CS-417 INTRODUCTION TO ROBOTICS AND INTELLIGENT SYSTEMS

Computer Vision
Guest Lecture by
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Why vision?

- Passive (emits nothing).
  - Discreet.
  - Energy efficient.
- Intuitive.
- Powerful (works well for us, right?)
- Long and short range.
- Fast.

So, what's the problem?

- How hard is vision? Why do we think is do-able?

Problems:

- Slow.
- Data-heavy.
- Impossible.
- Mixes up many factors.

The "Vision Problem"

The "Vision Problem"

Input → Vision Algorithm → Output

207	200	199	194	203	126	106	091	113	153	192	196	190	186	175
242	194	213	254	255	114	082	109	097	089	208	206	202	194	185
254	159	187	245	248	128	197	191	166	102	248	251	233	223	246
255	159	191	245	249	123	113	047	124	149	255	253	239	143	250
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248	244	163	227	252	091	071	185	079	021	252	251	255	254	138
253	254	169	241	253	141	053	180	005	019	253	253	255	253	201
253	250	170	242	253	138	199	193	216	146	255	253	253	253	233
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253	246	169	207	235	120	157	140	188	108	246	249	235	225	255
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221	215	189	207	220	221	003	063	209	006	204	203	232	229	216
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219	216	198	165	213	227	014	221	197	183	178	186	216	214	222
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226	232	177	184	175	230	214	199	146	255	134	225	205	216	181
253	254	194	192	196	168	032	193	194	196	040	198	190	207	185
045	030	167	163	210	041	206	144	129	170	086	190	161	193	191
200	205	135	143	100	174	027	175	189	113	121	150	190	209	184
202	205	138	213	088	037	164	194	194	182	076	077	107	211	181
196	208	155	063	055	068	180	200	193	160	220	082	070	210	181
161	132	058	146	048	076	172	165	218	189	186	063	004	187	185
157	080	191	119	044	025	089	115	063	192	223	146	116	186	187

020	067	073	058	055	076	069	050	074	064	065	066	066	059	023
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047	125	130	130	122	121	117	142	131	133	134	141	149	144	135
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025	161	174	172	167	049	200	193	112	028	120	169	173	177	173
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242	194	221	254	255	126	063	061	052	060	208	206	202	194	185
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Input → Vision Algorithm → Output

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242	194	222	254	255	124	074	082	072	076	208	206	202	194	185
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253	210	190	239	250	089	092	149	128	013	254	254	253	229	255
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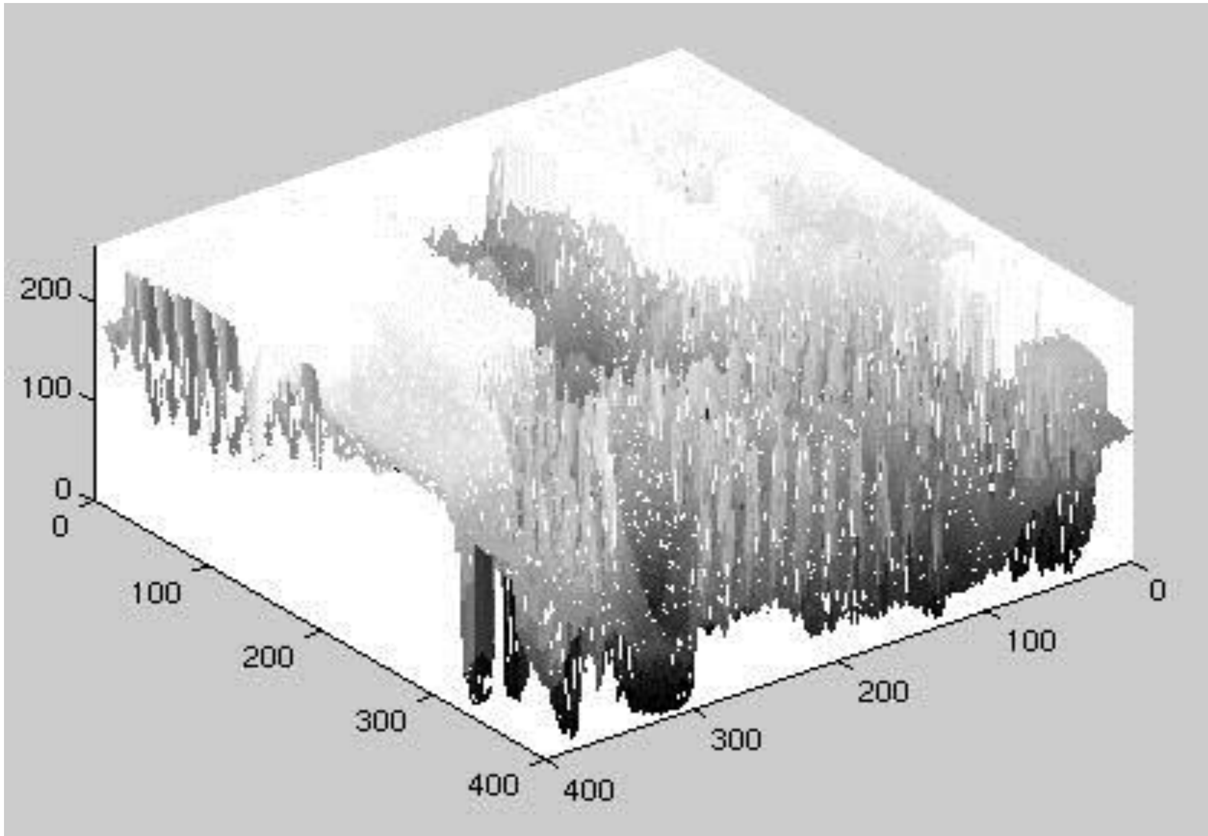
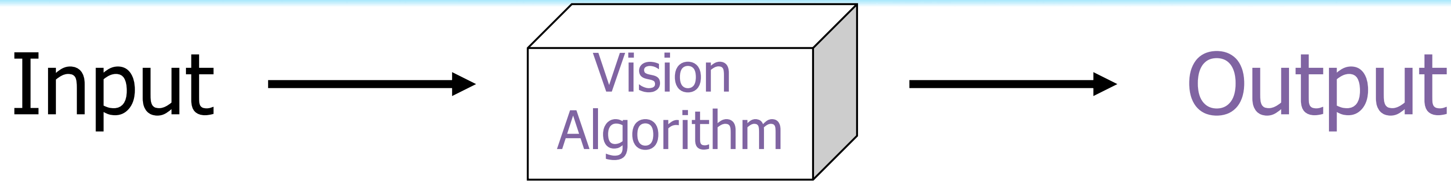


The “Vision Problem”



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254	234	167	212	217	110	070	049	098	074	244	246	239	207	254
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221	217	180	213	243	109	079	048	100	045	246	249	244	221	210
236	216	178	208	230	156	077	062	110	088	244	249	230	220	221
229	224	183	211	132	052	087	062	124	085	135	246	236	220	214
230	223	185	185	112	079	008	124	158	125	119	119	232	225	232
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253	254	079	072	116	089	020	068	103	074	031	130	106	052	161
047	034	090	045	145	027	135	109	082	082	048	113	087	061	157
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191	192	043	153	052	030	078	061	062	054	046	049	054	078	158
184	181	066	019	043	038	046	083	057	050	145	048	035	087	158
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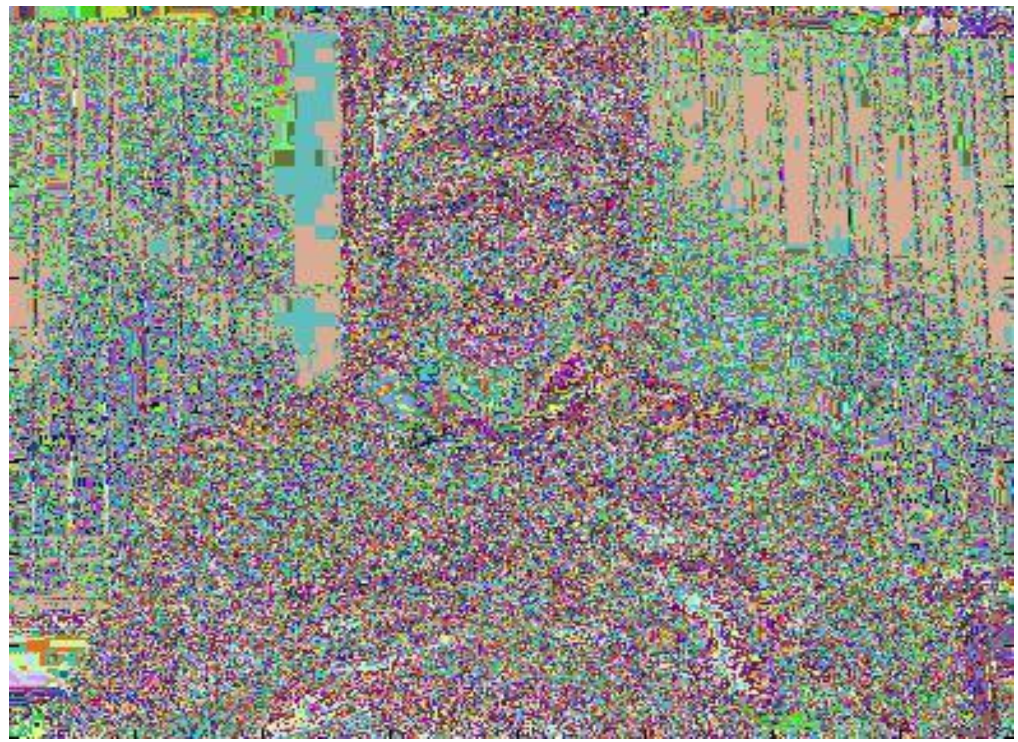

The "Vision Problem"

Input → Vision Algorithm → Output

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242	194	222	254	255	124	074	082	072	076	208	206	202	194	185
254	170	204	255	248	122	153	135	111	081	252	253	233	232	250
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248	248	169	227	252	111	066	118	061	021	252	251	255	255	142
253	255	171	254	253	142	037	132	006	017	253	253	255	254	201
253	250	170	255	253	139	134	127	156	078	255	253	253	254	237
254	228	169	213	235	146	123	096	090	130	230	250	253	254	254
252	244	140	215	245	125	055	043	081	077	252	234	253	253	253
254	250	169	211	235	117	108	093	119	078	246	249	235	225	255
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255	221	179	248	227	111	083	041	061	083	240	249	243	232	253
221	217	180	213	243	109	079	048	100	045	246	249	244	221	210
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138	074	030	082	030	038	076	041	141	046	045	040	009	063	149
135	016	057	071	035	025	040	062	030	084	130	043	059	113	151

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Input → Vision Algorithm → Output

020	067	073	058	055	076	069	050	074	064	065	066	066	059	023
047	109	107	118	107	115	110	120	120	124	120	128	124	132	131
047	125	130	130	122	121	117	142	131	133	134	141	149	144	135
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043	144	165	159	154	171	224	191	047	030	171	165	175	164	163
025	161	174	172	167	049	200	193	112	028	120	169	173	177	173
011	091	101	105	177	039	078	060	041	026	073	102	167	208	121
011	091	094	066	094	033	199	184	139	024	060	094	125	152	134
009	068	072	072	065	031	151	171	075	028	035	072	083	109	063
013	068	074	059	057	037	161	129	062	028	035	071	072	078	056
012	042	063	055	072	033	020	067	031	022	027	082	070	073	060
011	037	064	094	091	026	025	080	066	026	023	071	070	080	060
011	060	077	082	037	023	024	147	140	038	023	037	043	076	037
013	049	076	059	032	028	174	197	182	060	021	021	121	101	062
013	059	111	072	020	078	200	211	182	061	069	059	043	086	106
007	053	057	092	023	105	189	230	210	084	034	021	017	033	091
011	061	072	018	027	054	069	068	062	023	045	011	016	042	044
014	041	047	025	018	040	065	039	024	021	036	041	013	030	022
013	093	106	017	019	027	030	042	012	021	043	013	014	020	027
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022	026	018	030	020	012	017	010	008	011	007	015	008	016	034
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018	008	009	019	023	093	109	128	063	052	031	010	012	009	006
017	010	010	007	067	054	106	116	067	056	011	028	005	009	006
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016	010	008	011	039	025	020	016	011	007	008	007	006	010	003
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020	067	073	058	055	076	069	050	074	064	065	066	066	059	023
025	161	174	172	167	049	200	193	112	028	120	169	173	177	173

→

What does a robot need ?

doesn't need a full interpretation of available images

"This is Prof. X in his office offering me a can of spam."

does need information about what to do...

"Run Away!!"

reactive → deliberative

- avoiding obstacles (or predators)
- pursuing objects
- localizing itself
- Mapping
- finding targets
- reasoning about the world ...

} environmental interactions

What does a robot need ?

- What a camera does to the 3d world...

Shigeo Fukuda

squeezes away one dimension

http://www.psychologie.tu-dresden.de/i1/kaw/diverses Material/www.illusionworks.com/html/art_of_shigeo_fukuda.html

What does a robot need ?

- What a camera does to the 3d world...

Shigeo Fukuda

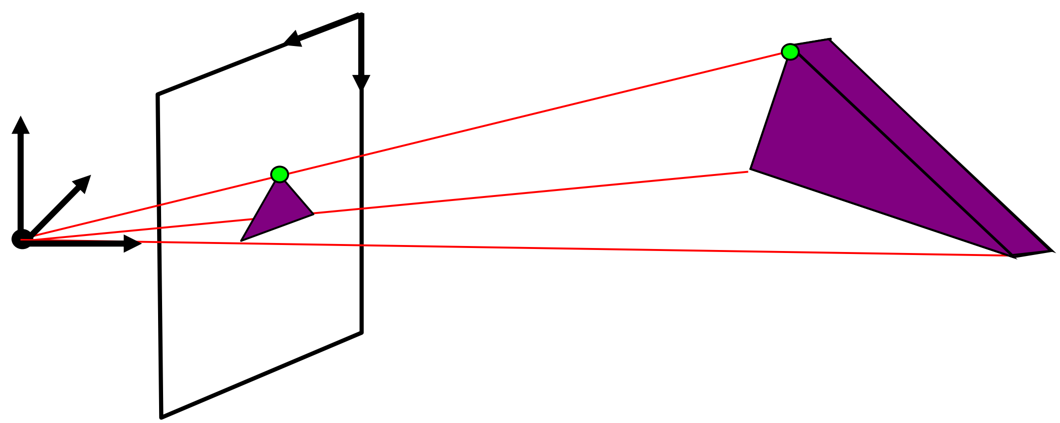
http://www.psychologie.tu-dresden.de/i1/kaw/diverses Material/www.illusionworks.com/html/art_of_shigeo_fukuda.html

Ill-posed

- In trying to extract 3d structure from 2d images, vision is an *ill-posed* problem.

The vision problem in general...

- In trying to extract 3d structure from 2d images, vision is an *ill-posed* problem.
- Basically, there are too many possible worlds that might (in theory) give rise to a particular image



Ill-posed

- In trying to extract 3d structure from 2d images, vision is an *ill-posed* problem.

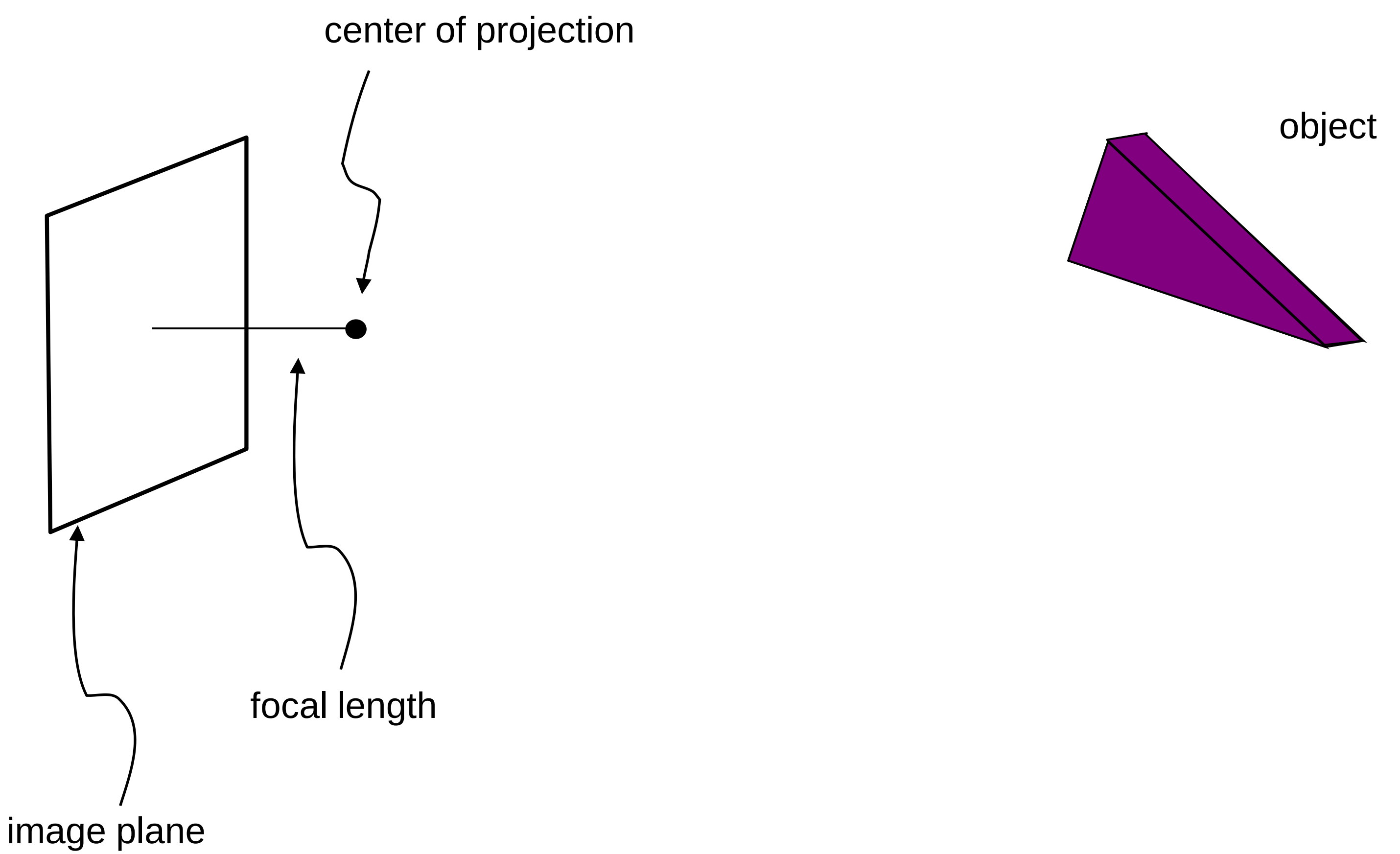
Ill-posed

- In trying to extract 3d structure from 2d images, vision is an *ill-posed* problem.

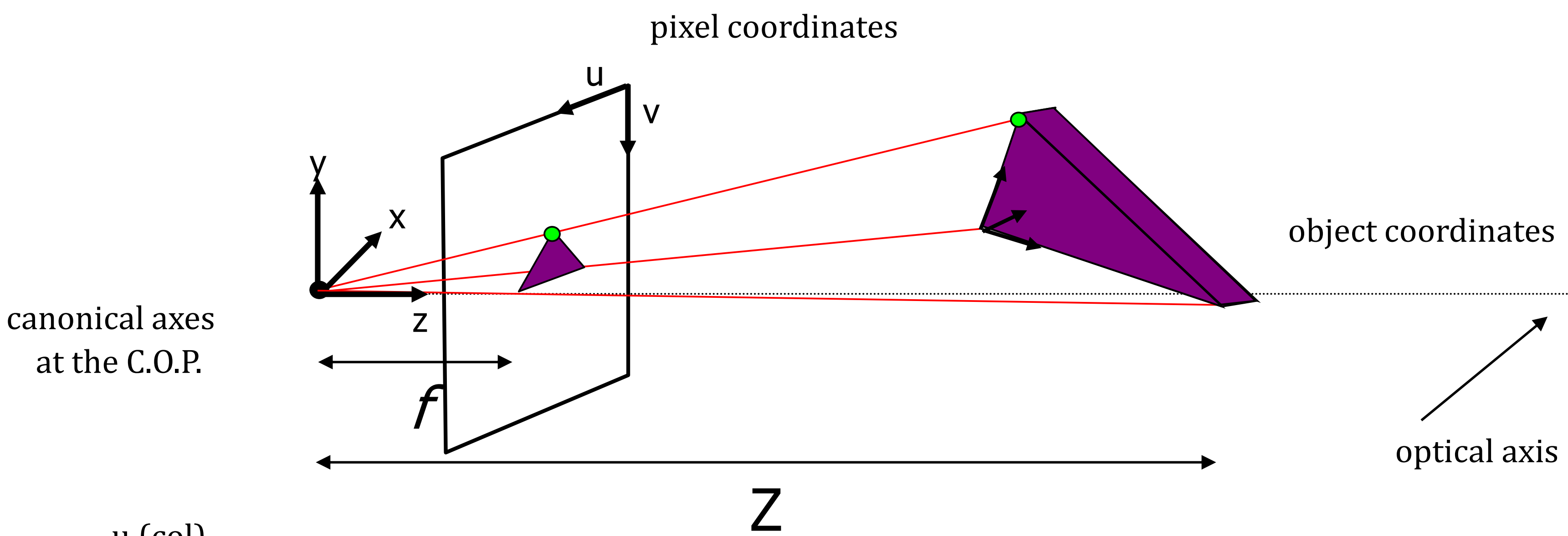
  – An image isn't enough to disambiguate the many possible 3d worlds that could have produced it.

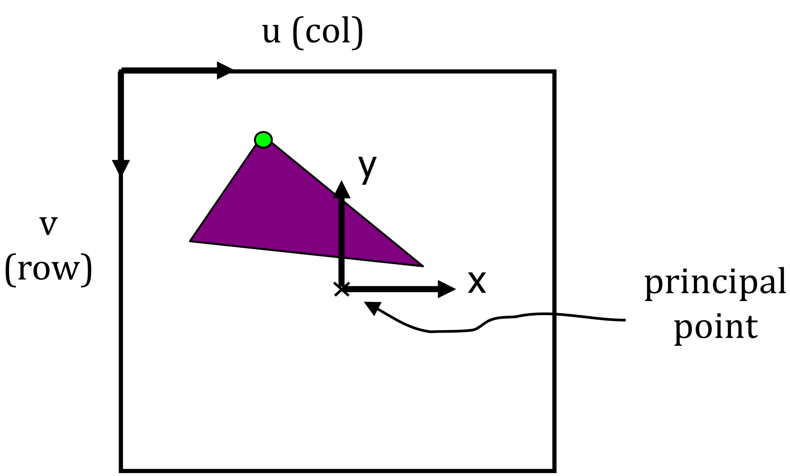
Camera Geometry

3D→2D transformation: perspective projection



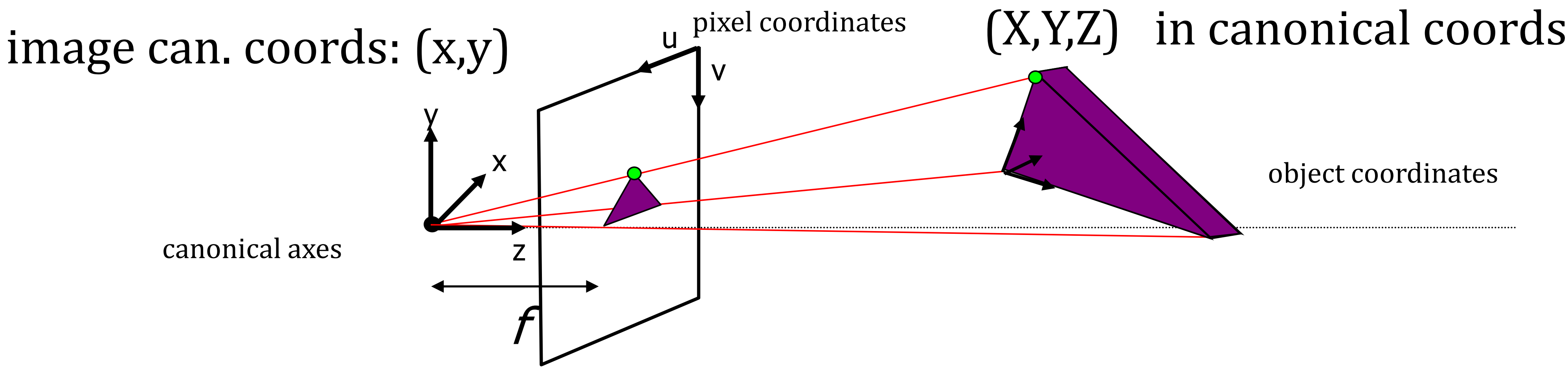
Coordinate Systems



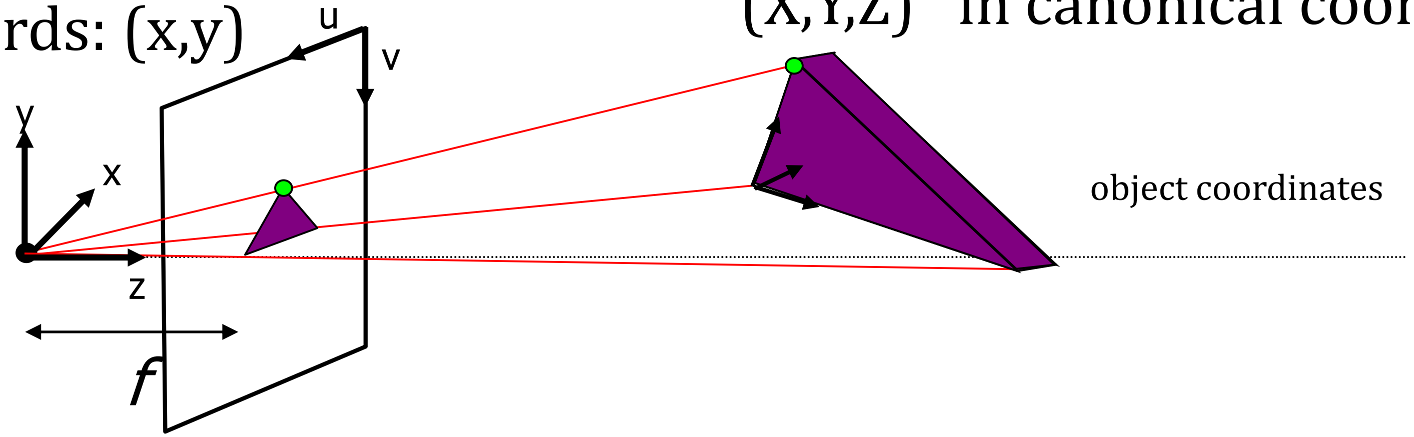


Add coordinate systems in order to describe feature points...

Coordinate Systems



From 3d to 2d



$$x = \frac{fX}{Z} \qquad y = \frac{fY}{Z}$$

a <u>nonlinear</u> transformation

goal: to recover information about (X,Y,Z) from (x,y)

Camera Calibration

- Camera Model
  - $[u\ v\ 1]$ Pixel coords
  - $\begin{bmatrix} x_w & y_w & z_w & 1 \end{bmatrix}^T$ World coords

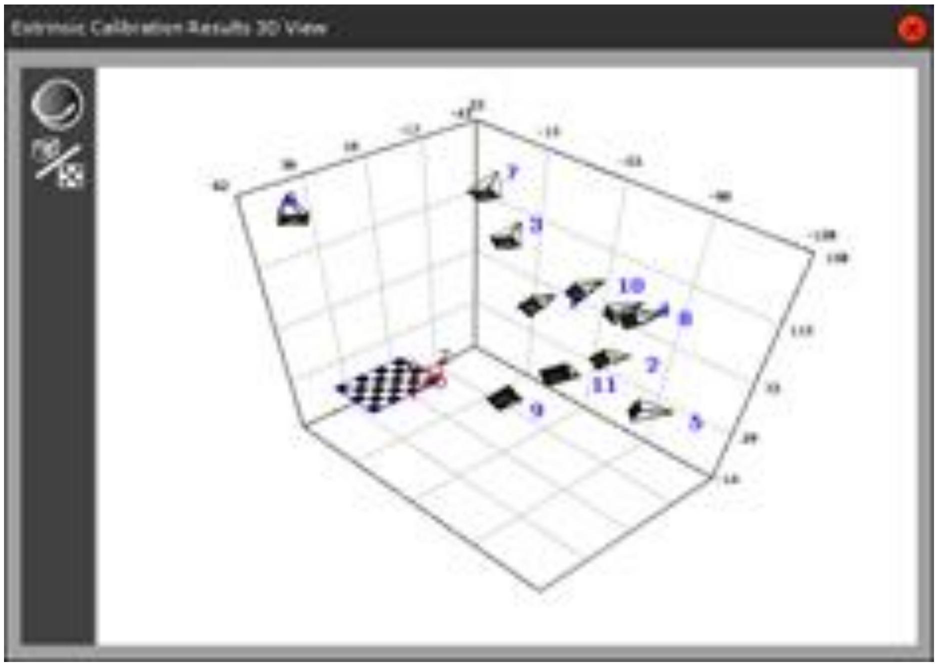
$$z_c \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = A \begin{bmatrix} R & T \end{bmatrix} \begin{bmatrix} x_w \\ y_w \\ z_w \\ 1 \end{bmatrix}$$

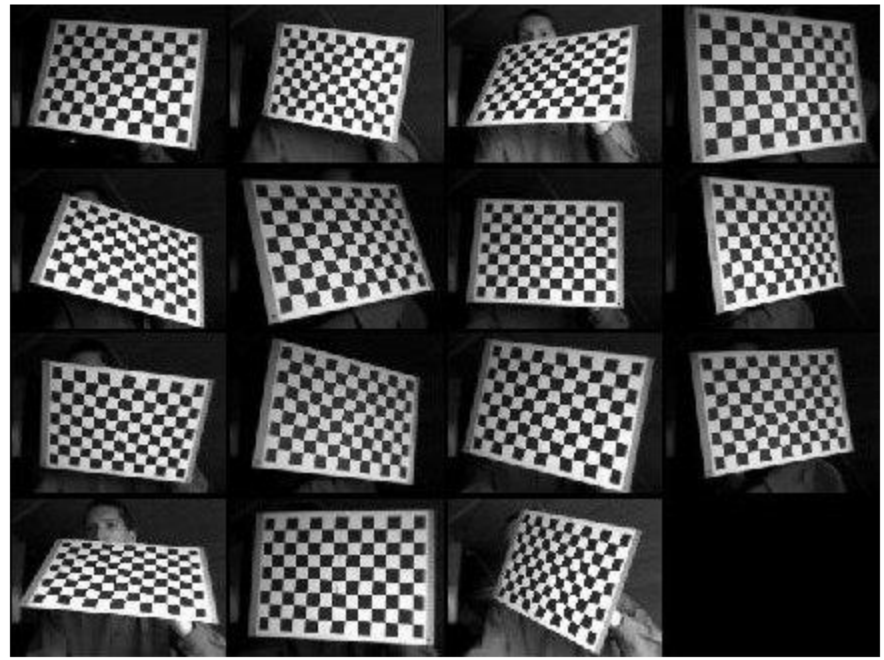
- Intrinsic Parameters
  - $\alpha_x = f \cdot m_x, \alpha_y = f \cdot m_y$ focal lengths in pixels
  - γ skew coefficient
  - u_0, v_o focal point

$$A = \begin{bmatrix} \alpha_x & \gamma & u_0 \\ 0 & \alpha_y & v_o \\ 0 & 0 & 1 \end{bmatrix}$$

- Extrinsic Parameters
  - $\begin{bmatrix} R & T \end{bmatrix}$ Rotation and Translation

Camera Calibration



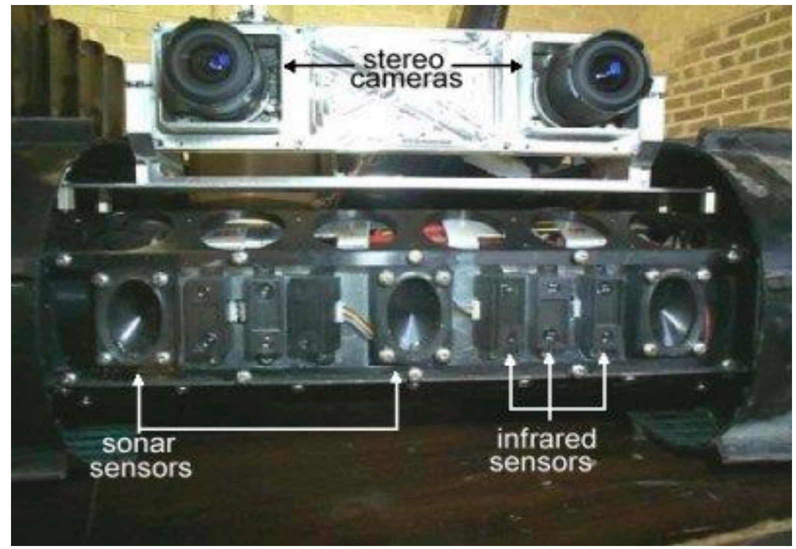


Existing packages in MATLAB, OpenCV, etc

A Vision “solution”

- If interpreting a single image is difficult... What about more ?!

multiple cameras



multiple times

Robot vision sampler

A brief overview of robotic vision processing...

(1) Image streams → simplified via generality
→ simplified via specificity

(2) Stereo vision → (or beyond...)

(3) Incorporating vision within robot control
↓ 3d reconstruction
↓ Visual "servoing"

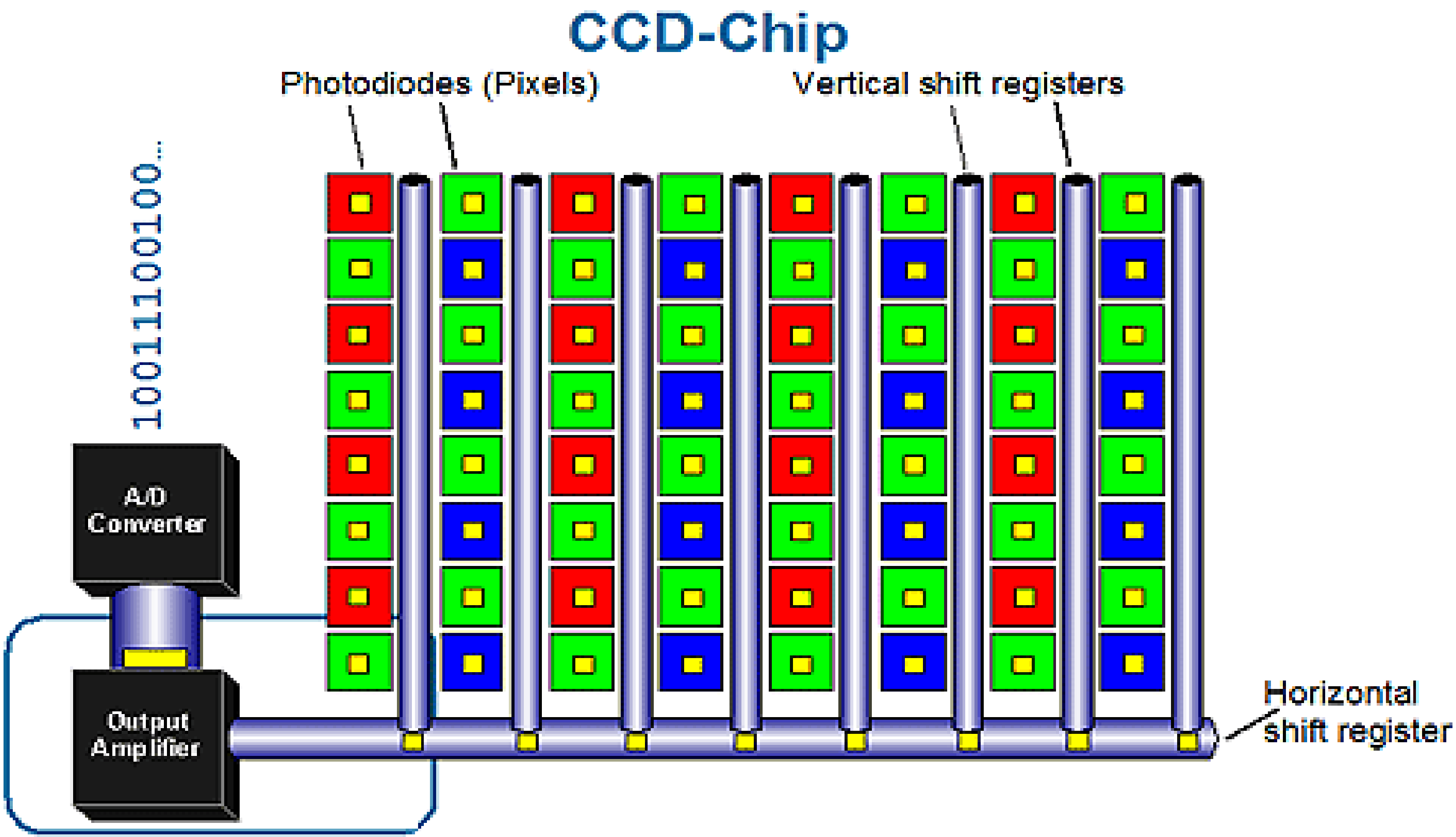
speaking of servoing...

Visual Servoing

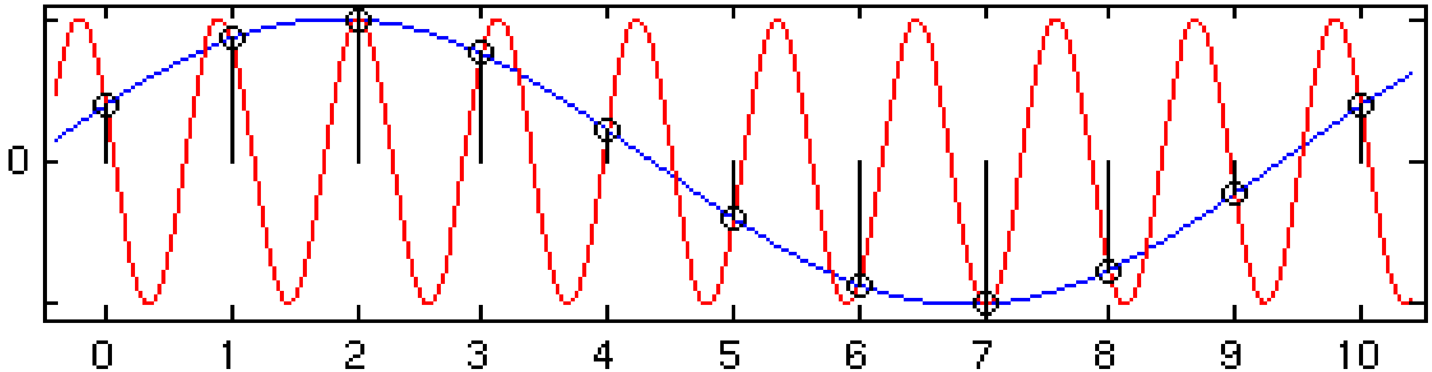
Details

- Images are not actually continuous.
- The sampling (and hardware) issues lead to a few other minor problems.

CCD (Charge-Coupled Device)

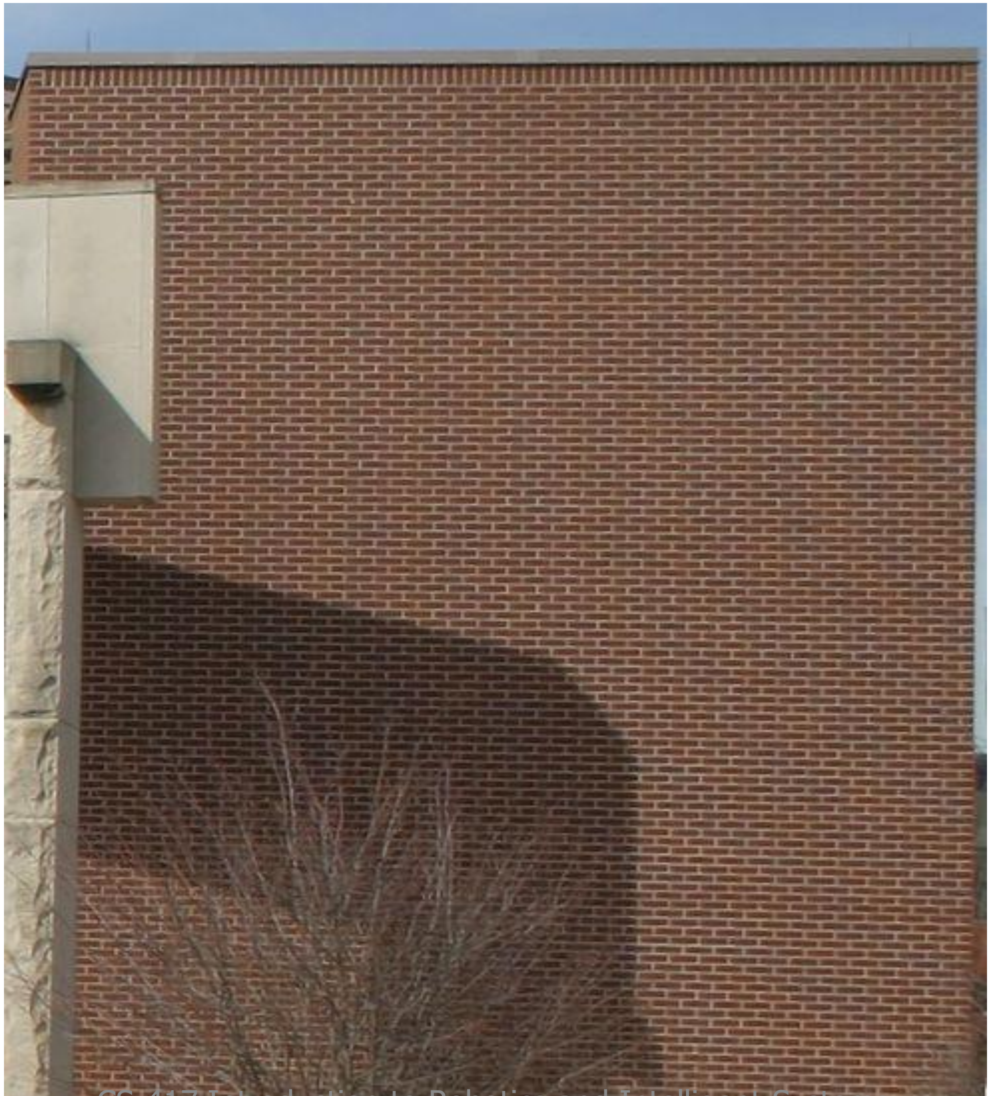


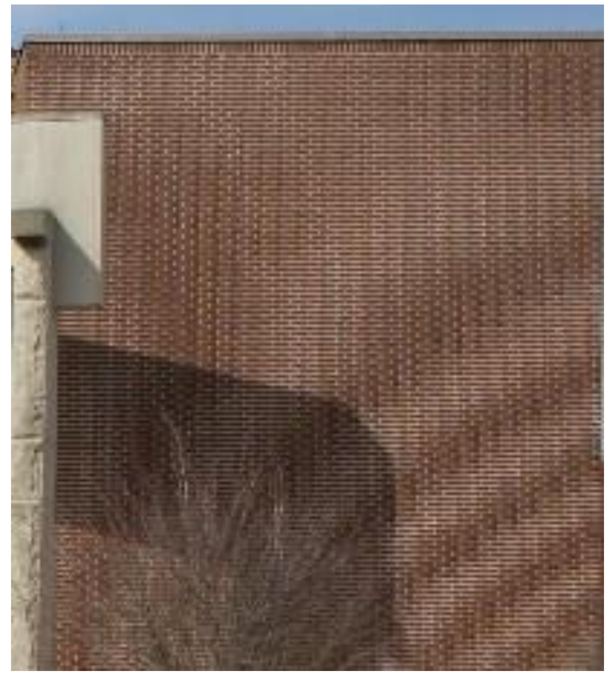
Aliasing.



- To avoid: $f_{sampling} > 2F_{max}$
  - Nyquist Rate

Aliasing: Moiré Patterns





Key problems

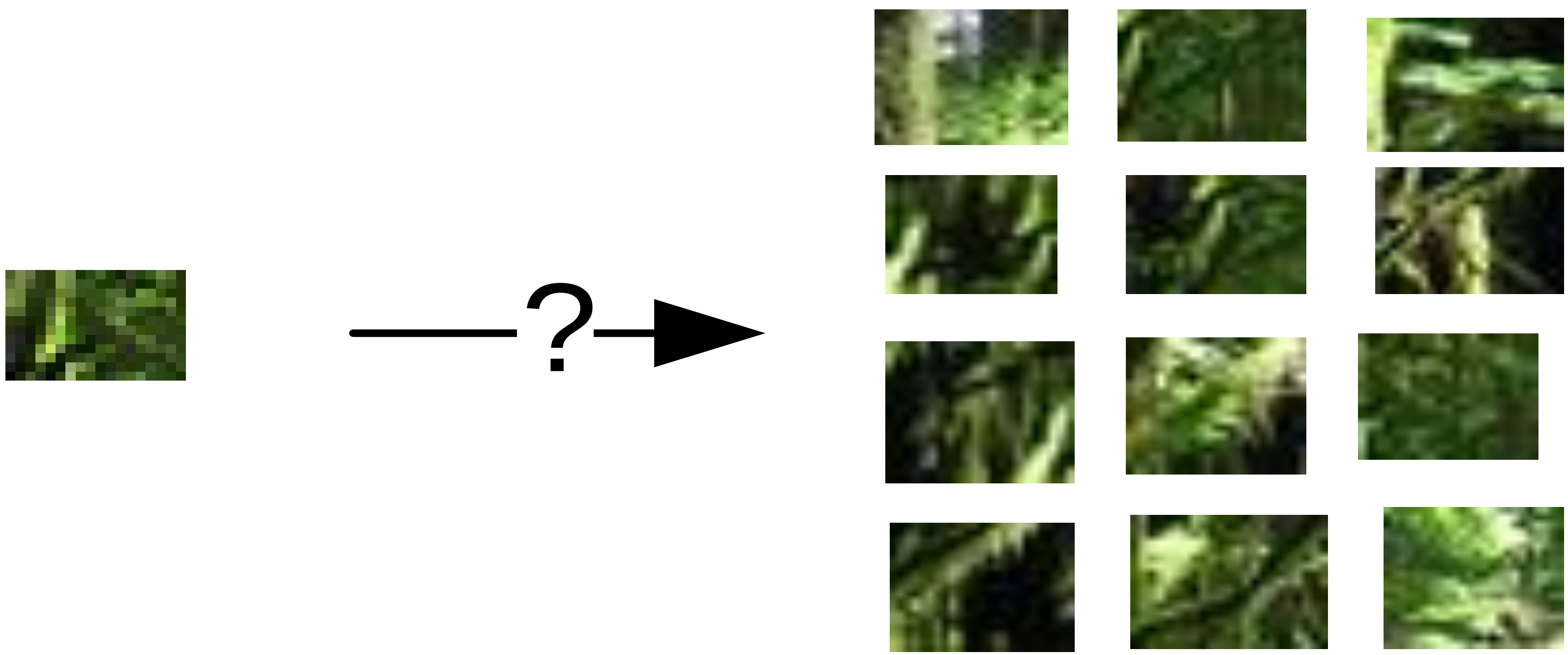
- Recognition:
  - What is that thing in the picture?
  - What are all the things in the image?
- Scene interpretation
  - Describe the image?
- Scene “reconstruction”:
  - What is the 3-dimensional layout of the scene?
  - What are the physical parameters that gave rise to the image?
  - What is a description of the scene?

Notion of an “inverse problem.”

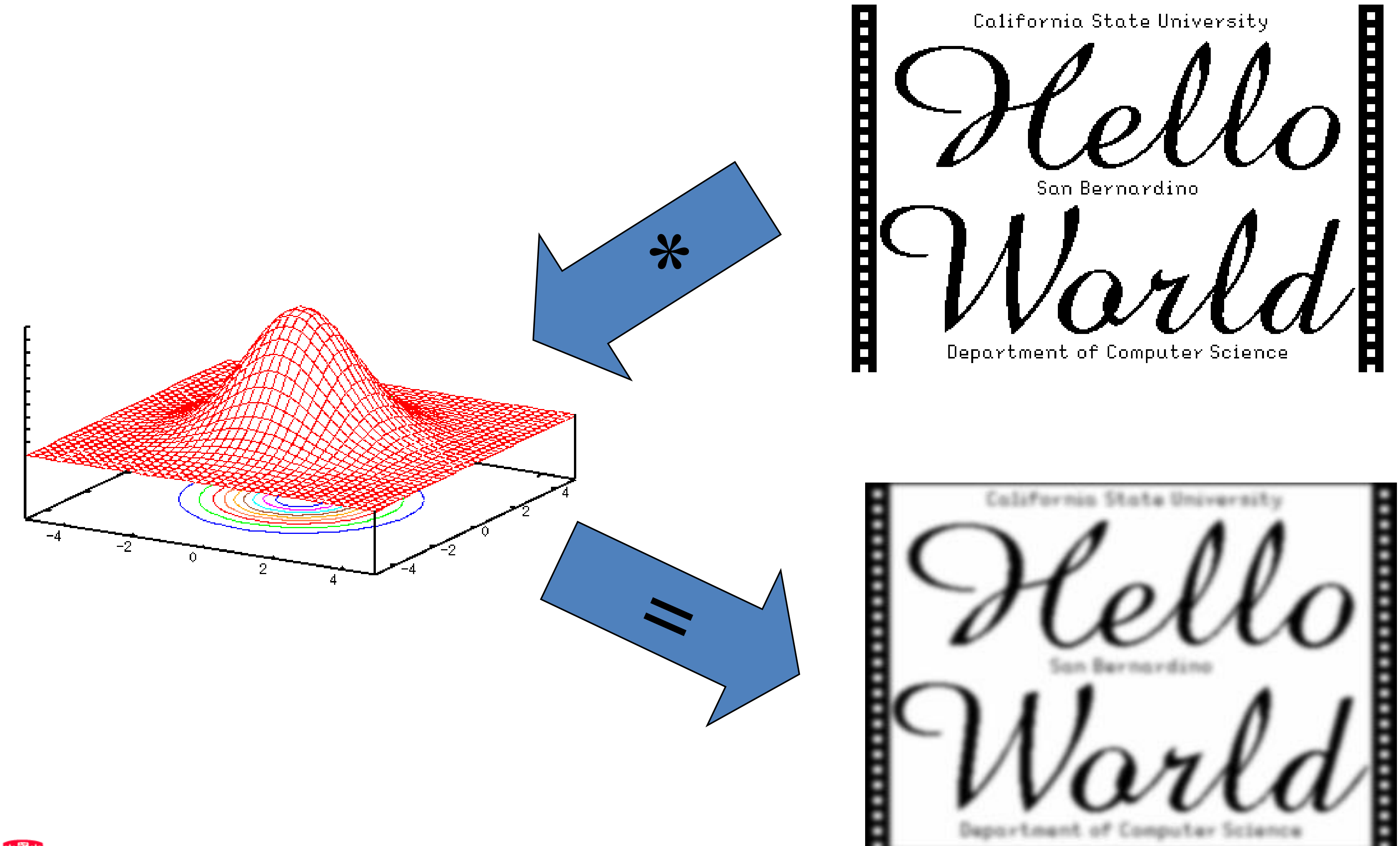
Correspondence Problem

Correspondence

From I_1 From I_2



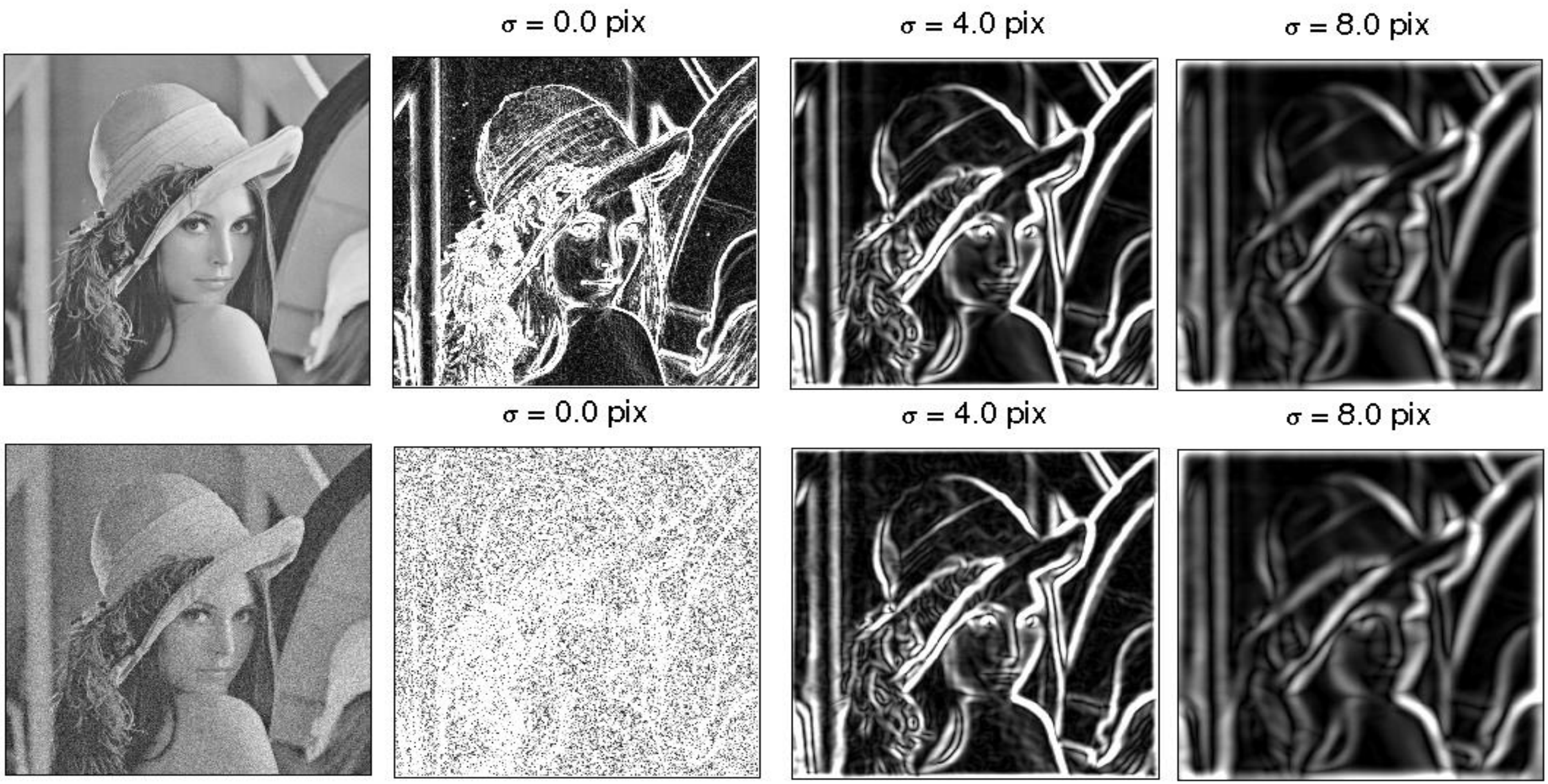
Gaussian Blur



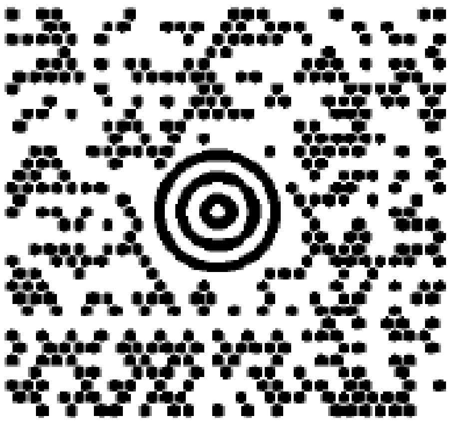
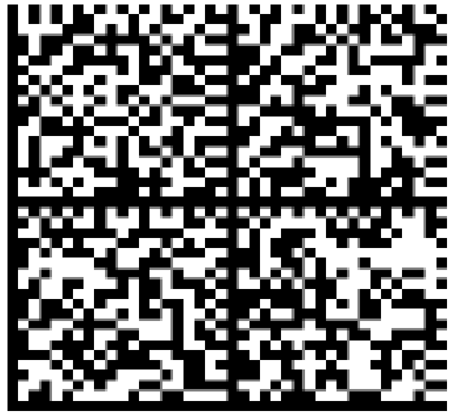
Gaussian Blur and Noise

Gaussian Blur and Noise

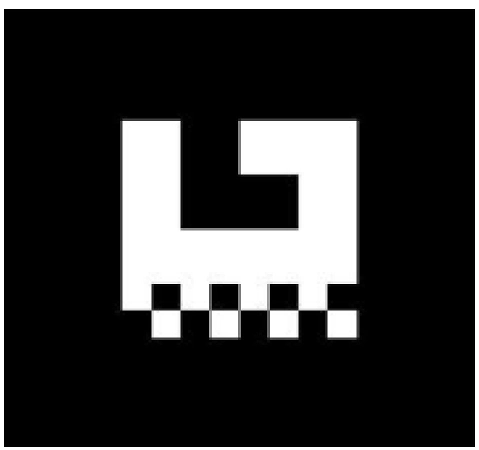
Gaussian Blur, Noise, Sobel



Fiduciary Markers/Fiducial

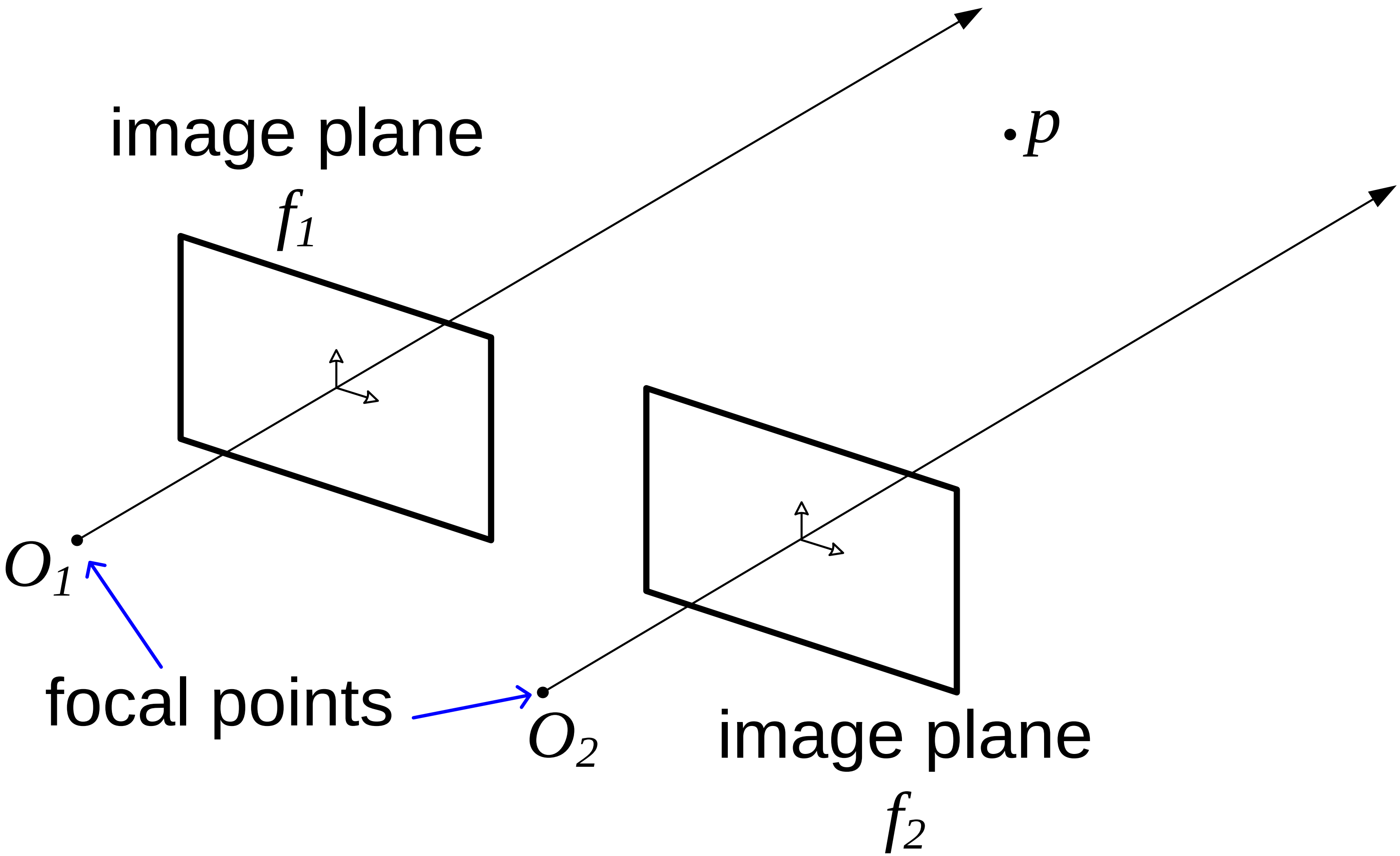
(a) MaxiCode (b) DataMatrixSymbol



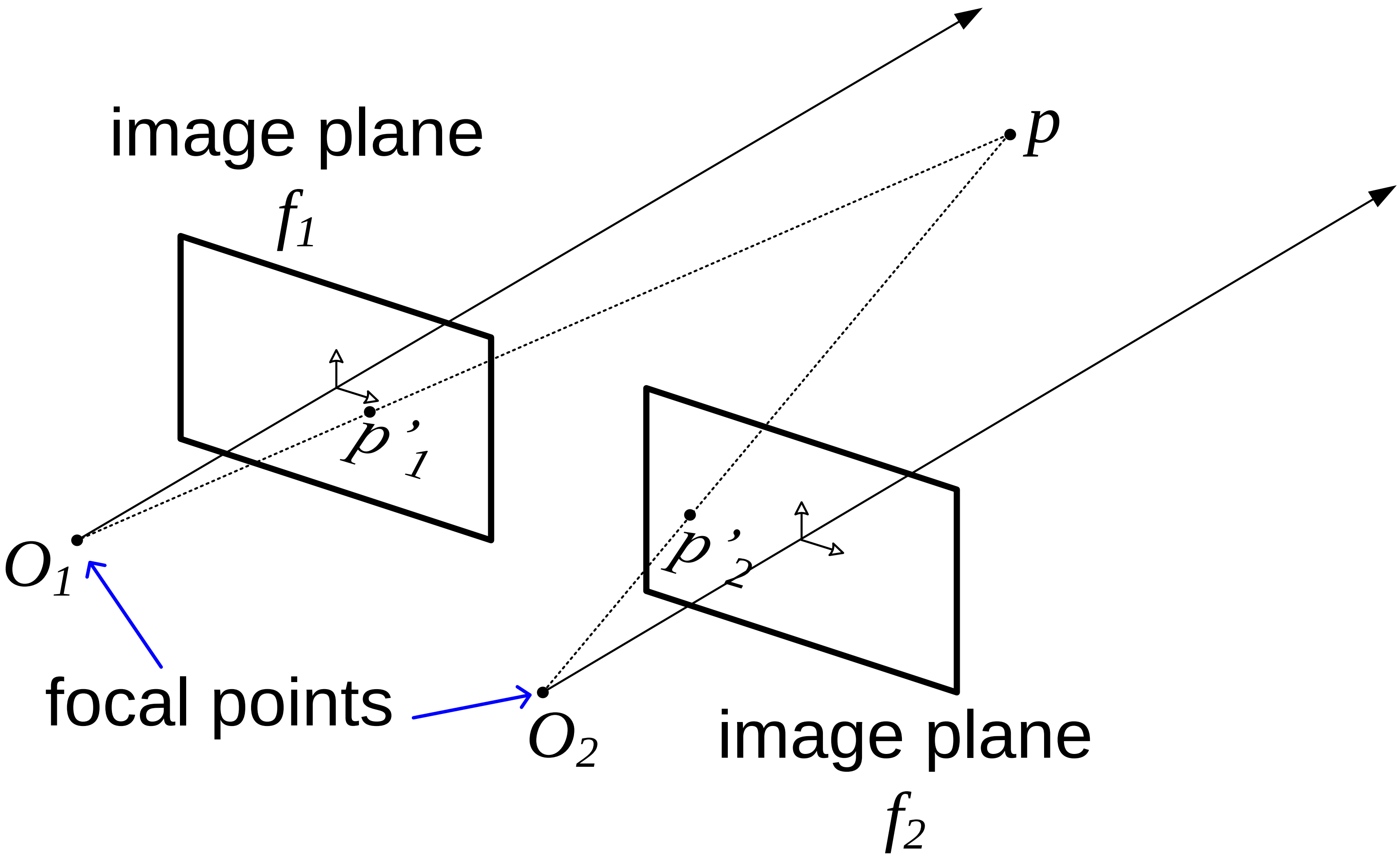

(c) ARToolkit (d) ARTag

Fourier Tag

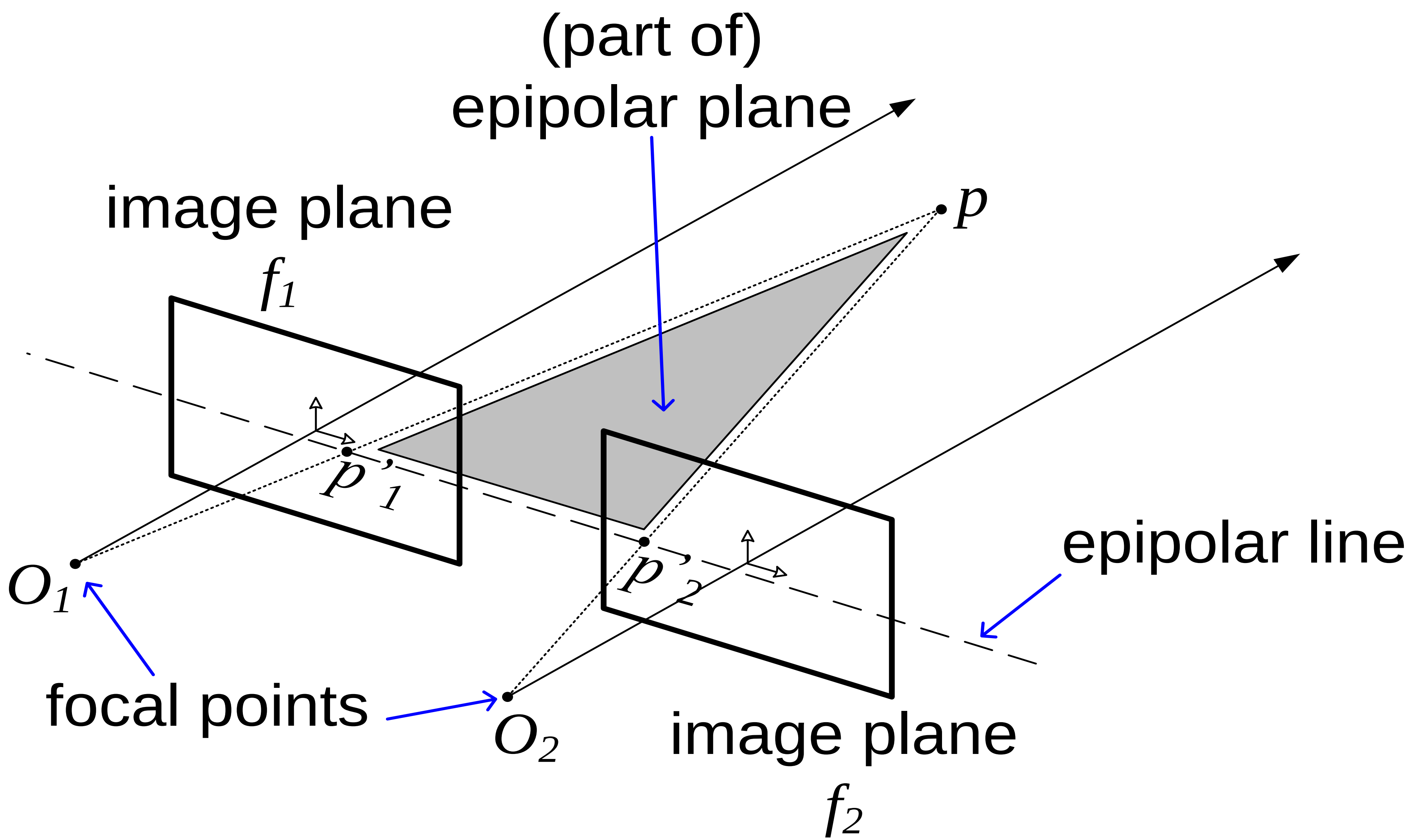
Stereo Vision: Pinhole Camera



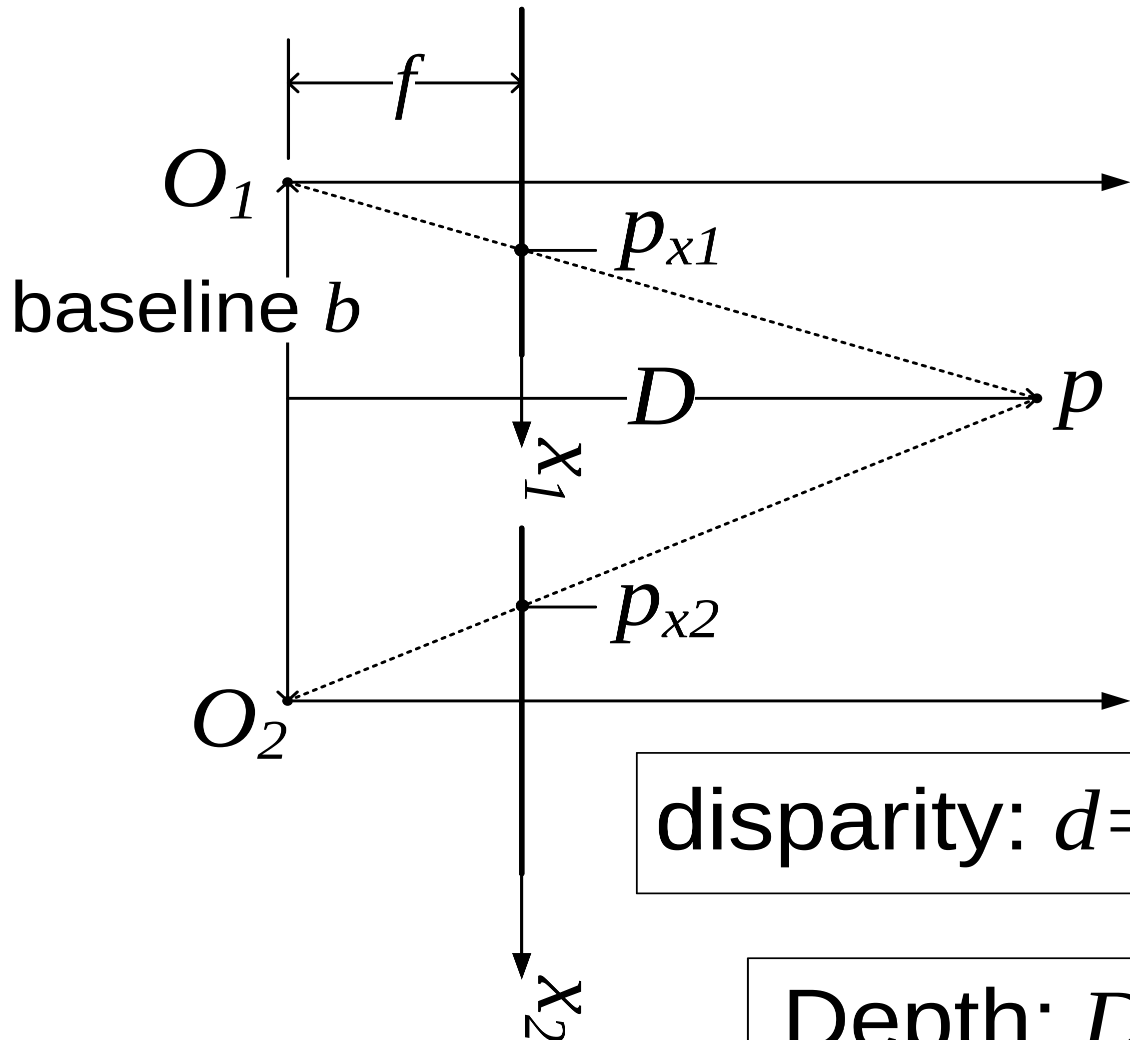
Stereo Vision: Pinhole Camera



Stereo Vision: Pinhole Camera



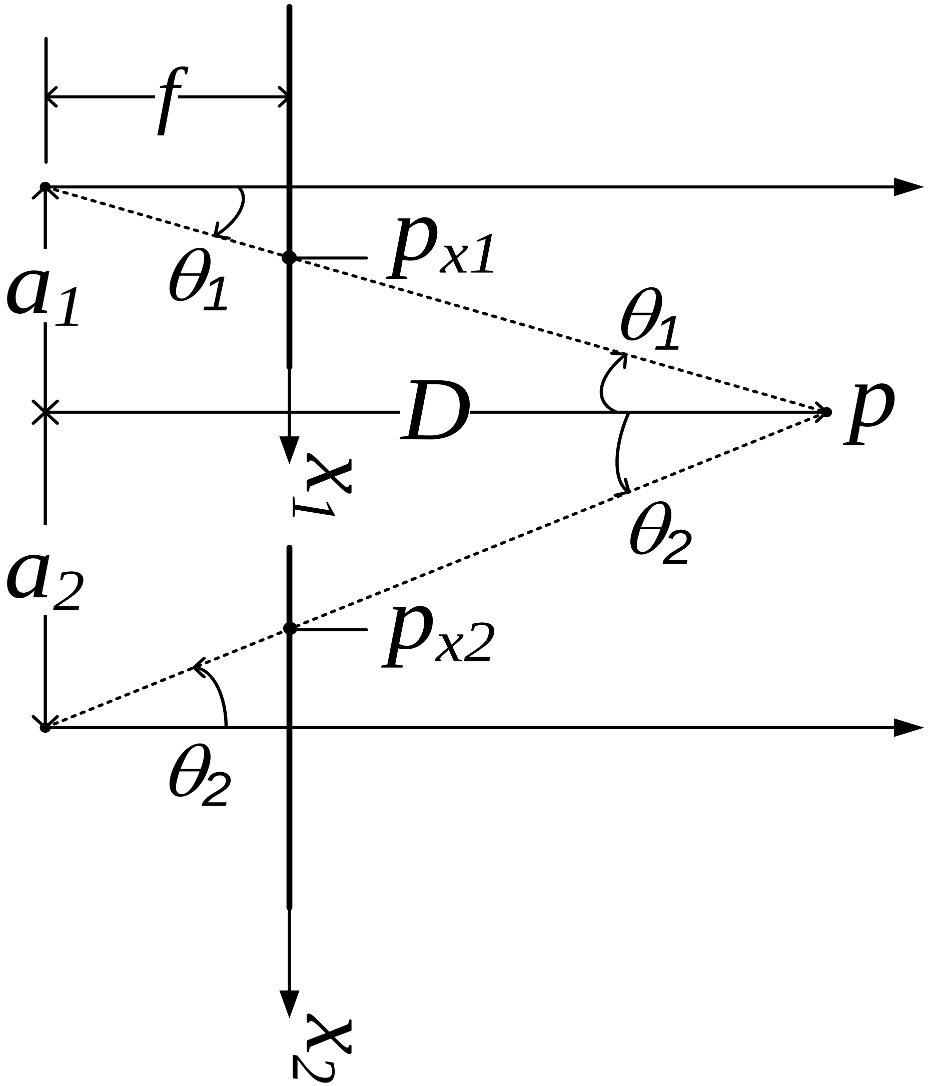
Stereo Vision: Pinhole



disparity: $d = p_{x1} - p_{x2}$

Depth: $D = fb/d$

Stereo Vision: Pinhole



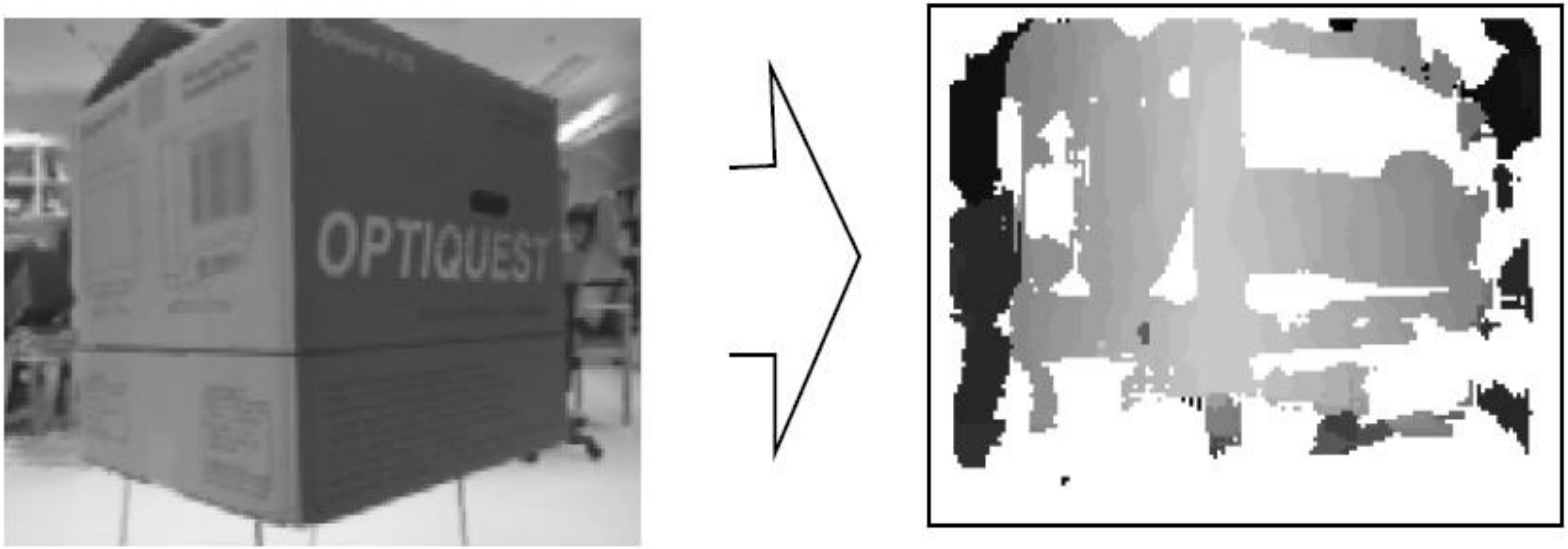
$$\frac{p_{x1}}{f} = \frac{a_1}{D}$$

$$\frac{p_{x2}}{f} = \frac{a_2}{D}$$

$$a_1 + a_2 = b$$

Large Baseline

Stereo: Disparity Map

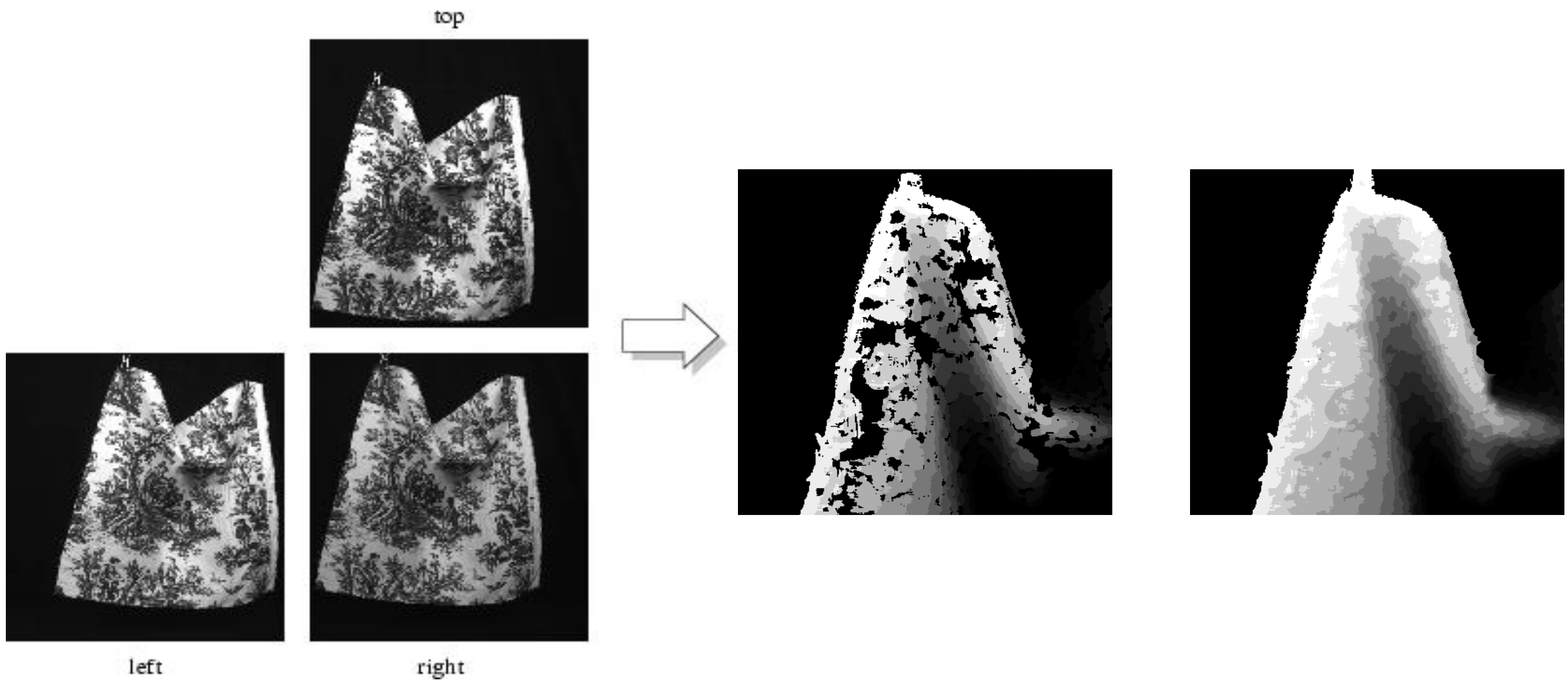


Using real-time stereo vision for mobile robot navigation

Don Murray   Jim Little

Computer Science Dept.
University of British Columbia
Vancouver, BC, Canada V6T 1Z4

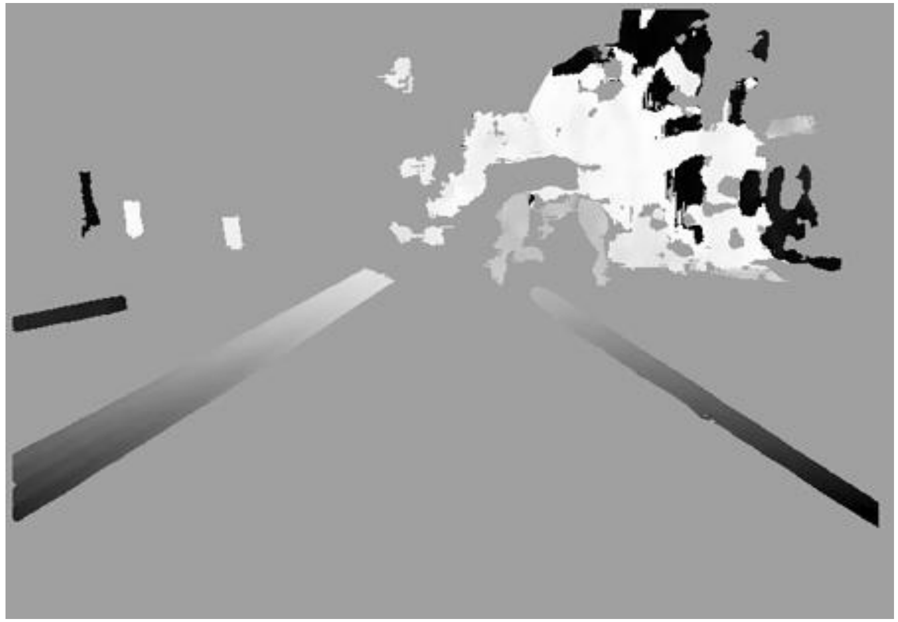
Another Example (Hole Filling)



Cloth Parameters and Motion Capture by David Pritchard

B.A.Sc., University of Waterloo, 2001

Depth Map in a City



Stereo Vision

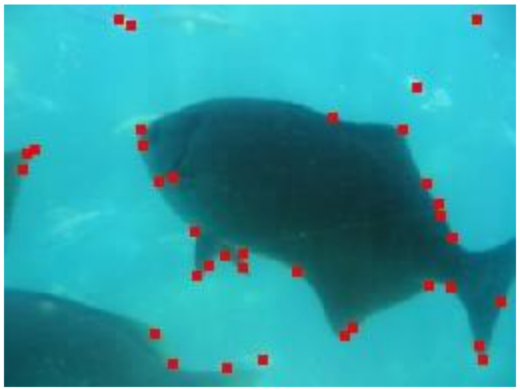
- Large number of algorithms out there:
  http://vision.middlebury.edu/stereo/

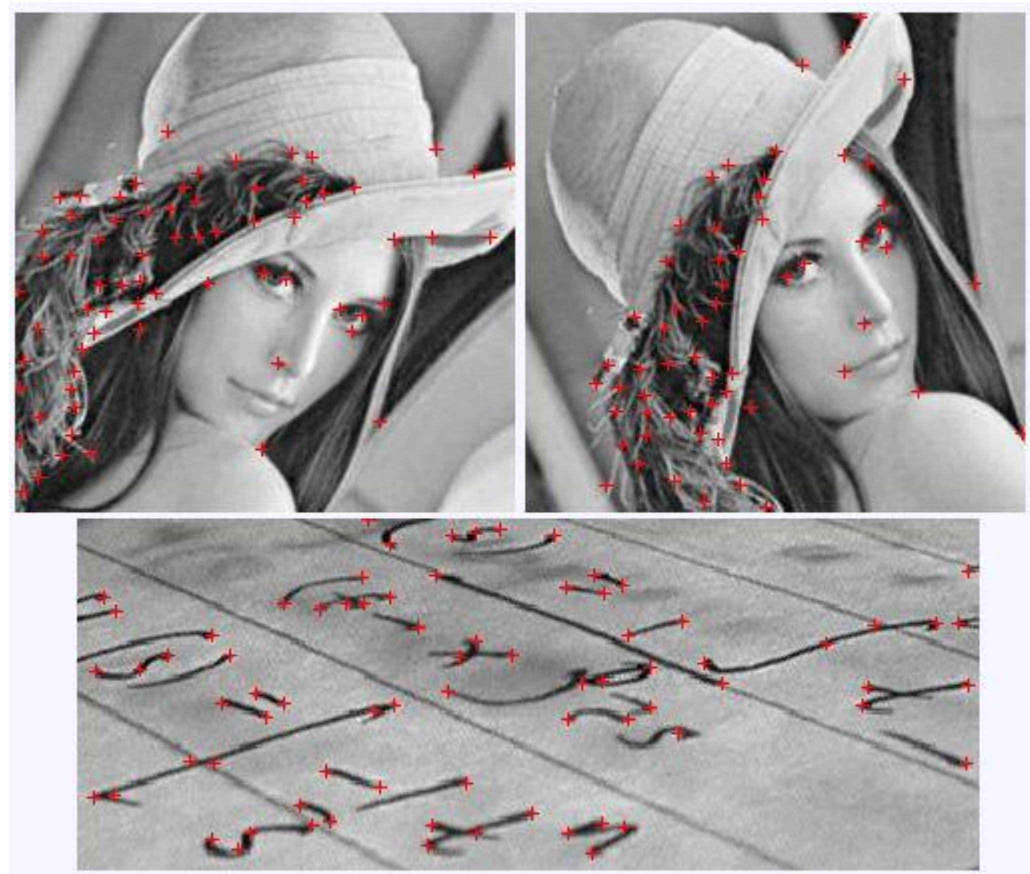
  rank 43 different algorithms.

Good Feature

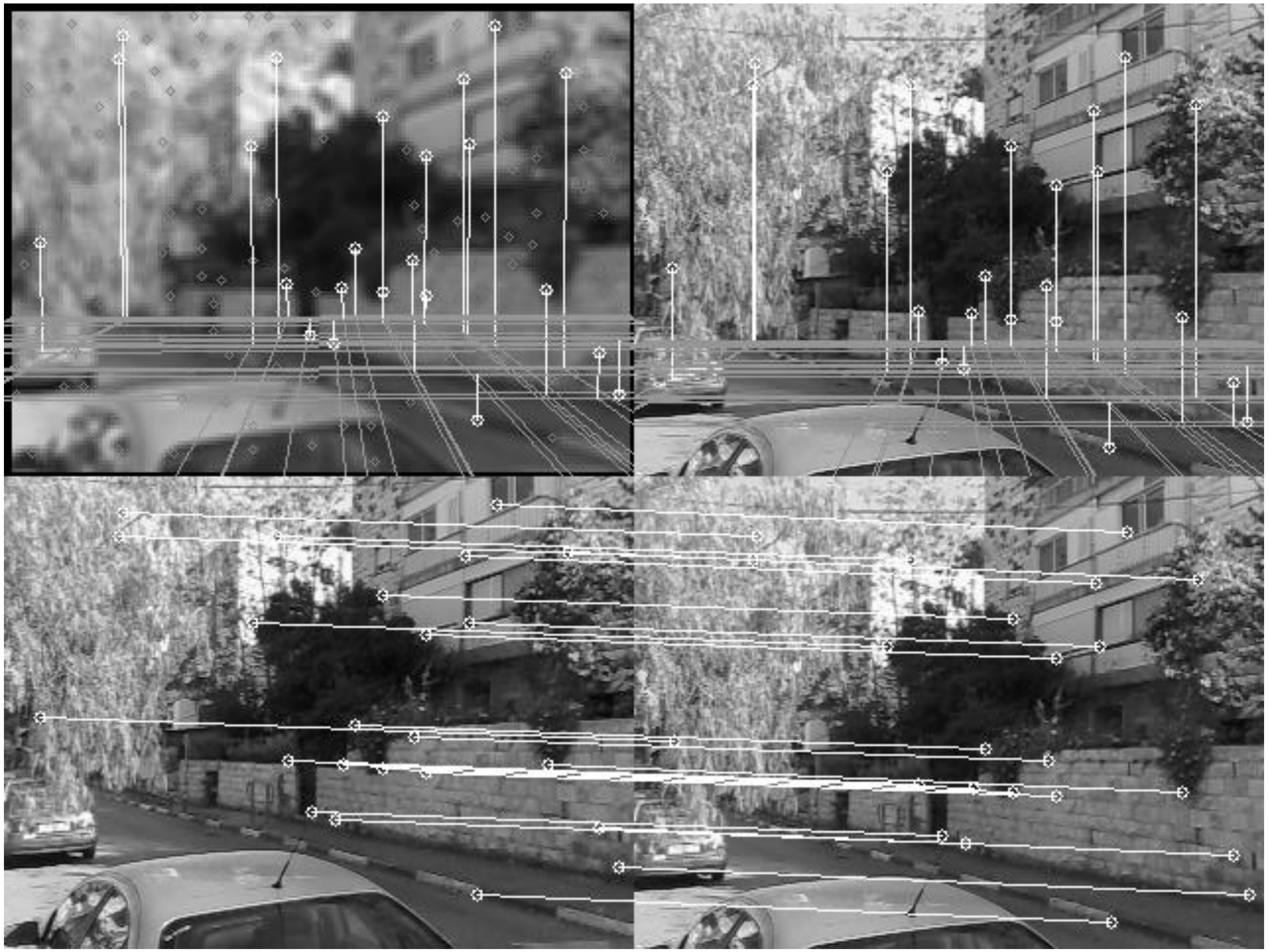
- High Recall
- Good Precision
- Feature Detection
- Feature Matching
- Several Alternatives:
  - Harris Corners (OpenCV)
  - SURF (OpenCV)
  - SIFT
  - etc

Harris Corners





SURF



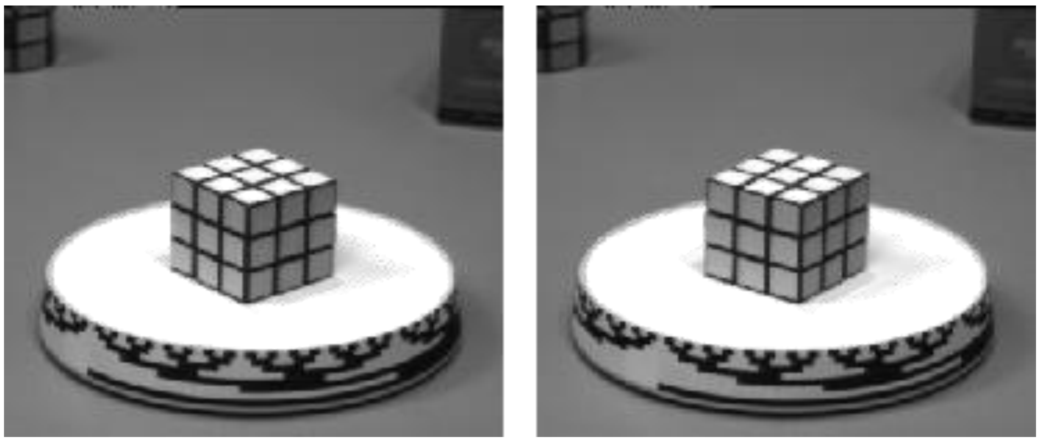
SIFT

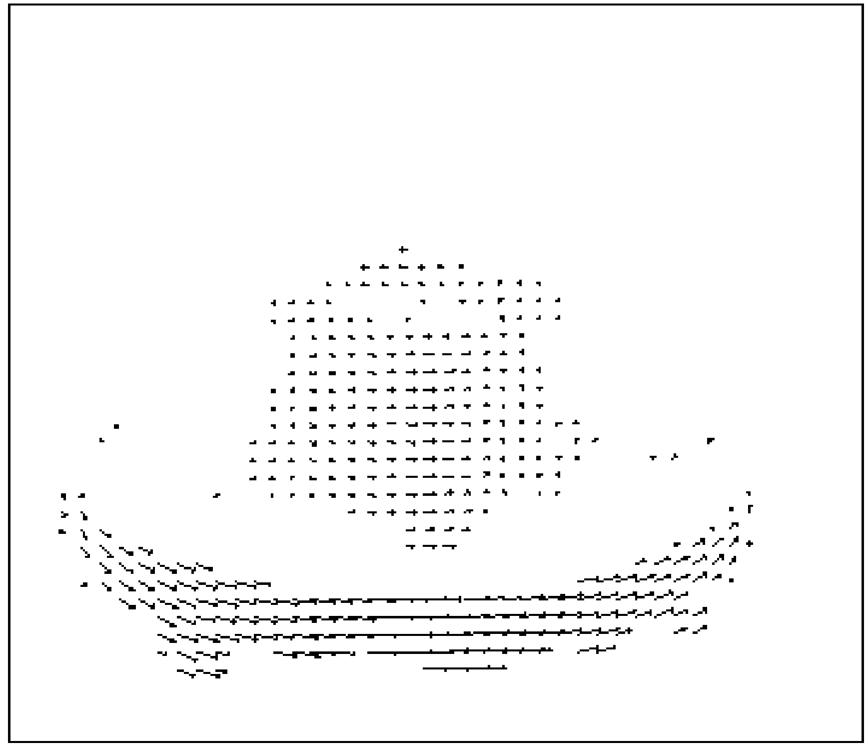

BASTONCINI
Crisp Almond Cookies
Peso Netto 250 g
NET WT 8.8 OZ

Optical Flow

- Definition:
  - *the pattern of apparent motion of objects, surfaces, and edges in a visual scene caused by the relative motion between an observer (an eye or a camera) and the scene.*

Optical Flow Field

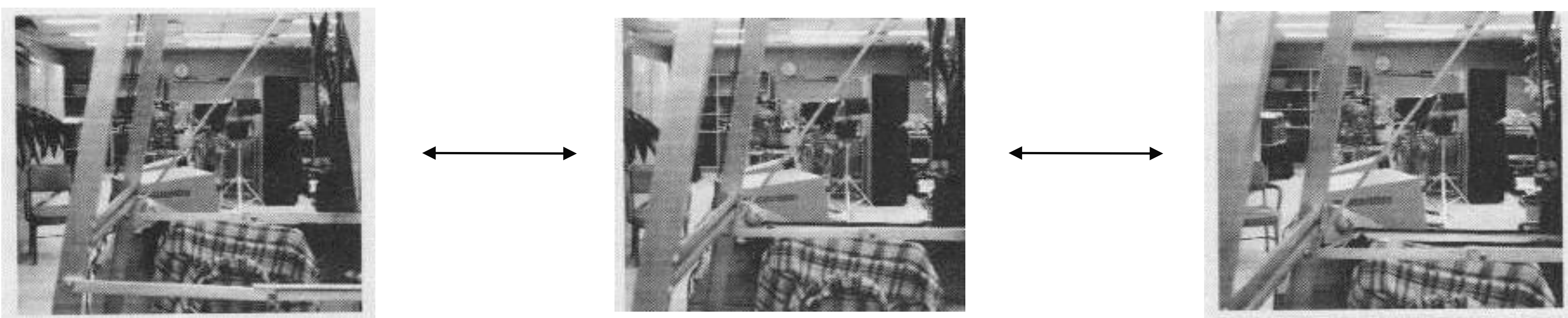




Optical flow

Information about *image motion* rather than the *scene.*
This is a classic ***reconstruction*** *problem.*

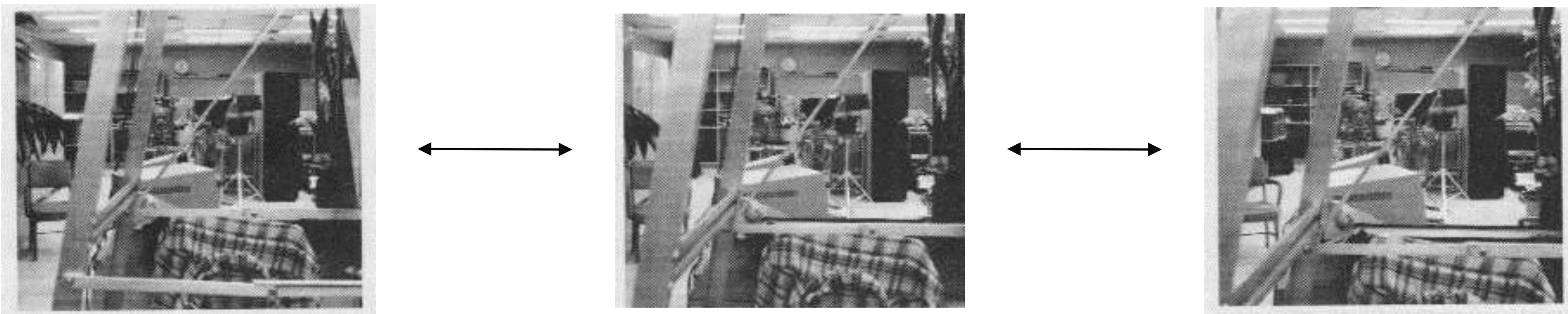
This next step might be to use the image motion to infer scene motion, robot motion or 3D layout.



time sequence of images

Optical flow

Information about *scene motion* rather than the *scene.*

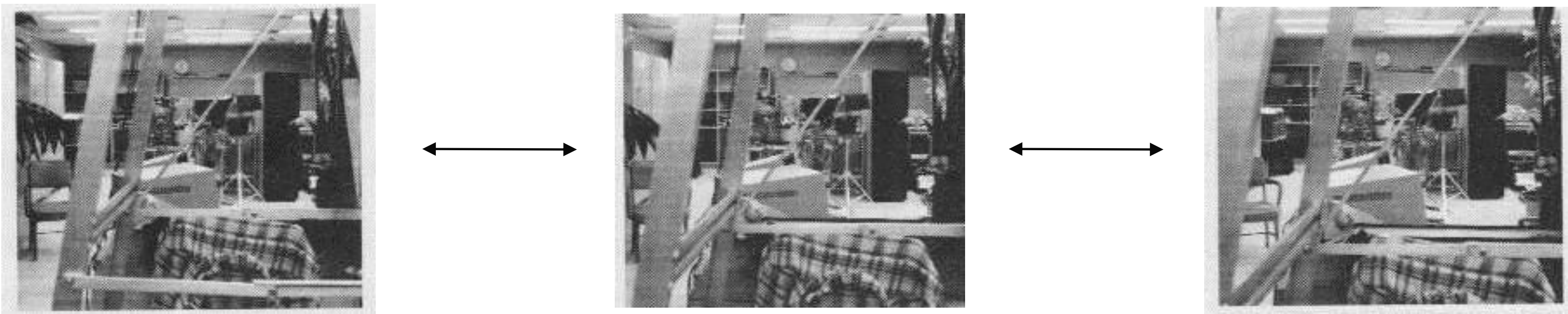


an "image cube"

$I(x,y,t)$

Optical flow

Information about *scene motion* rather than the *scene.*



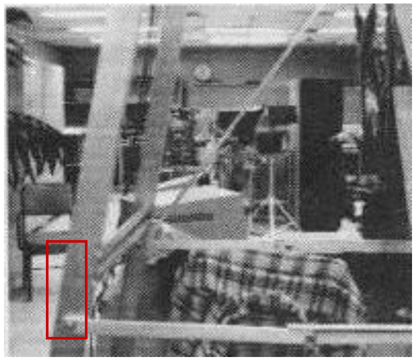
optical flow

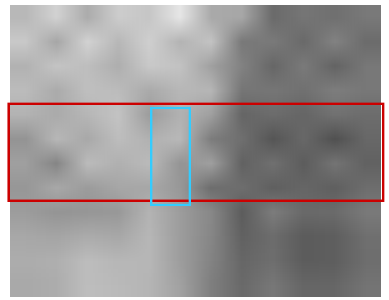
How ?

Optical Flow

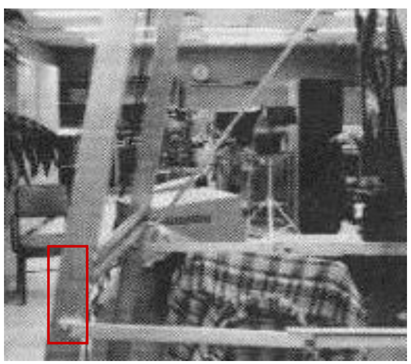
- By measuring the direction that intensities are moving...

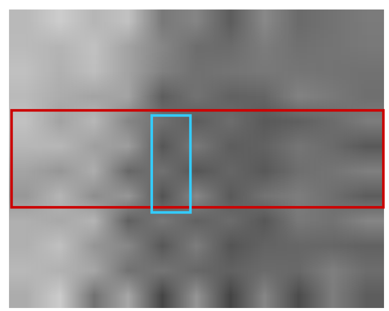
I(x,y,t)





99	90	90	70	40
95	90	70	40	40
90	90	70	40	40
90	90	70	40	40
90	70	50	40	30





90	90	70	40	25
90	70	40	40	25
90	70	40	40	25
90	70	40	40	20
70	50	40	30	15

- We can estimate things...

Observations & Warnings

- How can we do this?
- Assume the scene itself is static.
- Find matching chunks in the images.
- An instance of *correspondence*.

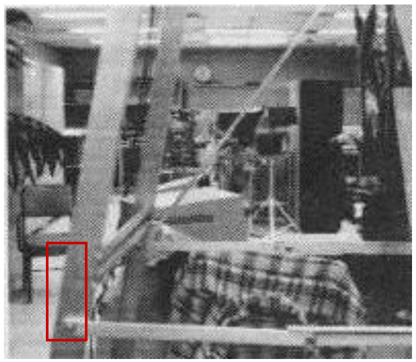
BUT

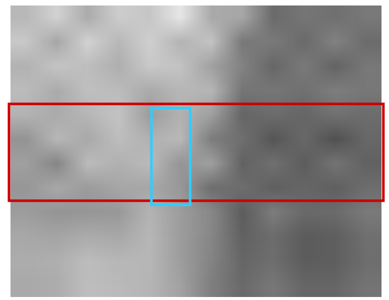
- World really isn't static.
- Lightning might change even in a static scene.

Optical Flow

By measuring the direction that intensities are moving...

$I(x,y,t)$



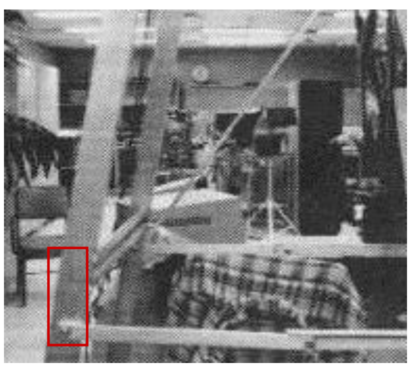


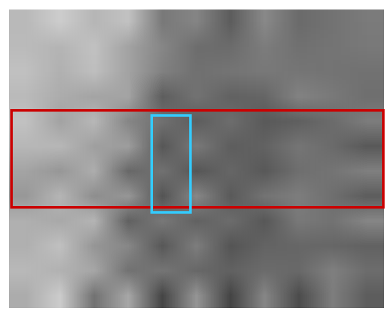
$I(x,y,0)$

99	90	90	70	40
95	90	70	40	40
90	90	**70**	40	40
90	90	70	40	**40**
90	70	50	40	30

$I(0,0,0)$

$I(2,-1,0)$





$I(x,y,1)$

90	90	70	40	25
90	70	40	40	25
90	70	**40**	40	25
90	70	40	40	20
70	50	40	30	15

$I(0,0,1)$

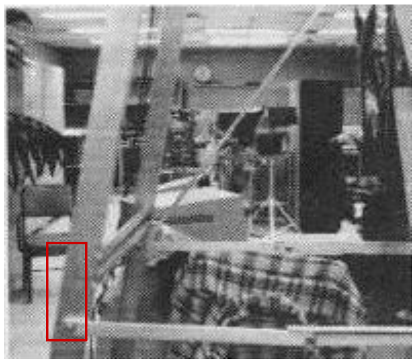
We can estimate things ...

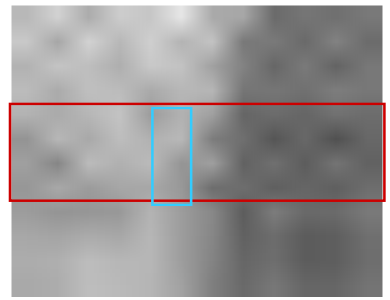
$$\frac{dI}{dx} = I_x \quad \text{at } (0,0,0)$$

Optical Flow

By measuring the direction that intensities are moving...

I(x,y,t)



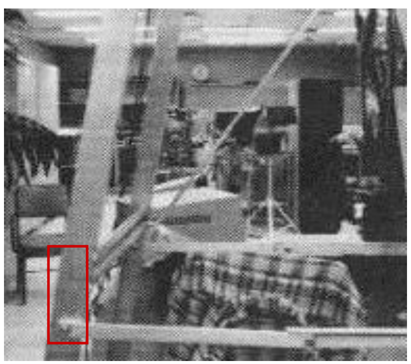


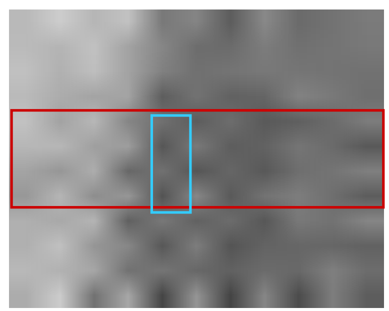
I(x,y,0)

99	90	90	70	40
95	90	70	40	40
90	90	**70**	40	40
90	90	70	40	**40**
90	70	50	40	30

I(0,0,0)

I(2,-1,0)





I(x,y,1)

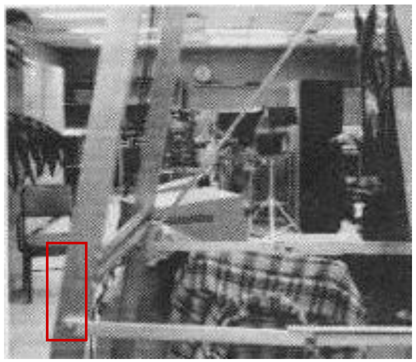
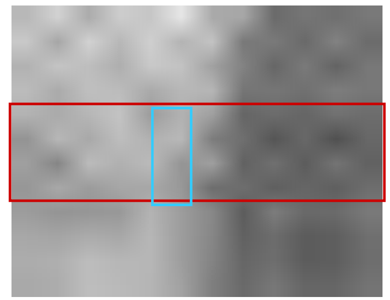
90	90	70	40	25
90	70	40	40	25
90	70	**40**	40	25
90	70	40	40	20
70	50	40	30	15

I(0,0,1)

We can estimate things like $\frac{dI}{dx} = I_x$ at (0,0,0) $= \frac{\Delta I}{\Delta x} = \frac{I(1,0,0) - I(0,0,0)}{1 - 0} = -30$

Optical Flow

By measuring the direction that intensities are moving...

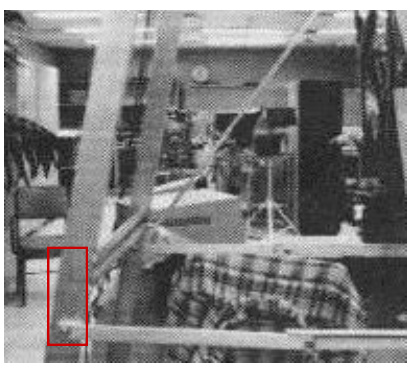
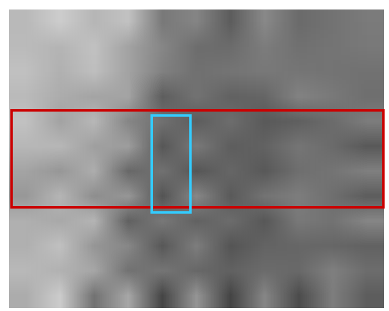
I(x,y,t)

I(x,y,0)

99	90	90	70	40
95	90	70	40	40
90	90	**70**	40	40
90	90	70	40	**40**
90	70	50	40	30

I(0,0,0)

I(2,-1,0)

I(x,y,1)

90	90	70	40	25
90	70	40	40	25
90	70	**40**	40	25
90	70	40	40	20
70	50	40	30	15

I(0,0,1)

We can estimate things like $\frac{dI}{dx} = I_x \quad \frac{dI}{dy} = I_y \quad \frac{dI}{dt} = I_t$ so...

Measuring Optical Flow

Let I(x,y,t) be the sequence of images.

Simplest assumption (constant brightness constraint):

$$I(x,y,t) = I(x + dx, y + dy, t + dt)$$

(x,y,t)

99	90	90	70	40
95	90	70	40	40
90	90	70	40	40
90	90	70	40	40
90	70	50	40	30

Measuring Optical Flow

Let I(x,y,t) be the sequence of images.

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$$I(x,y,t) = I(x + dx, y + dy, t + dt)$$

(x,y,t)

99	90	90	70	40
95	90	70	40	40
90	90	70	40	40
90	90	70	40	40
90	70	50	40	30

Reminder: $f(x + dx) = f(x) + f'(x)\, dx + f''(x)\, dx^2 /2 + \ldots$

Measuring Optical Flow

Let $I(x,y,t)$ be the sequence of images.

(x,y,t)

99	90	90	70	40
95	90	70	40	40
90	90	70	40	40
90	90	70	40	40
90	70	50	40	30

Simplest assumption (constant brightness constraint):

$$I(x,y,t) = I(x + dx, y + dy, t + dt)$$

Reminder: $f(x + dx) = f(x) + f'(x)\,dx + f''(x)\,dx^2/2 + \ldots$

$$I(x,y,t) = I(x,y,t) + I_x\,dx + I_y\,dy + I_t\,dt + \text{2nd deriv. + higher}$$

Measuring Optical Flow

Let $I(x,y,t)$ be the sequence of images.

(x,y,t)

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$$-I_t = I_x \frac{dx}{dt} + I_y \frac{dy}{dt}$$

intensity-flow equation

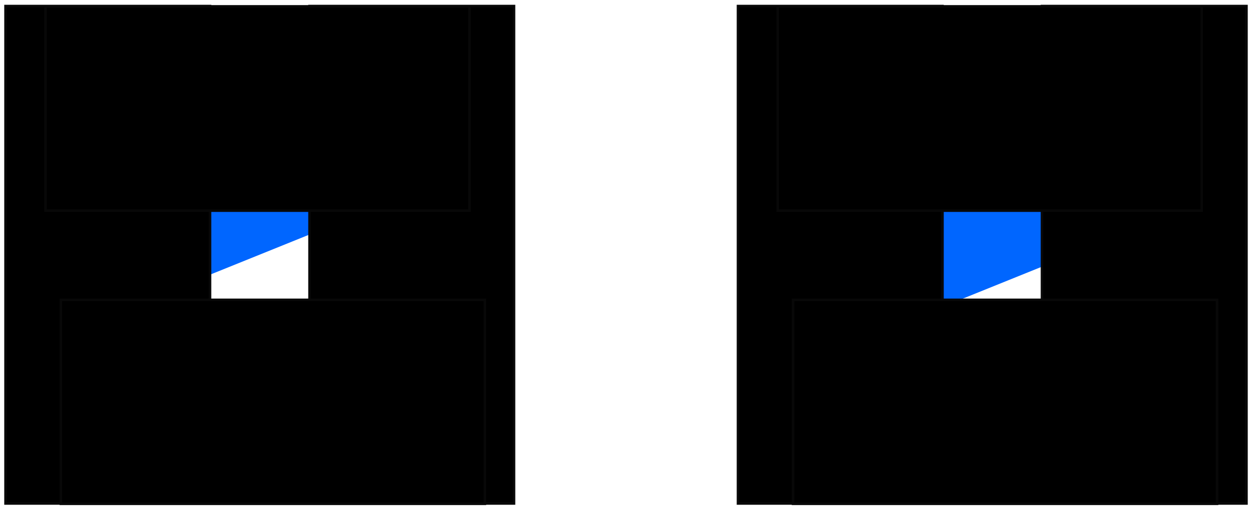
good and bad...

The “aperture” problem

$$-I_t = I_x \frac{dx}{dt} + I_y \frac{dy}{dt}$$

- The intensity-flow equation provides only one constraint on *two* variables (x-motion and y-motion)

→ It is only possible to find optical flow in one direction...



The "aperture" problem

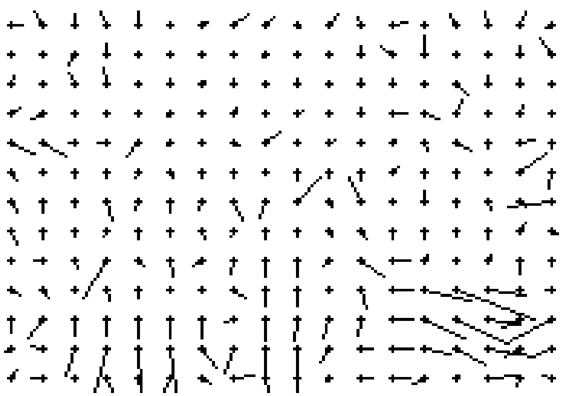
→ It is only possible to find optical flow in one direction...

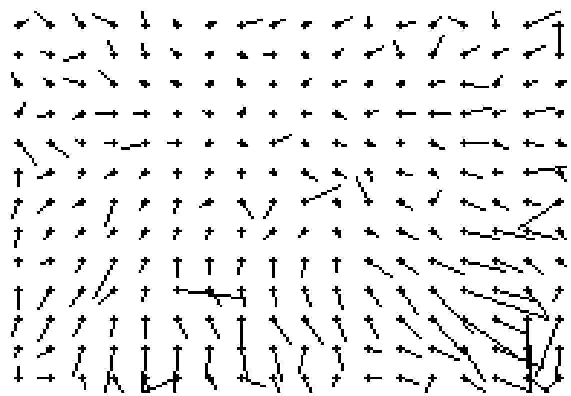
*at any **single** point in the image !*

img1

img2

raw optical flow





smoothed for ten iterations

Smoothing can be done by incorporating neighboring points' information.

Optical Flow Application

- Visual Odometry
  - Wheel slip detection on future Mars Rovers

Image Downsampling