COMP9517

Computer Vision

2023 Term 2 Week 1

Professor Erik Meijering



Image Formation



What is image formation?

Image formation occurs when a **sensor registers radiation** that has **interacted with physical objects**





Geometry of image formation

Mapping world coordinates (3D) to image coordinates (2D)

- Pinhole camera model
- Projective geometry
- Projection matrix



Idea 1: Put a piece of film in front of an object



Do we get a reasonable image?



Idea 1: Put a piece of film in front of an object



Do we get a reasonable image?



Idea 1: Put a piece of film in front of an object



Do we get a reasonable image?



Idea 1: Put a piece of film in front of an object



The resulting image is completely blurred

All object points are projected to all points on the film



Idea 2: Add a barrier to block off most of the rays



Pinhole camera model





Dimensionality reduction machine

3D world

2D image





Projection can be tricky...







Projective geometry





Projective geometry



What is lost? Length and angles are not preserved



Copyright (C) UNSW

COMP9517 23T2W1 Image Formation

Projective geometry



What is preserved?

Straight lines are still straight





Parallel lines in the 3D world intersect in the 2D image at a "vanishing point"









Photo from Criminisi















Projection mathematics

From world coordinates to image coordinates





Projection mathematics

From world coordinates to image coordinates



If x = 2, y = 3, z = 5, and f = 2, what are x' and y'?



Projection mathematics

From world coordinates to image coordinates



If x = 2, y = 3, z = 5, and f = 2, what are x' and y'?





Perspective projection

- Apparent size of object depends on its distance: far objects appear smaller
- By similar triangles:

$$(x', y', z') = (-f\frac{x}{z}, -f\frac{y}{z}, -f)$$

• Ignore third coordinate and mirror:

$$(x', y') = (f\frac{x}{z}, f\frac{y}{z})$$



Affine projection

- Suitable when scene depth is small relative to average distance from camera
- Let magnification $m = f/z_0$ be a positive constant and all points in the scene have approximately constant distance z_0 to the camera
- Leads to weak perspective projection:
 (x', y') = (mx, my)
- Orthographic projection when m = 1: (x', y') = (x, y)



Beyond pinholes: radial distortions

• Modern cameras use lenses instead of pinholes





Barrel distortion

Pincushion distortion

Image from Martin Habbecke





Barrel distortion corrected



Comparing with human vision

- Cameras imitate the frequency response of the human eye so it is good to know something about it
- Computer vision probably would not get as much attention if biological vision (especially human vision) had not proven that it is possible to make important judgements from 2D images



The Eye



Electromagnetic spectrum



https://sites.google.com/site/chempendix/em-spectrum



Normalized responsivity spectra of human cone cells (S, M, L types)



Colour represented by RGB images





Colour spaces: RGB

Default colour space in vision



Drawback: strongly correlated channels







Intuitive colour space



Drawback: confounded channels





Colour spaces: YCbCr

Fast to compute, good for compression, used by TV









Cb (Y=0.5,Cr=0.5)



Cr (Y=0.5,Cb=0.5)



Colour spaces: L*a*b*

"Perceptually uniform" colour space



Any numerical change corresponds to similar perceived change in color: Euclidean distances make sense





Digital image formation



34 UNSW

Digital image formation



1022225811822000<																		
0 2 11 76 136 164 85 11 5 2 2 0	0	2	2	2	5	8	11	8	2	2	0	0	0	0	0	0	0	0
0 2 25 172 181 133 133 164 90 14 5 2 2 0 0 0 0 0 2 5 175 130 104 127 141 164 206 65 31 11 2 2 0 0 0 0 0 2 28 212 124 110 204 164 232 133 155 218 87 14 2 2 0 10	0	0	2	11	76	136	164	85	11	5	2	2	0	0	0	0	0	0
2 5 175 130 104 127 141 164 206 65 31 11 2 2 0 0 0 0 2 28 121 124 110 204 164 232 133 155 218 87 144 2 2 0 0 0 2 73 178 133 121 195 34 31 198 175 204 167 104 14 5 0 0 0 2 45 262 141 113 184 53 59 70 122 133 136 167 199 11 22 0 0 0 2 70 184 102 163 59 70 155 141 184 53 161 175 121 130 163 161 175 161 121 130 155 147 121	0	2	25	172	181	133	133	164	90	14	5	2	2	0	0	0	0	0
2 28 212 124 110 204 164 232 133 155 218 87 14 2 2 0 0 0 2 73 178 133 121 195 34 31 198 175 204 167 104 14 5 0 0 0 2 75 164 113 184 53 59 70 125 138 136 167 99 11 2 0 0 0 2 70 184 102 116 155 161 175 155 141 184 255 138 34 5 2 0 0 0 5 141 121 133 209 155 147 121 130 150 151 151 151 121 130 155 161 121 124 121 133 153 151	2	5	175	130	104	127	141	164	206	65	31	11	2	2	0	0	0	0
2 73 178 133 121 195 34 31 198 175 204 167 104 14 5 0 0 0 2 45 266 141 113 184 53 59 70 192 133 138 167 99 11 2 0 0 0 2 70 184 102 116 155 161 175 155 141 184 255 138 34 5 2 0 0 2 70 184 121 133 209 215 133 206 121 130 153 140 150 164 12 133 161 121 121 130 153 161 133 161 121 121 121 133 153 151 117 121 121 124 133 153 121 121 131 131	2	28	212	124	110	204	164	232	133	155	218	87	14	2	2	0	0	0
2 45 226 141 113 184 53 59 70 192 133 138 167 99 11 2 0 0 0 2 70 184 102 116 155 161 175 155 141 184 255 138 34 5 2 0 0 0 5 141 121 133 209 151 133 206 124 121 130 104 8 2 0 0 0 2 73 164 124 198 252 147 121 124 133 153 153 19 2 0 0 2 73 164 124 125 144 121 133 161 133 161 121 124 124 133 153 15 12 0 0 0 0 5 138	2	73	178	133	121	195	34	31	198	175	204	167	104	14	5	0	0	0
02701841021161551611751551411842551383452 0 00514112113320921513320612412113013310482 0 00273164124121198252147121127130153104182< 0 00273164124121198252147121127121133104150192 0 00273164124121198125117121127121131141150151141151151141151121133153121131 <th< td=""><td>2</td><td>45</td><td>226</td><td>141</td><td>113</td><td>184</td><td>53</td><td>59</td><td>70</td><td>192</td><td>133</td><td>138</td><td>167</td><td>99</td><td>11</td><td>2</td><td>0</td><td>0</td></th<>	2	45	226	141	113	184	53	59	70	192	133	138	167	99	11	2	0	0
00514112113320921513320612412113015310482 0 00273164124121198252147121127119119150192< 0 0059315010211913012710412112413315315326 2 0 00553162102119130127104121124133153153262 2 000562153155119136198155127124137139292< 2 0000562153155119136198155127124137199222 2 000005621531551191361551271241371531531212137131415512712414115823215121200000111113164172184102121164153121212121212121212121212121212121212121	0	2	70	184	102	116	155	161	175	155	141	184	255	138	34	5	2	0
0 2 73 164 124 198 252 147 121 127 119 119 150 19 2 0 0 0 5 93 150 102 119 130 127 141 124 133 153 153 2 1 0 0 5 93 150 125 119 130 127 104 124 133 153 25 2 0 0 0 0 0 5 62 153 155 119 136 195 127 124 131 167 12 141 158 232 5 2 2 0 0 0 0 5 138 161 178 181 124 141 158 232 5 2 2 2 2 2 2 2 2 2 2 2 2 2 <td< td=""><td>0</td><td>0</td><td>5</td><td>141</td><td>121</td><td>133</td><td>209</td><td>215</td><td>133</td><td>206</td><td>124</td><td>121</td><td>130</td><td>153</td><td>104</td><td>8</td><td>2</td><td>0</td></td<>	0	0	5	141	121	133	209	215	133	206	124	121	130	153	104	8	2	0
0 0 0 5 93 150 102 119 130 127 104 121 124 133 153 25 2 12 0 0 0 0 5 55 153 155 119 136 195 127 124 121 124 187 19 2 2 0 0 0 0 5 5 138 161 176 126 127 124 187 19 2 2 0 0 0 0 5 138 161 178 155 127 124 141 187 19 2 2 0 0 0 0 10 13 164 172 184 102 121 144 153 12 12 12 14 143 15 12 12 12 12 12 12 12 12 12 12 12 12 12 12 12 12 12 12 12 1	0	0	2	73	164	124	121	198	252	147	121	127	119	119	150	19	2	0
0 0 0 5 62 153 155 19 186 195 127 124 187 19 2 2 0 0 0 0 0 0 5 138 161 178 155 124 141 158 232 5 2 2 0 0 0 0 0 10 11 113 164 172 184 102 121 164 79 2 2 2 2 0 0 0 0 10 11 113 164 172 184 102 121 164 79 2 2 2 2 0 0 0 0 10 11 113 164 172 184 102 121 164 79 2 2 2 12 14 155 12 12 12 12 12 12 12 12 12 12 12 12 12 12 12 12 12 <t< td=""><td>0</td><td>0</td><td>0</td><td>5</td><td>93</td><td>150</td><td>102</td><td>119</td><td>130</td><td>127</td><td>104</td><td>121</td><td>124</td><td>133</td><td>153</td><td>25</td><td>2</td><td>0</td></t<>	0	0	0	5	93	150	102	119	130	127	104	121	124	133	153	25	2	0
0 0 0 0 5 138 161 178 127 124 141 158 232 5 2 2 0 0 0 0 0 10 11 113 164 172 184 102 121 164 79 2 2 2 0 0 0 0 0 10 12 164 172 184 102 121 164 79 2 2 2 0 0 0 0 0 2 2 36 266 187 147 164 153 5 2 2 2 30 0 0 0 0 2 2 36 36 147 147 164 153 5 2 2 30	0	0	0	0	5	62	153	155	119	136	198	155	127	124	187	19	2	2
0 0 0 0 11 113 164 172 184 102 121 164 79 2 2 2 0 0 0 0 0 2 5 36 206 187 147 164 153 5 2 2 0 0 0 0 0 0 2 5 36 206 187 147 164 153 5 2 2 0 0 0 0 0 0 0 0 2 5 56 25 76 31 2 2 0	0	0	0	0	0	5	138	161	178	155	127	124	141	158	232	5	2	2
0 0 0 0 2 5 36 206 187 147 164 153 5 2 2 0 0 0 0 0 0 2 5 36 206 187 147 164 153 5 2 2 0 0 0 0 0 0 0 2 5 25 76 31 2 2 2 0 0 0	0	0	0	0	0	0	11	113	164	172	184	102	121	164	79	2	2	2
0 0 0 0 0 0 2 5 25 76 31 2 2 2 0 0 0 <td>0</td> <td>0</td> <td>0</td> <td>0</td> <td>0</td> <td>0</td> <td>2</td> <td>5</td> <td>36</td> <td>206</td> <td>187</td> <td>147</td> <td>164</td> <td>153</td> <td>5</td> <td>2</td> <td>2</td> <td>0</td>	0	0	0	0	0	0	2	5	36	206	187	147	164	153	5	2	2	0
0 0	0	0	0	0	0	0	0	0	2	5	25	76	31	2	2	2	0	0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0



Displaying a digital image

0	2	2	2	5	8	11	8	2	2	0	0	0	0	0	0	0	0
0	0	2	11	76	136	164	85	11	5	2	2	0	0	0	0	0	0
0	2	25	172	181	133	133	164	90	14	5	2	2	0	0	0	0	0
2	5	175	130	104	127	141	164	206	65	31	11	2	2	0	0	0	0
2	28	212	124	110	204	164	232	133	155	218	87	14	2	2	0	0	0
2	73	178	133	121	195	34	31	198	175	204	167	104	14	5	0	0	0
2	45	226	141	113	184	53	59	70	192	133	138	167	99	11	2	0	0
0	2	70	184	102	116	155	161	175	155	141	184	255	138	34	5	2	0
0	0	5	141	121	133	209	215	133	206	124	121	130	153	104	8	2	0
0	0	2	73	164	124	121	198	252	147	121	127	119	119	150	19	2	0
0	0	0	5	93	150	102	119	130	127	104	121	124	133	153	25	2	0
0	0	0	0	5	62	153	155	119	136	198	155	127	124	187	19	2	2
0	0	0	0	0	5	138	161	178	155	127	124	141	158	232	5	2	2
0	0	0	0	0	0	11	113	164	172	184	102	121	164	79	2	2	2
0	0	0	0	0	0	2	5	36	206	187	147	164	153	5	2	2	0
0	0	0	0	0	0	0	0	2	5	25	76	31	2	2	2	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0





Comparing the original and digital image







Digitisation by spatial sampling

- Digitisation converts an analog image to a digital image by sampling the image space
- Sampling discretises the coordinates x and y
 - Spatial discretisation of a picture function f(x, y)
 - Typically a rectangular grid of sampling points is used

 $x = j\Delta x$, $y = k\Delta y$ for $j = 0 \dots M - 1$, $k = 0 \dots N - 1$

- The Δx and Δy are called the sampling intervals





Digital colour images

Each channel is a digital image with the same number of rows and columns

	column																							
row	0.92	0.93	0.94	0.97	0.62	0.37	0.85	0.97	0.93	0.92	0.99	R												
- 1	0.95	0.89	0.82	0.89	0.56	0.31	0.75	0.92	0.81	0.95	0.91													
	0.89	0.72	0.51	0.55	0.51	0.42	0.57	0.41	0.49	0.91	0.92													
	0.96	0.95	0.88	0.94	0.56	0.46	0.91	0.87	0.90	0.97	0.95							\sim						
	0.71	0.81	0.81	0.87	0.57	0.37	0.80	0.88	0.89	0.79	0.85	0.37	0.85	0.97	0.93	0.92	0.99	G						
	0.49	0.62	0.60	0.58	0.50	0.60	0.58	0.50	0.61	0.45	0.33	0.31	0.75	0.92	0.81	0.95	0.91							
	0.86	0.84	0.74	0.58	0.51	0.39	0.73	0.92	0.91	0.49	0.74	0.42	0.57	0.41	0.49	0.91	0.92							
	0.96	0.67	0.54	0.85	0.48	0.37	0.88	0.90	0.94	0.82	0.93	0.46	0.91	0.87	0.90	0.97	0.95							
	0.69	0.49	0.56	0.66	0.43	0.42	0.77	0.73	0.71	0.90	0.99	0.37	0.80	0.88	0.89	0.79	0.85	0.37	0.85	0.97	0.93	0.92	0.99	В
	0.79	0.73	0.90	0.67	0.33	0.61	0.69	0.79	0.73	0.93	0.97	0.60	0.58	0.50	0.61	0.45	0.33	0.31	0.75	0.92	0.81	0.95	0.91	
•	0.91	0.94	0.89	0.49	0.41	0.78	0.78	0.77	0.89	0.99	0.93	0.39	0.73	0.92	0.91	0.49	0.74	0.42	0.57	0.41	0.49	0.91	0.92	
							0.96	0.67	0.54	0.85	0.48	0.37	0.88	0.90	0.94	0.82	0.93	0.46	0.91	0.87	0.90	0.97	0.95	
							0.69	0.49	0.56	0.66	0.43	0.42	0.77	0.73	0.71	0.90	0.99	0.37	0.80	0.88	0.89	0.79	0.85	
	0.79 0.73 0.90 0.67 0.33 0.61												0.69	0.79	0.73	0.93	0.97	0.60	0.58	0.50	0.61	0.45	0.33	
	0.91 0.94 0.89 0.49 0.41 0.78												0.78	0.77	0.89	0.99	0.93	0.39	0.73	0.92	0.91	0.49	0.74	
													0.96	0.67	0.54	0.85	0.48	0.37	0.88	0.90	0.94	0.82	0.93	
													0.69	0.49	0.56	0.66	0.43	0.42	0.77	0.73	0.71	0.90	0.99	
														0.73	0.90	0.67	0.33	0.61	0.69	0.79	0.73	0.93	0.97	
													0.91	0.94	0.89	0.49	0.41	0.78	0.78	0.77	0.89	0.99	0.93	



Spatial resolution

- Spatial resolution: number of pixels per unit of length
- Example: resolution decreases by one half each time (see right)
- Human faces can be recognized at 64 x 64 pixels per face
- Appropriate resolution is essential:
 - Too little resolution yields poor recognition
 - Too much resolution is slow and wastes memory

1/2

1/8



1/4

1/16

1/1

Quantisation

- Quantisation digitises the image intensity or amplitude values f(x, y)
 - Called intensity or gray-level quantisation
 - Gray-level resolution to be chosen per application
 - ✤ For example, 16, 32, 64,, 128, 256 levels
 - Should be high enough for human perception of shading details
 - The latter requires about 100 levels for a realistic image
 - Should not be higher than necessary to avoid wasting storage



Quantisation and bits per pixel

*****		•••	••••••	••••••	••••••	·····	•••••																
									••••••	••••••	••••••	••••••	••••••	••••••	••••••								
1 2 4	0	2	2	2	5	8	11	8	2	2	0	0	0	0	0	0	0	0	→ Pixel (<u>pict</u> ure <u>el</u> ement)				
Sec. 1	0	0	2	11	76	136	164	85	11	5	2	2	0	0	0	0	0	0					
	0	2	25	172	181	133	133	164	90	14	5	2	2	0	0	0	0	0					
* * *	2	5	175	130	104	127	141	164	206	65	31	11	2	2	0	0	0	0					
	2	28	212	124	110	204	164	232	133	155	218	87	14	2	2	0	0	0	Levels per pixel:				
	2	73	178	133	121	195	34	31	198	175	204	167	104	14	5	0	0	0	8 hits = $2^8 = 256$				
	2	45	ZZ6 70	141	113	184	53	59	10	192	133	138	167	99 120	11	2	0	0	0 bits = 2 = 200				
*	0	2	70 5	104	102	110	209	215	175	206	141	104	200	150	34 104	5 8	2	0	12 bits = 2^{12} = 4.096				
	0	0	2	73	164	133	121	198	252	147	124	127	119	119	150	19	2	0					
	0	0	0	5	93	150	102	119	130	127	104	121	124	133	153	25	2	0	16 bits = 2 ¹⁶ = 65,536				
	0	0	0	0	5	62	153	155	119	136	198	155	127	124	187	19	2	2	0.4 bit = 0.024 c = 0.777 c = 0.0000000000000000000000000000000000				
	0	0	0	0	0	5	138	161	178	155	127	124	141	158	232	5	2	2	24 DItS = 2^{21} = 16,777,216				
* * * * * * * * * * * * * * * * * * *	0	0	0	0	0	0	11	113	164	172	184	102	121	164	79	2	2	2					
	0	0	0	0	0	0	2	5	36	206	187	147	164	153	5	2	2	0					
	0	0	0	0	0	0	0	0	2	5	25	76	31	2	2	2	0	0					
* * *	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0					
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					



Further reading on discussed topics

- Chapter 2 of Szeliski
- Chapter 2 of Shapiro and Stockman



Acknowledgements

- Several slides from Derek Hoiem, Alexei Efros, Steve Seitz, and David Forsyth
- Some material drawn from referenced and associated online sources
- Image sources credited where possible

