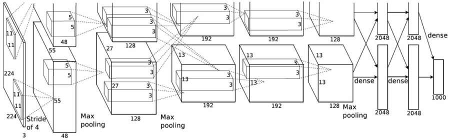
ImageNet

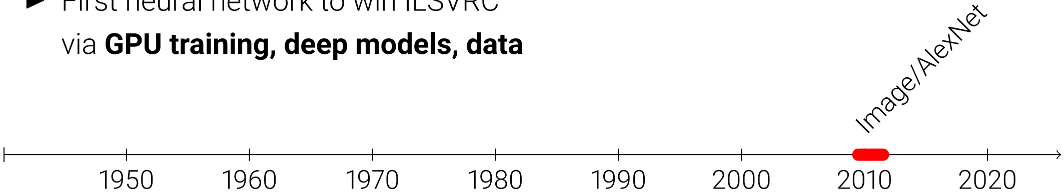
- Recognition benchmark (ILSVRC)
- 10 million annotated images
- 1000 categories

AlexNet

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






Krizhevsky, Sutskever and Hinton: ImageNet classification with deep convolutional neural networks. NIPS, 2012.

# A Brief History of Computer Vision

**2009-2012: ImageNet and AlexNet**

ImageNet

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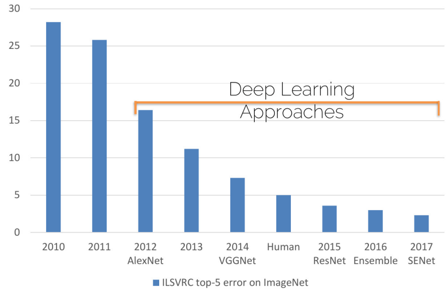
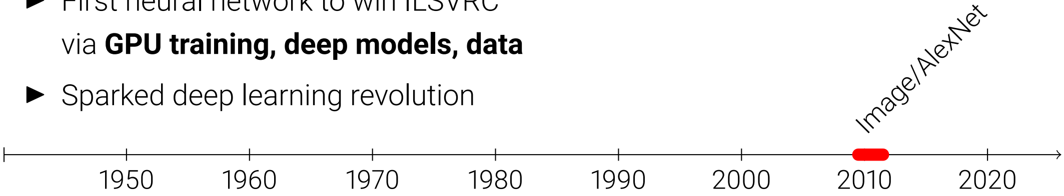
AlexNet

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



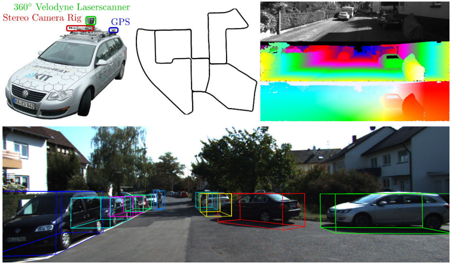



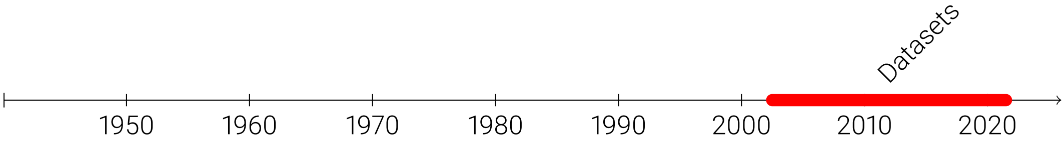

Krizhevsky, Sutskever and Hinton: ImageNet classification with deep convolutional neural networks. NIPS, 2012.

# 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



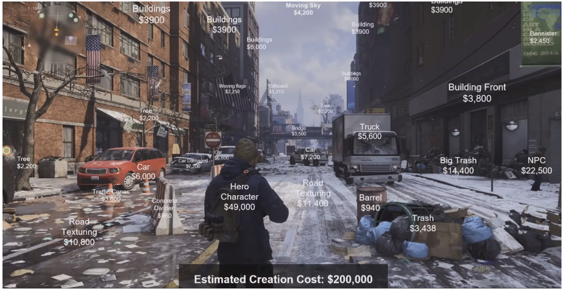



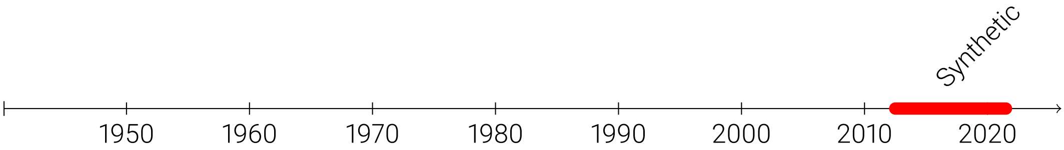

Geiger, Lenz and Urtasun: Are we ready for Autonomous Driving? The KITTI Vision Benchmark Suite. CVPR, 2012.

# A Brief History of Computer Vision

**2012-now: Synthetic Data**

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



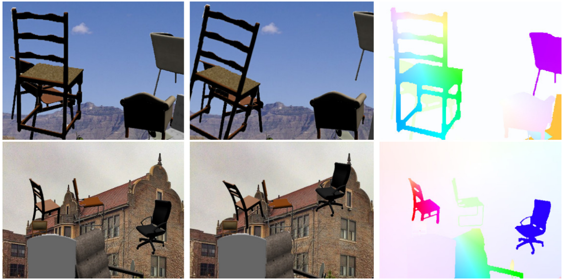



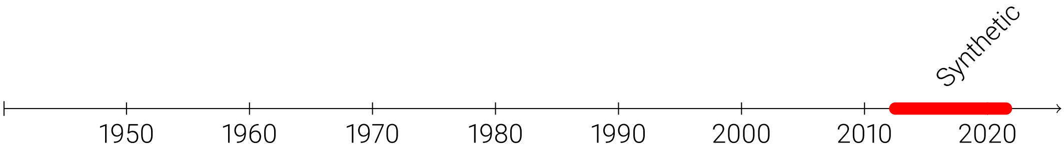

Dosovitskiy et al.: FlowNet: Learning Optical Flow with Convolutional Networks. ICCV, 2015.

# A Brief History of Computer Vision

**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)



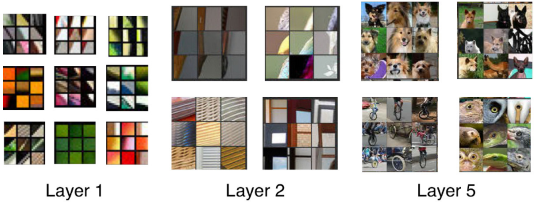


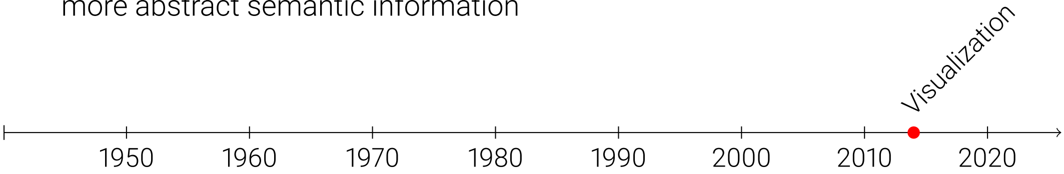

Dosovitskiy et al.: FlowNet: Learning Optical Flow with Convolutional Networks. ICCV, 2015.

# A Brief History of Computer Vision

**2014: Visualization**

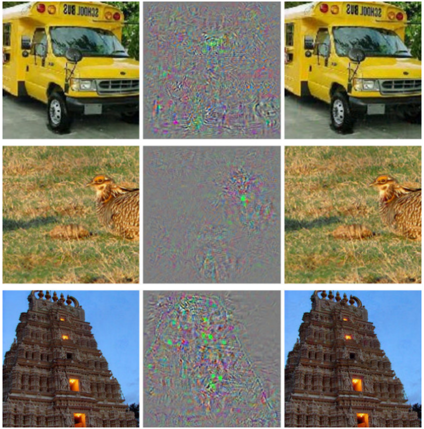
- Goal: provide insights into what the network (black box) has learned
- Visualized image regions that most strongly activate various neurons at different layers of the network
- Found that higher levels capture more abstract semantic information



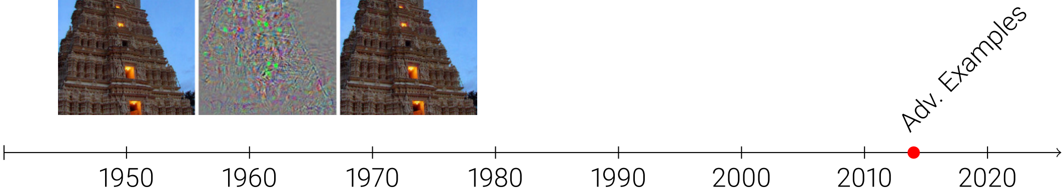

Zeiler and Fergus: CNN Features Off-the-Shelf: An Astounding Baseline for Recognition. CVPR Workshops, 2014.

# A Brief History of Computer Vision



**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”

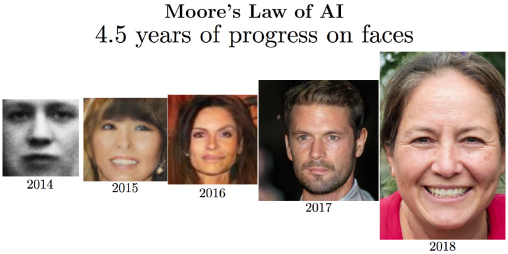


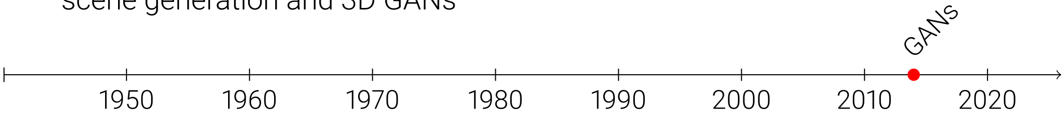

Szegedy et al.: Intriguing properties of neural networks. ICLR, 2014.

# A Brief History of Computer Vision

## 2014: Generative Adversarial Networks

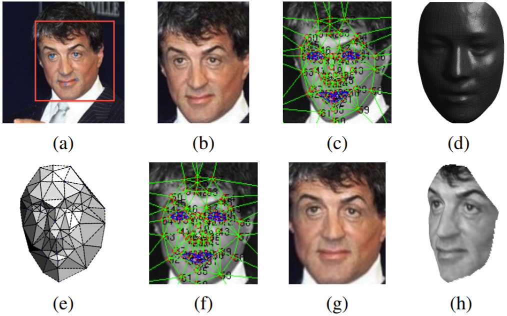
- Deep generative models (VAEs, GANs) produce compelling images
- StyleGAN2 is state-of-the-art
- Results on faces hard to distinguish from real images
- Active research on image translation, domain adaptation, content and scene generation and 3D GANs

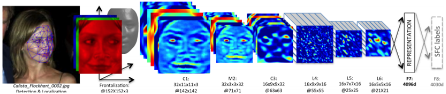



Goodfellow, Pouget-Abadie, Mirza, Xu, Warde-Farley, Ozair, Courville, Bengio: Generative Adversarial Networks. NIPS, 2014.

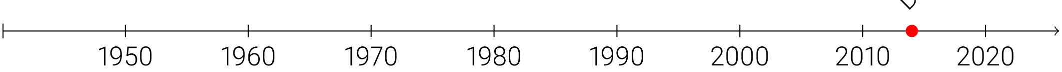
# A Brief History of Computer Vision



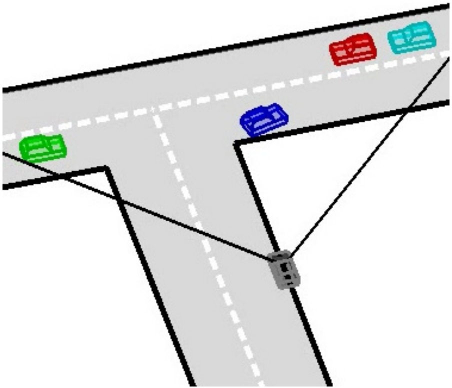

## 2014: DeepFace

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



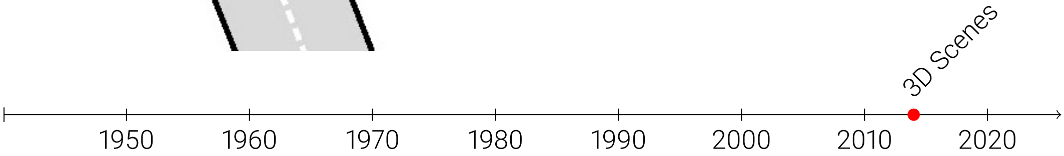

Taigman, Yang, Ranzato and Wolf: DeepFace: Closing the Gap to Human-Level Performance in Face Verification. CVPR, 2014.

# A Brief History of Computer Vision



**2014: 3D Scene Understanding**

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

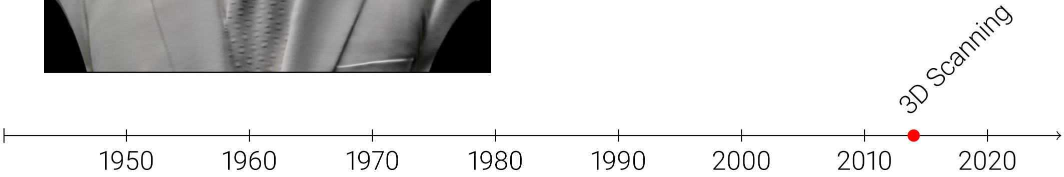



Geiger, Lauer, Wojek, Stiller and Urtasun: 3D Traffic Scene Understanding From Movable Platforms. PAMI, 2014.

# A Brief History of Computer Vision

**2014: 3D Scanning**

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

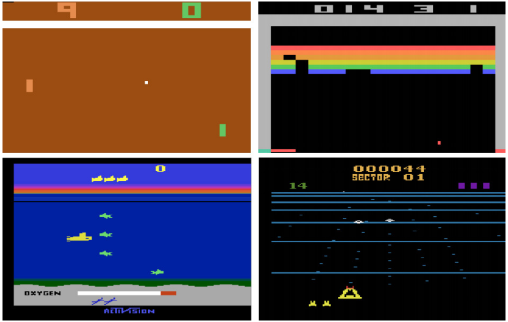


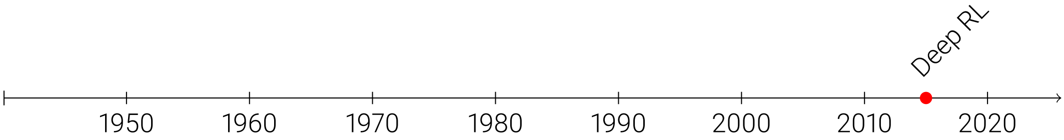

Metallo et al.: Scanning and printing a 3D portrait of president Barack Obama. SIGGRAPH Studio, 2015.

# A Brief History of Computer Vision

## 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



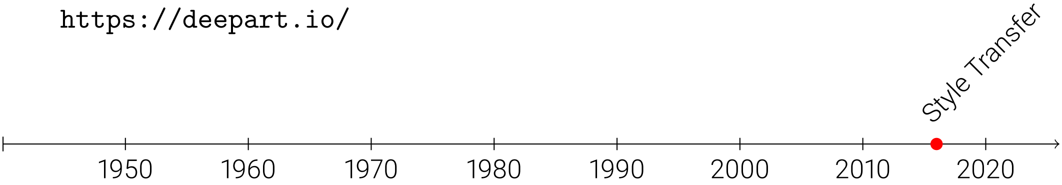




Mnih et al.: Human-level control through deep reinforcement learning. Nature, 2015.

# A Brief History of Computer Vision

**2016: Style Transfer**

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

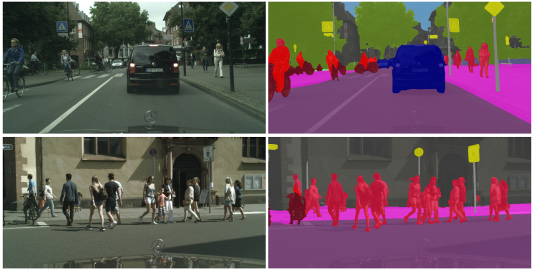


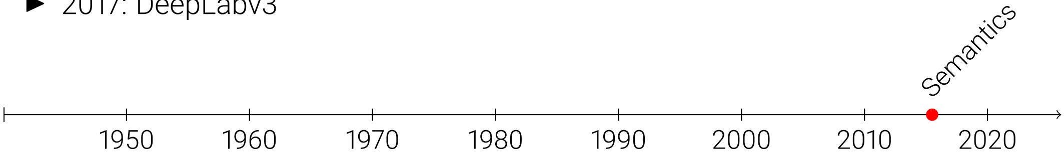

Gatys, Ecker and Bethge: Image Style Transfer Using Convolutional Neural Networks. CVPR, 2016.

# A Brief History of Computer Vision

**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



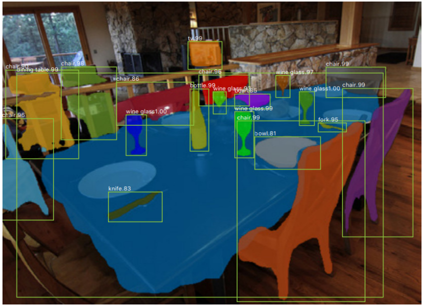


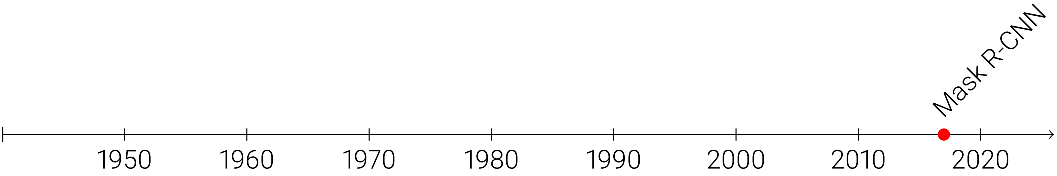

Kundu, Vineet and Koltun: Feature Space Optimization for Semantic Video Segmentation. CVPR, 2016.

# A Brief History of Computer Vision

## 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






He, Gkioxari, Dollár and Ross Girshick: Mask R-CNN. ICCV, 2017.

# A Brief History of Computer Vision

## 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


"little girl is eating piece of cake."


"baseball player is throwing ball in game."


"woman is holding bunch of bananas."

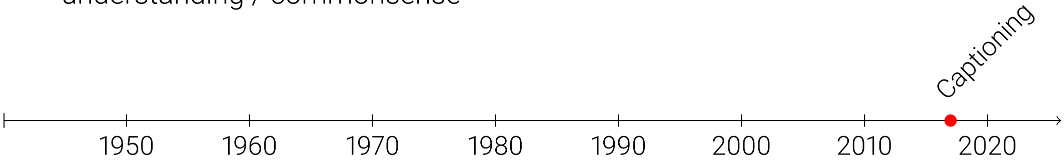

"black cat is sitting on top of suitcase."


"a young boy is holding a baseball bat."


"a cat is sitting on a couch with a remote control."

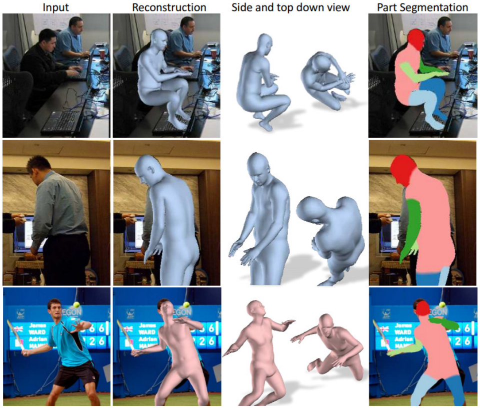

"a woman holding a teddy bear in front of a mirror."


"a horse is standing in the middle of a road."



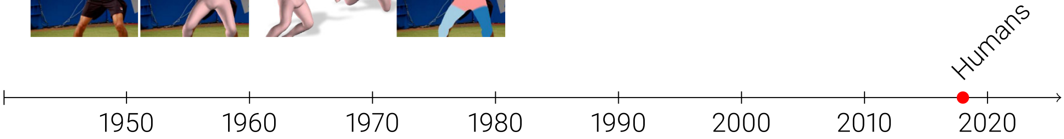

Karpathy and Fei-Fei: Deep Visual-Semantic Alignments for Generating Image Descriptions. PAMI, 2017.

# A Brief History of Computer Vision




**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

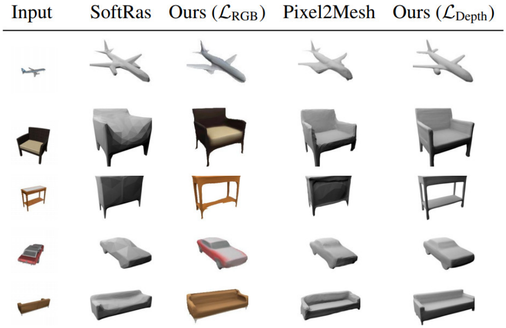


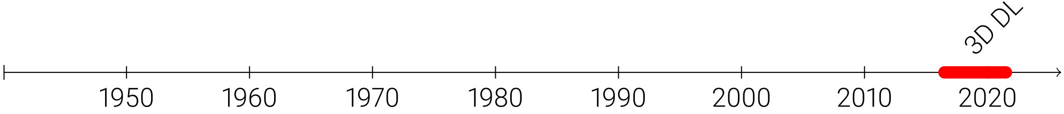

Kanazawa, Black, Jacobs and Malik: End-to-End Recovery of Human Shape and Pose. CVPR, 2018.

# A Brief History of Computer Vision

## 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




Niemeyer, Mescheder, Oechsle, Geiger: Differentiable Volumetric Rendering: Learning Implicit 3D Representations without 3D Supervision. CVPR, 2020.

# A Brief History of Computer Vision

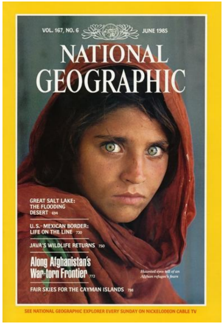
## Applications and Commercial Products

Google Portrait Mode


Skydio 2 Drone


Self-Driving Cars

Microsoft Hololens




Iris Recognition

# A Brief History of Computer Vision

**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