University of Birmingham

Computer Science Year 2
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Year 2 Study Guide

Contents

Chapter 1

Graphics

1.1 Surface Geometry

This section covers the basics introduced in how to represent shapes in a computer.

1.1.1 Notes

- Graphics Pipeline: It refers to the sequence of steps used to create a 2D raster representation of a 3D scene. It is the process of turning a 3D model into what the computer displays.
- Vertex: A point with three numbers representing its XYZ position in a plane
- Edge: An edge is the difference between two vertices; the segment connecting them
- Surface: A closed set of edges representing a face of a 3D object
- Polygon: A shape in space usually representing by a set of surfaces (other methods listed below)
- Polygon Table: A table containing a set of either vertices, edges and/or surfaces that is used to define the boundaries of a polygon. This is one method to define Polygons.
- Delaunay Triangulation: Given a set P of points in a plane, creates a triangular mesh DT(P) such that no point in P is inside the circumcircle of any triangle in DT(P).
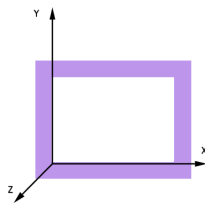
Figure 1.1: Coordinate system assumed throughout module

The default coordinate system assumed is right-handed: the positive x and y axes point right and up, and the negative z axis points forward. Positive rotation is counterclockwise about the axis of rotation.
Polygon Table consistency checks:
1. Every vertex is listed as an endpoint of at least two edges
2. Every surface is closed
3. Each surface has at least one shared edge
The order the vertices/edges are listed in a Geometric Polygon table do matter. Vertices written in clockwise order represent a surface pointing outwards. Whereas listing them counterclockwise represents an inwards pointing surface.

Meshes are a wireframe representation in which all vertices form a single set of continuous triangles, and all edges are a part of at least two triangles. Meshes can be generated by triangulation; but we covered just Delaunay Triangulation, defined above. Meshes can also be progressive. Detail in meshes is unnecessary at farther distances, so vertices can be removed and added to create less detailed or more detailed meshes, respectively. Progress meshes do this dynamically based on viewer distance.

There are a few ways to represent polygons in a space, with boundary representations being only one method.

1. Boundary Representation: Using vertices and drawing edges and surfaces from them
2. Volumetric Models: Using simple shapes and various operations to create more complex shapes
3. Implicit Models: Using implicit equations, such as that of a sphere, to generate shapes
4. Parametric Models: Uses parametric equations to plot the multiple axes of a shape
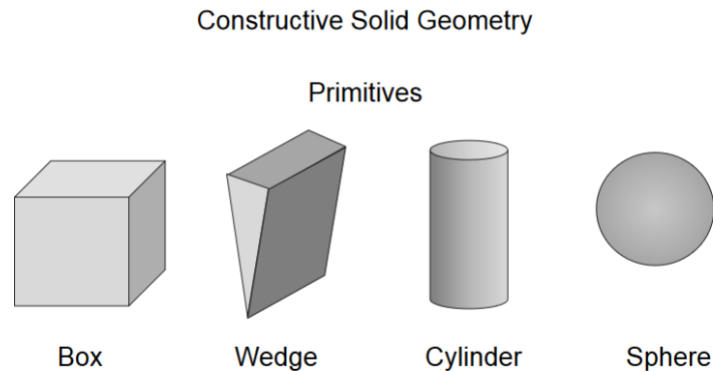
Figure 1.2: Constructive Solid Geometry (CSG) Primitives

We covered a few volumetric models in the module.

1. CSG: Uses primitve shapes and combines them uses set operations (union, difference, exclude, etc.) to generate new, more complex shapes.
2. Voxels: 3D Pixels, unit cubes
3. Octrees: Quad trees that divide in 3D space. Individual partitions are voxels
4. Sweep: Using a 2D shape, moves that shape across a path, generating a volume in position the 2D shape occupies during its path

One can also use implicit or parametric equations to generate shapes. Below is a list of equations that are common.

2D Circle:
$$\left(\frac{x}{r}\right)^2 + \left(\frac{y}{r}\right)^2 = 1 \tag{1.1}$$

2D Circle - Parametric:
$$\begin{aligned} x &= r\cos\theta \\ y &= r\sin\theta \\ -\pi &\leq \theta \leq \pi \end{aligned} \tag{1.2}$$

2D Ellipse - Parametric:
$$\begin{aligned} x &= r_x\cos\theta \\ y &= r_y\sin\theta \\ -\pi &\leq \theta \leq \pi \end{aligned} \tag{1.3}$$

3D Sphere:

$$\left(\frac{x}{r}\right)^2 + \left(\frac{y}{r}\right)^2 + \left(\frac{z}{r}\right)^2 = 1 \tag{1.4}$$

3D Ellipsoid:

$$\left(\frac{x}{r_x}\right)^2 + \left(\frac{y}{r_y}\right)^2 + \left(\frac{z}{r_z}\right)^2 = 1 \tag{1.5}$$

3D Sphere - Parametric:

$$\begin{aligned}
x &= r\cos\phi\cos\theta \\
y &= r\cos\phi\sin\theta \\
z &= r\sin\phi \\
-\pi &\le \theta \le \pi \\
-\pi/2 &\le \phi \le \pi/2
\end{aligned} \tag{1.6}$$

3D Ellipsoid - Parametric:

$$\begin{aligned}
x &= r_x\cos\phi\cos\theta \\
y &= r_y\cos\phi\sin\theta \\
z &= r_z\sin\phi \\
-\pi &\le \theta \le \pi \\
-\pi/2 &\le \phi \le \pi/2
\end{aligned} \tag{1.7}$$

1.1.2 Examples

Define a vertex table and a surface table for the pyramid, depicted on the right. The base of the pyramid is a square with the side a=2 centered in the origin. The height of the pyramid is equal to 2. Work in the right handed coordinate system.
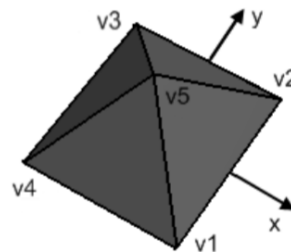
v1 [1; -1; 0]   f1 : v1 - v2 - v5
v2 [1; 1; 0]   f2 : v2 - v3 - v5
v3 [-1; 1; 0]   f3 : v3 - v4 - v5
v4 [-1; -1; 0]   f4 : v4 - v1 - v5
v5 [0; 0; 2]   f5 : v1 - v4 - v3 - v2

Figure 1.3:   Example from Lecture

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Further Examples are taken from quizzes and assignments

Consider the following vertex table and edge table for a convex 3D shape. Create the corresponding polygon (surface) table for that shape. Use vertex indices in your table.

vertex table

vertices	x	y	z
V1	2	0	-2
V2	0	1	-3
V3	1	2	-5.5
V4	2	3	-8
V5	4	3	-9
V6	5	1	-5.5
V7	4	2	4

edge table

E1	V7	V1
E2	V7	V2
E3	V7	V3
E4	V7	V4
E5	V7	V5
E6	V7	V6
E7	V1	V2
E8	V2	V3
E9	V3	V4
E10	V4	V5
E11	V5	V6
E12	V6	V1

Figure 1.4: Example from Quiz

Surfaces:
S1 = V1, V2, V3, V4, V5, V6
S2 = V1, V7, V2
S3 = V2, V7, V3
S4 = V2, V7, V3
S5 = V4, V7, V5
S6 = V5, V7, V6
S7 = V6, V7, V1

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1.1.3 Normal Vectors

The normal vector of a surface points outwards from the surface. This is later used for lighting, projection and culling. Calculating normal vectors is a fairly simple task. For boundary polygons, the normal of a face is the cross product of two edges. Assuming vectors A and B, the cross product is the determinant of the following matrix;

$$
\begin{bmatrix}
i & j & k \\
A_x & A_y & A_z \\
B_x & B_y & B_z
\end{bmatrix}
\tag{1.8}
$$

Which can be minimized to the following (longer) equation;

$$
N = \begin{bmatrix}
A_y B_z - A_z B_y \\
A_z B_x - A_x B_z \\
A_x B_y - A_y B_x
\end{bmatrix}
\tag{1.9}
$$

To know which vectors to use for A and B, simply select an edge on a surface, and you use your right hand with your thumb pointing outwards and curl your hand around in the direction until the first vector hits your hand. Alternatively, you can piece it together by looking at the figure.

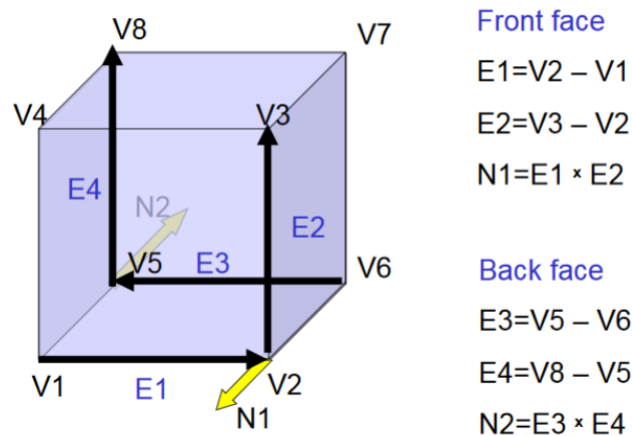Figure 1.5: Normal Vector of cube from lecture

Front face
E1=V2 – V1
E2=V3 – V2
N1=E1 × E2

Back face
E3=V5 – V6
E4=V8 – V5
N2=E3 × E4

1.1.4 Further Sources

Surface Representations
Alternate Lecture

1.2   Transforms

This section covers simple transformation matrices.

1.2.1   Notes

- Transformation: a function that can be applied to each of the points in a geometric object to produce a new object.
- Translation: A geometric transform that adds a given translation amount to each co-ordinate of a point. Translation is used to move objects without changing their size or orientation.
- Rotation: A geometric transform that rotates each point by a specified angle about some point (in 2D) or axis (in 3D).
- Scaling: A geometric transform that multiplies each coordinate of a point by a number called the scaling factor. Scaling increases or decreases the size of an object, but also moves its points closer to or farther from the origin.

Transformations are applied to geometric objects to move them around. This is valuable when considering camera positions, or when laying out a world in a video game. Transformations can be applied as equations for each dimensions eg.

$$T_x = x + t_x$$

is the new x-position when applying the translation. However, there is a lack of uniformity between different transforms, some requiring x and y more than once, others being matrices. To standardize transforms, we instead use *Homogeneous Transformation Matrices*. Convert a 2D point to a 3D point by setting z = 1, and apply the transforms as matrices by replacing the variable found in each matrix template. This is an easy way of standardizing the equations, and allows for easy transforms by multiplying the transformations together before multiplying them with the point.

For example, applying a Translation T and then a Rotation R can be done by multiplying RT first and then multiplying the new transform matrix with the original points. This also makes it more efficient to move more than one point when they share the same transform, as it only need one multiplication per-point rather than one per-transform per-point.

1.2.2   Transformation Matrices

$$T_{2D} = \begin{bmatrix} 1 & 0 & T_x \\ 0 & 1 & T_y \\ 0 & 0 & 1 \end{bmatrix} \tag{1.10}$$

$$S_{2D} = \begin{bmatrix} S_x & 0 & 0 \\ 0 & S_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1.11}$$

$$R_{2D} = \begin{bmatrix} \cos\theta & -\sin\theta & T_x \\ \sin\theta & \cos\theta & T_y \\ 0 & 0 & 1 \end{bmatrix} \tag{1.12}$$

$$T_{3D} = \begin{bmatrix} 1 & 0 & 0 & T_x \\ 0 & 1 & 0 & T_y \\ 0 & 0 & 1 & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1.13}$$

$$S_{3D} = \begin{bmatrix} S_x & 0 & 0 & 0 \\ 0 & S_y & 0 & 0 \\ 0 & 0 & S_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1.14)$$

$$R_{3D_X} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta & 0 \\ 0 & \sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1.15)$$

$$R_{3D_Y} = \begin{bmatrix} \cos\theta & 0 & \sin\theta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta & 0 & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1.16)$$

$$R_{3D_Z} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1.17)$$

1.2.3 Examples

MATLAB Assignment Rotating

```
2. Apply rotation transformation to bowl object mesh model
%%% Define matrices for rotation of the bowl object around x, y and z ...
    axes by 20, 80 and 55 degrees respectively.
%%% Apply these three transformations to the original ...
    (non-transformed) bowl object in the given order
%%% and visualize the result using trisurf function.
%%% Save the result of your visualization to "2.png" file and include ...
    this file in your submission.
rx = [1 0 0 0; 0 cosd(20) -sind(20) 0; 0 sind(20) cosd(20) 0; 0 0 0 1];
ry = [cosd(80) 0 sind(80) 0; 0 1 0 0; -sind(80) 0 cosd(80) 0; 0 0 0 1];
rz = [cosd(55) -sind(55) 0 0; sind(55) cosd(55) 0 0; 0 0 1 0; 0 0 0 1];
rotated_object_vertices = rz*ry*rx*obj_v4;
```

Scaling

```
%% 3. Apply scaling transformation to bowl object mesh model
%%% Define a matrix for scaling of bowl object with scaling factor f = ...
    [3.5, 1.5, 2] in direction of x, y and
%%% z axes. Apply this matrix to your original bowl object ...
    (non-transformed) and visualize the result
%%% using trisurf function. Save the result of your visualization to ...
    "3.png"? file and include this file in your
%%% submission.

scaling = [3.5 0 0 0; 0 1.5 0 0; 0 0 2 0; 0 0 0 1];
scaled_object_vertices = scaling*obj_v4;
```

Translating

```matlab
%% 4. Apply translation transformation to bowl object mesh model
%%% Define a matrix for translation of bowl object by [-500, 50, -100] in ...
    direction of x, y and z axes. Apply
%%% this matrix to your original bowl object and visualize the result ...
    using trisurf function. Save the result
%%% of your visualization to "4.png"? file and include this file in your ...
    submission.

translate = [1 0 0 -500; 0 1 0 50; 0 0 1 -100; 0 0 0 1];
translated_object_vertices = translate*obj_v4;
```

3-in-1 Wombo Combo

```matlab
%% 5. Apply all 3 transformations defined above to your original ...
    (non-transformed) bowl object one after the other in the given order.
%%% Display transformed meshes in the figure using trisurf.
%%% Save the result of your visualisation to "5.png" file and include ...
    this file to you submission folder.

%% Compute transformations (4x4 transformation matrices)

object_transformation = translate*scaling*rz*ry*rx;
```

1.2.4 References

Quick Overview

1.3 Lighting

This section covers things related to lighting and shading of objects in a scene.

1.3.1 Notes

- Diffuse: Non-shiny illumination
- Specular: Shiny reflections
- Ambient: background illumination

Ambient Light

- Global background light
- No direction
- Does not depend on anything

Diffuse Light

- Parallel Light Rays originating from a source direction
- Contributes to Diffuse and Specular Term

Spot Light

- Originates from a single source point
- Conic dispersion of light, intensity is a function of distance
- More realistic

Surface Properties

- Geometry - Position, orientation
- Colour - reflectance and Absorption spectrum
- Micro-structure - defines reflectance properties

Shading Models

- Flat shading is the simplest shading model. Each rendered polygon has a single normal vector; shading for the entire polygon is constant across the surface of the polygon. With a small polygon count, this gives curved surfaces a faceted look.
- Phong shading is the most sophisticated of the three. Each rendered polygon has one normal vector per vertex; shading is performed by interpolating the vectors across the surface and computing the color for each point of interest.
- Gouraud shading is in between the two: like Phong shading, each polygon has one normal vector per vertex, but instead of interpolating the vectors, the color of each vertex is computed and then interpolated across the surface of the polygon.
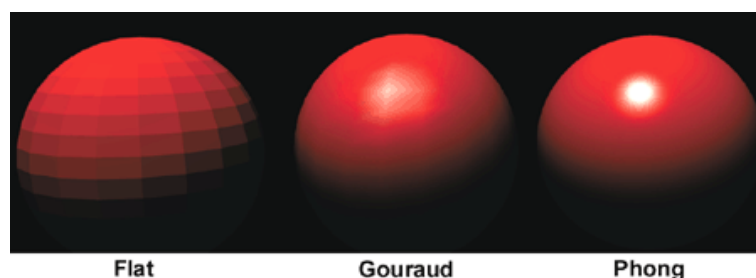
Figure 1.6: Shading Model Differences

1.3.2 Phong Shading Equation

$$Colour = Ambient + Diffuse + Specular$$
$$Colour = I_a K_a + I_d K_d \cos \theta_L + I_s K_s \cos^n \theta_S$$
(1.18)

Ambient Term This is very easy. It is the K_a term multiplied with the Ambient intensity I_a.

$$Ambient = I_a K_a$$
(1.19)

Diffuse Term The diffuse term is usually straight forward.. It is the K_d term multiplied with the Light source intensity I_d. The angle θ between the light source and the normal of the surface is then computed, and the $cos(\theta)$ is multiplied to obtain the full term.

$$Diffuse = I_d K_d \cos \theta_L$$
(1.20)
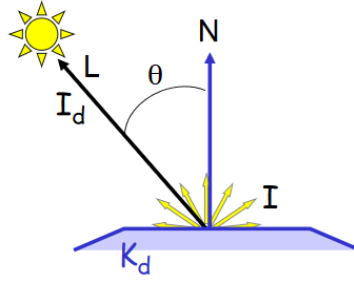
Figure 1.7: Diffuse term overview

Specular Term The specular term needs a few more steps. It is the K_s term multiplied with the reflected Light source intensity I_s. This is the ray that is bounced off of the surface, and is θ_L away from the normal of the surface. This intensity is multiplied by the cos of the angle θ_S, the angle between the reflected ray and the line of sight from the camera. The cos is raised to the n_{th} power, a factor known as a shininess factor that is usually given.

$$Diffuse = I_d K_d \cos^n \theta_S$$
(1.21)
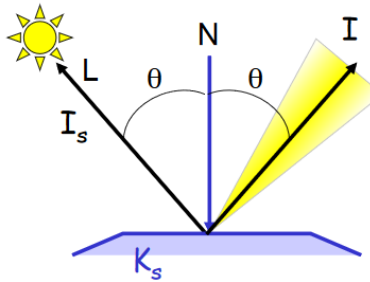
Figure 1.8: Specular term overview

1.3.3 Examples

MATLAB Assignment

Calculating Ambient Term

```matlab
1  function colour = calcAmbient_skeleton(pixel_colour_current, Ia,Ka)
2
3  % Colour at current pixel
4  colour = pixel_colour_current;
5
6  % TO DO: Compute colour of the pixel here and write values to the
7  % corresponding place in image ImA
8
9  ambient = Ia.* Ka;
10 for i = 1:size(colour, 3)
11 colour(:,:,i) = ambient(i,i,:);
12 end
13 end
```

Calculating Diffuse Term

```matlab
1  function colour = calcDiffuse_skeleton(pixel_colour_current, ...
       point_position, light_position, surface_normal, Id, Kd)
2
3  % Colour at current pixel
4  colour = pixel_colour_current;
5
6  %TO DO: Calculate light direction from light position and point position
7  light_direction = light_position - point_position;
8  %TO DO: Calculate normalised light direction
9  normalised_light = light_direction / norm(light_direction);
10 %TO DO: Calculate cos light direction, removing negative
11 %values
12 cos_light = dot(surface_normal, normalised_light);
13
14 %TO DO: Compute colour colour of the pixel here and write
15 % values to the corresponding place in image ImD
16 diffuse = Id.*(Kd.*cos_light);
17 for i = 1:size(colour, 3)
18 colour(:,:,i) = colour(:,:,i) + diffuse(i);
19 end
20 end
```

Calculating Specular Term

```matlab
1  function colour = calcSpecular_skeleton(pixel_colour_current, ...
       point_position, light_position, surface_normal,normal_towardsViewer, ...
       shininess_factor, Is, Ks)
2
3  % Colour at current pixel
4  colour = pixel_colour_current;
5
6  %TO DO: Calculate light direction from light position and point position
7  light_direction = point_position - light_position;
8
9  %TO DO: Normalised light direction
10 normalised_light = light_direction / norm(light_direction);
11 %TO DO: Normal component
12 n = surface_normal / norm(surface_normal);
13 %TO DO: Reflected Ray (tangent + ray in one step)
14 R = n*2*dot(n, -1*normalised_light) + normalised_light;
15 %TO DO: Normalised Reflected Ray
16 normalised_reflection = R / norm(R);
17 %TO DO: Calculate cos_spec, removing negative values
18 cos_light = dot(normal_towardsViewer, normalised_reflection);
19 if (cos_light < 0)
20 cos_light = 0;
21 end
22 %TO DO:  compute colour colour of the pixel here and write
23 % values to the corresponding place in image ImS
24 specular = Is.*(Ks.*(cos_light^shininess_factor));
25 for i = 1:size(colour, 3)
26 colour(:,:,i) = colour(:,:,i) + specular(i);
27 end
28
29 end
```

1.3.4   References

[WebGL Specular Term](#)

1.4 Projection

This section deals with the virtual camera and how objects are projected from a proposed 'world' to a camera space.

1.4.1 Notes

- View Reference Point (VRP): The centre point/position where the eyes/camera is positioned
- Viewing Plane: The 2D plane in which images are rendered onto in relation to the camera
- Gaze Vector (N): The direction vector from the VRP facing towards the viewing plane
- Up Vector (U): The vector perpendicular to the normal facing upwards in relation to the Gaze Vector
- Handedness Vector (V): The vector perpendicular to the Gaze and Up Vectors facing right in relation to the gaze vector.
- Camera Coordinate System: The coordinate system formed by the N, U and V vectors acting as axes
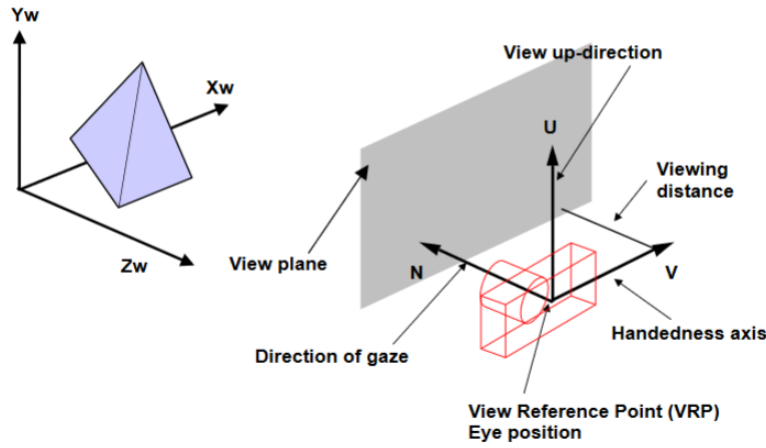
Figure 1.9: Visualised definitions

When rendering to camera, you first need to have a World Coordinate System and objects in that world. From there, you should know VRP and the Viewing Plane. (TP is the position on the Viewing Plane the camera points to.) Using this information, we can calculate the Camera Coordinate System (N V U).

$$\begin{aligned}
\text{U}_{temp} &= [0 \ 1 \ 0] \\
\text{N} &= \text{TP - VRP} \\
\text{V} &= \text{U}_{temp} \text{ x N} \\
\text{U} &= \text{N x V}
\end{aligned}$$

We use transformation matrices to move objects form the World Coordinate System to the Camera Coordinate System. Translate to the camera position, rotate to orient with the camera, then scale the x-axis -1 to convert to the left-hand coordinate system to avoid mirroring.

$$T_{cam} = \begin{bmatrix} 1 & 0 & 0 & -x_{vrp} \\ 0 & 1 & 0 & -y_{vrp} \\ 0 & 0 & 1 & -z_{vrp} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1.22}$$

$$R_{cam} = \begin{bmatrix} \frac{V_x}{|\mathbf{V}|} & \frac{V_y}{|\mathbf{V}|} & \frac{V_z}{|\mathbf{V}|} & 0 \\ \frac{U_x}{|\mathbf{U}|} & \frac{U_y}{|\mathbf{U}|} & \frac{U_z}{|\mathbf{U}|} & 0 \\ \frac{N_x}{|\mathbf{N}|} & \frac{N_y}{|\mathbf{N}|} & \frac{N_z}{|\mathbf{N}|} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1.23}$$

$$S_{cam} = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1.24}$$

- Centre of Project (COP): The view point the perspective is drawn from, usually the camera position
- Perspective Projection: Objects further away from the COP are scaled smaller
- Orthographic Projection: All objects are on the same scale, regardless of COP

Figure 1.10:   Projection Lines meet at the COP

The centre of project can be placed at either the centre/origin of the viewing coordinate system with the viewing plane on the positive z size, or the negative z side with the viewing plane placed on the centre/origin of the viewing coordinate system. Depending on which method is chosen, the computation differs slightly.

COP at Z=0

Figure 1.11:   COP $= 0$

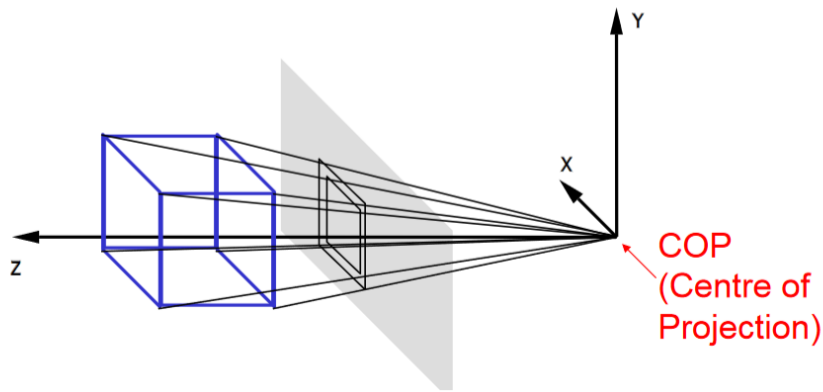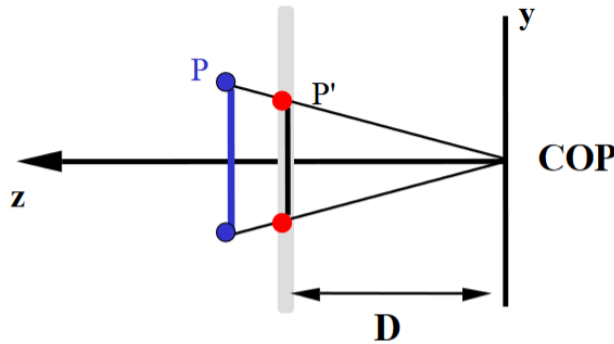$$P_{per} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 1/\mathbf{D} & 0 \end{bmatrix} \qquad (1.25)$$

Where $\mathbf{D}$ is the distance from the COP and the viewing plane. The generated matrix after multiplication is not homogenous; to convert it to homogenous form we simply divide all terms by the 4th term, which equates to

$$z/D$$

With the perspective project matrix, we can create a general form for moving the object from the World Space to the Camera Space.

$$C = P_{per} * S_{cam} * R_{cam} * T_{cam} \qquad (1.26)$$

With the new vector converted to homogenous coordinates after applying C. All new coordinates should also have their Z coordinate equal to te Z coordinate of the viewing plane.
COP at Z¡0 When the viewing plane is at the origin, P_{per} changes slightly.

$$P_{per} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 1/\mathbf{D} & 1 \end{bmatrix} \qquad (1.27)$$

Converting to homogenous would also be slightly different, but will still be fairly simple. All Z coordinates should end up at Z=0.

1.4.2 Examples

The questions here are from the quiz.
Consider the following vertex coordinates:

$$V1 = [0, 10, 0]$$
$$V2 = [5, 0, 5]$$
$$V3 = [15, 5, 0]$$
$$V4 = [5, 10, 15]$$

Define the viewing (camera) coordinate system by computing its axes, i.e., direction of gaze N, handedness vector V, and vector U which is the correct up-vector. Camera view reference point is VRP = [60, 30, 100], and the target point TP is at the origin ([0, 0, 0]). The camera coordinate system should be defined in the same way as it is shown in the lecture slides: using temporary up vector of [0,1,0] to compute handedness and up vectors of the camera.
  1. What is the direction of the gaze vector?
  2. What is the handedness vector?
  3. What is the up vector?
  4. Compute the matrix C_1 to transform an object from the world coordinate system to the camera coordinate system (without project).
  5. Compute the matrix C_2 to transform an object from the world coordinate system to the camera coordinate system with the COP at the origin and the viewing plane at z= +40.
  6. Compute the positions of the final transformed vertices.

Answers to the previous questions

1. $N = [-0.50, -0.25, -0.83]$
2. $V = [-0.86, 0, 0.51]$
3. $U = [-0.13, 0.97, -0.21]$
4. $C_1 = \begin{bmatrix} 0.857 & 0 & -0.514 & 0 \\ -0.128 & 0.968 & -0.214 & 0 \\ -0.498 & -0.249 & -0.830 & 120 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
5. $C_2 = \begin{bmatrix} 0.857 & 0 & -0.514 & 0 \\ -0.128 & 0.968 & -0.214 & 0 \\ -0.498 & -0.249 & -0.830 & 120 \\ -0.013 & -0.006 & -0.021 & 3.010 \end{bmatrix}$
6. $V_1 = [0.00, 3.29, 40.0]$
   $V_2 = [0.60, -0.60, 40]$
   $V_3 = [4.61, 1.05, 40]$
   $V_4 = [-1.33, 2.27, 40]$

1.4.3   References

No external references were needed on this section.

1.5   Misc. Definitions

This section covers general algorithms and definitions from Rendering to Texture Mapping. Since the exam will focus more on the previous parts for the more technical questions, this part will mostly be structured as a set of definitions.

1.5.1   Rasterisation

- Rasterisation: Converting an object from vector world coordinates to a raster image to display
- Digital Differential Analyzer (DDA): Rasterisation algorithm, interpolates values in an interval by computing separate equations for (x, y). Is expensive and inefficient.
- Bresenham Algorithm: Incremental, integer only algorithm. Has many implementations.
- Antialiasing: utilizes blending techniques to blur the edges of the lines and provide the viewer with the illusion of a smoother line.

Circles can be plotted either directly with a circle equation, directly with polar coordinates, or using Bresenhams by looping across a set of values until all values on a circle are plotted. Bresenham and Polar methods abuse the symmetry of a circle's points.
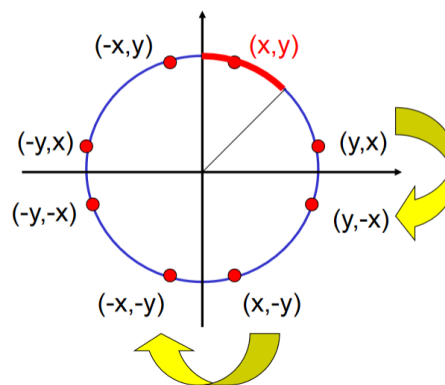
Figure 1.12:   Symmetry of circle

1.5.2   Texture Mapping

Texture mapping can be defined as using an image and pasting the image onto a geometric model. There are three types of Texture Mapping.

1. Texture Image: uses iamges to fill inside polygons; inverse mapping using an intermediate surface
2. Environment/Reflection: uses a picture of the scene for texture maps
3. Bump: Emulates altering normal vectors during render process
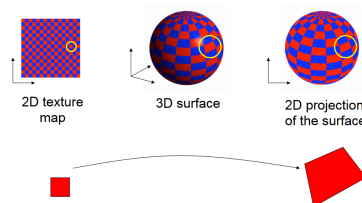

Figure 1.13:   Image Mapping flow

When it comes to image mapping, there are two main methods.

1. Forward: copy pixel at source (u, v) to image destination (r, c). Its easy to compute but leaves holes.
2. Backward: for image pixels (r, c), grab texture pixel (u, v). Harder to compute but looks better.

Environment mapping uses the direction of te reflected ray to index a texture map rather than using the ray projected to its surface. This approach isn't completely accurate as it assumes all reflected rays begin from the same point and that all objects in a scene are the same distance from that point.

Bump mapping is a method used to make a surface look rough. There are two variants.

1. Displacement Mapping: Height filed is used to perturb surface point along the direction of its surface normal. Inconvenient to implement since map must perturb geometry of model.
2. Bump Mapping: A perturbation is applied to the surface normal according to the corresponding value in the map. Convenient to implement as it automatically changes the shading parameters of a surface.

There is also mip-mapping. Mapping can cause aliasing to occur; mip-mapping is an anti-aliasing technique that stores texture as a pyramid of progressive resolution images, filtered down from the original. The further away a point is to be rendered, the lower lower resolution MIP-map is used.
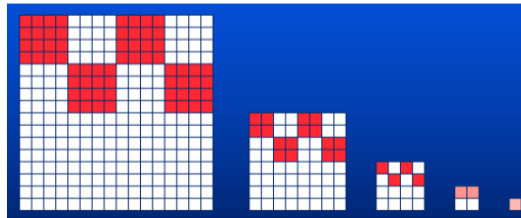
Figure 1.14: MIP-map examples

1.5.3 Hidden Surface Removal

1. Object-space method (OS): Operate on 3D Object entities.(vertices, edges, surfaces)
2. Image-sped (IS): Operate on 2D images (pixels)

There are a few algorithms to go over.

- Polygon Culling: removes all surfaces pointing away from the viewer; renders only what is visible; can be done by comparing if the z-value of the surface normal has the same sign as the z-value of the gaze vector. (If same, remove surface)
- Z-buffer Algorithm: Test visibility of surfaces one point at a time. Easy to implement, fits well with render pipeling, but some inefficiency with large distances. Standard algorithm in many packages, eg. OpenGL
- Painter's Algorithm: OS algorithm; Draw surfaces from back to front. Problems occur with overlapping polygons; as it will always render an object either above or below absolutely.
- Depth Sort: Painter's extension; sorts objects by depth like painters, but resolves overlap issues, splitting polygons if necessary. Does overlap/collision testing and splits on intersection point.

1.5.4 Splines

Splines are smooth curves generated from an input set of user-specified control points.
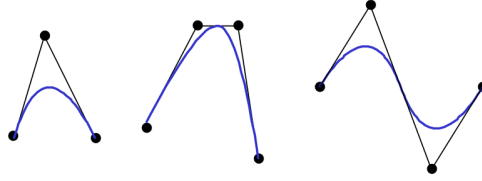
Figure 1.15: Splines with different control points

Bezier curves are generated by forming a set of polynomial functions formed from the coordinates of the control points. In parametric form, a Bezier Function $P(u)$ can be represented as

$$P(u) = \sum_{k=0}^{n} p_k B_{kn}(u)$$

There are many ways to formulate Bezier curves. One such method is the de Casteljau algorithm. This algorithm describes the curve as a recursive series of linear interpolations. We draw lines between each of our control points in order, then continuously Lerp (linearly interpolate) each of the points generated by the previous Lerp until a curve is formed.

Bezier curve shape is influenced by all of its control points. There are B-splines that are only influenced by up to four of the nearest control points. This allows for interesting shapes without the inefficient calculations from insanely high polynomial Bezier curves.

Bezier surfaces are similar to Bezier curves, but instead of just one parameter t, there are two parameters s and t, and instead of a curve, it is a surface mesh.

Chapter 2

Computational Vision

2.1 Light Capturing Devices

This section deals with the basic evolution of light capturing devices.

2.1.1 Notes

Initially, there was a single cell 1D capture of light. This had many problems, but the main one being it can only capture light from one direction, and had no understanding of the intensity of it (binary). Using multiple 1D Cells allowed for more directions to be captured. Having

Figure 2.1: 1D Cell

multiple cells curved allowed for capture of light from various directions, somewhat conic. But it had difficulty keeping track of an image, as the same image would be hitting too many cells, so it would be all over the place. The concept of a pinhole camera was the next step, but there

Figure 2.2: 1D Cell Curved Array

was an issue. With the wide aperture, the images were bright but they were fuzzy. With the pinhole, the images were sharp but they were too dim. How can we get the positives without the negatives? Simple, refraction from lenses. By having a lens refract light into the pinhole

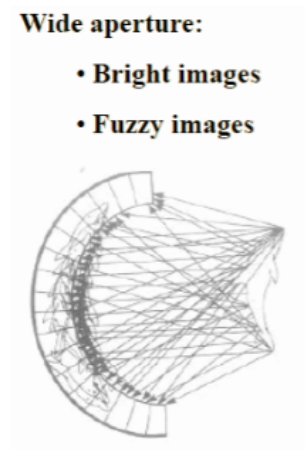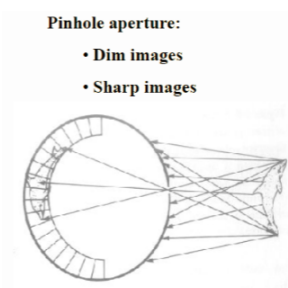Figure 2.3: Pinhole

camera, or image point, it would allow for all the light to pass through the pinhole and hit different cells based on the initial angle the light hit the lens, maintaining the brightness from the wide aperture with the clarity of the pinhole aperture.

The virtual image created is upside down, and our eyes, based on this concept, simply allow the brain to flip it back.
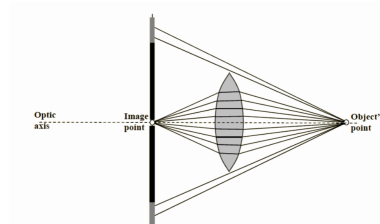
Figure 2.4: Lens in action

2.2 Human Vision

This section deals with human vision, a fairly straight forward topic (at least in our scope, this stuff can get wild pretty fast).

2.2.1 Notes

The human retina contains two types of photo receptor cells. Rods, of where there are 120 million, and Cones, of which there are 6 million. Rods are extremely sensitive to light and respond to single photons. They have poor spatial resolutions as multiple of them converge to the same neuron for data handling. However, thanks to their sensitivity, they help us see light in the dark. This is different with cones, which are active at higher light levels. Several neurons process Cone data, so they have higher spatial resolution than rods.

Receptive Field

The receptive field is the area on which light must fall for neurons to be stimulated. The size of a receptive field determines a few things. Small receptive fields are stimulated by high spatial frequencies; and large spatial fields are stimulated by low spatial frequencies. There are differences between the centre and periphery of field. We can't talk about these without talking about ganglion cells. There are two types of ganglion cells, on-centre and off-centre, as seen in the image. On-centre cells are stimulated when the center is exposed to light, and are inhibited when the surrounded area is exposed. This works opposite for off-centre cells, as the name suggests.

Ganglion cells have a higher action potential rate depending on the intensity and location of light hit. This allows us to have a grasp at contrast, as it responds differently to different
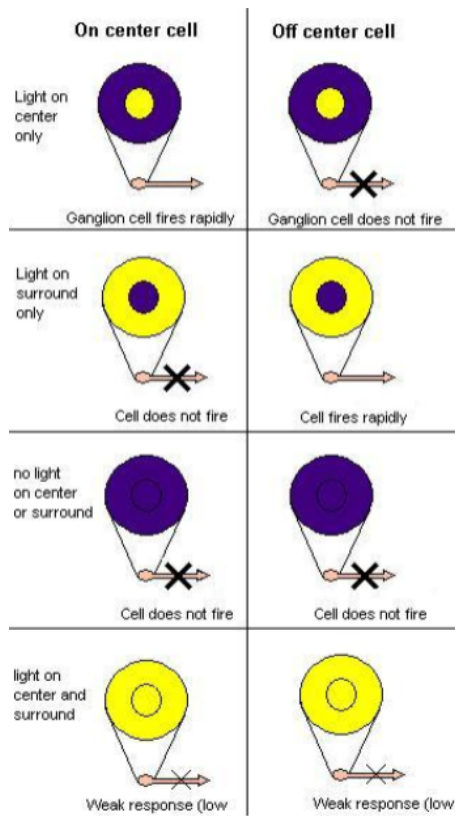
Figure 2.5: Ganglion responses

intensities of light.

Visual Pathway

1. Vision generated by photoreceptors in the eyes (as explained above)
2. The information leaves the eye by way of the optic nerve. Special note: The humans have a blind spot in the eye that does not allow them to see at one specific part of the eye; this is the optic nerve's location. Without it, we wouldn't be able to actually see.
3. There is a partial crossing of axons at the optic chiasm; this allows the brain to receive data on the same visual field from both eyes, superimposing images, creating a sense of depth, etc.
4. The axons following the chiasm, also known as the optic tract, wraps around the midbrain to get to the lateral geniculate nucleus (LGN).
5. The LGN axons fan out to the deep white matter of the brain before ultimately travelling to the primary visual cortex at the back of the brain, where the magic happens.
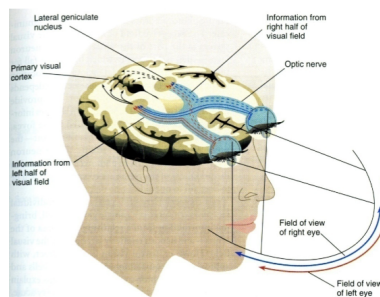
Figure 2.6: Visualising the visual pathway

2.3 Edge Detection

2.3.1 Convolving a Matrix
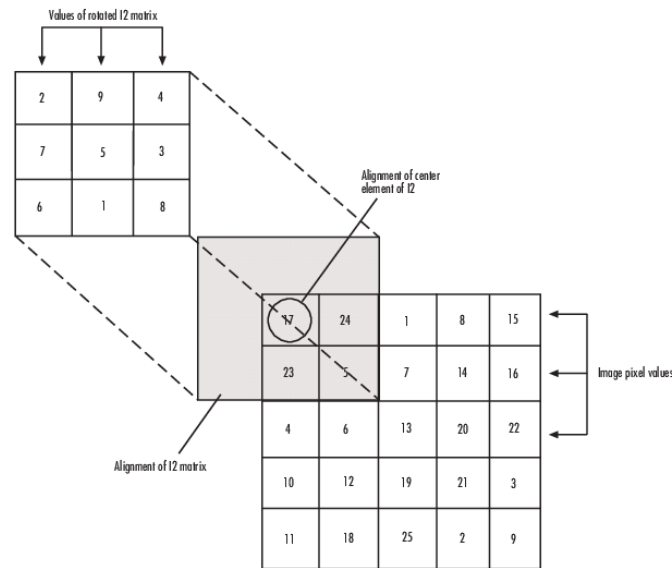
Figure 2.7: 3x3 convolution example

2D convolution of matrices is basically what the course is built off of, at least for edge detection. So its important to know how to do it. Given a 3x3 kernel and an MxN matrix, how does one convolve? Looking at the image, you will create a new matrix by overlaying the kernel with the matrix, multiplying each term on the kernel with the value it overlays and then sum them all up. The new generated value will then be placed in the same position as the centre of the overlay.

Note: for even kernels, you can select either the top-left or top-right centre value as the "centre" of the matrix.

2.3.2 First Order Operators

Edge detection operators are approximation of the first order derivative of the colours. The change in intensity of the colour from a set of points. The gradient of the intensity of colours. I could explain it in mnay different ways, but basically since edges are generally a different shade from its background, checking for a larger change in the intensity would usually return an edge point.

The approximations take the form of different kernels. Small kernels usually don't give a good enough approximation, and using too large a kernel would just blur all the values together and miss edges.

1. Sobel Operator: The sobel operator uses two kernels; one for the x-gradient and one fo the y-gradient. $G_x = \begin{bmatrix} -1 & 0 & +1 \\ -2 & 0 & +2 \\ -1 & 0 & +1 \end{bmatrix}$ and $G_y = \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ +1 & +2 & +1 \end{bmatrix}$

2. Roberts Operator: The roberts operator can also use two kernels, but it instead measures the change diagonally. $G_x = \begin{bmatrix} +1 & 0 \\ 0 & -1 \end{bmatrix}$ and $G_y = \begin{bmatrix} 0 & +1 \\ -1 & 0 \end{bmatrix}$

Once we have applied G_x and G_y, and assuming we have a threshold h (the threshold can be found either with trial and error or setting up some Ai to test with a control set); the final edge

pixels can be generated with the approximation:

$$I = (h > |G_x| + |G_y|) \tag{2.1}$$

Edges generated like this might be susceptible to noise, because derivatives are looking for changes in the intensity. Noise are not part of the source, but rather a bi product from the limitation of our cameras and files. (JPG compressed image for example) When a derivative filter is used, it will simply return the change in intensity from the noise as part of the image. Depending on the quantity of noise, it could end up being a complete mess.

We can remove noise using the most common kernel, with the power of Gaussian. It is a gaussian distribution in the form of a 2D kernel, with the highest value in the centre of the matrix. The size of the matrix alters the effect of the noise filtering. A smaller matrix won't filter much, since it's not looking at a large enough space, and using too large a matrix will just blur the image together, removing edges.
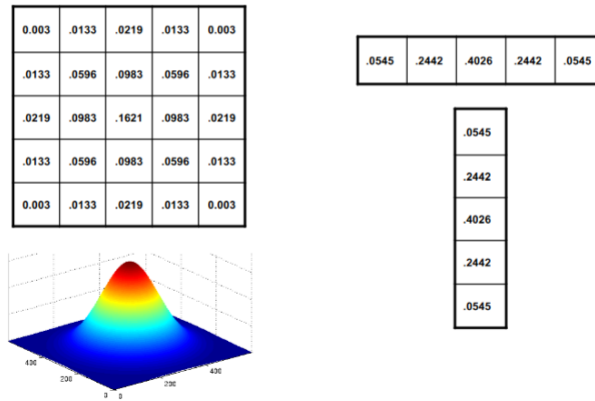
Figure 2.8: Gaussian Noise Filter overview

Rather than convolving the 2D Gaussian with the image, there is a more efficient way to go about this. You can create two 1D matrices $(1xn, nx1)$ and convolve those instead. The result will be the same, and it will be much faster than just doing the 2D matrix as there are less computations to deal with.

2.3.3 Second Order Operators

There is also the option of using Second Order Derivative operators. These function slightly different than first order, as seen in the image. Second Order Derivates look for the zero-crossings. These are the points the values of the graph change signs by crossing the 0-point of the axis. These points are the local maxima/minima in the first order operators. This method is very susceptible to noise, as noise will cause the function to cross zero many times. To alleviate these potential errors, we can apply a gaussian noise filter and a threshold for the distance needed to travel after crossing 0 to be counted as a "zero-crossing". The second order

operator, Laplacian Operator, can be derived as follows:

$$
\begin{aligned}
\frac{\partial^2 f}{\partial x^2} &= \frac{\partial G_x}{\partial x} \\
&= \frac{\partial (f[i,j+1] - f[i,j])}{\partial x} \\
&= \frac{\partial f[i,j+1]}{\partial x} - \frac{\partial f[i,j]}{\partial x} \\
&= (f[i,j+2] - f[i,j+1]) - (f[i,j+1] - f[i,j]) \\
&= f[i,j+2] - 2f[i,j+1] + f[i,j]
\end{aligned}
\tag{2.2}
$$

The equation above is centred on $[i, j+1]$; if we want to centre it on j, we simply do -1 on all terms, and up with the following stuff.

$$
\begin{aligned}
\frac{\partial^2 f}{\partial x^2} &= f[i,j+1] - 2f[i,j] + f[i,j-1] \\
\frac{\partial^2 f}{\partial y^2} &= f[i+1,j] - 2f[i,j] + f[i-1,j] \\
\Delta^2 &\approx \begin{bmatrix} 0 & 1 & 0 \\ 1 & -4 & 1 \\ 0 & 1 & 0 \end{bmatrix}
\end{aligned}
\tag{2.3}
$$

We can also place the equation inside of a gaussian distribution function, and end up with a Laplacian of Gaussian (LoG), a potentially efficient second order operator.

2.3.4 Canny Edge Detection

Our new friend and scientist, J. Canny, has shown that the first derivative of the Gaussian closely approximates the operator that optimizes the product of signal - to - noise ratio and localization.

Canny Edge Detection is sort of a standard (its pretty good). There are four major steps to canny edge detection.

1. Find $f_x = f * G_x$ and $f_y = f * G_y$ where $G(x, y)$ is the gaussian function and $G_{x/y}$ is the derivative with respect to the required variable. $G_a = \frac{-a}{\sigma^2}(G(x,y))$
2. Compute the gradient magnitude and direction.

$$mag(x,y) = |f_x| + |f_x y|$$

$$dir(x,y) = \arctan \frac{f_y}{f_x}$$

3. Apply non-maxima suppression. In simpler maths terms, check if the gradient magnitude at a pixel is a local maximum along the gradient direction.
4. Apply hysteresis thresholding. This is fancy for applying a threshold at a low value t_l and a high value t_h, which is usually twice t_l. First mark the edges generated from the high threshold, as these are strong edges and are generally genuine. Trace an edge with the bidirectional information and, while tracing, apply the lower threshold to trace faint sections of edges that have a start point.

2.3.5 References

Canny Edge Detection
A paper on Edge Detection
Good Lecture on Topic

2.4 Facial Recognition

This section deals with the general idea of Facial Recognition.

2.4.1 Eigenfaces

Lets start by thinking of the face as a weighted combination of different components or representations of said face. These components are referred to as Eigenfaces (because who needs real words). Luckily, we can represent all these components as vectors. Eigenfaces are used in two ways; either as a form to store faces for later reconstruction or for recognition of a new image of a familiar face. We can do the learning using Principle Component Analysis (PCA). Given a set of points in 2D, as in the image, you can use vectors in the place of the usual line of best fit. When we use vectors, we would ideally want it to be in normal form with a scaling factor applied to it. This is where Eigenvectors come in. Eigenvectors take the following form:

$$A\vec{v} = \mu\vec{v}$$

where μ is referred to as the "eigenvalue". Eigenvectors are obtained from a matrix, and follow some rules.

- Only square matrices have eigenvectors
- Different matrices have different eigenvectors
- Not all square matrices have eigenvectors
- An $n \times n$ matrix has at most n distinct eigenvectors
- All distinct eigenvectors of a matrix are orthogonal

You ask, where do we get the matrix in this instance? We do it by finding a covariance matrix. Since we have a 2D plot of points, we can generate a 2x2 covariance matrix. This can be done by the following equations, the first for the covariance matrix, and the other for the variance function.

$$C = \begin{bmatrix} Var(x_1) & Covar(x_1, x_2) \\ Covar(x_1, x_2) & Var(x_2) \end{bmatrix}$$

$$Covar(x_1, x_2) = \frac{\sum_{i=1}^{n}(x_1^i - \bar{x_1})(x_2^i - \bar{x_2})}{n-1}$$

With faces, we treat the face as a point in a high-dimensional space, and then treat the training set of faces as our set of points. We calculate the eigenvectors of our training set, and these become our eigenfaces. **TL;DR Eigenfaces are eigenvectors of covariance matrix of training set of faces**
When given an image of a face, we can transform it into face space (Facebook?) by applying the following equation:

$$w_k = x^i(\vec{v_k})$$

where k is the number of eigenfaces, with the ith face in image space, and a corresponding weight w. Image recognition becomes easy, simply find the euclidean distance of the desired face and all faces stored; the closest face is most likely our match. You can also reconstruct a face from the eigenfaces. The more eigenfaces the better the reconstruction.

2.4.2 References

Just the slides

2.5 Vision Systems

This section deals with feature detection of vision systems.

2.5.1 Invariants

Ideally, we would like some invariance in different settings for what we would like to see.
1. Illumination: Can be achieved by normalising the light levels and storing the new normal intensities. Can also used difference based metrics (sift).
2. Scaling: Store pyramids of the image, with each step half the size of the original. Find pixel values with Gaussian blur. Can also use Scale Space method, using Difference Gaussians to find repeatable points (invariant) in scale.
3. Rotation: Rotate all features to go the same way in a determined manner. Take histogram of gradient directions and rotate to the most dominant.

2.5.2 Feature Detection

In motion tracking, our goal is to see things that move between a set of images. You can begin by knowing which of the four following cases fits best:
1. Stationary Camera, Stationary Objects
2. Stationary Camera, Moving Object
3. Moving Camera, Stationary Objects
4. Moving Camera, Moving Object

When detecting change, you can compare the intensity at one point in time with its previous incarnation (or any other, if you need something specific). However, this lends to issues appearing from random noise, which will pop up everywhere. What we want is to then filter out our noise, but how do we do such a thing?

We can use the idea of 8 or 4 connectedness. Two pixels are 4-neighbours if they share an edge, and are 8-nieghbours if they share a corner. Two pixels are 8-connected if we can create a path of 8-neighbours from one to another. We can use these concepts and group pixels into clusters. We can then threshold the clusters and remove any clusters that are below said threshold, ideally leaving behind just the changes and removing noise. However, just seeing the difference in

Figure 2.9: Gaussian Moravec Operator Overview

pixels might not be enough. Ideally, we would want to find our points of interest and compare

those points between images. For this, we can use the Moravec operators, a corner detector. Corners are better than edges for this task because corners can measure the highest intensity change, as oppose to edges. The image explains how the Moravec operators works. Once we obtain our new values from our friend Moravec, we can just keep the local maxima.

Motion Correspondence has three main principles we need to worry about.
1. Discreteness: Measure of the distinctiveness of individual points
2. Similarity: Measure of how closely two points resemble one another
3. Consistency: Measure of how well a match conforms with nearby matches

2.5.3   Object Detection

Object recognition needs the following components:
1. Model Database: Stores all models known by the system; information stored depending on approach for recognition. Generally, these values are abstract (shape, colour, size, etc.)
2. Feature Detector: Applies operators to image and identifies location of features. How a feature detector works depends on what types of models are stored in the database.
3. Hypothesizer: Assigns likelihoods to objects present to reduce computational expense.
4. Hypothesis Verifier: Uses object models to verify hypothesis and refines the hypothesizer likelihood.

Each of these components come with issues, mostly related to what sort of thing you want to do. (2D vs 3D, model vs object, etc.)

Chapter 3

Models of Computation

(Thanks to Liam for helping out on this section)

3.1 Regular Expressions

3.1.1 Regular Language

Strings can be broken down as "regular expressions", a logical expression that can be used to solve matching and searching problems. A matching problem can be checking if a string is a valid password that contains at least X characters and at least Y digits. A searching problem can be, given a string, list all occurrences of an email address in it. Regexps are used to solve problems like these.

For example, the regular expression **c(bb|ca)*** will return true when matched with **cbbbbca** but return false when matched with **bca**. To solve problems using regexps, we can use Deterministic Finite Automatons (DFAs). They are deterministic because the initial state and the result of each transition are specified, and finite because there set of states is a finite set. When given a string, in the DFA seen, it will process each letter one at a time, going from state and following the transitions.

Figure 3.1: Example of a DFA

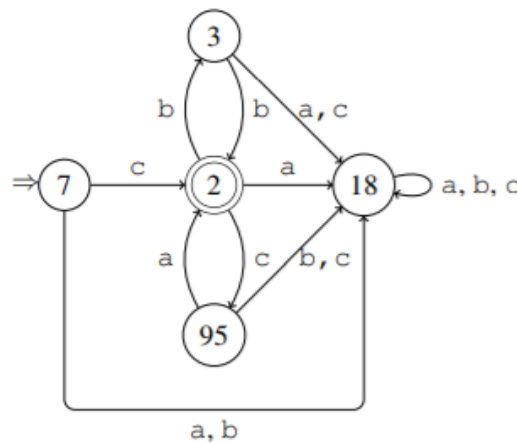As you can see, there are a few loops/areas where the DFA will definitely return false once it reaches a certain point. A more efficient way to deal with these things is to completely remove the transitions, and have it return a failure at points we know it will definitely fail. These are called partial DFAs, denoted by the δ symbol (δDFA). These are usually faster to write and run faster.

What happens when the DFA is not deterministic? An NFA if you will. NFAs differ from DFAs in two ways.

- An NFA can have several initial states
- From a given state, when a is input, there can be several possible next states.

NFAs are a relation and not a function. They can still return acceptable words, but a program can make no use of it since its, well, non-deterministic. However, there are ways to determinize an NFA. The best, basic way to accomplish this is to combine states into a set of state transitions if they match similar inputs/outputs. Conversion can take a few steps, but it's fairly simple and systematic in this regard.

Some trouble can pop up from NFAs with an ϵ transition, or an empty transitions. These bad boys can change from one state to another for literally no reason. These NFAs are called ϵNFAs, which seems obvious. With this out of the way, let's make note of Kleene's Theorem.

For a language L, the following are equivalent:
- L is regular
- The matching problem for L can be solved by a DFA.

A systematic way to turn a regexp to an equal DFA:

1. Convert the regexp into an ϵNFA
2. Convert it down to an NFA
3. Convert it further down to a DFA.
4. Minimize DFA size by identifying equivalent states, removing unreachable states and just general refactoring.

3.1.2 Non-regular Language

We know that some languages are not regular, because there are uncountably many languages and only countably many regexps. An example of a useful non-regular language is the language of well-balanced brackets. The check for balance can be done in a stack, pushing and popping from a stack when reading '(' and ')' respectively. However, if we have a large amount of '(', the stack will overflow thanks to our finite memory. When talking about non-regular languages,

$$\Rightarrow A \quad ::= \quad 3 \mid 5 \mid A + A \mid A \times A \mid (A) \mid \text{if } B \text{ then } A \text{ else } A$$
$$B \quad ::= \quad A > A \mid B \text{ and } B \mid (B)$$

Figure 3.2: Example of a BNF

we can talk about context-free grammars. Grammars are written in Backus-Naur Form (BNF) and, in basic terms, represent different characters as symbols and use these symbols to derive a word. These symbols are either terminal or non-terminal; terminal means it can be expanded to a final value of sorts. The grammars we covered are context-free because you can apply a production rule to any non-terminal regardless of the other symbols in the word.
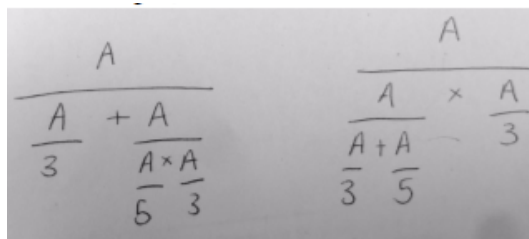

Figure 3.3: Ambiguous derivation tree

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Some Definitions
- Leftmost Derivation: Converting a grammar to a word by replacing the leftmost non-terminal
- Derivation Tree: A tree structure representing a derived word where each leaf is a non-terminal.
- Ambiguous: A grammar is ambiguous when there is more than 1 derivation tree possible with left-most derivation

3.2 Turing Machines

3.2.1 Turing Machines

A turing machine is the precise model of computation (roll credits) that are used to determine decidability and complexity of programs. A turing machine has finitely many states, but it also has access to an external, infinite memory in the form of a tape. The machine has a head that sits over one of the cells in a tape. A concise definition of the turing machine consists of the following data:
- A finite state X of states
- An initial state p
- A transition function δ from X to:
  1. Read
  2. Write
  3. Left
  4. Right
  5. No-op
  6. Return

There are also a few variants that expand on the basic turing machine.

Auxiliary Characters In addition to the input alphabet and "blank", a turing machine can have auxiliary characters that are used during the completion of a program, but these characters cannot appear at the start or at the end of a task.

Auxiliary Tape A two-tape Turing Machine has, well, two tapes. A program is now capable of completing tasks that read/write etc. on two tapes (Main x, Aux x). The copy-reverse problem can be solved in linear time using a two-tape machine.

2D Turing Machine Instead of a tape, a 2D machine has a sheet instead of a tape, so it can go up and down. It must ensure that all but one row are blank on completion of a program.

3.3 Complexity

3.3.1 Complexity of Programs

When trying to find the number of steps, it is helpful to remember some laws of summations. The most important part of complexity for our course is to practice deriving worst case and average case complexities. Hopefully you remember how Big O worked from Year 1 DSA. There's a bit more in Models than what we learned, a more interesting way of deriving it.

$$\exists M.\exists C.\forall n \geq M.f(n) \leq C \times g(n)$$

$$0 + 1 + 2 + \cdots + (n-1) = \frac{1}{2}n(n-1)$$

$$1 + 2 + 3 + \cdots + n = \frac{1}{2}n(n+1)$$

$$1 + b + b^2 + \cdots + b^{n-1} = \frac{b^n - 1}{b - 1} \quad (b \neq 1)$$

$$1 + b + b^2 + \cdots + b^n = \frac{b^{n+1} - 1}{b - 1} \quad (b \neq 1)$$

Figure 3.4: Helpful sums to memorize

M is an arbitrary number. The set from $n = [M, +\inf]$ will hold true.
There is one more variation to this for polynomial complexity. Polynomial time solutions are said to be *feasible*.

$$\exists M.\exists C.\exists k.\forall n \geq M.f(n) \leq C \times n^k$$

3.3.2 P and NP

Definitions
- Search Problem: Relation from the set of words (problems) to the set of words (solutions).
- NP Search Problem: Search problems with solution of polynomial size and checked in polynomial time. Will have a solution in exponential time.

What is the NP = P problem? It is the question, can every NP search problem be solved in polynomial time? If the answer is yes for Sudoku, then it's yes for every NP search problem. This is because Sudoku is a special kind of NP search problem called "NP-complete", meaning that it's as hard as an NP search problem can be. Any NP search problem can be reduced (in polynomial time) to Sudoku. By contrast, it is not known whether factorization is NP-complete, so showing that factorization can be solved in polynomial time won't prove anything major.

3.3.3 NP-Completeness

SAT A problem instance of this NP search problem consists of propositional variables and a formula built from this variables. The formulas are generated from a specific grammar. A satisfying assignment is an assignment of truth variables that makes the formula true. SAT is useful in solving constraint problems, like "I need to study Models with Jon and I need to study Security with Clair, but all of our free times can only coincide once." You can use SAT to potentially find the magic timings.

Cook's Theorem Any NP problem can be reduced to SAT, like nSudoku for example. Find a mapping of different characters and constraints to propositional logic, and you have reduced your problem to SAT.

3.4 Decidability

A decision problem is said to be decidable when there is some program that, when given an argument, says whether the answer is Yes/No.

3.4.1 Reduction and Decidability

Church's Thesis   Any decision problem on words that can be solved by an algorithm can be solved by a Turing machine.

Reduction   Suppose we have two problems P and Q. Suppose that we show how to solve Q using a black box that solves P. Then is called reducing problem Q to problem P. For example, I saw a recipe for profiteroles that said "take some pastry balls" and "take some chocolate sauce". The author reduced the problem of making profiteroles to the problems of making pastry balls and making chocolate sauce. Suppose we've reduced problem Q to problem P.
- If P is decidable, then Q is decidable
- If Q is undecidable, then P is undecidable

Halting Problem   Some programs run forever, others halt. Usually we want our programs to halt; if they run forever, that's a bug. Can we test this automatically? Our main man Turing proved the halting problem to be undecidable. We begin the proof by assuming it is decidable. Consider the unary halting problem: given a unary Java method.

```
void f(String x) {
    ...
}
```

and a String y, does f terminate when called with argument y? We can reduce this problem to a nullary one. Take the code of f and replace x with y; then the nullary method (g) terminates when called if f terminates when called with argument y. Since the nullary problem is, on assumption, decidable, the unary one is too. So we have a program:

```
boolean haltcheck(String somemethod, String y)
```

Where *somemethod* is the body of a unary method. When applied to M and y, this method returns true if M applied to y terminates, otherwise it returns false.
2. Next, we turn this into a program.

```
hangcheck(String somemethod, String y) {
    if haltcheck(somemethod, y) {
        while (true) {}
    } else {
        return;
    }
}
```

This method, when applied to M and y, hangs if M and applied to y terminates, otherwise it returns.
3. Next, we turn this into a program:

```
void doublehang(String y) {
    hangcheck(y,y);
}
```

This method, when applied to y (the body of a unary method), will hang if y applied to y terminates, otherwise it returns.
4. Finally let z be the body of *doublehang*. We see that *doublehang*, when applied to z, terminates if it hangs. Contradiction. (Objection!)

Semantics   Semantic properties of a code are properties that affect the behaviour of the program. For example, does this software only print polite words? Does this software, when supplied with two positive integers, always return the highest common factor? Surprise surprise, we can't. Thanks to our good friend from down the tape, Rice's Theorem states that, in all but two cases, every semantic property is undecidable. That's because there are three cases, and Rice only covers the third one, since the other two are decidable.

1. A property never holds (decidable)
2. A property always holds (decidable)
3. A property sometimes holds and sometimes doesn't (Undecidable due to Rice's Theorem)

3.5   Lambda Calculus

Conventions λx is equivalent to **fun x** $\rightarrow$ in OCaml. Just a quick convention comparison to get you up to speed.

- Juxtaposition is application
- Application has highest precedence
- λx has lowest precedence
- Arithmetic Operations are intermediate
- Application associates to the left (MNP is bracketed as $(MN)P$ not as $M(NP)$)

$$(\underline{3} + \underline{5}) \times (\underline{2} + \underline{1}) \rightsquigarrow \underline{8} \times (\underline{2} + \underline{1})$$

$$(\underline{3} + \underline{5}) \times \underline{3} \rightsquigarrow \underline{8} \times \underline{3} \rightsquigarrow \underline{24}$$
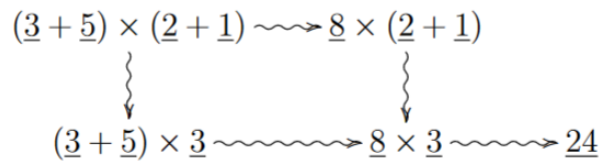
Figure 3.5:   Reduction Graph with more than one order

3.5.1   Reduction and Equivalence

There are two types of reduction, δ-reduction and β-reduction.

- δ-reduction: Basic arithmetic reduction ($m x n \rightarrow mn$)
- β-reduction: Applies λ-abstractions (($\lambda x.x + 3)7 \rightsquigarrow_\beta (7 + 3)$)

We use a combination of both to formulate reduction graphs. Reduction can branch of and be done in different evaluation orders, as seen in the figure. There is also the notion of α-equivalence, which is simply when two lambda function evaluate to the same result despite being different originally.

Chapter 4

Introductory Databases

4.1 Databases and Sets

This section deals with some definitions and how to formulate SQL Queries

4.1.1 Definitions

Relations
- Domain (D): An arbitrary (non-null) set of atomic values
- Attribute Name (A): A symbol with an associate domain
- Relational Schema (R): A finite set of attribute names
- Tuple (t): a mapping from the attributes of a relational schema to the union of their domains
- Relation (r): A finite set of tuples of relational schema
- Degree: Number of attributes [columns in an SQL table]
- Cardinality: Number of tuples [rows in an SQL table]

Keys
- Superkey: a set of attributes that can *always* be used to differentiate one tuple from another
- Key - a minimal superkey
- Concatenated Key - a key with more than one attribute
- Candidate Key - any key
- **Primary Key** - one of the candidate keys used to reference from other relations
- **Foreign Key** - an attribute of the relation which is a key for another relation

Data Types
- BOOLEAN: TRUE, FALSE, or NULL
- Strings:
  - CHAR(length)
  - CHARACTER(length)
  - VARCHAR
  - TEXT
- INTEGER
- REAL: A floating point

- Arbitrary Precision:
  - NUMERIC
  - DECIMAL
  - MONEY
- Date and Time
  - TIMESTAMP
  - DATE
  - TIME

Constraints
- DOMAIN: The domain/type of the attributes; eg INTEGER, VARCHAR
- NOT NULL: Ensures the column will not have a null value
- UNIQUE: Ensures uniqueness
- PRIMARY KEY: Not-null, unique column used as a primary identifier of a row
- FOREIGN KEY: Unique identifier to a row from another table
- CHECK(condition): Ensures all values in the column meet the defined condition (eg. cost > 10)
- DEFAULT(default): Sets the value to the given value if no other value is specified on creation

Foreign Key Syntax
- ON DELETE (action): Does the specified action when the key or referenced table is deleted
- ON UPDATE (action): Does the specified action when the key or referenced table is updated
- NO ACTION: Action - Does nothing
- RESTRICT: Action - will not allow user to delete/update the key/referenced table
- CASCADE: Action - cascades the change on the original to the value found in the foreign table
- SET NULL: Action - sets the value to null in the foreign table
- SET DEFAULT: Action - sets the value to default in the foreign table

4.1.2 SQL Statements

CREATE

```
CREATE TABLE tableName (
    attributeName TYPE CONTRAINTS,
    attributeName2 TYPE CONTRAINTS,
    exampleID TYPE CONSTRAINTS,
    exampleID2 TYPE CONSTRAINTS,

    PRIMARY KEY (exampleID),
    FOREIGN KEY (exampleID2) REFERENCES  otherTable(id)
        ON UPDATE action
        ON DELETE action;
)
```

INSERT

```
INSERT INTO tableName VALUES  (valueA, valueB, valueC, ...);

INSERT INTO tableName(attributeA, attributeB, attributeC)
    VALUES  (valueA, valueB, valueC);
```

UPDATE

```
UPDATE tableName SET attributeA = valueA WHERE id = valueID;
```

DELETE

```
DELETE FROM tableName WHERE attributeA = valueA;
```

SELECT

```
SELECT * AS resultTableName FROM tableName WHERE condition;
```

Selections
- *: Returns every attribute
- attributeName1, attributeName2, ...: Returns the requested attributes only
- tableName1.attributeName, tableName2.attributeName: Returns values from multiple tables

ORDER BY

```
SELECT * FROM tableName ORDER BY column1, column2, ... ASC|DESC;
```

Orders the result table in the defined ordered. Can be in ascending (ASC) or descending (DESC) order. Usually defaults to ASC.

DISTINCT

```
SELECT DISTINCT column1 FROM tableName;
```

The SELECT DISTINCT statement is used to return only distinct (different) values. Inside a table, a column often contains many duplicate values; and sometimes you only want to list the different (distinct) values.

WHERE

```
SELECT * AS resultTableName FROM tableName WHERE condition AND|NOT condition;
```

Where uses a boolean condition and returns a resultTable where each row matches the given condition (or conditions)

LIKE

```
SELECT * AS resultTableName FROM tableName WHERE condition LIKE pattern;
```

Like is used in the where condition and allows for checking of a specified pattern. There are two wildcard characters you can use in LIKE.
- % - Represents zero, one, or multiple characters (eg. %a% matches with Faisal)
- _ - Represents a single character (eg. a_ does not match with Rajhi)

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FUNCTIONS

```
SELECT FUNCTION(column) AS resultTableName FROM tableName;
```

Some predefined functions:
- COUNT(): Returns the number of rows in the supposed resultant table
- SUM(): Returns the sum of a numerical column
- AVG(): SUM()/COUNT()

JOIN

```
SELECT a.column, b.column
FROM tableName1 a
(INNER|LEFT|RIGHT|FULL OUTER) JOIN tableName2 b
ON a.column = b.column;
```

A JOIN clause is used to combine rows from two or more tables, based on a related column between them. There are a few types of joins. Joins also removed duplicates, a sort of built in DISTINCT
- INNER: Returns records that have matching values in both tables
- LEFT: Return all records from the left table and the matched record from the right table
- RIGHT: Return all records form the right table and the matched record from the left table
- FULL OUTER: Return all records matched from either table

UNION

```
SELECT * AS resultTableName1 FROM tableName1
UNION (ALL|)
SELECT * AS resultTableName2 FROM tableName2;
```

Union combines the query from multiple SELECT statements. It automatically removes duplicates, to maintain duplicates, use UNION ALL.

SUBQUERY

```
SELECT * AS resultTableName1
    FROM (
        SELECT * FROM tableName2
    ) ;
```

Subqueries run a query on a result table instead of a table/set of tables from the database. Just us normal parenthesis ().

GROUP BY

```
SELECT COUNT(column1), column2
FROM tableName
GROUP BY column2
ORDER BY COUNT(column1) DESC;
```

Usually used with functions, groups resultant values with one or more columns. For example, counting how many times each country appears in a table; using group by will place the count next to its respective country.

HAVING

```
SELECT COUNT(column1), column2
FROM tableName
GROUP BY column2
HAVING condition //eg HAVING COUNT(column1) > 3
ORDER BY COUNT(column1) DESC;
```

HAVING exists because SQL people realized WHERE didn't work with functions. Use this with count, sum and all that jazz.

4.2   JDBC

We won't be covering details regarding JDBC and how to use it (such as using Connection objects or how to insert password) since that is more programming and should be covered already.

4.2.1   Statements

There are two types of statement objects; Statement and PreparedStatement. Statements are simply strings that get converted to an SQL Query, whereas PreparedStatements are a little more modular. PreparedStatements are a generic sort of strings, with a variable, usually denoted by ?, that can be replaced and dynamically altered. There a few benefits to using PreparedStatements;
1. Reusable and dynamic, so its faster
2. Seperates logic of query and parameters, so its clearer to code for
3. No need to convert parameters to Strings, so its faster and uses less bandwidth
4. More generic, so its type safe
5. Protects against SQL injection (mostly), so its more secure

SQLInjection is a sort of security hax that injects SQL code as an input from the user and returns undesired results. Sanitizing results can help against such security risks, but its much easier to at the very least use preparedStatements for most queries.

Note; concurrency and race conditions can also cause issues for databases that need to be accurate, such as banks. Databases can handle these things via "transactions", but also these issues can arise from code. Each concurrency issue needs to be handled on its own. A race condition needs synchronicity, but it could cause large queues and slow downs. The solution to these issues is on a system to system basis, but they should be noted.

4.3   ER Diagrams

Entity Relation (ER) Diagrams are graphical representations of tables, and are a database design practice used to, well, design a database. ER Diagrams are easily converted to SQL Create statements and tables. Shapes in an ER diagram mean different things.
- DIAMOND: A relation set (A shop needs customers and an inventory; the shop is a relation set)
- RECTANGLE: An entity set (The customers and inventory are entities)
- OVAL: An attribute (The customers have names; these are attributes)

We also use some special marks or labels that can different meanings.
- Line: Defines a connection/relationship between two things

- Cardinality: Number placed next to the shape on a line. For example, [Students] 3 -¿ 1 [Course] means that Each Student has only 1 course, and each course has 3 Students.
- Underline: Underlining an attribute represents that at is a Primary Key
- Double Outline: An entity with a double outline is a weak entity; one that depends entirely on another.

Consider this example from the lecture. Every rental must record the date and time at which the rental started and finished, the details of the driver and the details of the car rented. Each car has its registration number recorded, the date it was purchased and a record of all maintenance work undertaken. For a driver, the company needs to have their name, driver's licence number, address and at least one telephone number.
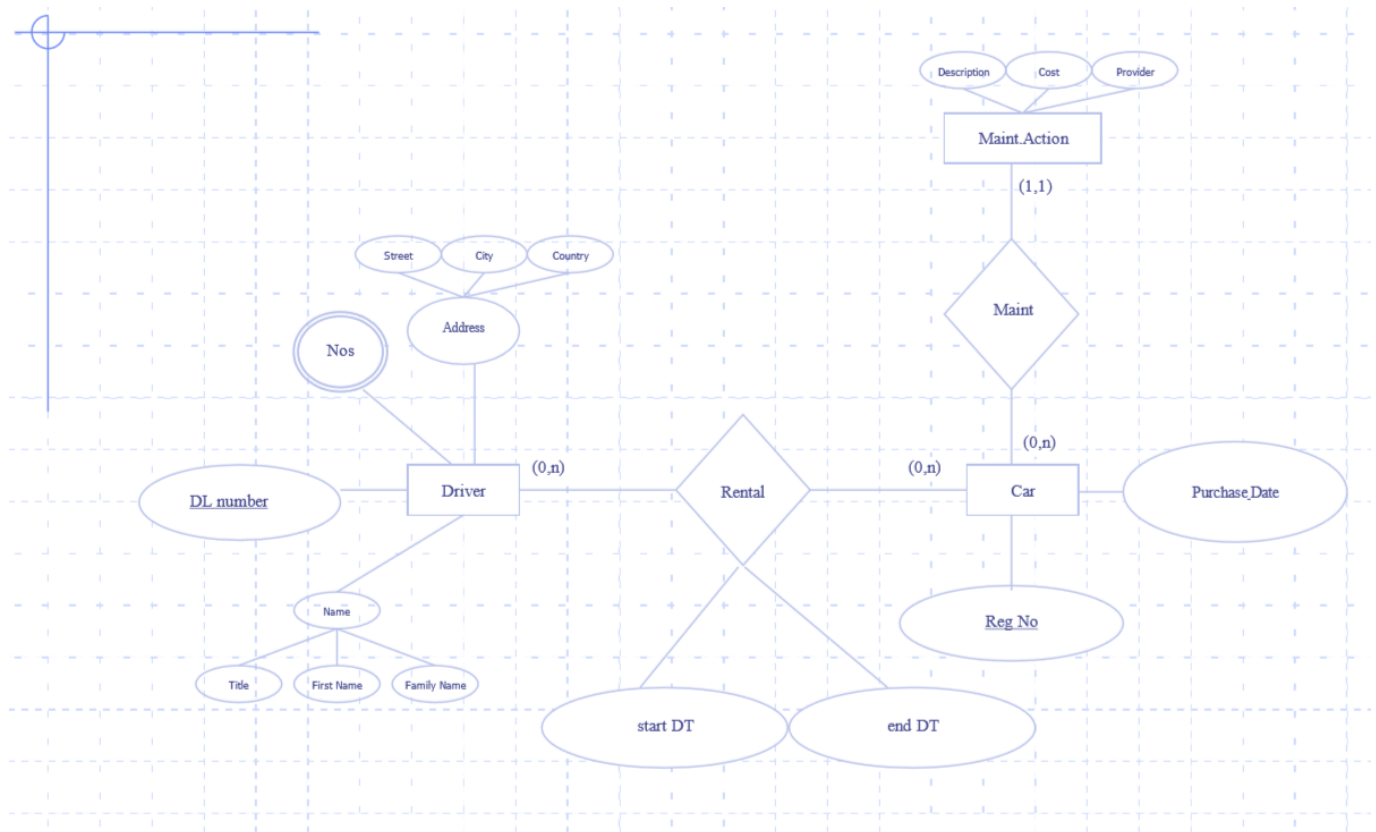

Figure 4.1: ER Diagram Example Solution

NOTE: Your ER diagram does not have to look like this to be correct, there can be multiple variations.

Chapter 5

Computer Systems & Architecture

5.1   Number Representations

5.1.1   Types

integers binary hex float conversion

5.1.2   Arithmetic

basic negative and two's complement floating point

5.2   Logic

5.2.1   Logic Gates

basic logic gates (AND, NOT, OR NOR, NAND, XOR) boolean algebra

5.2.2   ALU

multiplexer adders/halfadder

5.3   Architecture

5.3.1   von Neumann

memory, load/store unit, registers, instruction register, alu, program counter,

5.3.2   cycles

cpu cycles instruction cycle: fetch-decode-execute

5.4   MIPS Microarchitecture

5.4.1   Datapath

instruction fetch (r-type) load/store (i-type) multiplexing integrating them jump instruction

5.4.2 Controls

cpu controls alu control main control

5.5 Memory Hierarchy

cache locality associativity c/c++ matrices example

Chapter 6

C/C++

6.1 The Stack

functions on stack arrays objects

6.2 C

This section deals with the basics of C and things you will using a lot in C.

6.2.1 Memory Management

malloc, free pointers * and & declarations

6.2.2 Structs and Union

struct union

6.2.3 Optimization

speed, memory, flexibility eg. matrix multiplication eg. assignment 1 field order

6.3 C++

classes and inheritance smart pointers polymorphisms templates exception handling

Chapter 7

Mathematical Techniques for Computer Science

7.1 Vectors and Matrices

This section deals with operations on vectors and matrices that are commonly used.

7.1.1 Vector Operations

Magnitude

$$\left\| \vec{V} \right\| = \sqrt{\sum_{i=1}^{n} v_i^2} \tag{7.1}$$

Dot Product

$$\vec{V} \cdot \vec{U} = \sum_{i=1}^{n} v_i u_i \tag{7.2}$$

3x3 Cross Product

$$\vec{V} \times \vec{U} = \begin{bmatrix} v_2 u_3 - v_3 u_2 \\ v_3 u_1 - v_1 u_3 \\ v_1 u_2 - v_2 u_1 \end{bmatrix} \tag{7.3}$$

Equations with angles

$$\cos \theta = \frac{\vec{V} \cdot \vec{U}}{\left\| \vec{V} \right\| \left\| \vec{U} \right\|} \tag{7.4}$$

$$\sin \theta = \frac{\vec{V} \times \vec{U}}{\left\| \vec{V} \right\| \left\| \vec{U} \right\|} \tag{7.5}$$

7.1.2 Matrix Operations

Multiply

$$axb = comingsoon \tag{7.6}$$

2x2 Determinant 3x3 Determinant Row Operations Inverting a Matrix

7.2 Fields

This section deals with the little we need to know about Galois Fields, primarily GF(2).

7.2.1 Notes

7.2.2 Proofs

7.3 Lines and Planes

This section covers everything done regarding systems of equations regarding lines and planes.

7.3.1 Notes

7.3.2 Examples

7.4 Set Theory

This section covers the basics of Set Theory, with some examples.

7.4.1 Notes

7.4.2 Examples

7.5 Functions

Expanding from Set Theory, this section deals with Functions and our new understanding of them.

7.5.1 Notes

7.5.2 Examples

7.6 Probability

Continuing from Year 1 AI, probability.

7.6.1 Notes

7.6.2 Examples

7.7 Random Variables

This section deals with the handling of both discrete and continuous random variables. Don't go gambling after you cover this section.

7.7.1 Discrete

7.7.2 Continuous

7.7.3 Examples

7.8 Equations

Appending-like area to store all equations that will likely be used in the exam.

Chapter 8

Introduction to Computer Security

8.1 Cryptography

different modes of AES RSA and Diffie Helman MACs and Validation attack example

8.2 Access Rights

reading access rights privilege elevation

8.3 Web Security

8.3.1 Communication Protocols

8.3.2 Web Security

php, sql injection, file injection, SSH

8.4 Assembly

the stack reverse engineering overflow injection code injection

Chapter 9

Professional Computing

Chapter 10

Functional Programming

10.1 Functional Programming

define key features pure vs not so pure examples

10.2 Algebraic Data Types

algebra and logic isomorphism

10.3 Imperitive OCaml

I/O and machine efficiency assignment and dereferencing records exceptions example

10.4 Modules and Functors

modules mathematical functor ocaml functor type abstraction ocaml abstraction lifehack fix

10.5 Monads

monad lift and bind the option monad mult, unit, identity state monad monads in ocaml

10.6 GADTs

overview example

10.7 Lazy Programming

evaluation order streams example