## Cameras

- First photograph due to Niepce
- First on record shown in the book - 1822
- Basic abstraction is the pinhole camera
- lenses required to ensure image is not too dark
- various other abstractions can be applied


## Pinhole cameras

- Abstract camera model box with a small hole in it
- Pinhole cameras work in practice


Set: Cameras
Slides by D A Forsyth


## Parallel lines meet

Common to draw film plane
in front of the focal point.
Moving the film plane merely scales the image.

## Vanishing points

- each set of parallel lines (=direction) meets at a different point
- The vanishing point for this direction
- Sets of parallel lines on the same plane lead to collinear vanishing points.
- The line is called the horizon for that plane
- Good ways to spot faked images
- scale and perspective don't work
- vanishing points behave badly
- supermarket tabloids are a great source.



## The equation of projection



## The equation of projection

- Cartesian coordinates:
- We have, by similar triangles, that
( $\mathrm{x}, \mathrm{y}, \mathrm{z}$ ) -> (f x/z, fy/z, -f)
- Ignore the third coordinate, and get

$$
(x, y, z) \rightarrow\left(f \frac{x}{z}, f \frac{y}{z}\right)
$$

## Homogenous coordinates

- Add an extra coordinate and use an equivalence relation
- for 2D
- equivalence relation
$\mathrm{k}^{*}(\mathrm{X}, \mathrm{Y}, \mathrm{Z})$ is the same as (X,Y,Z)
- for 3D
- equivalence relation
- Basic notion
- Possible to represent points "at infinity"
- Where parallel lines intersect
- Where parallel planes intersect
- Possible to write the action of a perspective camera as a matrix
$\mathrm{k}^{*}(\mathrm{X}, \mathrm{Y}, \mathrm{Z}, \mathrm{T})$ is the same as (X,Y,Z,T)


## The camera matrix

- Turn previous expression into HC's
- HC's for 3D point are (X,Y,Z,T)
- HC's for point in image are (U,V,W)

$$
\left(\begin{array}{c}
U \\
V \\
W
\end{array}\right)=\left(\begin{array}{llll}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 / f & 0
\end{array}\right)\left(\begin{array}{l}
X^{\prime} \\
Y \\
Z \\
T
\end{array}\right)
$$

## Weak perspective

- Issue
- perspective effects, but not over the scale of individual objects
- collect points into a group at about the same depth, then divide each point by the depth of its group
- Adv: easy

- Disadv: wrong


## Orthographic projection



## The projection matrix for orthographic projection

$$
\left(\begin{array}{l}
U \\
V \\
W
\end{array}\right)=\left(\begin{array}{llll}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1
\end{array}\right)\left(\begin{array}{l}
X \\
Y \\
Z \\
T
\end{array}\right)
$$

Pinhole too big -
many directions are averaged, blurring the image

Pinhole too smalldiffraction effects blur the image


Generally, pinhole cameras are dark, because a very small set of rays from a particular point hits the screen.



## Spherical aberration



Lens systems


## Vignetting



## Other (possibly annoying) phenomena

- Chromatic aberration
- Light at different wavelengths follows different paths; hence, some wavelengths are defocussed
- Machines: coat the lens
- Humans: live with it
- Scattering at the lens surface
- Some light entering the lens system is reflected off each surface it encounters (Fresnel's law gives details)
- Machines: coat the lens, interior
- Humans: live with it (various scattering phenomena are visible in the human eye)
- Geometric phenomena (Barrel distortion, etc.)


## Camera parameters

- Issue
- camera may not be at the origin, looking down the z-axis
- extrinsic parameters
- one unit in camera coordinates may not be the same as one unit in world coordinates
- intrinsic parameters - focal length, principal point, aspect ratio, angle between axes, etc.
$\left(\begin{array}{l}U \\ V \\ W\end{array}\right)=\left(\begin{array}{l}\text { Transformation } \\ \text { representing } \\ \text { intrinsic parameters }\end{array}\right)\left(\begin{array}{llll}1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0\end{array}\right)$ (ransformation $\left.\begin{array}{l}\text { extrinsic parameters }\end{array}\right)\left(\begin{array}{l}X \\ Y \\ Z \\ T\end{array}\right)$


## Camera calibration

- Issues:
- what are intrinsic parameters of the camera?
- what is the camera matrix? (intrinsic+extrinsic)
- General strategy:
- view calibration object
- identify image points
- obtain camera matrix by minimizing error
- obtain intrinsic parameters from camera matrix
- Error minimization:
- Linear least squares
- easy problem numerically
- solution can be rather bad
- Minimize image distance
- more difficult numerical problem
- solution usually rather good,
- start with linear least squares
- Numerical scaling is an issue


## Geometric properties of projection

- Points go to points
- Lines go to lines
- Planes go to whole image
- Polygons go to polygons
- Degenerate cases
- line through focal point to point
- plane through focal point to line



## Polyhedra project to polygons

- (because lines project to lines)


## Junctions are constrained

- This leads to a process called "line labelling"
- one looks for consistent sets of labels, bounding polyhedra
- disadv - can't get the lines and junctions to



## Curved surfaces are much more interesting

- Crucial issue: outline is the set of points where the viewing direction is tangent to the surface
- This is a projection of a space curve, which varies from view to view of the surface


