Neural Network Tutorial:
Use of `train.c` and `nnTrain.m`

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1 Introduction

This tutorial briefly introduces the error back-propagation algorithm and cross-validation with early-stopping. Then the use of `train.c` and the Matlab function `nnTrain.m` are explained. This was written for students at Colorado State University who wish to use my code for class or research, but is available to all. It assumes you are familiar with Unix and C. If you have Matlab installed on your Unix system, you can use the `nnTrain.m` function to run `train.c`. The LaTeX source for this document is also available on-line to give you an example to learn from.

Please let me know if you have success or problems with this code. Also, I'd like to hear any suggestions you have for improvements. You may send me email at `anderson@cs.colostate.edu` or visit my web page at `http://www.cs.colostate.edu/~anderson`.

2 Data Sets and the Algorithm

One of the simplest and most useful neural network algorithms is the error back-propagation training algorithm applied to a feedforward network, which is a network with no cycles in its connection structure, i.e., it is not a recurrent network. Implementing this kind of network is very straightforward. I have done this in a single C source file named `train.c`. This tutorial explains how to run `train.c` independently or from within Matlab using the function named `nnTrain`. See the Mathworks, Inc. home page at `http://www.mathworks.com` for information on Matlab.

First, we must address the method used in presenting data to the network for training and for testing. `train.c` employs *cross-validation* and *early stopping*. The available data is divided into the following three disjoint sets:

Training set This data is used to train the network.

Validation set The error of the network averaged over this data is used to decide when the training algorithm has found the best approximation to the data without overfitting.

Testing set The best network, given by the validation test, is applied to the test set and the error averaged over the test set is taken as a prediction of how well the network will generalize to novel data.

Training is accomplished by calculating the derivative of the network's error with respect to each weight in the network when presented a particular input pattern. This derivative indicates which direction each weight should be adjusted to reduce the error. Each weight is modified by taking a small step in this direction. With a nonzero momentum factor, a fraction of the previous weight change is added to the new weight value. This accelerates learning in some cases. The patterns in the training set are stepped through one by one. A pass through all training patterns is called an *epoch*. The training data is repetitively presented for multiple epochs, until a specified number of epochs have been taken.

After each epoch, the error of the network applied to the validation set of patterns is calculated. If the current network scores the lowest error so far on the validation set, this network's weights are saved. At the conclusion of training, the network's best weights are used to calculate the network's error on the testing set.

3 Using `train.c`

After compiling `train.c` into an executable named `train`, typing the command `train` produces the following usage statement:

```
Usage: train spec-file <hammer>
             Example of a spec-file:
-ninputs 1 -noutputs 1 (these must appear before file names)
-nhiddens1 5 -nhiddens2 5 (-nhiddens2 n is optional)
-train one.data two.data (list of one or more files to compose train set)
-validate three.data (optional. list of one or more for validate set)
-test four.data (list of one or more files for test set)
-orate 0.001 -hrate 0.1 (for hammer, hrate is at most 15*orate)
-mom .9 -epochs 1000
-summarize   (optional. to specify short output, one line per run)
-end   (says end of run specification.  Now do it.)
-orate 0.01 (additional runs, all unspecified values same as previous run)
-end
-orate 0.1 -end  (any whitespace may separate tokens)
```

Each part of the specification file (spec-file) will be explained in the order they appear in the example.

1. `-ninputs`: Number of input components in each pattern.
2. `-noutputs`: Number of output components in the patterns.
3. `-nhiddens1`: Number of hidden units to be used in the first, and possibly only, hidden-unit layer of the network. Start with 1, then try higher numbers. If more than one number appears here, then multiple runs with different numbers of hidden units will be performed.
4. `-nhiddens2`: Number of hidden units to be used in the second hidden-unit layer of the network. Can be zero, and if this line is not included, the default value is zero. If more than one number appears here then multiple runs with different numbers of hidden units will be performed.
5. `-train`: Names of data files to be concatenated to form training data.
6. `-validate`: Names of validation data files.
7. `-test`: Names of testing data files.
8. `-orate`: Learning rates, possibly more than one, to try for output layer. Start with something like 0.01 or 0.1.
9. `-hrate`: Learning rates, possibly more than one, for hidden layer. Try values 1 to 10 times the output layer rate.
10. `-mom`: The momentum rates. Should be 0 or greater and less than 1.
11. `-epochs`: The number of passes to make through the training data set.
12. `-summarize`: Produce short format output. Without this token, output is in long format.
13. `-end`: Terminates the specification for one call to `train.c`. Another may start immediately after this in the spec-file. Each set of specifications must end with `-end`.

4 Example

For an example, let's try to approximate a sine wave with a neural network. The network will receive a single number as input, call it x. The network will produce a single output that we will try to make match $\sin(13x)$. I chose 13 for the following reason. My x values range from 0 to 1 and I wanted a value of $x = 1$ to roughly correspond to 4π, to get two periods of data.) I used Matlab to produce the data. You could write a short C program to do it. Here is my Matlab code:

```
x = [1:10] * 0.1;
sineTrain = [x ;  0.5+0.5*sin(13*x)]';
sineValidate = [x+0.03 ; 0.5+0.5*sin(13*(x+0.03))]';
sineTest = [x-0.03 ; 0.5+0.5*sin(13*(x-0.03))]';
```

This is what the matrix sineTrain contains. The first column is the x value and the second column is the corresponding target value.

```
    0.1000    0.9818
    0.2000    0.7578
    0.3000    0.1561
    0.4000    0.0583
    0.5000    0.6076
    0.6000    0.9993
    0.7000    0.6595
    0.8000    0.0861
    0.9000    0.1190
    1.0000    0.7101
```

Better yet, let's just plot them in Matlab:

```
plot(sineTrain(:,1),sineTrain(:,2),'y-',...
  sineValidate(:,1),sineValidate(:,2),'g--',...
  sineTest(:,1),sineTest(:,2),'c:');
legend('train','validate','test');
hold on;
plot(sineTrain(:,1),sineTrain(:,2),'yo',...
  sineValidate(:,1),sineValidate(:,2),'g*',...
  sineTest(:,1),sineTest(:,2),'c+');
```

I included the results of these commands in Figure 1. I made this postscript figure from within Matlab by doing

```
print sine-matlab.ps
```

after the plot commands.

Now the data has been generated. We are going to try to fit a network to the training data. At some point, we will overfit the training data, resulting in higher error on the validation set. Let's use one hidden layer with 2, 5, 10, or 20 hidden units and examine the results. Here is the Matlab command and the output it produces:

```
nnTrain([sineTrain;sineValidate;sineTest],[10 10 10],1,[2 5 10 20],0,1,1,0.1,0.9,20000,...
  'c=1 f=sine.results o=long m=scruggs')
Training with this command:
! ( cd /s/parsons/c/fac/anderson/pub/trainvt/nn.dir483101; train nn.exp>>& ../sine.results &)
>>
```

Notice that one of the options is `f=sine.results`. This tells `nnTrain` the file to which the results are to be appended.

Here is the first part of `sine.results`, showing the results for 2 hidden units:

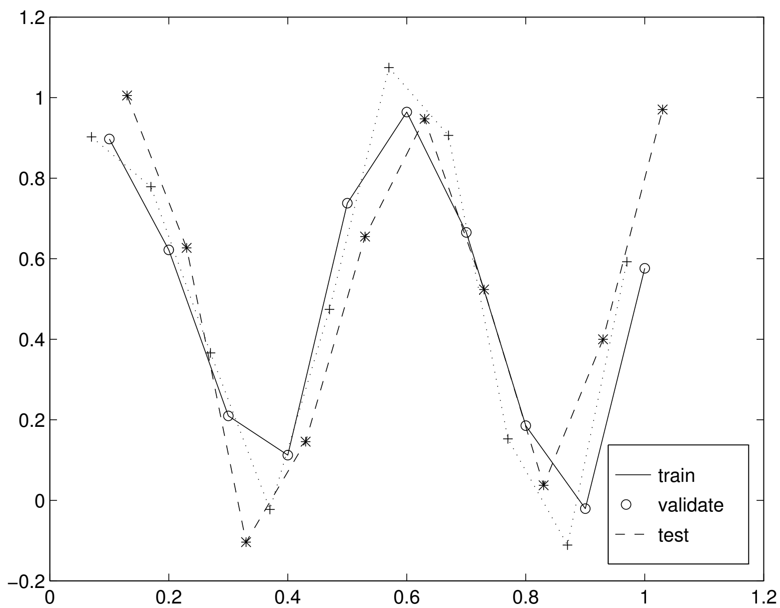


Figure 1: Sine data as generated by Matlab

```
i 1 h1 2 h2 0 o 1 hr   1.000 or   0.100 mr 0.900 ep 20000 linOut 0 hamm 0 Wed Jul 31 16:03:26 1996
epoch  1000 train   0.268933 validate   0.275306 test   0.256840 fracCorr 0.800 Rsq   0.487254
epoch  2000 train   0.264290 validate   0.271144 test   0.252319 fracCorr 0.800 Rsq   0.503340
epoch  3000 train   0.261402 validate   0.269677 test   0.248564 fracCorr 0.800 Rsq   0.454797
epoch  4000 train   0.244782 validate   0.270356 test   0.233664 fracCorr 0.800 Rsq   0.605068
epoch  5000 train   0.233136 validate   0.249864 test   0.201022 fracCorr 0.900 Rsq   0.595055
epoch  6000 train   0.228222 validate   0.244088 test   0.213365 fracCorr 0.900 Rsq   0.690250
epoch  7000 train   0.237138 validate   0.237559 test   0.210108 fracCorr 0.800 Rsq   0.667753
epoch  8000 train   0.235266 validate   0.241505 test   0.175006 fracCorr 0.900 Rsq   0.624432
epoch  9000 train   0.329206 validate   0.256115 test   0.193513 fracCorr 0.800 Rsq   0.688182
epoch 10000 train   0.226783 validate   0.236409 test   0.233568 fracCorr 0.800 Rsq   0.835990
epoch 11000 train   0.230554 validate   0.300122 test   0.237735 fracCorr 0.800 Rsq   0.897800
epoch 12000 train   0.226999 validate   0.324536 test   0.235912 fracCorr 0.800 Rsq   0.916458
epoch 13000 train   0.225132 validate   0.332334 test   0.235029 fracCorr 0.800 Rsq   0.924635
epoch 14000 train   0.224050 validate   0.335962 test   0.234517 fracCorr 0.800 Rsq   0.929193
epoch 15000 train   0.223299 validate   0.338128 test   0.234149 fracCorr 0.800 Rsq   0.932493
epoch 16000 train   0.222726 validate   0.339570 test   0.233857 fracCorr 0.800 Rsq   0.935121
epoch 17000 train   0.222267 validate   0.340591 test   0.233613 fracCorr 0.800 Rsq   0.937311
epoch 18000 train   0.221886 validate   0.341343 test   0.233403 fracCorr 0.800 Rsq   0.939183
epoch 19000 train   0.221562 validate   0.341911 test   0.233218 fracCorr 0.800 Rsq   0.940810
epoch 20000 train   0.221281 validate   0.342350 test   0.233052 fracCorr 0.800 Rsq   0.942244
epoch 20001 train   0.221281 validate   0.342350 test   0.233052 fracCorr 0.800 Rsq   0.942244
pat     1 targets   0.894752 outputs   0.916477 errors  -0.021725
pat     2 targets   0.901286 outputs   0.849012 errors   0.052274
pat     3 targets   0.319935 outputs   0.458843 errors  -0.138908
pat     4 targets   0.002380 outputs   0.011837 errors  -0.009457
pat     5 targets   0.413840 outputs   0.000525 errors   0.413314
pat     6 targets   0.951524 outputs   0.934578 errors   0.016946
pat     7 targets   0.827725 outputs   0.649450 errors   0.178275
pat     8 targets   0.223808 outputs   0.444056 errors  -0.220248
pat     9 targets   0.024513 outputs   0.377322 errors  -0.352809
pat    10 targets   0.521808 outputs   0.357026 errors   0.164782
```

```
Best epoch 10453 validate   0.229888 test   0.206307 fracCorr   0.900000 Rsq   0.850088

Weights
11.680829
-5.029750

58.467415
-29.105097


-21.651245
18.311790
2.711500
```

First you see the parameters you specified. Then the errors are printed every 1,000 epochs (this depends on the total number of epochs you specify). Notice that the validation error decreases, then increases. However, the training error continues to decrease. The net begins overfitting about epoch 10,000.

Just how well did this network approximate our sine function? The next output section helps answer this question. It shows a list of the test data patterns by their indices and the desired output (target), the actual output, and the error for that pattern.

Finally, the weights are given at the end of this file so they can be read in by other programs for further analysis of the weights. First the hidden unit weights appear, followed by the output unit weights.

One way to summarize the results is via the `summshort.awk` awk script, shown below:

```
# Each line of the short output has this format:
# 20  20   0.100   0.010 0.000     0.1473   581     0.2266     0.2444 0.925
#         Copyright (c) 1996 by Charles W. Anderson

NF == 10 && $1 != "ld.so.1:" {
  ind = "h1 " $1 " h2 " $2 " rh " $3 " ro " $4 " m " $5;
  if (notin(ind))
    indices[numindices++] = ind;
  corr_sum[ind] += $10;
  corr_sqsum[ind] += $10*$10;
  epoch_sum[ind] += $7;
  epoch_sqsum[ind] += $7 * $7;
  rms_sum[ind] += $9;
  rms_sqsum[ind] += $9 * $9;
  num[ind]++;
}

END {
  for (i=0; i<numindices; i++) {
    ind = indices[i];
    printf("%33s %d fc %.3f %.3f RMS %.4f %.4f ep %.1f %.1f\n",
   ind,num[ind],
   corr_sum[ind]/num[ind],
   confint(corr_sum[ind],corr_sqsum[ind],num[ind]),
   rms_sum[ind]/num[ind],
   confint(rms_sum[ind],rms_sqsum[ind],num[ind]),
   epoch_sum[ind]/num[ind],
   confint(epoch_sum[ind],epoch_sqsum[ind],num[ind]));
  }
}

function notin(ind) {
  for (i=0; i<numindices; i++) {
    if (indices[i] == ind)
```

```
      return 0;
  }
  return 1;}

function stdev(sum, sumsq, n) {
  if (n > 2)
    return sqrt((n * sumsq - sum * sum) / (n * (n - 1)));
  else
    return 0.
}

function confint(sum, sumsq, n) {
  s = stdev(sum,sumsq,n);
  return 1.6449 * s / sqrt(n);
}

function fraction_correct(thresh) {
  n = 0;
  numc = 0.;
  while ($1 == "pat") {
    n++;
    if (($4 < thresh && $6 < thresh) ||
($4 > thresh && $6 >= thresh))
       numc++;
    getline;
  }
  return numc / n;
}
```

This script parses the short format of results. I usually combine it with a call to the unix sort command, using a shell script like this:

```
#!/bin/csh
gawk -f ~/res/nettools/train/summshort.awk $1 | \
 gawk '{printf("%2d %3d %.3f %.3f %3d %6.3f %6.3f %8.1f\n", $2, $4, $6, $8,
               %$11, $13, $16, $19)}' | \
 sort -n +6 -7 | more
```

However, our results are in long output format. So, first let's generate a short version from the long version using the `nnlong-to-short.awk` script:

```
$3 == "h1" {
  h1 = $4; h2 = $6; hr = $10; or = $12; mr = $14; maxep = $16;
}
$1 == "epoch" && $2 == maxep {
  trerror = $4;
}
$1 == "Best" {
  ep = $3; valerror = $5; testerror = $7; frcor = $9;
  printf("%3d%4d%8.3f%8.3f%6.3f%11.4f%6d%11.4f%11.4f%6.3f\n",
  h1,h2,hr,or,mr,trerror,ep,valerror,testerror,frcor);
}
```

Again, I usually call this with a shell script like:

```
#!/bin/csh
gawk -f ~/res/nettools/train/nnlong-to-short.awk $1 | \
 gawk -f ~/res/nettools/train/summshort.awk | \
 gawk '{printf("%2d %3d %.3f %.3f %3d %6.3f %6.3f %8.1f\n", $2, $4, $6, $8, $11, $13, $16, $19)}' | \
 sort -n +6 -7 | more
```

If I call this script `summlong`, then I summarize our results as follows:

```
> summlong sine.results
20   0 1.000 0.100   1  1.000  0.068   2021.0
10   0 1.000 0.100   1  1.000  0.071   2349.0
 5   0 1.000 0.100   1  1.000  0.086   6159.0
 2   0 1.000 0.100   1  0.900  0.206  10453.0
```

The seventh column is the test error, the final column is the best epoch. From this we see that the network with 20 hidden units achieved the lowest test error of 0.068 after the fewest epochs of 2,021.

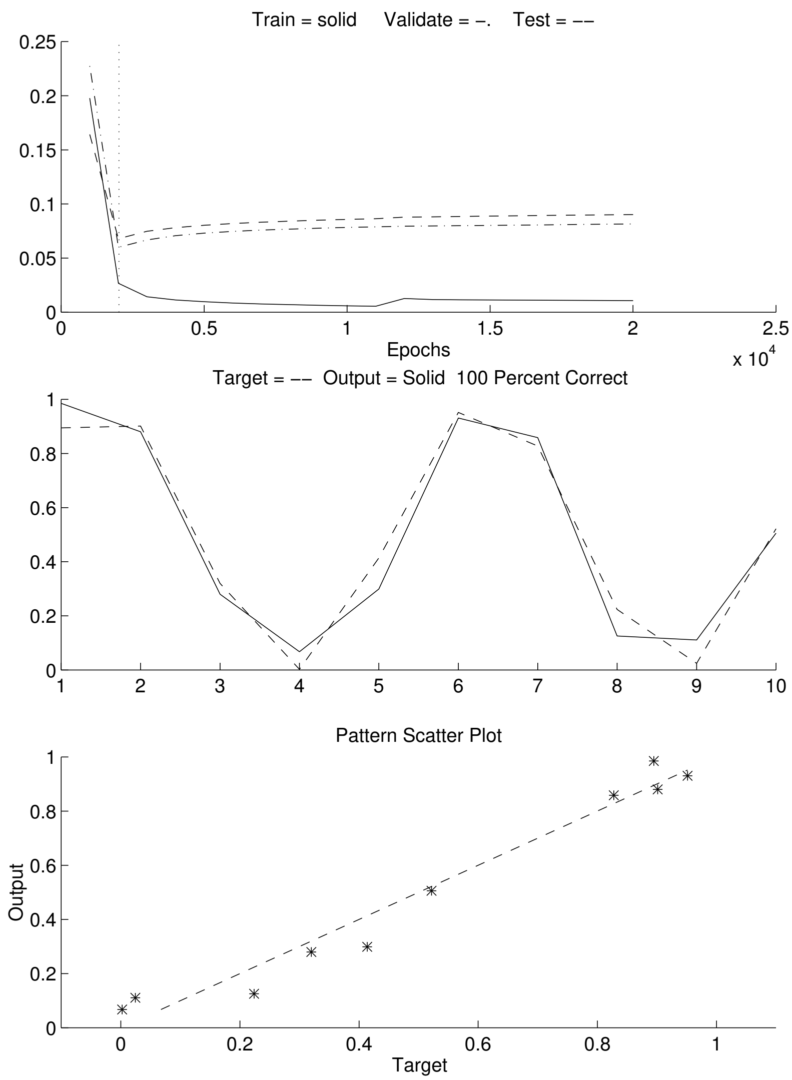
Now let's see more details of the 20-hidden unit run. Do this in Matlab with `nnResults`:

```
>> nnResults('sine.results',1)
nnE =
    0.2063
nnEp =
       10453
Quit, save, or next? (q, s, enter)

nnE =
    0.0862
nnEp =
        6159
Quit, save, or next? (q, s, enter)

nnE =
    0.0708
nnEp =
        2349
Quit, save, or next? (q, s, enter)

nnE =
    0.0681
nnEp =
        2021
Quit, save, or next? (q, s, enter) q
```

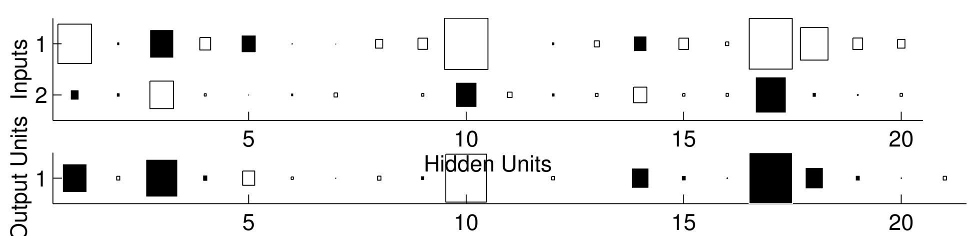
I pressed enter after each prompt to get to the final run, the one with 20 hidden units. For each run, two windows are displayed. The window displays for the 20 hidden units run are shown in Figure 2. Figure 2a contains three graphs. The top graph is three learning curves showing RMS error versus epoch, one for each data set. The training error decreases quickly to near-zero error. However, the validation and test data errors decrease below 0.1, but then start to climb. This is the point at which the network is over-fitting the training data. This means that the network is no longer smoothly approximating the curve sampled by the training data and is now beginning to precisely match the training data. This often results in poor interpolation between the training samples resulting in higher error for the validation and test data. We want to keep the weight values near epoch 2,000. This is exactly what is done.

These best weights are used for the next two graphs. The middle graph shows the test data target values and the values predicted by the network using the best weights. There is a pretty close match. Further training would produce less of a match. The bottom graph is a plot of the network's output value versus the target value for the test data. The diagonal represents an exact match between target and output.

Figure 2b is a simple but effective way to visualize the network's weights. The hidden layer weights can be arranged in a matrix, with columns corresponding to hidden units and rows to inputs. Our network has 20 hidden units, so the hidden layer matrix has 20 columns. We have one variable input and one constant input with a value of 1, so the hidden layer weights form a 2 x 20 matrix. The values are drawn as boxes with positive weights shown as unfilled boxes and negative as filled boxes and their widths represents the weights' magnitude. The output layer has one unit so its weights form a 21 x



a. Window 1



b. Window 2

Figure 2: Two Matlab displays for 20 hidden-unit network.

1 matrix, receiving 20 inputs from the hidden units plus a constant input with value 1. Figure 2b displays these two matricies with the hidden layer matrix on top and the output layer matrix below and transposed. Imagine information flowing from the inputs at the upper left of the diagram down through the hidden layer matrix, into the output layer matrix and out to the right.

5 Now what?

You will want to play with the number of hidden units and the learning rates to try to get the lowest testing error possible. Here is how to set up a long experiment for which the number of hidden layers and units and learning rates are varied. This took about 5 hours on a Sun UltraSparcStation.

```
nnTrain([sineTrain;sineValidate;sineTest],[10 10 10],1,[2 5 10 20],[0 2 10 20],1,[0.1 1 10],...
  [0.01 0.1 1 5],[0 0.9],10000,'c=1 f=sine.results o=short m=scruggs')
Training with this command:
! ( cd /s/parsons/c/fac/anderson/pub/trainvt/nn.dir483101; train nn.exp>>& ../sine.results &)
>>
```

Now I will use the `summshort` command to rank the results from best to worst. Here are the first 20 lines of the result:

```
summshort sine.results
10  10 10.000 1.000   1  1.000  0.049   4892.0
 2  20 10.000 0.100   1  1.000  0.051  10000.0
 5  20 0.100 0.100   1  0.900  0.055   6454.0
 5  10 0.100 1.000   1  1.000  0.057   3400.0
10  10 0.100 1.000   1  1.000  0.059   5777.0
 5  20 10.000 1.000   1  1.000  0.060   5509.0
20   0 1.000 1.000   1  0.900  0.060   2308.0
20   0 10.000 0.010   1  1.000  0.060   3720.0
20  20 0.100 0.100   1  1.000  0.060   4442.0
 5  20 10.000 0.100   1  1.000  0.061   9778.0
20  10 0.100 1.000   1  1.000  0.061   2283.0
 5  20 0.100 1.000   1  1.000  0.062   6363.0
20   0 1.000 1.000   1  1.000  0.062   6448.0
10  20 1.000 5.000   1  1.000  0.063   5429.0
10   0 1.000 1.000   1  1.000  0.065   9199.0
 5  20 1.000 5.000   1  1.000  0.066   5793.0
10  20 10.000 5.000   1  1.000  0.066   3477.0
20   0 0.100 0.100   1  0.900  0.066   6095.0
10   0 0.100 0.100   1  0.900  0.067  10000.0
 5   0 0.100 0.100   1  1.000  0.068   7368.0
```

The best results were for a network with two hidden layers and 10 units in each layer. Since there isn't a lot of different in the test RMS error (seventh column) among the top finishers, to draw any conclusions regarding the best network architecture you must repeat this many times. If `sine.results` contained multiple runs with the same network size and learning parameters differing only in initial weight values, the `summshort` will average over the multiple runs.