A Practical Bayesian Framework for Backprop Networks

David J.C. MacKay
Computation and Neural Systems*
California Institute of Technology 139–74
Pasadena CA 91125
mackay@hope.caltech.edu

Abstract

A quantitative and practical Bayesian framework is described for learning of mappings in feedforward networks. The framework makes possible: (1) objective comparisons between solutions using alternative network architectures; (2) objective stopping rules for network pruning or growing procedures; (3) objective choice of magnitude and type of weight decay terms or additive regularisers (for penalising large weights, etc.); (4) a measure of the effective number of well–determined parameters in a model; (5) quantified estimates of the error bars on network parameters and on network output; (6) objective comparisons with alternative learning and interpolation models such as splines and radial basis functions. The Bayesian 'evidence' automatically embodies 'Occam's razor,' penalising over–flexible and over–complex models. The Bayesian approach helps detect poor underlying assumptions in learning models. For learning models well matched to a problem, a good correlation between generalisation ability and the Bayesian evidence is obtained.

Prerequisite

This paper makes use of the Bayesian framework for regularisation and model comparison described in the companion paper 'Bayesian interpolation' (MacKay, 1991a). This framework is due to Gull and Skilling (Gull, 1989a).

1 The gaps in backprop

There are many knobs on the black box of 'backprop' (learning by back–propagation of errors (Rumelhart *et. al.*, 1986)). Generally these knobs are set by rules of thumb, trial and error, and the use of reserved test data to assess generalisation ability (or more sophisticated cross–validation). The knobs fall into two classes: (1) parameters which change the effective learning model, for example, number of hidden units, and weight decay terms; and (2) parameters concerned with function optimisation technique, for example, 'momentum' terms. This paper is concerned with making objective the choice of the parameters in the first class, and with ranking alternative solutions to a learning problem in a way which makes full use of all the available data. Bayesian techniques will be described which are both theoretically well–founded and practically implementable.

*Address from January 1st 1992: Darwin College, Cambridge CB2 9EU, U.K. mackay@eng.cam.ac.uk

Let us review the basic framework for learning in networks, then discuss the points at which objective techniques are needed. The training set for the mapping to be learned is a set of input–target pairs $D = \{\mathbf{x}^m, \mathbf{t}^m\}$, where m is a label running over the pairs. A neural network architecture $\mathcal{A}$ is invented, consisting of a specification of the number of layers, the number of units in each layer, the type of activation function performed by each unit, and the available connections between the units. If a set of values $\mathbf{w}$ is assigned to the connections in the network, the network defines a mapping $\mathbf{y}(\mathbf{x}; \mathbf{w}, \mathcal{A})$ from the input activities $\mathbf{x}$ to the output activities $\mathbf{y}$.[1] The distance of this mapping to the training set is measured by some error function; for example the error for the entire data set is commonly taken to be

$$E_D(D\,|\mathbf{w}, \mathcal{A}) = \sum_m \frac{1}{2}\Big(\mathbf{y}(\mathbf{x}^m; \mathbf{w}, \mathcal{A}) - \mathbf{t}^m\Big)^2 \tag{1}$$

The task of 'learning' is to find a set of connections $\mathbf{w}$ which gives a mapping which fits the training set well, *i.e.* has small error E_D; it is also hoped that the learned connections will 'generalise' well to new examples. Plain backpropagation learns by performing gradient descent on E_D in $\mathbf{w}$–space. Modifications include the addition of a 'momentum' term, and the inclusion of noise in the descent process. More efficient optimisation techniques may also be used, such as conjugate gradients or variable metric methods. This paper will not discuss computational modifications concerned only with speeding the optimisation. It will address however those modifications to the plain backprop algorithm which implicitly or explicitly modify the objective function, with decay terms or regularisers.

It is moderately common for extra regularising terms $E_W(\mathbf{w})$ to be added to E_D; for example terms which penalise large weights may be introduced, in the hope of achieving a smoother or simpler mapping (Hinton and Sejnowski, 1986, Ji *et. al.*, 1990, Nowlan, 1991, Rumelhart, 1987, Weigend *et. al.*, 1991). Some of the 'hints' in (Abu–Mostafa, 1990b) also fall into the category of additive weight–dependent energies. A sample weight energy term is:

$$E_W(\mathbf{w}|\mathcal{A}) = \sum_i \frac{1}{2} w_i^2 \tag{2}$$

The weight energy may be implicit, for example, 'weight decay' (subtraction of a multiple of $\mathbf{w}$ in the weight change rule) corresponds to the energy in (2). Gradient–based optimisation is then used to minimise the combined function:

$$M = \alpha E_W(\mathbf{w}|\mathcal{A}) + \beta E_D(D\,|\mathbf{w}, \mathcal{A}) \tag{3}$$

where α and β are 'black box' parameters.

The constant α should not be confused with the 'momentum' parameter sometimes introduced into backprop; in the present context α is a decay rate or regularising constant. Also note that α should not be viewed as causing 'forgetting'; E_D is defined as the error on the entire data set, so gradient descent on M treats all data points equally irrespective of the order in which they were acquired.

What is lacking

The above procedures include a host of free parameters such as the choice of neural network architecture, and of the regularising constant α. There are not yet established ways of

[1] The framework developed in this paper will apply not only to networks composed of 'neurons,' but to any regression model for which we can compute the derivatives of the outputs with respect to the parameters, $\partial \mathbf{y}(\mathbf{x}; \mathbf{w}, \mathcal{A})/\partial \mathbf{w}$.

objectively setting these parameters, though there are many rules of thumb (see Ji *et. al.*, 1990, Weigend *et. al.*, 1991 for examples).

One popular way of comparing networks trained with different parameter values is to assess their performance by measuring the error on an unseen test set or by similar cross–validation techniques. The data are divided into two sets, a training set which is used to optimise the parameters $\mathbf{w}$ of the network, and a test set, which is used to optimise control parameters such as α and the architecture $\mathcal{A}$. However the utility of these techniques in determining values for the parameters α and β or for comparing alternative network solutions, etc., is limited because a large test set may be needed to reduce the signal to noise ratio in the test error, and cross–validation is computationally demanding. Furthermore if there are several parameters like α and β, it is out of the question to optimise such parameters by repeating the learning with all possible values of these parameters and using a test set. Such parameters must be optimised on line.

It is therefore interesting to study objective criteria for setting free parameters and comparing alternative solutions which depend only on the data set used for the training. Such criteria will prove especially important in applications where the total amount of data is limited, so that one doesn't want to sacrifice good data for use as a test set. Rather, we wish to find a way to use *all* our data in the process of optimising the parameters $\mathbf{w}$ *and* in the process of optimising control parameters like α and $\mathcal{A}$.

This paper will describe practical Bayesian methods for filling the following holes in the neural network framework just described:

1. **Objective criteria for comparing alternative neural network solutions, in particular with different architectures $\mathcal{A}$.**

   Given a single architecture $\mathcal{A}$, there may be more than one minimum of the objective function M. If there is a large disparity in M between the minima then it is plausible to choose the solution with smallest M. But where the difference is not so great it is desirable to be able to assign an objective preference to the alternatives.

   It is also desirable to be able to assign preferences to neural network solutions using different numbers of hidden units, and different activation functions. Here there is an 'Occam's razor' problem: the more free parameters a model has, the smaller the data error E_D it can achieve. So we cannot simply choose the architecture with smallest data error. That would lead us to an over–complex network which generalises poorly. The use of weight decay does not fully alleviate this problem; networks with too many hidden units still generalise worse, even if weight decay is used (see section 4).

2. **Objective criteria for setting the decay rate α.** As in the choice of $\mathcal{A}$ above, there is an 'Occam's razor' problem: a small value of α in equation (3) allows the weights to become large and overfit the noise in the data. This leads to a small value of the data error E_D (and a small value of M), so we cannot base our choice of α only on E_D or M. The Bayesian solution presented here can be implemented on–line, *i.e.* it is not necessary to do multiple learning runs with different values of α in order to find the best.

3. **Objective choice of regularising function E_W.**

4. **Objective criteria for choosing between a neural network solution and a solution using a different learning or interpolation model**, for example, splines or radial basis functions.

The probability connection

Tishby *et. al.* (1989) introduced a probabilistic view of learning which is an important step towards solving the problems listed above. The idea is to force a probabilistic interpretation onto the neural network technique so as to be able to make objective statements. This interpretation does not involve the addition of any new arbitrary functions or parameters, but it involves assigning a meaning to the functions and parameters that are already used.

My work is based on the same probabilistic framework, and extends it using concepts and techniques adapted from Gull and Skilling's (1989a) Bayesian image reconstruction methods. This paper also adopts a shift in emphasis from Tishby *et. al.*'s paper. Their work concentrated on predicting the average generalisation ability of one network trained on a task drawn from a known prior ensemble of tasks. This is called *forward probability*. In this paper the emphasis will be on quantifying the relative plausibilities of many alternative solutions to an interpolation or classification task; that task is defined by a single data set produced by the real world, and we do not know the prior ensemble from which the task comes. This is called *inverse probability*. This paper avoids using the language of statistical physics, in order to maintain wider readability, and to avoid concepts that would sound strange in that language; for example 'the probability distribution of the temperature' is unfamiliar in physics, but 'the probability distribution of the noise variance' is its innocent counterpart in literal terms.

Let us now review the probabilistic interpretation of network learning.

- **Likelihood.** A network with specified architecture $\mathcal{A}$ and connections $\mathbf{w}$ is viewed as making predictions about the target outputs as a function of input $\mathbf{x}$ in accordance with the probability distribution:

$$P(\mathbf{t}^m|\mathbf{x}^m, \mathbf{w}, \beta, \mathcal{A}) = \frac{\exp(-\beta E(\mathbf{t}^m|\mathbf{x}^m, \mathbf{w}, \mathcal{A}))}{Z_m(\beta)}, \tag{4}$$

  where $Z_m(\beta) = \int d\mathbf{t} \exp(-\beta E)$. E is the error for a single datum, and β is a measure of the presumed noise included in $\mathbf{t}$. If E is the quadratic error function then this corresponds to the assumption that $\mathbf{t}$ includes additive gaussian noise with variance $\sigma_\nu^2 = 1/\beta$.

- **Prior.** A prior probability is assigned to alternative network connection strengths $\mathbf{w}$, written in the form:

$$P(\mathbf{w}|\alpha, \mathcal{A}, \mathcal{R}) = \frac{\exp(-\alpha E_W(\mathbf{w}|\mathcal{A}))}{Z_W(\alpha)} \tag{5}$$

  where $Z_W = \int d^k\mathbf{w} \exp(-\alpha E_W)$. Here α is a measure of the characteristic expected connection magnitude. If E_W is quadratic as specified in equation (2) then weights are expected to come from a gaussian with zero mean and variance $\sigma_W^2 = 1/\alpha$. Alternative 'regularisers' $\mathcal{R}$ (each using a different energy function E_W) implicitly correspond to alternative hypotheses about the statistics of the environment.

- The **posterior probability** of the network connections $\mathbf{w}$ is then:

$$P(\mathbf{w}|D, \alpha, \beta, \mathcal{A}, \mathcal{R}) = \frac{\exp(-\alpha E_W - \beta E_D)}{Z_M(\alpha, \beta)} \tag{6}$$

  where $Z_M(\alpha, \beta) = \int d^k\mathbf{w} \exp(-\alpha E_W - \beta E_D)$. Notice that the exponent in this expression is the same as (minus) the objective function M defined in (3).

So under this framework, minimisation of $M = \alpha E_W + \beta E_D$ is identical to finding the (locally) most probable parameters $\mathbf{w}_{\rm MP}$; minimisation of E_D alone is identical to finding the maximum likelihood parameters $\mathbf{w}_{\rm ML}$. Thus an interpretation has been given to back-propagation's energy functions E_D and E_W, and to the parameters α and β. It should be emphasised that 'the probability of the connections $\mathbf{w}$' is a measure of *plausibility* that the model's parameters should have a specified value $\mathbf{w}$; this has nothing to do with the probability that a particular algorithm might converge to $\mathbf{w}$.

This framework offers some partial enhancements for backprop methods: The work of Levin *et. al.* (1989) makes it possible to predict the average generalisation ability of neural networks trained on one of a defined class of problems. However, it is not clear whether this will lead to a practical technique for choosing between alternative network architectures for real data sets.

Le Cun *et. al.* (1990) have demonstrated how to estimate the 'saliency' of a weight, which is the change in M when the weight is deleted. They have used this measure successfully to simplify large neural networks. However no stopping rule for weight deletion was offered other than measuring performance on a test set.

Also Denker and Le Cun (1991) demonstrated how the Hessian of M can be used to assign error bars to the parameters of a network and to its outputs. However, these error bars can only be quantified once β is quantified, and how to do this without prior knowledge or extra data has not been demonstrated. In fact β can be estimated from the training data alone.

2 Review of Bayesian regularisation and model comparison

In the companion paper (MacKay, 1991a) it was demonstrated how the control parameters α and β are assigned by Bayes, and how alternative interpolation models can be compared. It was noted there that it is not satisfactory to optimise α and β by finding the joint maximum likelihood value of $\mathbf{w}, \alpha, \beta$; the likelihood has a skew peak whose maximum is not located at the most probable values of the control parameters. The companion paper also reviewed how the Bayesian choice of α and β is neatly expressed in terms of a measure of the number of well–determined parameters in a model, γ. However that paper assumed that $M(\mathbf{w})$ only has one significant minimum which was well approximated as quadratic. (All the interpolation models discussed in (MacKay, 1991a) can be interpreted as two–layer networks with a fixed non–linear first layer and adaptive linear second layer.) In this section I briefly review the Bayesian framework, retaining that assumption. The following section will then discuss how the framework can be modified to handle neural networks, where the landscape of $M(\mathbf{w})$ is certainly not quadratic.

Determination of α and β

By Bayes' rule, the posterior probability for these parameters is:

$$P(\alpha, \beta \,|D, \mathcal{A}, \mathcal{R}) = \frac{P(D|\alpha, \beta, \mathcal{A}, \mathcal{R}) P(\alpha, \beta)}{P(D|\mathcal{A}, \mathcal{R})} \tag{7}$$

Now if we assign a uniform prior to (α, β), the quantity of interest for assigning preferences to (α, β) is the first term on the right hand side, the **evidence** for α, β, which can be written

as[2]

$$P(D|\alpha,\beta,\mathcal{A},\mathcal{R}) = \frac{Z_M(\alpha,\beta)}{Z_W(\alpha)Z_D(\beta)} \tag{8}$$

where Z_M and Z_W were defined earlier and $Z_D = \int d^N D\, e^{-\beta E_D}$.

Let us use the simple quadratic energy functions defined in equations (1,2). This makes the analysis easier, but more complex cases can still in principle be handled by the same approach. Let the number of degrees of freedom in the data set, *i.e.* the number of output units times the number of data pairs, be N, and let the number of free parameters, *i.e.* the dimension of $\mathbf{w}$, be k. Then we can immediately evaluate the gaussian integrals Z_D and Z_W: $Z_D = (2\pi/\beta)^{N/2}$, and $Z_W = (2\pi/\alpha)^{k/2}$. Now we want to find $Z_M(\alpha,\beta) = \int d^k\mathbf{w}\, \exp(-M(\mathbf{w},\alpha,\beta))$. Supposing for now that M has a single minimum as a function of $\mathbf{w}$, at $\mathbf{w}_{\rm MP}$, and assuming we can locally approximate M as quadratic there, the integral Z_M is approximated by:

$$Z_M \simeq e^{-M(\mathbf{w}_{\rm MP})}(2\pi)^{k/2}\det{}^{-\frac{1}{2}}\mathbf{A} \tag{9}$$

where $\mathbf{A} = \nabla\nabla M$ is the Hessian of M evaluated at $\mathbf{w}_{\rm MP}$.

The maximum of $P(D|\alpha,\beta,\mathcal{A},\mathcal{R})$ has the following useful properties:

$$\chi^2_W \equiv 2\alpha E_W = \gamma \tag{10}$$

$$\chi^2_D \equiv 2\beta E_D = N - \gamma \tag{11}$$

where γ is the effective number of parameters determined by the data,

$$\gamma = \sum_{a=1}^{k} \frac{\lambda_a}{\lambda_a + \alpha} \tag{12}$$

where λ_a are the eigenvalues of the quadratic form βE_D in the natural basis of E_W.

Comparison of different models

To rank alternative architectures and penalty functions E_W in the light of the data, we simply evaluate the evidence, $P(D\,|\mathcal{A},\mathcal{R})$, which appeared as the normalising constant in (7). Integrating the evidence for (α,β), we have:

$$P(D|\mathcal{A},\mathcal{R}) = \int P(D|\alpha,\beta,\mathcal{A},\mathcal{R})P(\alpha,\beta)\,d\alpha\,d\beta \tag{13}$$

The evidence is the Bayesian's transportable quantity for comparing models in the light of the data.

3 Adapting the framework

For neural networks, $M(\mathbf{w})$ is not quadratic. Indeed it is well known that M typically has many local minima. And if the network has a symmetry under permutation of its parameters, then we know that $M(\mathbf{w})$ must share that symmetry, so that every single minimum belongs to a family of symmetric minima of M. For example if there are H hidden units in a single layer then each non–degenerate minimum is in a family of size $g = H!2^H$. Now it may be the case that the significant minima of M are locally quadratic,

[2]The same notation, and the same abuses thereof, will be used as in (MacKay, 1991a).

so we might be able to evaluate Z_M by evaluating (9) at each significant minimum and adding up the Z_Ms; but the number of those minima is unknown, and this approach to evaluating Z_M would seem dubious.

Luckily however, we do not actually want to evaluate Z_M. We would need to evaluate Z_M in order to assign a posterior probability over α, β for an entire model, and to evaluate the evidence for alternative entire models. This is not quite what we wish to do: when we use a neural network to perform a mapping, we typically only implement one neural network at a time, and this network will have its parameters set to a *particular solution* of the learning problem. Therefore the alternatives we wish to rank are the different solutions of the learning problem, *i.e.* the different minima of M. We would only want the evidence as a function of the number of hidden units if we were somehow able to simultaneously implement the entire posterior ensemble of networks for one number of hidden units. Similarly, we do not want the posterior over α, β for the entire posterior ensemble; rather, it is reasonable to allow each solution (each minimum of M) to choose its own optimal value for these parameters. The same method of chopping up a complex model space is used in the unsupervised classification system, AutoClass (Hanson *et. al.*, 1991).

Having adopted this slight shift in objective, it turns out that to set α and β and to compare alternative solutions to a learning problem, the integral we now need to evaluate is a local version of Z_M. Assume that the posterior probability consists of well separated islands in parameter space each centred on a minimum of M. We wish to evaluate how much posterior probability mass is in each of these islands. Consider a minimum located at $\mathbf{w}^*$, and define a solution $S_{\mathbf{w}^*}$ as the ensemble of networks in the neighbourhood of $\mathbf{w}^*$, and all symmetric permutations of that ensemble. Let us evaluate the posterior probability for alternative solutions $S_{\mathbf{w}^*}$, and the parameters α and β:

$$P(S_{\mathbf{w}^*}, \alpha, \beta, \mathcal{A}, \mathcal{R}|D) \propto g \frac{Z^*_M(\mathbf{w}^*, \alpha, \beta)}{Z_W(\alpha) Z_D(\beta)} P(\alpha, \beta) P(\mathcal{A}, \mathcal{R}) \tag{14}$$

where g is the permutation factor, and $Z^*_M(\mathbf{w}^*, \alpha, \beta) = \int_{S_{\mathbf{w}^*}} d^k\mathbf{w} \, \exp(-M(\mathbf{w}, \alpha, \beta))$, where the integral is performed only over the neighbourhood of the minimum at $\mathbf{w}^*$. I will refer to the quantity $g \frac{Z^*_M(\mathbf{w}^*, \alpha, \beta)}{Z_W(\alpha) Z_D(\beta)}$ as the evidence for $\alpha, \beta, S_{\mathbf{w}^*}$. The parameters α and β will be chosen to maximise this evidence. Then the quantity we want to evaluate to compare alternative solutions is the evidence[3] for $S_{\mathbf{w}^*}$,

$$P(D, S_{\mathbf{w}^*}|\mathcal{A}, \mathcal{R}) = \int g \frac{Z^*_M(\mathbf{w}^*, \alpha, \beta)}{Z_W(\alpha) Z_D(\beta)} P(\alpha, \beta) \, d\alpha \, d\beta. \tag{15}$$

I propose that the gaussian approximation for Z^*_M may meet our needs:

$$Z^*_M \simeq e^{-M(\mathbf{w}^*)} (2\pi)^{k/2} \det{}^{-\frac{1}{2}} \mathbf{A} \tag{16}$$

where $\mathbf{A} = \nabla\nabla M$ is the Hessian of M evaluated at $\mathbf{w}^*$. For general α and β this approximation is probably unacceptable; however we only need it to be accurate for the small range of α and β close to their most probable value. The regime in which this approximation will definitely break down is when the number of constraints, N, is small relative to the number

[3] Bayesian model comparison is performed by evaluating and comparing the evidence for alternative models. Gull and Skilling defined the evidence for a model $\mathcal{H}$ to be $P(D|\mathcal{H})$. The existence of multiple minima in neural network parameter space complicates model comparison. The quantity in (15) is not $P(D|S_{\mathbf{w}^*}, \mathcal{A}, \mathcal{R})$ (it includes the prior for $S_{\mathbf{w}^*}|\mathcal{A}, \mathcal{R}$), but I have called it the evidence because it is the quantity we should evaluate to compare alternative solutions with each other and with other models.

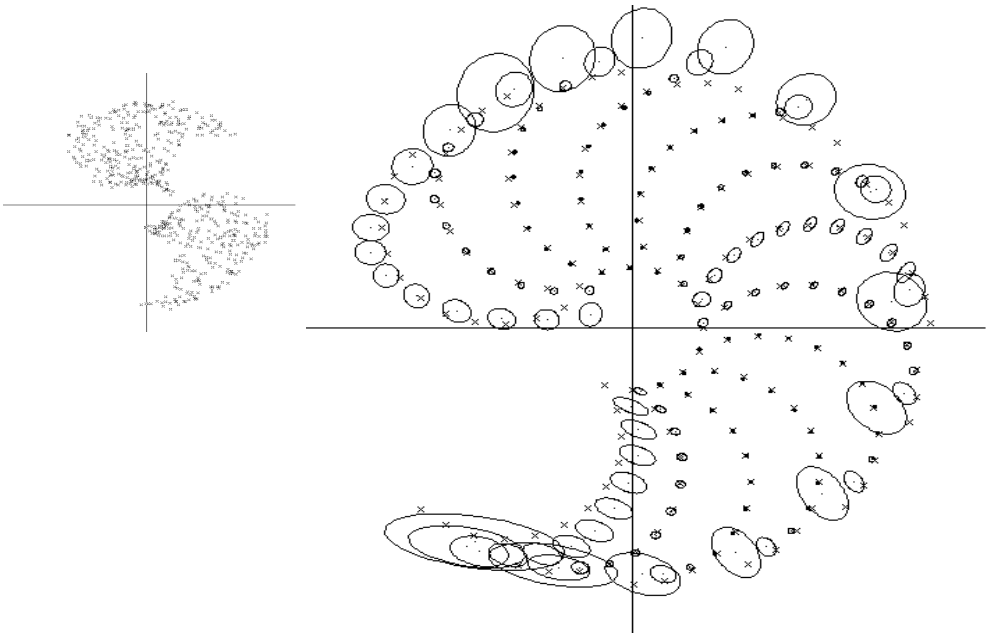

Figure 1: **Typical neural network output.** (Inset – training set)
This is the output space (y_a, y_b) of the network. The target outputs are displayed as small x's, and the output of the network with 1σ error bars is shown as a a dot surrounded by an ellipse. The network was trained on samples in two regions in the lower and upper half planes (inset). The outputs illustrated here are for inputs extending a short distance outside the training regions, and bridging the gap between them. Notice that the error bars get much larger around the perimeter. They also increase slightly in the gap between the training regions. These pleasing properties would not have been obtained had the diagonal Hessian approximation of Denker and Le Cun (1991) been used. The above solution was created by a three layer network with 19 hidden units.

of free parameters, k. For large N/k the central limit theorem encourages us to use the gaussian approximation (Walker, 1967). It is a matter for further research to establish how large N/k must be for this approximation to be reliable.

What obstacles remain to prevent us from evaluating the local Z_M^*? We need to evaluate or approximate the inverse Hessian of M, and we need to evaluate or approximate its determinant and/or trace (MacKay, 1991a).

Denker and Le Cun (1991) *et. al.* (1990) have already discussed how to approximate the Hessian of E_D for the purpose of evaluating weight saliency and for assigning error bars to weights and network outputs. The Hessian can be evaluated in the same way that back-propagation evaluates ∇E_D (see Bishop, 1991 for a complete algorithm and the appendix of this paper for a useful approximation). Alternatively $\mathbf{A}$ can be evaluated by numerical methods, for example second differences. A third option: if variable metric methods are used to minimise M instead of gradient descent, then the inverse Hessian is automatically generated during the search for the minimum. It is important, for the success of this Bayesian method, that the off–diagonal terms of the Hessian should be evaluated. Denker *et. al.*'s method can do this without any additional complexity. The diagonal approximation is no good because of the strong posterior correlations in the parameters.

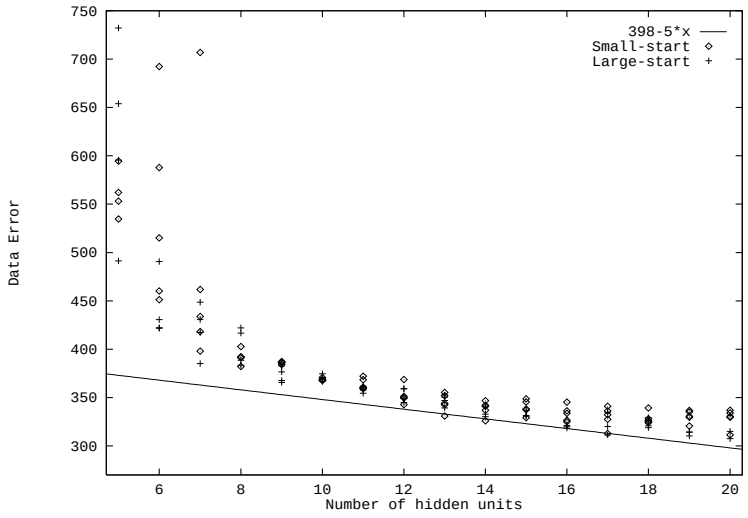

Figure 2: **Data error versus number of hidden units.**
Each point represents one converged neural network, trained on a 200 i/o pair training set. Each neural net was initialised with different random weights and with different values for the initial value of $\sigma_W^2 = 1/\alpha$. The two point–styles correspond to small and large initial values for σ_W. The error is shown in dimensionless χ^2 units such that the expectation of error relative to the truth is 400 ± 20. The solid line is $400 - k$, where k is the number of free parameters.

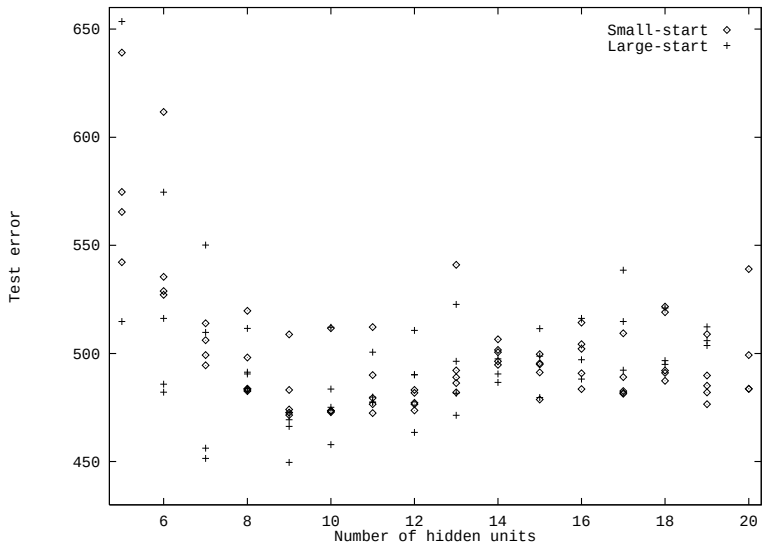

Figure 3: **Test error versus number of hidden units**
The training set and test set both had 200 data points. The test error for solutions found using the first regulariser is shown in dimensionless χ^2 units such that the expectation of error relative to the truth is 400 ± 20.

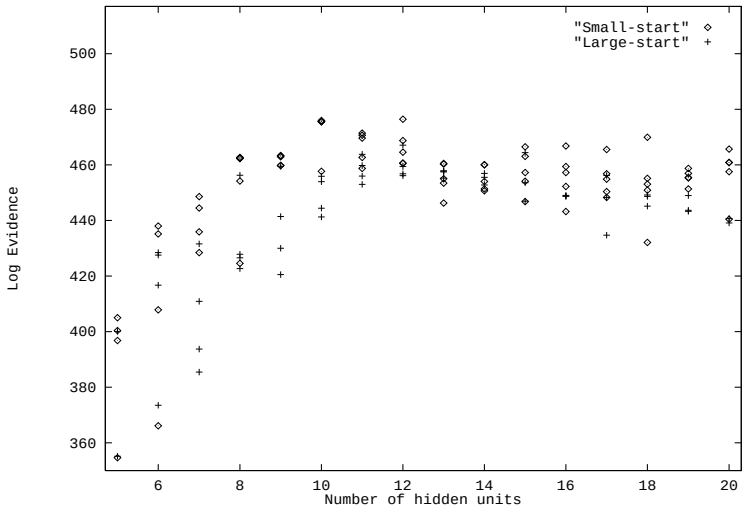

Figure 4: **Log Evidence for solutions using the first regulariser.**
For each solution, the evidence was evaluated. Notice that an evidence maximum is achieved by neural network solutions using 10, 11 and 12 hidden units. For more than $\sim$ 19 hidden units, the quadratic approximations used to evaluate the evidence are believed to break down. The number of data points N is 400 (*i.e.* 200 i/o pairs); *c.f.* number of parameters in a net with 20 hidden units = 102.

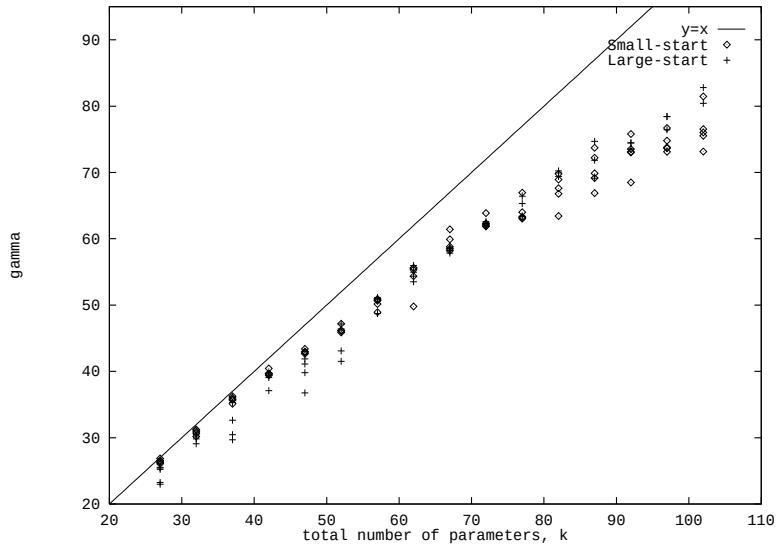

Figure 5: **The number of well–determined parameters.**
This figure displays γ as a function of k, for the same network solutions as in figure 4.

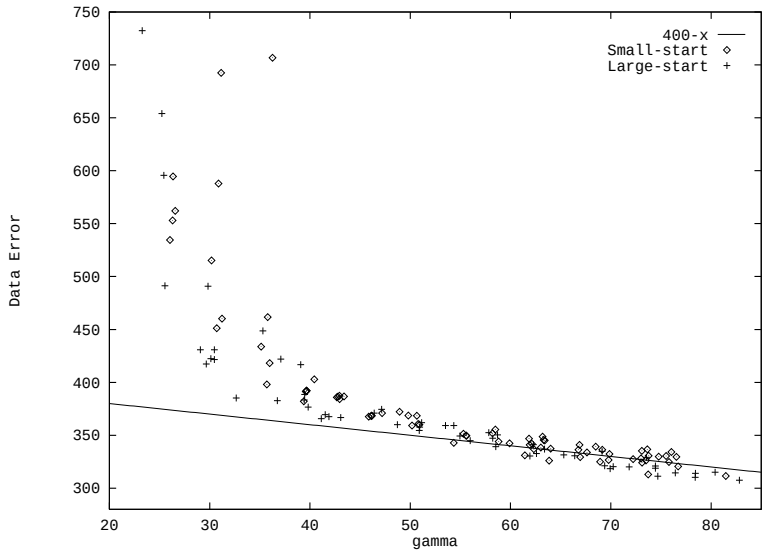

Figure 6: **Data misfit versus γ.**
This figure shows χ^2_D against γ, and a line of gradient -1. Towards the right, the data's misfit χ^2_D is reduced by 1 for every well–measured parameter. When the model has too few parameters however (towards the left), the misfit gets worse at a greater rate.

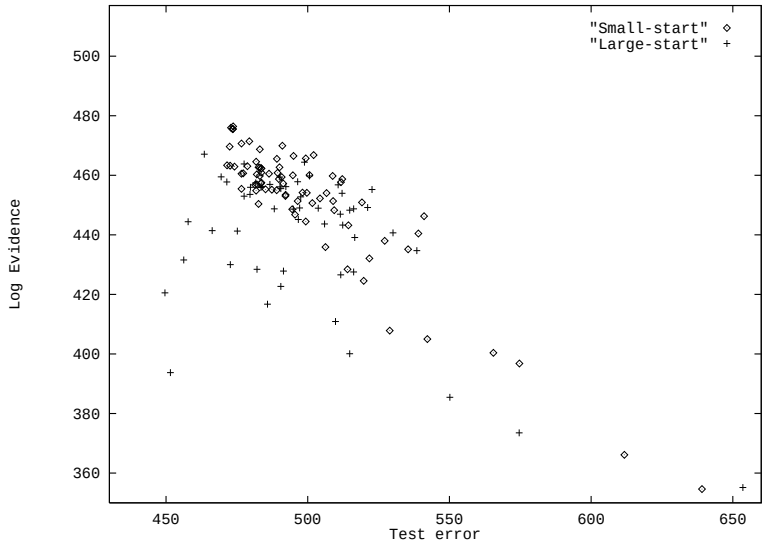

Figure 7: **Log Evidence versus Test error for the first regulariser**
The desired correlation between the evidence and the test error has negative slope. A significant number of points on the lower left violate this desired trend, so we have a failure of Bayesian prediction. The points which violate the trend are networks in which there is a significant difference in typical weight magnitude between the two layers. They are all networks whose learning was initialised with a large value of σ_W. The first regulariser is ill–matched to such networks, and the low evidence is a reflection of this poor prior hypothesis.

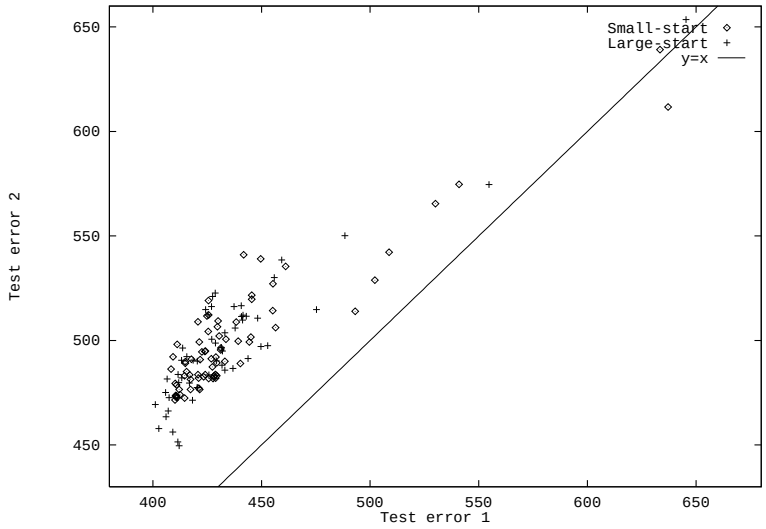

Figure 8: **Comparison of two test errors.**
This figure illustrates how noisy a performance measure the test error is. Each point compares the error of a trained network on two different test sets. Both test sets consist of 200 data points from the same distribution as the training set.

4 Demonstration

This demonstration examines the evidence for various neural net solutions to a small interpolation problem, the mapping for a two joint robot arm,

$$(\theta_1, \theta_2) \rightarrow (y_a, y_b) = (r_1 \cos\theta_1 + r_2 \cos(\theta_1 + \theta_2), r_1 \sin\theta_1 + r_2 \sin(\theta_1 + \theta_2)).$$

For the training set I used $r_1 = 2.0$ and $r_2 = 1.3$, random samples from a restricted range of (θ_1, θ_2) were made, and gaussian noise of magnitude 0.05 was added to the outputs. The neural nets used had one hidden layer of sigmoid units and linear output units. During optimisation, the regulariser (2) was used initially, and an alternative regulariser was introduced later; β was fixed to its true value (to enable demonstration of the properties of the quantity γ), and α was allowed to adapt to its locally most probable value.

Figure 1 illustrates the performance of a typical neural network trained in this way. Each output is accompanied by error bars evaluated using Denker *et. al.*'s method, *including off–diagonal Hessian terms.* If β had not been known in advance, it could have been inferred from the data using equation (11). For the solution displayed, the model's estimate of β in fact differed negligibly from the true value, so the displayed error bars are the same as if β had been inferred from the data.

Figure 2 shows the data misfit versus the number of hidden units. Notice that, as expected, the data error tends to decrease monotonically with increasing number of parameters. Figure 3 shows the error of these same solutions on an unseen test set, which does not show the same trend as the data error. The data misfit cannot serve as a criterion for choosing between solutions.

Figure 4 shows the evidence for about 100 different solutions using different numbers of hidden units. Notice how the evidence maximum has the characteristic shape of an 'Occam

hill' — steep on the side with too few parameters, and shallow on the side with too many parameters. The quadratic approximations break down when the number of parameters becomes too big compared with the number of data points.

The next figures introduce the quantity γ, discussed in (MacKay, 1991a), the number of well–measured parameters. In cases where the evaluation of the evidence proves difficult, it may be that γ will serve as a useful tool. For example, frequentist theory predicts that the addition of redundant parameters to a model should reduce χ^2_D by one unit per well–measured parameter; a stopping criterion could detect the point at which, as parameters are deleted, χ^2_D started to increase faster than with gradient 1 with decreasing γ (figure 6).[4] This use of γ requires prior knowledge of the noise level β; that is why β was fixed to its known value for these demonstrations.

Now the question is how good a predictor of network quality the evidence is. The fact that the evidence has a maximum at a reasonable number of hidden units is promising. A comparison with figure 3 shows that the performance of the solutions on an unseen test set has similar overall structure to the evidence. However, figure 7 shows the evidence against the performance on a test set, and it can be seen that a significant number of solutions with poor evidence actually perform well on the test set. Something is wrong! It is time for a discussion of the relationship between the evidence and generalisation ability. We will return later to the failure in figure 7 and see that it is rectified by the development of new, more probable regularisers.

Relation to 'generalisation error'

What is the relationship between the evidence and the generalisation error (or its close relative, cross–validation)? A correlation between the two is certainly expected. But the evidence is not necessarily a good predictor of generalisation error (see discussion in MacKay, 1991a). First, as illustrated in figure 8, the error on a test set is a noisy quantity, and a lot of data has to be devoted to the test set to get an acceptable signal to noise ratio. Furthermore, imagine that two models have generated solutions to an interpolation problem, and that their two most probable interpolants are completely identical. In this case, the generalisation error for the two solutions must be the same, but the evidence will not in general be the same: typically, the model that was *a priori* more complex will suffer a larger Occam factor and will have smaller evidence. Also, the evidence is a measure of plausibility of the whole ensemble of networks about the optimum, not just the optimal network. Thus there is more to the evidence than there is to the generalisation error.

What if the Bayesian method fails?

I do not want to dismiss the utility of the generalisation error: it can be important for detecting failures of the model being used. For example, if we obtain a poor correlation between the evidence and the generalisation error, such that Bayes fails to assign a strong preference to solutions which actually perform well on test data, then we are able to detect and attempt to correct such failures.

A failure indicates one of two things, and in either case we are able to learn and improve: either numerical inaccuracies in the evaluation of the probabilities caused the failure; or else the alternative models which were offered to Bayes were a poor selection, ill–matched to the real world (for example, using inappropriate regularisers). When such a failure is detected,

[4] This suggestion is closely related to Moody's (1991) 'generalised prediction error', GPE $= \frac{1}{N}(\chi^2_D + 2\gamma)$.

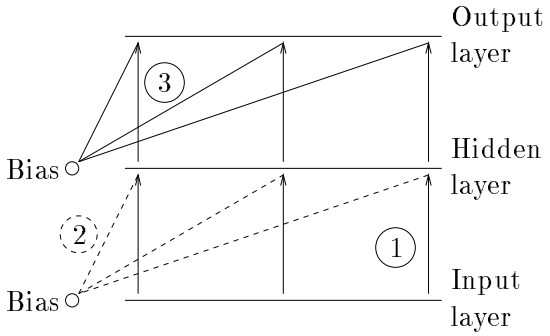

Figure 9: **The three classes of weights under the second prior**
1: Hidden unit weights. 2: Hidden unit biases. 3: Output unit weights and biases. The weights in one class c share the same decay constant α_c.

it prompts us to examine our models and try to discover the implicit assumptions in the model which the data didn't agree with; alternative models can be tried until one is found that makes the data more probable.

We have just met exactly such a failure. Let us now establish what assumption in our model caused this failure and *learn* from it. Note that this mechanism for human learning is not available to those who just use the test error as their performance criterion. Going by the test error alone, there would have been no indication that there was a serious mismatch between the model and the data.

Back to the demonstration: comparing different regularisers

The demonstrations thus far used the regulariser (2). This is equivalent to a prior that expects all the weights to have the same characteristic size. This is actually an inconsistent prior: the input and output variables and hidden unit activities could all be arbitrarily rescaled; if the same mapping is to be performed (a simple consistency requirement), such transformations of the variables would imply *independent* rescaling of the weights to the hidden layer and to the output layer. Thus the scales of the two layers of weights are unrelated, and it is inconsistent to force the characteristic decay rates of these different classes of weights to be the same. This inconsistency is the major cause of the failure illustrated in figure 7. *All the networks deviating substantially from the desired trend have weights to the output layer far larger than the weights to the input layer;* this poor match to the model implicit in the regulariser causes the evidence for those solutions to be small.

This failure enables us to progress with insight to new regularisers. The alternative that I now present is a prior which is not inconsistent in the way explained above, so there are theoretical reasons to expect it to be 'better.' However, we will allow the data to choose, by evaluating the evidence for solutions using the new prior; we will find that the new prior is indeed *more probable*.

The second prior has three independent regularising constants, corresponding to the characteristic magnitudes of the weights in three different classes c, namely hidden unit weights, hidden unit biases, and output weights and biases (see figure 9). The term αE_W is replaced by $\sum_c \alpha_c E_W^c$, where $E_W^c = \sum_{i \in c} w_i^2/2$. Hinton and Nowlan (1991) have used a similar prior modelling weights as coming from a gaussian mixture, and using Bayesian re–estimation techniques to update the mixture parameters; they found such a model was

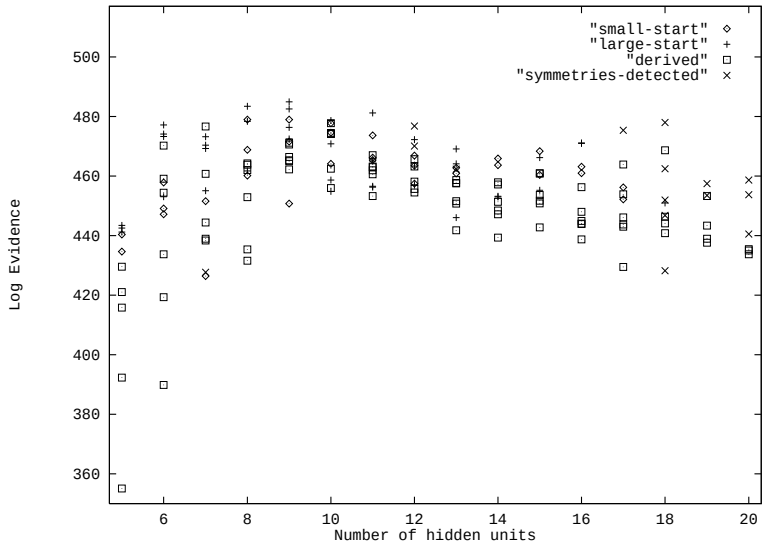

Figure 10: **Log Evidence versus number of hidden units for the second prior** The different point styles correspond to networks with learning initialised with small and large values of σ_W; networks previously trained using the first regulariser and subsequently trained on the second regulariser; and networks in which a weight symmetry was detected (in such cases the evidence evaluation is possibly less reliable).

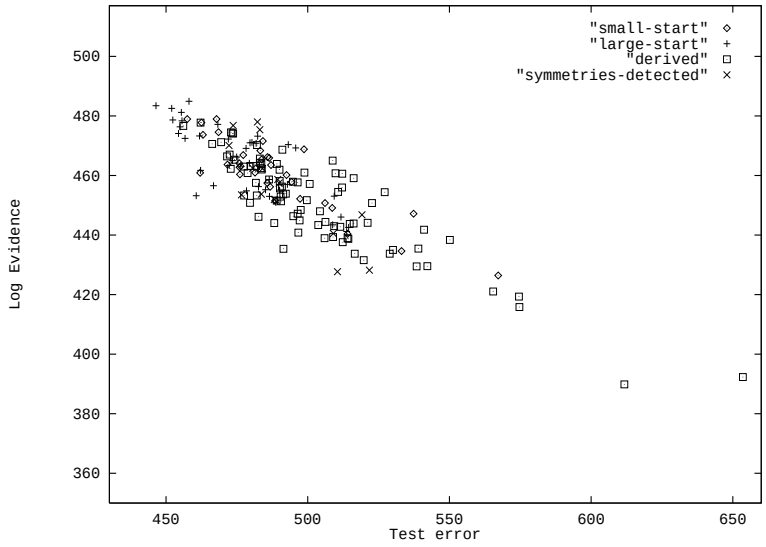

Figure 11: **Log Evidence for the second prior versus test error.** The correlation between the evidence and the test error for the second prior is very good. Note that the largest value of evidence has increased relative to figure 7, and the smallest test error has also decreased.

good at discovering elegant solutions to problems with translation invariances.

Using the second prior, each regularising constant is independently adapted to its most probable value by evaluating the number of well–measured parameters γ_c associated with each regularising function, and finding the optimum where $2\alpha_c E_W^c = \gamma_c$. The increased complexity of this prior model is penalised by an Occam factor for each new parameter α_c (see MacKay, 1991a). Let me preempt questions along the lines of 'why didn't you use four weight classes, or non–zero means?' — any other way of assigning weight decays is just another model, and you can try as many as you like; by evaluating the evidence you can then find out what preference the data have for the alternative decay schemes.

New solutions have been found using this second prior, and the evidence evaluated. The evidence for these new solutions with the new prior is shown in figure 10. Notice that the evidence has increased compared to the evidence for the first prior. For some solutions the new prior is more probable by a factor of 10^{30}.

Now the crunch: does this more probable model make good predictions? The evidence for the second prior is shown against the test error in figure 11. The correlation between the two is greatly improved. Notice furthermore that not only is the second prior more probable, the best test error achieved by solutions found using the second prior is slightly better than any achieved using the first prior, and the number of good solutions has increased substantially. Thus the Bayesian evidence is a good predictor of generalisation ability, and the Bayesian choice of regularisers has enabled the best solutions to be found.

5 Discussion

The Bayesian method that has been presented is well–founded theoretically, and it works practically, though it remains to be seen how this approach will scale to larger problems. For a particular data set, the evaluation of the **evidence** has led us objectively from an inconsistent regulariser to a more probable one. The evidence is maximised for a sensible number of hidden units, showing that Occam's razor has been successfully embodied with no ad hoc terms. Furthermore the solutions with greatest evidence perform better on a test set than any other solutions found. I believe there is currently no other technique that could reliably find and identify better solutions using only the training set. Essential to this success was the simultaneous Bayesian optimisation of the three regularising constants (decay terms) α_c. Optimisation of these parameters by any orthodox search technique such as cross–validation would be laborious; if there were many more than three regularising constants, as could easily be the case in larger problems, it is hard to imagine any such search being possible.[5]

This brings up the question of how these Bayesian calculations scale with problem size. In terms of the number of parameters k, calculation of the determinant and inverse of the Hessian scales as k^3. Note that this is a computation that needs to be carried out only a small number of times compared with the immense number of derivative calculations involved in a typical learning session. However, for large problems it may be too demanding to evaluate

[5] Radford Neal (personal communication) has pointed out that it is possible to evaluate the gradient of a validation error with respect to parameters such as $\{\alpha_c\}$, using $\partial E_{\rm val}/\partial\alpha_c = \partial E_{\rm val}/\partial \mathbf{w}_{\rm MP} \cdot \partial \mathbf{w}_{\rm MP}/\partial\alpha_c$. The first quantity could be evaluated by backprop, and the second term could be found within the quadratic approximation which gives $\partial \mathbf{w}_{\rm MP}/\partial\alpha_c = \mathbf{A}^{-1}\mathbf{I}_c\mathbf{w}_{\rm MP}$, where $\mathbf{I}_c$ is the identity matrix for the weights regularised by α_c, and zero elsewhere. Alternatively, Radford Neal has suggested that the gradients $\partial E_{\rm val}/\partial\alpha_c$ could be more efficiently calculated using 'recurrent backpropagation' (Pineda, 1989), viewing $\mathbf{w}$ as the vector of activities of a recurrent network, and $\mathbf{w}_{\rm MP}$ as the fixed point whose error $E_{\rm val}$ we wish to minimise.

the determinant of the Hessian. If this is the case, numerical methods are available to approximate the determinant or trace of a matrix in k^2 time (Skilling, 1989b).

Application to classification problems

This paper has thus far discussed the evaluation of the evidence for backprop networks trained on interpolation problems. Neural networks can also be trained to perform classification tasks. A future publication (MacKay, 1991d) will demonstrate that the Bayesian framework for model comparison can be applied to these problems too.

Relation to V–C dimension

Some papers advocate the use of V–C dimension (Abu–Mostafa, 1990a) as a criterion for penalising over–complex models (Abu–Mostafa, 1990b, Lee and Tenorio, 1991). V–C dimension is most often applied to classification problems; the evidence, on the other hand, can be evaluated equally easily for interpolation and classification problems. V–C dimension is a worst case measure, so it yields different results from Bayesian analysis (Haussler, 1991). For example, V–C dimension is indifferent to the use of regularisers like (2), and to the value of α, because the use of such regularisers does not rule out absolutely any particular network parameters. Thus V–C dimension assigns the same complexity to a model whether or not it is regularised.[6] So it cannot be used to set regularising constants α or to compare alternative regularisers. In contrast, the preceding demonstrations show that careful objective choice of regulariser and α is essential for the best solutions to be obtained.

Worst case analysis has a complementary role alongside Bayesian methods. Neither can substitute for the other.

Future tasks

Further work is needed to formalise the relationship of this framework to the pragmatic model comparison technique of cross–validation. Moody's (1991) work on 'generalised prediction error' (GPE) is an interesting contribution in this direction. His sampling theory approach predicts that the generalisation error, in χ^2 units, will be $\frac{1}{N}(\chi^2_D + 2\gamma)$. However, I have evaluated the GPE for the interpolation models in this paper's demonstration, and found the correlation between GPE and the actual test error was poor. More work is needed to understand this.

The gaussian approximation used to evaluate the evidence breaks down when the number of data points is small compared to the number of parameters. For the model problems I have studied so far, the gaussian approximation seemed to break down significantly for $N/k < 3 \pm 1$. It is a matter for further research to characterise this failure and investigate techniques for improving the evaluation of the integral Z^*_M, for example the use of random walks on M in the neighbourhood of a solution.

It is expected that evaluation of the evidence should provide an objective rule for deciding whether a network pruning or growing procedure should be stopped, but a careful study of this idea has yet to be performed.

It will be interesting to see the results of evaluating the evidence for networks applied to larger real–world problems.

[6] However, E. Levin (personal communication) has mentioned that a measure of 'effective VC dimension' of a regularised model is being developed. It is speculated that this measure may be identical to γ, equation (12).

Appendix: Numerical methods

Quick and dirty version

The three numerical tasks are automatic optimisation of α_c and β, calculation of error bars, and evaluation of the evidence. I will describe a cheap approximation for solving the first of these tasks without evaluating the Hessian. If we neglect the distinction between well–determined and poorly–determined parameters, we obtain the following update rules for α and β:

$$\begin{aligned} \alpha_c &:= k_c/2E_W^c \\ \beta &:= N/2E_D \end{aligned}$$

If you want an easy–to–program taste of what a Bayesian framework can offer, try using this procedure to update your decay terms.

Hessian evaluation

The Hessian of M, $\mathbf{A}$, is needed to evaluate γ (which relates to Trace $\mathbf{A^{-1}}$), to evaluate the evidence (which relates to det $\mathbf{A}$), and to assign error bars to network outputs (using $\mathbf{A^{-1}}$).

I used two methods for evaluating $\mathbf{A}$: a) an approximate analytic method and b) second differences. The approximate analytic method was, following Denker *et. al.*, to use backprop to obtain the second derivatives, neglecting terms in f'', where f is the activation function of a neuron. The Hessian is built up as a sum of outer products of gradient vectors:

$$\nabla\nabla E_D \simeq \sum_{i,m} \mathbf{g}_i^m \mathbf{g}_i^{m\mathrm{T}} \tag{17}$$

where $\mathbf{g}_i^m = \frac{dy_i(\mathbf{x}^m)}{d\mathbf{w}}$. Unlike Denker *et. al.*, I did not ignore the off–diagonal terms; the diagonal approximation is not good enough! For the evaluation of γ the two methods gave similar results, and either approach seemed satisfactory. However, for the evaluation of the evidence, the approximate analytic method failed to give satisfactory results. The 'Occam factors' are very weak, scaling only as $\log N$, and the above approximation apparently introduces systematic errors greater than these. The reason that the evidence evaluation is more sensitive to errors than the γ evaluation is because γ is related to the sum of eigenvalues, whereas the evidence is related to the product; errors in small eigenvalues jeopardise the product more than the sum. I expect an exact analytic evaluation of the second derivatives (Bishop, 1991) would resolve this. To save programming effort I instead used second differences, which is computationally more demanding ($\sim kN$ backprops) than the analytic approach ($\sim N$ backprops). There were still problems with errors in small eigenvalues, but it was possible to correct these errors, by detecting eigenvalues which were smaller than theoretically permitted.

Demonstrations

The demonstrations were performed as follows:
Initial weight configuration: random weights drawn from a gaussian with $\sigma_W = 0.3$.
Optimisation algorithm for $M(\mathbf{w})$: variable metric methods, using code from (Press *et. al.*, 1988), used several times in sequence with values of the fractional tolerance decreasing from

10^{-4} to 10^{-8}. Every other loop, the regularising constants α_c were allowed to adapt in accordance with the re–estimation formula:

$$\alpha_c := \gamma_c / 2E_W^c \tag{18}$$

Precaution

When evaluating the evidence, care must be taken to verify that the permutation term g is appropriately set. It may be the case (probably mainly in toy problems) that the regulariser makes two or more hidden units in a network adopt identical connection values; alternatively some hidden units might switch off, with all weights set to zero; in these cases the permutation term should be smaller. Also in these cases, it is likely that the quadratic approximation will perform badly (quartic rather than quadratic minima are likely), so it is preferable to automate the deletion of such redundant units.

References

Y.S. Abu-Mostafa (1990a). 'The Vapnik–Chervonenkis dimension: information versus complexity in learning', *Neural Computation* **1** 3, 312–317.

Y.S. Abu-Mostafa (1990b). 'Learning from hints in neural networks', *J. Complexity* **6**, 192–198.

C.M. Bishop (1991). 'Exact calculation of the Hessian matrix for the multilayer perceptron', to appear in *Neural Computation*.

J.S. Denker and Y. Le Cun (1991). 'Transforming neural-net output levels to probability distributions', in *Advances in neural information processing systems 3,* ed. R.P. Lippmann *et. al.*, 853–859, Morgan Kaufmann.

S.F. Gull (1989a). 'Developments in Maximum entropy data analysis', in J. Skilling, ed. (1989a), 53–71.

R. Hanson, J. Stutz and P.Cheeseman (1991). 'Bayesian classification theory', NASA Ames TR FIA–90-12-7-01.

D. Haussler, M. Kearns and R. Schapire (1991). 'Bounds on the sample complexity of Bayesian learning using information theory and the VC dimension', preprint.

G.E. Hinton and T.J. Sejnowski (1986). 'Learning and relearning in Boltzmann machines', in *Parallel Distributed Processing*, Rumelhart *et. al.*, MIT Press.

C. Ji, R.R. Snapp and D. Psaltis (1990). 'Generalizing smoothness constraints from discrete samples', *Neural Computation* **2** 2, 188-197.

Y. Le Cun, J.S. Denker and S.S. Solla (1990). 'Optimal Brain Damage', in *Advances in neural information processing systems 2*, ed. David S. Touretzky, 598–605, Morgan Kaufmann.

W.T. Lee and M.F. Tenorio (1991). 'On Optimal Adaptive Classifier Design Criterion — How many hidden units are necessary for an optimal neural network classifier?', Purdue University TR-EE-91-5.

E. Levin, N. Tishby and S. Solla (1989). 'A statistical approach to learning and generalization in layered neural networks', in *COLT '89: 2nd workshop on computational learning theory*, 245–260.

D.J.C. MacKay (1991a) 'Bayesian interpolation', *Neural Computation*, this volume.

D.J.C. MacKay (1991d) 'The evidence framework applied to classification networks', in preparation.

J.E. Moody (1991). 'Note on generalization, regularization and architecture selection in nonlinear learning systems', in *First IEEE–SP Workshop on neural networks for signal processing*, IEEE Computer society press.

S.J. Nowlan (1991). 'Soft competitive adaptation: neural network learning algorithms based on fitting statistical mixtures', Carnegie Mellon University Doctoral thesis CS–91–126.

F.J. Pineda (1989). 'Recurrent back–propagation and the dynamical approach to adaptive neural computation', *Neural Computation* **1** 161–172.

W.H. Press, B.P. Flannery, S.A. Teukolsky and W.T. Vetterling (1988). *Numerical recipes in C*, Cambridge.

D.E. Rumelhart, G.E. Hinton and R.J. Williams (1986). 'Learning representations by back propagating errors', *Nature* **323**, 533–536.

D.E. Rumelhart (1987). Cited in Ji *et. al.* (1990).

J. Skilling, editor (1989a). *Maximum Entropy and Bayesian Methods, Cambridge 1988*, Kluwer.

J. Skilling (1989b). 'The eigenvalues of mega–dimensional matrices', in J. Skilling, ed. (1989a), 455–466.

N. Tishby, E. Levin and S.A. Solla (1989). 'Consistent inference of probabilities in layered networks: predictions and generalization', in *Proc. IJCNN*, Washington.

A.M. Walker (1967). 'On the asymptotic behaviour of posterior distributions', *J. R. Stat. Soc. B* **31**, 80–88.

A.S. Weigend, D.E. Rumelhart and B.A. Huberman (1991). 'Generalization by weight–elimination with applications to forecasting', in *Advances in neural information processing systems 3.*, ed. R.P. Lippmann *et. al.*, 875–882, Morgan Kaufmann.

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