Computer Model of a "Sense of Humour".
II. Realization in Neural Networks

I. M. Suslov
P.N. Lebedev Physical Institute,
119334 Moscow, USSR

Abstract
The computer realization of a "sense of humour" requires the creation of an algorithm for solving the "linguistic problem", i.e. the problem of recognizing a continuous sequence of polysemantic images. Such an algorithm can be realized in the Hopfield model of a neural network, if it is suitably modified.

In [1] we analysed the general algorithm of information processing and showed that on fulfillment of the natural requirements imposed by its biological purpose such an algorithm will possess a "sense of humour". The present paper proposes a possible realization of the algorithm in a system of formal neurons.

Description of the model
Following Hopfield [2] we shall consider that the state of the i-th neuron is described by the variable \( V_i \) assuming two values: \( V_i = 1 \) (excited state) and \( V_i = 0 \) (state of rest). The link of the neuron \( i \) with the neuron \( j \) is determined by the parameter \( T_{ij} \). The state of the system changes with time \( t \) according to the algorithm:

\[
V_i(t + \delta t) = \frac{1}{2} + \frac{1}{2} \text{sign} \left\{ \sum_j T_{ij} V_j(t) - U_i \right\},
\]

where \( U_i \) is the excitation threshold of the \( i \)-th neuron and the number \( i \) is chosen randomly.

The proposed model of the nervous system is a modification of the trilayer perceptron [3] adapted for work in real time. It contains the following elements (Fig. 1).

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1 Present address:
P.L. Kapitza Institute for Physical Problems,
119337 Moscow, Russia
E-mail: suslov@kapitza.ras.ru
The associative memory \((A\text{-layer})\) represents the neural network which for simplicity we consider as described by the Hopfield model: the neurons of the \(A\text{-layer}\) are linked with each other with \(T_{ij} = T_{ji}, U_i = 0\). Within the \(A\text{-layer}\) evolution according to (1) leads from the arbitrary initial state \(\{V_i\}\) to one of the local minima of energy
\[
E = - \sum_{ij} T_{ij} V_i V_j ,
\]
which are identified with the images written in the memory \(\{V_{is}^s\}, s = 1, 2, \ldots, p\). The recorded images determine the matrix of the links \(T_{ij}\) [2]:
\[
T_{ij} = \sum_{s=1}^{p} \mu_s (2V_{i}^{s} - 1) (2V_{j}^{s} - 1), \quad i \neq j \quad (\mu_s > 0), \quad T_{ii} = 0
\]

The sensory system \((S\text{-layer})\) receives signals from the outside world (for example, from the retina of the eye). The sensory neurons are not linked between themselves, but each \(S\)-neuron is bound to one of the memory neurons: the links \(S \rightarrow A\) are positive (exciting) and the back links \(A \rightarrow S\) are negative (inhibiting) (Fig. 1).

The reacting system \((R\text{-layer})\) consists of a set of neurons each of which corresponds to one of the images recorded in the memory: to the \(s\)-th neuron of the \(R\)-layer converge the positive (exciting) links from those neurons \(i\) of the memory for which \(V_{i}^{s} = 1\) (we shall refer the last neurons as a carrier of the image \(\{V_{i}^{s}\}\)). The back negative (inhibiting) links run from the \(R\)-neurons to the memory neurons; the \(R\)-neurons are not linked between themselves (Fig. 1). The thresholds \(U_i\) for the \(R\)-neurons are adjusted in such a manner that the excitation of the \(s\)-th neuron of the \(R\)-layer occurs only when the configuration of the \(A\)-neurons is sufficiently close to the image \(\{V_{i}^{s}\}\).

We consider that the image is realized by the biological individual only when there is excitation of the corresponding \(R\)-neuron, i.e. the \(R\)-layer represents the consciousness of the individual.

The centre coordinates the work of the system by acting according to the built-in program: it exercises control over the macroscopic parameters of the system. The concrete functions of the centre consist in the following.

1. The centre has links with a small part of the memory neurons evenly distributed in the \(A\)-layer which allows it to register (a) the presence of excited neurons in a certain portion of the memory and (b) the stationarity or nonstationarity of this portion.

2. The centre produces local changes of "temperature" in the \(A\)-layer. Since the temperature of the neural network is determined by the noise level in it (which can be taken into account by introducing the random force \(f_j(t)\) into the braces (1)) then the regulatable noise source should be at the disposal of the centre.

3. The centre produces local switching on the "magnetic field" in the \(A\)-layer which corresponds to the addition in energy (2) of the term
\[
\sum_i h_i V_i
\]
Figure 1: Proposed model of the nervous system is a modification of the three-layer perceptron [3]: filled circles are neurons; solid lines are constantly acting links between neurons; broken lines are links switched on the command from the centre; the symbols $+$ and $-$ indicate the excitatory and inhibitory character of the links; the $S$–layer is the sensory system; the $A$–layer is the associative memory; the $R$–layer is the reacting system or "consciousness". Roman numerals mark: (I) information from the $A$–layer, (II) the control of the links, (III) the outer world, (IV) the motor cortex. Inset in the right upper corner shows possible realization of the controllable link.
(in (1) \(h_i\) are added to the thresholds \(U_j\)). Switching on the field is achieved with the aid of a "magnet" — group of neurons controlled from the centre, each of which is connected with a certain region of the \(A\)-layer.

(4) The centre carries out the control of the links shown in Fig. 1 by a broken line. The simplest realization of the controllable link \(AB\) is possible with the aid of the intermediate neuron \(C\) (see Fig. 1), the threshold of which is so adjusted that it is excited only in the simultaneous presence of the exciting signal from the neuron \(A\) and from the centre. In the presence of a signal from the centre the neuron \(A\) excites or inhibits the neuron \(B\) — the link is switched on, in the absence of a signal from the centre the neuron \(A\) cannot act upon the neuron \(B\) — the link is switched off. The command for switching on and off is given not to the individual links but simultaneously to their large groups.

(5) The centre gives the command for the learning of the plastic links.

**Recognition of a separate image**

Recognition of the images occurs with the links \(A \rightarrow S\) and \(R \rightarrow A\) switched on. In the initial state of the system all the neurons are not excited. Since the state of the \(A\)-layer with \(V_i \equiv 0\) is unstable (see (1) at \(U_i = 0\)), so the presence of the stabilizing magnetic field is necessary.

Let the stimulus \(\tilde{B} = B + \delta B\) (i.e. the "noisy" image \(B\)) is presented to the sensory system; this induces excitation of some of the \(S\)-neurons (Fig. 2,a). Then the centre switches out the magnetic field and excitation is transmitted to the \(A\)-neurons (Fig. 2,b) which, in turn, quench the sensory neurons (Fig. 2,c) (it is assumed that the links \(S \rightarrow A\) and \(A \rightarrow S\) are sufficiently strong). Then in the \(A\)-layer there is free evolution according to (1) which ends in relaxation to the stable state corresponding to the image \(B\) (Fig. 2,d); the neuron responsible for this image is excited in the \(R\)-layer (Fig. 2,e). The back signal is send into the memory, quenching the excited neurons (Fig. 2,f) and the image \(B\) is deleted from the "consciousness" (Fig. 2,g): the system returns to the initial state and is ready for the perception of a new image.

**Learning**

The links between the \(A\)-neurons are plastic and change according to the rule [2]

\[
\delta T_{ij} \sim (2V_i - 1)(2V_j - 1)\delta t \quad (i \neq j),
\]

if the neurons \(i\) and \(j\) stay in the states \(V_i\) and \(V_j\) during the time \(\delta t\). If in the initial state \(T_{ij} \equiv 0\) then the presentation to the system of \(p\) configurations \(\{V_i^s\}, s = 1, 2, ..., p\) leads to the matrix of links (3). Since \(T_{ij}\) may have any sign, the neurons of the \(A\)-layer
Figure 2: Sequential states of the system in the course of recognition of a separate image; open circles (I) are excited neurons, dark circles (II) — not excited ones. For clarity, only the links are shown along which excitation was transmitted at the preceding moment of time.
must have both exciting and inhibiting synapses (specialization of the synapses is known [4, pp. 62–65] to have invariant character).

The links $A \rightarrow R$ in the initial state have a zero value and can be learned only in one, positive direction

$$
\delta T_{ij} = \begin{cases} 
    c\delta t & (c > 0) \quad \text{for } V_i = V_j = 1 \\
    0 & \text{(in other cases)}
\end{cases}
$$

i.e. have only exciting synapses. The remaining links ($R \rightarrow A$, $S \rightarrow A$, $A \rightarrow S$) are not plastic and have inborn character.

The learning of the system is similar to the learning of a child: a certain image $B$ is presented to it generating in the $S$–layer a certain configuration of excited neurons; then it is asked to "memorize $B$", which excites one of the neurons of the $R$–layer appointed to be responsible for the image $B$. Learning occurs with the $A \rightarrow S$ and $R \rightarrow A$ links cut out (Fig. 3), so that the configuration of the $S$–neurons is projected into the $A$–layer and persists for a certain time: the links $T_{ij}$ in the $A$–layer change according to (5) forming the matrix (3), while the links $A \rightarrow R$ change according to (6) ensuring the connection of the $s$-th neuron of the $R$–layer with a carrier of the image $\{V_i^s\}$.

In the resting state $V_i \equiv 0$ the system spends a considerable time and the learning according to (5) should result in "ferromagnetic" interaction between the neurons ($T_{ij} > 0$ for all $i, j$) and the single state $V_i \equiv 1$ being stable. Therefore, we suppose that there is
no learning in the state $V_i \equiv 0$, and the learning command is given only on presentation of the image.

**Short-range action of the links and localization of images**

In the usual Hopfield model [2] all the neurons are linked with each other and the carriers of images $\{V_i^s\}$ are spread out over the whole neural net. In reality the links $T_{ij}$ have a finite radius of action $\xi$: in the human brain each neuron has $\sim 10^4$ synapses, while a complete number of neurons $\sim 10^{11}$ [4, pp. 31–33]. Experimental indications on localization of the images also exist [3, pp. 64, 65].

We shall consider that each image $\{V_i^s\}$ is written in a certain region $\Omega_s$ containing many neurons, but small as compared with the size of the whole neural network; so that $V_i^s = 0$ for $i$ not belonging to $\Omega_s$ (the carrier $\{V_i^s\}$ is localized in $\Omega_s$) and for $i \in \Omega_s$ the magnitudes $V_i^s$ with equal probability assume the values 0 and 1. Since recognition of the images in any event must be preceded by translational shift, rotation and change of the scale (which can be achieved by a certain modification of the Hopfield model [5]) then the assumption on the localization of images does not have any serious consequences. The command for switching off the magnetic field, change in temperature (see below) and learning of plastic links is given only on presentation of the image $\{V_i^s\}$ and only for neurons of the region $\Omega_s$.

Taking all this into account, we accept that the learning rule for the $A$–neurons instead of (5) has the form

$$\delta T_{ij} \sim D_{ij} \delta_i^s \delta_j^s (2V_i - 1) (2V_j - 1) \delta t \quad (i \neq j)$$

when the image $\{V_i^s\}$ is presented; here

$$D_{ij} = \begin{cases} 1, & \text{for } r_{ij} < \xi, \quad i \neq j \\ 0, & \text{in other cases} \end{cases}, \quad \delta_i^s = \begin{cases} 1, & \text{for } i \in \Omega_s \\ 0, & \text{for } i \notin \Omega_s \end{cases}$$

and $r_{ij}$ is the distance between the neurons $i$ and $j$. The matrix of the links after writing $p$ images instead of (3) assumes the form

$$T_{ij} = D_{ij} \sum_{s=1}^{p} \delta_i^s \delta_j^s \mu_s (2V_i^s - 1)(2V_j^s - 1), \quad \mu_s > 0.$$ 

To demonstrate stability of $\{V_i^s\}$ let us compose the combination [2]

$$H_i^s = \sum_j T_{ij} V_j^s = \sum_{s'} \mu_{s'} \delta_i^{s'} (2V_i^{s'} - 1) \sum_{j \in \Omega_{s'}} D_{ij} V_j^s (2V_j^{s'} - 1),$$

\(^2\)To raise the stability of the system relative to the destruction of some of the neurons the region $\Omega_s$ can be multiply connected.
where $\Omega_{ss'}$ is the intersection of $\Omega_s$ and $\Omega_{s'}$. By virtue of the randomness of $V_i^s$ and the large number of terms in the sum for $j$ the latter is close to its mean:

$$H_i^s = \frac{1}{2} \mu_i \delta_i^s \sum_{j \in \Omega_s} D_{ij} (2V_i^s - 1)$$  \hspace{1cm} (11)

For $i \in \Omega_s$ the sum over $j$ is positive and $\delta_i^s = 1$ so that the configuration of $\{V_i^s\}$ is stable by virtue of the algorithm (1); for $i \notin \Omega_s$ the state $V_i = 0$ is maintained by the magnetic field.

Because of the localization of the images it suffices for the $s$-th neuron of the $R$-layer to have links only with the neurons of the region $\Omega_s$ of the $A$-layer.

**Recognition of the ambiguous image**

Above it was assumed that the stimulus presented, $\tilde{B} = B + \delta B$, is close to image $B$ contained in the memory so that the initial state $\tilde{B}$ always relaxes to the final state $B$, i.e. the interpretation of the image $\tilde{B}$ is clearcut. In terms of energy this means that the state $\tilde{B}$ lies in a potential well, whose minimum corresponds to the image $B$ and evolution occurs at zero temperature.

Now let us consider the recognition of an ambiguous image. We have in mind the modelling of the following situation: the word $B$ is shown to the person and it is explained to him that this word may assume several meanings; in the memory of the person the images $B + b_1$, $B + b_2$, \ldots are fixed where $b_1$, $b_2$, \ldots are the elements of the given explanation; if now the word $B$ is presented for recognition its interpretation will be ambiguous leading to one of the results $B + b_i$. For modelling it suffices to assume that recognition begins at the temperature $T$ exceeding the potential barriers between images $B + b_1$, $B + b_2$, \ldots and then the temperature decreases and the system relaxes to one of the local minima corresponding to the images $B + b_i$. Hereafter, we shall consider that decrease of temperature from the initial value $T_0$ occurs adiabatically so that the system with overwhelming probability relaxes to the deepest of the local minima.

**Simultaneous recognition of several images**

Suppose that after presentation of the stimulus $A$ the system relax to one of the images $A_1$, $A_2$, \ldots and after presentation of the stimulus $B$ to one of the images $B_1$, $B_2$, \ldots. What will happen, if the stimuli $A$ and $B$ are presented simultaneously?

The process of recognition begins with switching out the magnetic field in the portion of the $A$-layer, where the image carrier is localized. Let presentation of the images $A$ and $B$ requires switching out the field in the regions $\Omega_A$ and $\Omega_B$ of the associative layer. Let us assume for simplicity that the regions $\Omega_A$ and $\Omega_B$ do not overlap (the qualitative
picture persists in the general case; then \( V_i = V_i^A + V_i^B \) where \( V_i^A \) and \( V_i^B \) differ from zero respectively for the neurons \( i \) lying in the regions \( \Omega_A \) and \( \Omega_B \). The energy (2) assumes the form

\[
E\{V_i^A + V_i^B\} = -\sum_{ij} T_{ij} V_i^AV_j^A - \sum_{ij} T_{ij} V_i^BV_j^B - 2\sum_{ij} T_{ij} V_i^AV_j^B
\] (12)

If the stimuli \( A \) and \( B \) are presented separately, then correspondingly \( V_i^B \equiv 0 \) or \( V_i^A \equiv 0 \), so that only the first or second term remains in the right part of (12). The third term in (12) shows that with the simultaneous presentation of the stimuli \( A \) and \( B \), they exert on each other an effect equivalent to the presence of a magnetic field. The result of such interaction is particularly clear if the configurations \( A_1, A_2, \ldots \) and respectively \( B_1, B_2, \ldots \) are almost degenerate. If the links \( T_{ij} \) between the regions \( \Omega_A \) and \( \Omega_B \) are absent then the equilibrium states of the system have the form \((A_s, B_s')\) and are almost degenerate. Inclusion of the weak links \( T_{ij} \) between the regions \( \Omega_A \) and \( \Omega_B \) does not change significantly the equilibrium configurations, but changes the relative position on the energy scale. If on separate recognition of the images \( A \) and \( B \) certain configurations (e.g. \( A_1 \) and \( B_2 \) in Fig. 4) are energetically advantageous, then on their simultaneous recognition other configurations may prove more advantageous (e.g. \( A_2 \) and \( B_1 \)). It may be visually imagined that the interaction change the potential relief where \( A \) and \( B \) relax (Fig. 4). As a result, the interpretation of the polysemantic image proves to depend on the context.

In the preceding paper [1], the existence of an algorithm was postulated for the recog-
Recognition of a continuous sequence of images

Above we assumed that all the images \( \{V_i^s\} \) have localized carriers. Due to short-range nature of links \( T_{ij} \), the associatively-related images should have closely positioned or overlapping carriers, while the uncorrelated images have the carriers localized in the remote parts of the memory. Therefore, presentation of a continuous sequence of stimuli \( A_1, A_2, \ldots \) give rise to sequential excitation of the regions \( \Omega_1, \Omega_2, \ldots \) in the associative layer, which looks like ”diffusion“ (Fig. 5): the nearest in succession images are correlated and their carriers form conglomerations, whereas to the remote images in sequence correspond carriers remote in space, as a result of weakening of the correlations. It gives the possibility to establish the correspondence of the time of appearance of the image with the position of its carrier in space, which greatly simplifies the work of the centre. After fixing the appearance of the excited neurons in a certain portion of the A–layer, the centre raises the temperature of this portion to the value \( T_0 \), and after the characteristic time \( \tau_0 \) begins...
its adiabatic decreasing. This stimulates establishment of the steady state, the bringing of the corresponding images into the $R$–layer and the zeroing of the corresponded portion of the memory (Fig. 2,d–g). Thereby, the trajectory of the ”diffusion” movement (Fig. 5) is ”wiped off” after a certain time so that at each moment only its finite segment exists in the memory; recognition of a continuous sequence of images is thereby reduced to the simultaneous recognition of a finite number of images (see above).

**Time delays and humorous effect**

Let at the moment of time $t = 0$ the neurons are excited in a certain portion of memory (Fig. 2,b). at the moment $\tau_0$ the corresponding image is brought into consciousness (Fig. 2,e) and at the moment $\tau_1$ the portion of memory under consideration is zeroed (Fig. 2,f). The delay $\tau_0$ corresponds to the interval $AC$ and the delay $\tau_1$ to the interval $AB$ in Fig. 2 of the paper [1]; the latter is related to the fact that the possibility of reinterpreting the image persists until the corresponding portion of memory is nullified. Obviously, $\tau_1 \geq \tau_0$: this result was derived in [1] from requirements of the optimal processing of the algorithm, but now it holds due to the constructive features of the model.

The delay $\tau_0$ is determined by the rate of decreasing of temperature (see above), while the delay $\tau_1$ by the moment of activation (from the centre) of the $R \rightarrow A$ links. The optimal choice of the parameters $\tau_0$ and $\tau_1$ is determined by different principles: the parameter $\tau_0$ corresponds to the delay from the moment information is received by the brain till its appearance in consciousness and is upwardly limited by the value $\tau_{\text{max}}$ [1], while the parameter $\tau_1$ regulates the loading of memory, i.e. the fraction of excited neurons in the $A$–layer (Fig. 5). This fraction should not be too small for the operative possibilities of the brain to be used in full, and not too large for interference of the images arriving at different times not to appear.

Let at the moment $t = 0$ the image $A$ enters the memory; evolution in the corresponding potential relief (Fig. 4, continuous curve) leads at the moment $t = \tau_0$ to stabilization of the memory neurons in the configuration $A_1$ and excitation of the corresponding $R$–neuron. Let in the interval between $\tau_0$ and $\tau_1$ new image $B$ enters the memory and changes the potential relief for $A$ (Fig. 4, broken line). If the temperature at this moment is sufficient to overcome the barrier, the system begins to relax to the configuration $A_2$ (in fact, leaving of the state $A_1$ is possible even at $T = 0$ since the minimum corresponding to $A_1$ may disappear). Such breaking of stationarity in a certain memory region after exciting of the corresponding $R$–neuron is considered as a sign of the humorous effect [1]. The image $A_1$ (or, in the general case, a version consisting of several images) is realized as ”false” and should be immediately deleted from consciousness; however, it cannot be done in the course of the usual routine (Fig. 2,e,g) because of the need to obtain a new steady configuration $A_2$.

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3 Unlike the general case [1], in the present model there is no special operative memory.
Mechanism of laughter

The "emergency" deletion of the false version from the \( R \)-layer is achieved by activation of the links between the \( R \)-layer and the motor cortex (Fig. 1); excitation of the \( R \)-neurons is transmitted to the motoneurons and produce the contraction of certain muscles, i.e. laughter.

In fact we return to the old idea by G. Spencer [6] that the humorous effect is accompanied by release from the mental process of nervous energy which is directed at the muscular reaction. This idea was supported by Darwin [7] and Freud [8] but was criticized by later investigators [9] in view of the difficulty to introduce the concept of "nervous energy". In fact, the definition of energy for neural networks may be given only under condition \( T_{ij} = T_{ji} [2] \), which is not very realistic and does not hold for the considered model as a whole; so the concept of "nervous energy" should not be taken seriously. Nevertheless, the qualitative picture agrees with Spencer's hypothesis: it looks as if the energy of excitation is expelled from the \( R \)-neurons into the motor cortex.

The release of nervous energy in the presence of the humorous effect was validated by Spencer using the concept of "descending incongruity" — transition from a high to low style, i.e. from the state with rich associations to the state with poor associations. Such an interpretation of the humorous effect is surely limited and cannot lay claim to universality. In the proposed scheme the "release of nervous energy" (in the conditional sense indicated above) is related with the need to delete the false version from consciousness, which requires "zeroing" of a certain portion of the \( R \)-layer (i.e. transition of the excited neurons to the nonexcited state).

Since laughter is interpreted as an unconditioned reflex to the humorous effect, the known cases of "ousting" of laughter by secondary emotions require an explanation. Laughter may be ousted by the emotions of indignation (an indecent anecdote is told to a puritan), fear (a bush suddenly turns out to be a bear), compassion (a man in front of you slips on a water melon rind and badly hurts himself), shame (you slipped on a water melon rind) and so on. Within the Spencer hypothesis [6] all these instances are explained by the fact that the "released nervous energy" is directed not to the motoneurons but to other parts of the nervous system and goes on the formation of a secondary emotion (the \( R \)-layer is connected not to the motor cortex but to the limbic system). The same ideas [8] are used to explain the known fact that a joke produces the greatest effect if it is told extremely laconically: laconicity reduces the probability of formation of secondary associations liable to absorb the "nervous energy".

Casting the excitation of the neurons into different portions of the motor cortex, a man can regulate the level of the muscular reaction: this can explain its dependence on mood, the psychological setting, the presence of a laughing enviroment [10] and so on.
Conclusion

The realization of a sense of humour requires a quite intricately organized system. We would emphasize, however, that this complex organization is entirely governed by the task of treating a continuous sequence of polysemantic images; the existence of the humorous effect is a secondary consequence. It is well-known [4, pp. 219–241], that different parts of the brain have their own specialization; the proposed model may lay claim to be a description of only the region of the brain where the linguistic functions are concentrated (so-called Broca and Wernicke zones); other portions of the brain may have a different organization.

The author is grateful to D. S. Chernavskii for fruitful discussions.

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