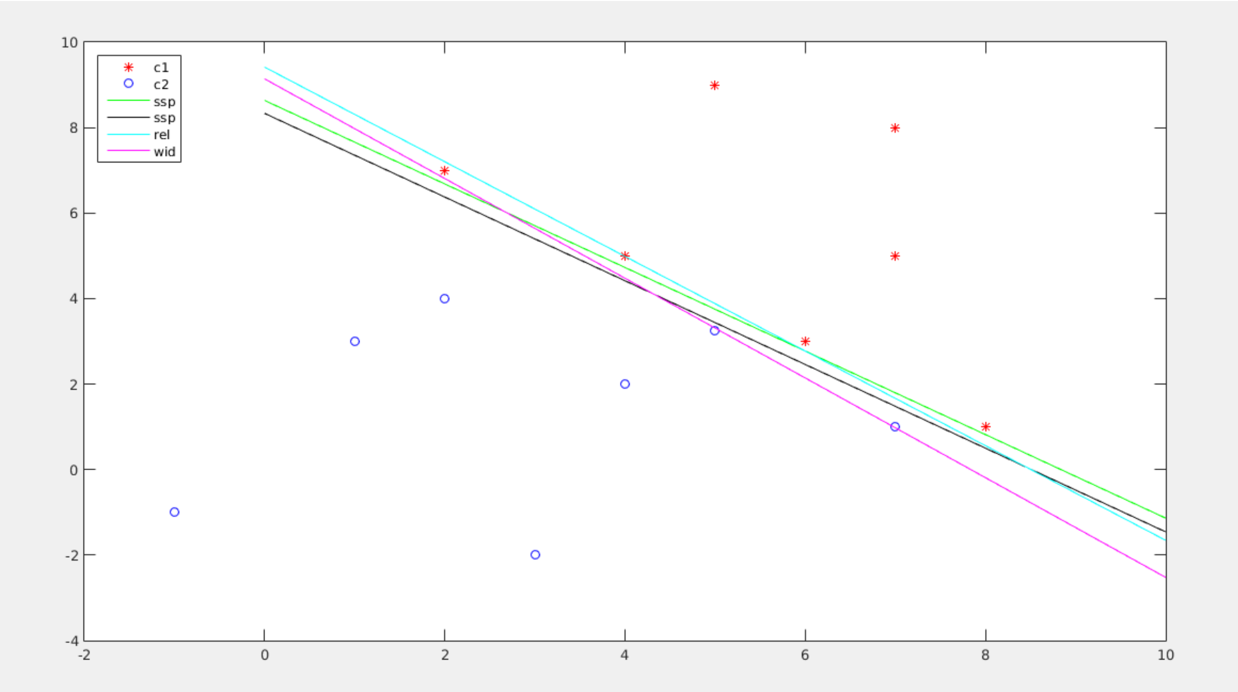
Problem 1

I. Graph



II. Single Sample Perceptron:

Initial Weight	Time
$[\ 1\ 1\ 1]^T$	0.077s
$[\ 2\ -1\ 1]^T$	0.055s
$[\ 2\ 3\ 3]^T$	0.049s

Single Sample Perceptron with Margin:

Initial Weight	Time
$[\ 1\ 1\ 1]^T$	0.06s
$[\ 2\ -1\ 1]^T$	0.07s
$[\ 2\ 3\ 3]^T$	0.048s

Relaxation procedure with Margin:

Initial Weight	Time

[1 1 1]^T	0.081s
[2 -1 1]^T	0.089s
[2 3 3]^T	0.091s

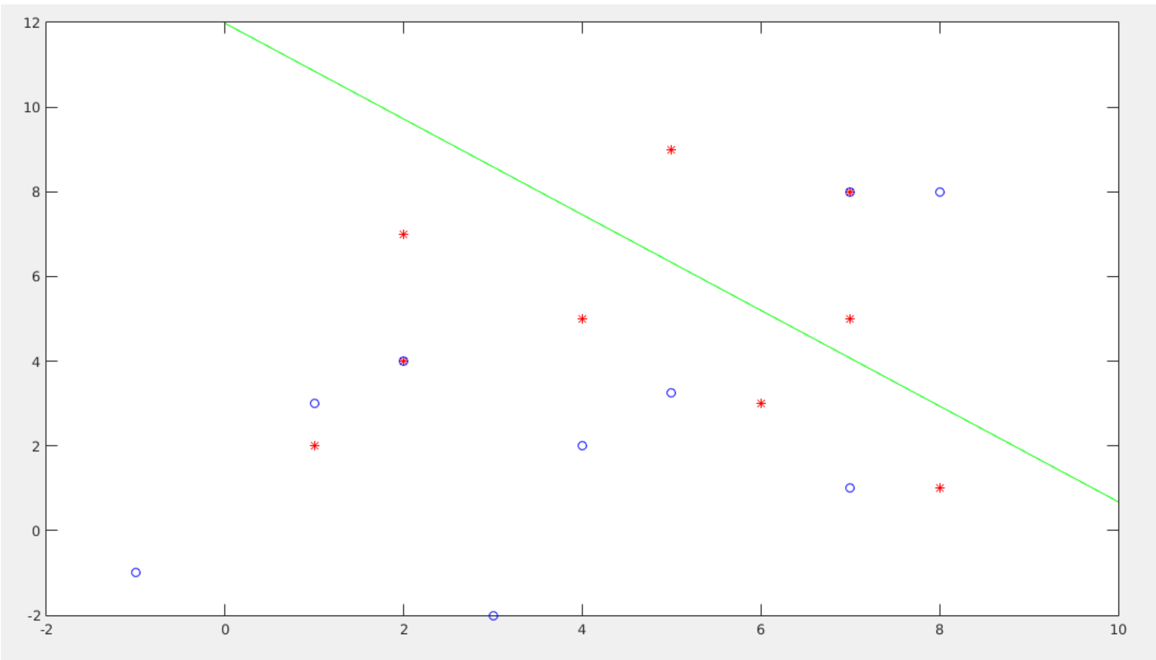
Widrow Hoff procedure:

Initial Weight	Time
[1 1 1]^T	0.049s
[2 -1 1]^T	0.054s
[2 3 3]^T	0.067s

In general convergence time is less when initial weights are closer to the desired weights. Relaxation procedure with margin and widrow hoff are showing exception to this observation.

III. Higher the margin, the better and more accurate is the solution boundary. Convergence time was almost the same (~0.074 sec) for different values of margin (0.1, 0.5, 1, 2, 3) for relaxation with margin. Convergence time was lower (~0.07s) for margin 0.1, 0.5, 2, 3 but for margin value 1, it was higher (~0.09s) for Widrow hoff procedure. The trend was thus increasing then decreasing.

IV. Added non linearly separable points. Still approximately acceptable boundary.



V. Single Sample Perceptron Code:

```
% Initialize data samples and normalise them
w1 = [1 2 7;
    1 8 1;
    1 7 5;
    1 6 3;
    1 7 8;
    1 5 9;
    1 4 5
    ];

w2 = [1 4 2;
    1 -1 -1;
    1 1 3;
    1 3 -2;
    1 5 3.25;
    1 2 4;
    1 7 1
    ];

% Negate samples of one class
samples = [w1; -w2];

n = size(samples, 1);

MAX_ITER = 100000;

misclassified = true;

iter = 0;

% Initialize weight vector
a = [-95; 10; 10];

% Loop until there is a misclassified sample. Also keep a limit on maximum
% number of iterations in case we diverge
while(misclassified && iter < MAX_ITER)

    % Increment iteration count
    iter = iter + 1;
    misclassified = false;
    sampl = 1;

    % Find a sample which is misclassified and add it to weight vector
    while(sampl <= n)

        if(samples(sampl, :)*a < 0)

            a = a + samples(sampl, :)';
            misclassified = true;
            break;

        end

        sampl = sampl + 1;

    end

end

figure,
```

```
% Plot the data points
plot(w1(:, 2), w1(:, 3), 'r*');
hold on;
plot(w2(:, 2), w2(:, 3), 'bO');
hold on;

x = linspace(0,10,11);

% Equation of line is given by a*[1 x y]=0
y = (-a(3)/a(2))*x - a(1)/a(2);

plot(x,y,'g');
```

Single Sample Perceptron with margin:

```
% Initialize data samples and normalise them
w1 = [1 2 7;
    1 8 1;
    1 7 5;
    1 6 3;
    1 7 8;
    1 5 9;
    1 4 5
    ];

w2 = [1 4 2;
    1 -1 -1;
    1 1 3;
    1 3 -2;
    1 5 3.25;
    1 2 4;
    1 7 1
    ];

% Negate samples of one class
samples = [w1; -w2];

n = size(samples, 1);

MAX_ITER = 100000;

misclassified = true;

iter = 0;

% Keep some margin
margin = 1;

% Initialize weight vector
a = [1; 1; 1];

% Loop until there is a misclassified sample. Also keep a limit on maximum
% number of iterations in case we diverge
while(misclassified && iter < MAX_ITER)

    iter = iter + 1;
    misclassified = false;
    sampl = 1;
```

```
    % Find a sample which is misclassified and add it to weight vector
    while(sampl <= n)

        if(samples(sampl, :)*a < margin)

            a = a + samples(sampl, :)';
            misclassified=true;
            break;

        end

        sampl = sampl + 1;

    end

end

figure,

% Plot the data points
plot(w1(:,2), w1(:,3), 'r*');
hold on;
plot(w2(:,2), w2(:,3), 'bO');
hold on;

x = linspace(0,10,11);

% Equation of line is given by a*[1 x y]=0
y = (-a(3)/a(2))*x - a(1)/a(2);

plot(x,y,'g');
```

Relaxation procedure with Margin:

```
% Initialize data samples and normalise them
w1 = [1 2 7;
    1 8 1;
    1 7 5;
    1 6 3;
    1 7 8;
    1 5 9;
    1 4 5
    ];

w2 = [1 4 2;
    1 -1 -1;
    1 1 3;
    1 3 -2;
    1 5 3.25;
    1 2 4;
    1 7 1
    ];

% Negate samples of one class
samples = [w1; -w2];

n = size(samples, 1);

misclassified = true;

% Initialize weight vector
```

```
a = [1; 1; 1];

% Keep some margin
margin = 1;

% Initialize convergence rate
convergenceRate = 1;

% Factor by which convergence rate decreases each iteration
annealingFactor = 0.9;

% Minimum allowed absolute change in weight vector
threshold = 0.0001;

change = norm(a);

% Loop until there is a misclassified sample and change is greater than
% threshold
while(misclassified && change > threshold)

    misclassified = false;
    sampl = 1;

    while(sampl <= n)

        if(samples(sampl, :)*a < margin)

            % gradient is given by (b-ay).y/||y||^2
            delta = samples(sampl, :)*(margin - (samples(sampl, :)*a)) /
(norm(samples(sampl, :))^2);

            % change in weight is eta times gradient
            change = norm(convergenceRate*delta');
            a = a + convergenceRate*delta';
            misclassified=true;

        end

        sampl = sampl + 1;

    end

    convergenceRate = convergenceRate*annealingFactor;

end

figure,

% Plot the data points
plot(w1(:,2), w1(:,3), 'r*');
hold on;
plot(w2(:,2), w2(:,3), 'bO');
hold on;

x = linspace(0,10,11);

% Equation of line is given by a*[1 x y]=0
y = (-a(3)/a(2))*x - a(1)/a(2);

plot(x,y,'g');
```

Widrow Hoff procedure:

```
% Initialize data samples and normalise them
w1 = [1 2 7;
    1 8 1;
    1 7 5;
    1 6 3;
    1 7 8;
    1 5 9;
    1 4 5;
% Add these to make data linearly non-separable
%   1 2 4;
%   1 1 2
    ];

w2 = [1 4 2;
    1 -1 -1;
    1 1 3;
    1 3 -2;
    1 5 3.25;
    1 2 4;
    1 7 1;
% Add these to make data linearly non-separable
%   1 8 8;
%   1 7 8
    ];

% Negate samples of one class
samples = [w1; -w2];

n = size(samples, 1);

misclassified = true;

% Initialize weight vector
a = [1; 1; 1];

% Initialize weight vector
margin = 0.1;

% Initialize convergence rate
convergenceRate = 1;

% Factor by which convergence rate decreases each iteration
annealingFactor = 0.9;

% Minimum allowed absolute change in weight vector
threshold = 0.0001;

change = norm(a);

% Loop until there is a misclassified sample and change is greater than
% threshold
while(misclassified && change > threshold)

    misclassified = false;
    sampl = 1;

    while(sampl <= n)

        if(samples(sampl, :)*a < margin)
```

```
            % gradient is given by y(b-ay)
            delta = samples(sampl, :)*(margin - samples(sampl, :)*a);

            % change in weight is eta times gradient
            change = norm(convergenceRate*delta');
            a = a + convergenceRate*delta';
            misclassified=true;

        end

        sampl = sampl + 1;

    end

    convergenceRate = convergenceRate*annealingFactor;

end

figure,

% Plot the data points
plot(w1(:,2), w1(:,3), 'r*');
hold on;
plot(w2(:,2), w2(:,3), 'bO');
hold on;

x = linspace(0,10,11);

% Equation of line is given by a*[1 x y]=0
y = (-a(3)/a(2))*x - a(1)/a(2);

plot(x,y,'g');
```

Problem 2

I. Digits Used 3, 5 and 7

II. Digitized and downsampled to 8X8 using imresize(samples((i:i+31),:),0.25,'bilinear'); and sample = uint8(sample);

III. Classifier Code:

```
% Open the file
fileID = fopen('optdigits-orig.tra', 'r');

% Read the text
C = textscan(fileID, '%s');

% This gives C as a column vector of lines as strings
C = C{1};

numLines = size(C, 1);

% Initialize sample inputs and results as NULL matrices
sample = [];
res = [];

% Digits chosen 3, 5 and 7 denoted by output 00, 01 and 10 respectively
for i = 33:33:numLines
```

```
    if (C{i} == '3')
        sample = [sample; C((i-32):(i-1))];
        res = [res; [0 0]];
    end
    if(C{i} == '5')
        sample = [sample; C((i-32):(i-1))];
        res = [res; [0 1]];
    end
    if(C{i} == '7')
        sample = [sample; C((i-32):(i-1))];
        res = [res; [1 0]];
    end

end

% Initialize samples for storing inputs in double data type
samples = zeros(size(sample, 1), 32);

% This converts lines into row vectors
sample = cell2mat(sample);

for i = 1:size(sample, 1)

    for j = 1:32
        % Convert strings to double data type
        samples(i, j) = str2double(sample(i, j));
    end

end

% Initialize sample as NULL matrix, to be used for storing 8X8 bitmaps as
% row vectors
sample = [];

for i = 1:32:size(samples, 1) - 31

    % Downsize 32X32 to 8X8.
    % Bilinear uses weighted average of 2X2 windows to avoid aliasing
    temp = imresize(samples((i:i+31), :), 0.25, 'bilinear');

    % Append 8X8 bitmap as a row vector of size 64
    sample = [sample; temp(:)'];

end

% Apppend x0=1 to each sample to account for bias weights
sample = [sample ones(size(sample, 1), 1) ];

% Initialize error to some large value
error = 10000;

% numX stores number of inputs (65 in this case)
numX = size(sample, 2);

% numNH stores number of hidden units (generally numX/10)
numNH = 6;

% numZ stores number of outputs (2 in this case)
numZ = 2;

% eta is the convergence rate. Chosen optimally by hit and trial
```

```
eta = 0.1;

% dimensionality of input data is 64
dim = 64;

lim = 1 / sqrt(numX);

% w1 stores the weights from input to hidden layer. Chosen optimally between
% -1/root(dim) to +1/root(dim)
w1 = -lim + 2 * lim * rand(numX, numNH);

lim = 1 / sqrt(numNH);

% w2 stores the weights from hidden to output layer. Chosen optimally
% between -1/root(nH) to +1/root(nH)
w2 = -lim + 2 * lim * rand(numNH + 1, numZ);

% keep a limit on maximum number of iterations just in case we diverge
MAX_ITER = 10000;

iter = 0;

while(error > 0.1 && iter < MAX_ITER)

    % Increment iteration count
    iter = iter + 1;

    % Calculate net for each hidden unit for each input
    netJ = sample * w1;

    % Apply activation function sigmoid to netJ
    yJ = 1./(1 + exp(-netJ));

    % Apppend y0=1 to each output to account for bias weights for hidden to
    % output layer
    yJ = [yJ ones(size(yJ,1),1) ];

    % Calculate net for each hidden unit for each output
    netK = yJ*w2;

    % Apply activation function sigmoid to netK
    zK = 1./(1 + exp(-netK));

    % Compute error as 0.5*||t-z||^2
    error = 0.5.*((norm(res - zK))^2)

    % Compute delta2 as (t-z)*f'(netK) and we know for sigmoid f'=f(1-f)
    delta2 = (res - zK).*(zK.*(1 - zK));

    % Compute delta1 as summation over k(delta2*w2)*f'(netJ)
    delta1 = (delta2*w2').*(yJ.*(1 - yJ));

    % Discard the last column as it is extra, due to bias weights from
    % hidden to output layer
    delta1(:,size(delta1,2)) = [];

    % Change in weights is given by eta.delta.x and eta.delta.y
    dw1 = eta.*(sample'*delta1);
    dw2 = eta.*(yJ'*delta2);

    % Compute new weights
    w1 = w1 + dw1;
```

```
  w2 = w2 + dw2;

end

w1;
w2;
```

Weights for number of hidden units as 6:

```
w1 =


   -0.1056    0.0999   -0.0815    0.0848    0.0305
    0.1012    0.1022   -0.1095    0.0018   -0.1062
   -0.0546    0.0259   -0.0233   -0.0966    0.1167
    0.0285   -0.0337   -0.0092   -0.0024    0.0275
    0.0405    0.0246   -0.0743    0.0249   -0.0291
   -0.0750    0.0421    0.0924   -0.1024   -0.1174
    0.1150    0.0986    0.0245    0.1196    0.0894
    0.0413   -0.1032   -0.1192    0.0383    0.0259
    0.0103    0.0098    0.0999   -0.0097    0.0870
   -0.0368   -0.6527    0.5044    0.3765    0.2023
   -0.4348   -0.1305   -0.0669   -0.2295    0.3840
   -0.3669   -0.0348   -0.1057   -0.0336    0.3751
    0.1082   -0.0814    0.1593    0.0292   -0.1472
    0.1629   -0.1080    0.1169    0.1647   -0.0345
    0.0590   -0.1225    0.0288   -0.0640   -0.0872
    0.0203   -0.1356   -0.0954    0.1304    0.0788
   -0.0035   -3.4548    2.9167    2.0068    0.2511
   -0.7493   -4.9180    4.1010    2.3519    1.3865
   -2.2367   -0.9678    0.2344   -0.6482    2.5767
   -1.7879   -0.6291    0.2127   -0.6136    2.0109
    0.6869   -0.3823    0.5292    0.5977   -0.6232
    0.7569   -0.0768    0.2292    0.3381   -0.7297
    0.0464   -1.9151    1.7165    1.0580   -0.0049
    0.2473   -3.8707    3.2062    2.3377    0.0862
    0.6790   -5.7834    5.0524    3.6540   -0.1857
```

0.0420	-4.3438	3.7922	2.5519	0.1188
-1.1358	-1.0243	0.7336	0.0069	1.1645
-0.6256	-4.0067	3.3687	2.0716	0.9307
1.4908	-2.9228	2.7873	2.5000	-1.3778
2.1503	-0.3757	0.9709	1.5416	-2.3375
1.2575	-2.5215	2.5226	2.0876	-1.2537
0.2657	-5.8696	5.0134	3.3120	0.4634
0.5226	-5.4342	4.9549	3.3340	-0.0772
1.0486	-5.3030	4.7575	3.5232	-0.6490
1.2805	-4.4175	4.0266	3.2483	-1.0569
1.3424	-5.6169	5.1136	3.8892	-1.0347
1.6253	-5.1121	4.8243	3.8132	-1.4234
0.9165	-1.6400	1.4914	1.4783	-0.9826
-1.1393	-3.1766	2.6299	1.2188	1.4143
-1.2739	-5.0191	3.8990	1.9258	1.9874
0.6508	-2.0833	1.9657	1.6334	-0.3865
1.7384	-4.0513	3.9021	3.3531	-1.7506
2.6468	-3.2717	3.3231	3.3356	-2.6361
1.9389	-2.2429	2.4657	2.6048	-2.0933
1.4908	-4.6954	4.2414	3.4357	-1.2421
-0.7538	-5.1748	4.2667	2.3749	1.3694
-1.1060	-5.2187	4.3677	2.4245	1.6349
-0.1936	-2.4688	1.9915	1.3379	0.4985
0.8282	-0.2452	0.3076	0.5238	-0.7544
1.1225	-0.2258	0.4581	0.7400	-1.0451
0.4828	-0.1644	0.2063	0.5072	-0.7107
0.4163	0.0447	0.1479	0.3318	-0.6365
0.3935	-0.3498	0.3499	0.2818	-0.4728
0.0626	-1.6006	1.3620	0.9515	0.2361
0.0109	-1.3720	1.0947	0.7085	0.2597
0.0221	-0.1592	0.2503	0.0429	-0.0885
-0.0463	-0.1286	-0.0302	-0.0094	-0.1359
-0.0636	-0.1141	-0.0119	-0.0059	-0.0643

0.0940	-0.0443	0.0044	0.0737	0.0661
-0.0199	-0.1004	-0.1095	-0.1153	0.0061
-0.0031	-0.0825	-0.0672	0.0567	0.0636
-0.0099	-0.0322	-0.0954	0.0932	-0.0826
0.0039	-0.1151	-0.1003	-0.0535	0.0432
-0.0570	0.0523	0.0976	0.0392	0.0297
0.6278	-5.8847	5.1192	3.6721	-0.3885

w2 =

-12.3852	-13.4197
-12.8251	-15.1118
-12.5723	-17.0805
-14.3059	-13.6774
-16.5653	-17.3229
-27.5850	-31.8622

Weights for number of hidden units as 10:

w1 =

0.0166	0.0128	-0.0093	-0.1180	-0.0619	-0.0936	0.0297	0.0038	0.1066
0.0635	-0.1121	-0.0926	0.0524	0.1125	0.0364	-0.1033	-0.1117	0.0035
0.0049	-0.0481	0.0123	0.1013	0.0312	-0.0157	-0.0311	0.0859	-0.0767
0.0215	0.1164	0.1174	0.0915	-0.0733	0.0282	-0.0782	0.0237	0.0257
-0.0773	0.1079	-0.0145	-0.0952	-0.0976	0.0594	0.0776	0.0478	-0.0755
0.0009	-0.0305	0.0227	0.1138	0.0165	-0.0492	0.0558	0.0368	-0.0224
-0.1123	0.0294	-0.0973	-0.0148	-0.0564	-0.1143	0.0437	0.0309	0.0883
-0.1110	0.0156	-0.0750	0.0939	-0.1072	0.0839	0.1035	0.1135	-0.0177
-0.0412	0.0826	-0.0843	0.0912	-0.0854	-0.0327	0.0802	-0.0808	0.1064
-0.0900	-0.0663	0.2644	0.2278	-0.3292	-0.2637	-0.1135	-0.3548	-0.3128

-0.0157	-0.0679	0.3399	0.3912	-0.1258	-0.0251	-0.5855	-0.2678	-0.4381
-0.0134	0.1323	0.1337	0.2789	-0.0126	-0.1061	-0.3609	-0.1799	-0.2409
0.0649	-0.0028	-0.1028	-0.1754	0.1034	0.1357	0.0996	0.1258	-0.0039
0.0627	-0.0899	-0.1428	-0.1497	-0.0388	0.0923	0.1833	-0.0350	0.0495
0.0750	-0.0696	0.1246	-0.0308	0.0990	0.0728	0.0858	0.0479	0.1062
0.0365	0.0422	0.0137	-0.0824	0.0201	0.0274	0.1115	0.0940	-0.1152
-0.5060	-1.0387	1.4688	0.8485	-1.0537	-1.4654	0.0962	-1.4565	-0.8169
-0.9803	-1.3665	2.8078	2.1208	-1.6755	-2.3201	-0.9921	-2.6380	-2.1441
-0.4857	0.2628	1.9945	1.7603	-0.8807	-0.5998	-2.3540	-1.9155	-2.4853
-0.5372	0.1896	1.5970	1.5594	-0.6661	-0.4724	-1.8660	-1.5046	-2.0053
0.0332	-0.2711	-0.0429	-0.2022	0.0181	-0.0101	0.3287	0.1779	0.4469
0.1684	-0.1927	-0.3971	-0.3057	0.2326	0.1868	0.6751	0.4457	0.5619
-0.3324	-0.7005	0.8072	0.5977	-0.5853	-0.7374	0.1577	-0.7569	-0.3006
-0.4751	-1.2755	1.5207	1.1356	-0.9096	-1.5466	-0.0323	-1.6247	-0.8820
-0.7863	-1.8168	2.3021	1.3815	-1.3918	-2.4515	0.2924	-2.0017	-0.9844
-0.5754	-1.2877	2.0643	1.3279	-1.2586	-1.7981	-0.1002	-1.8363	-1.0059
-0.4272	-0.1797	1.3184	1.0096	-0.5873	-0.6679	-1.0568	-1.0471	-1.4077
-0.6275	-1.2143	2.2479	1.5461	-1.3353	-1.8956	-0.6244	-2.0857	-1.6767
-0.0784	-1.0869	0.4826	0.0679	-0.5306	-1.0366	1.1370	-0.3465	0.5130
0.3455	-0.3083	-1.0737	-1.1431	0.4627	0.0382	1.6886	0.9443	1.8436
-0.2477	-0.9304	0.2472	0.0451	-0.2587	-0.7841	1.0271	-0.2800	0.3882
-0.9257	-1.7213	2.7059	1.7516	-1.5502	-2.5822	-0.2403	-2.4557	-1.4094
-0.8109	-1.7766	2.1142	1.2844	-1.2817	-2.2477	0.3144	-2.0386	-1.0478
-0.6765	-1.7293	1.5912	1.0099	-1.2345	-2.0730	0.8278	-1.4829	-0.3798
-0.4916	-1.5404	0.9854	0.3084	-0.9102	-1.7537	1.2673	-0.9780	0.1843
-0.7077	-1.9928	1.4991	0.7041	-1.2432	-2.1738	1.1142	-1.4879	-0.1743
-0.4098	-1.8405	1.2784	0.6910	-1.0758	-2.1164	1.3382	-1.2197	0.1482
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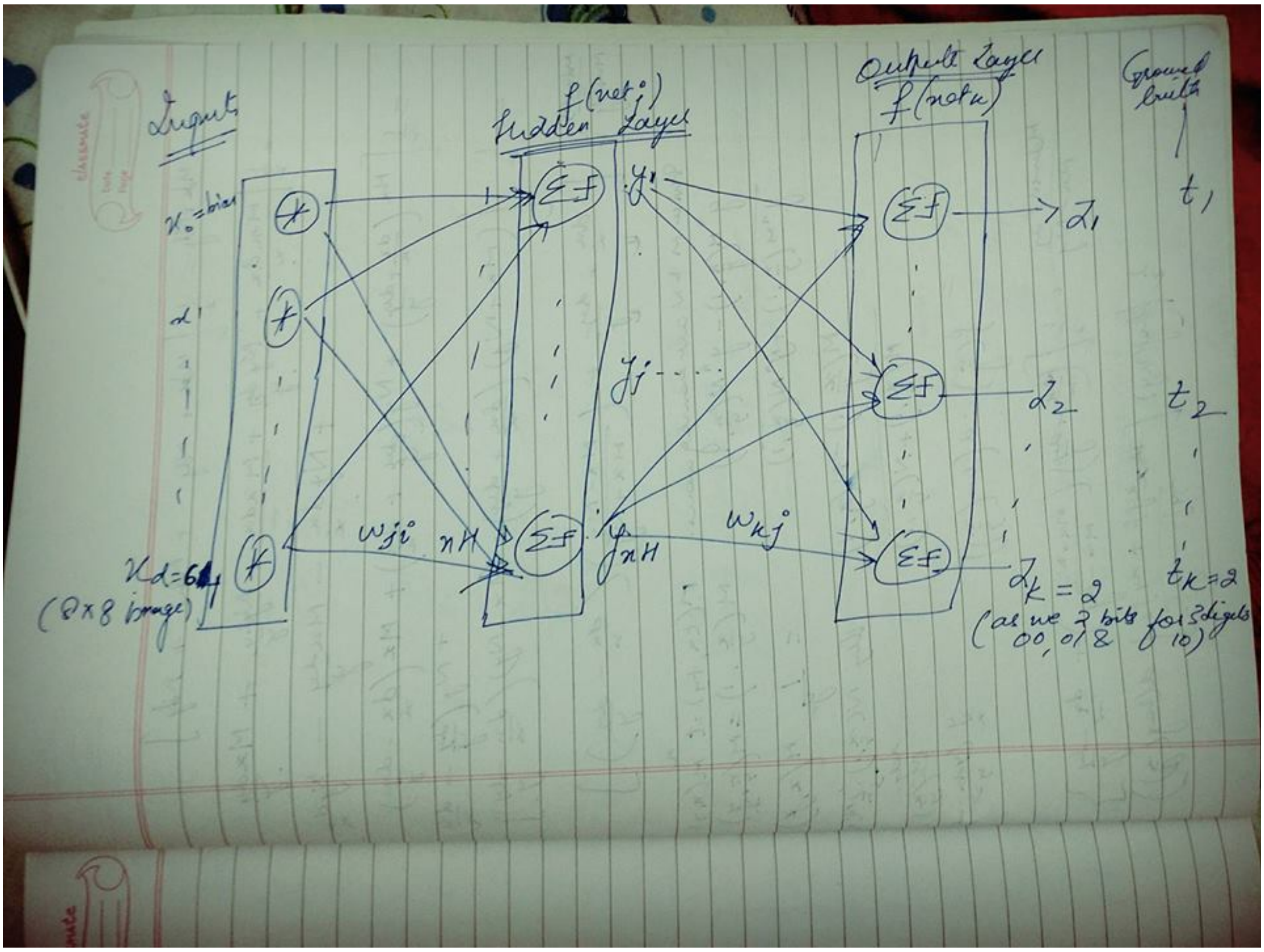
Architecture:



For digit 3:

netJ after learning is over:

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For digit 3:

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