

A HYBRID NEURAL NETWORK OF ADDRESSABLE AND CONTENT-ADDRESSABLE MEMORY

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We investigate the memory structure and retrieval of the brain and propose a hybrid neural network of addressable and content-addressable memory which is a special database model and can memorize and retrieve any piece of information (a binary pattern) both addressably and content-addressably. The architecture of this hybrid neural network is hierarchical and takes the form of a tree of slabs which consist of binary neurons with the same array. Simplex memory neural networks are considered as the slabs of basic memory units, being distributed on the terminal vertexes of the tree. It is shown by theoretical analysis that the hybrid neural network is able to be constructed with Hebbian and competitive learning rules, and some other important characteristics of its learning and memory behavior are also consistent with those of the brain. Moreover, we demonstrate the hybrid neural network on a set of ten binary numeral patters.

Keywords: Forward neural network; addressable memory; content-addressable memory; associative memory; Hebbian learning; competitive learning.

\mathbf{n} \mathbf{o} , \mathbf{c}_{r} \mathbf{on}

₽-e ev o nde. nd n nd ode n 🏎 n **J**-0 nfo. nе ence on epe en ed nd ♣ e♣-e,e♣o, ed n e o, y een .е de of o, on h-e , c , e of e o, y¹ се. " e, ♣∿, e no een fo nd ye de n 🛩 e n .**⊭**o **⊮**e, **_**_ ny pyeloo c e pe. een 🏎 o n У 0. 4 nfo. on е n e o,v ,e en dd, e e nd con en dd.e e nf c one eco n ze 🏎 f, end f, o p⊩ooo, (ren of р, ce n 🏎 **₽**-e e of f. end een e o, zed е ,e, ∉ed con en / dd.e у n#-, n Con en dd.e e e o,v yp. nd of oc ∉e e o,y n♣e, n nd♣e,e \mathbf{c} ♣~, 🛩 e een 🖝 e. ode o de c, e **(**e ef 2 nd On the other, the nd e po, ed V od nfo. on p. oce n nd eq en **€**-√ 0. ۰e oo 🖉 e yd yf nc on n o e en ¢. n

ne, p, e n d o, y nd n n n е nfo -e nfo. on e n e o₂y ♣-o d e 0 o. de. ^{4,5} in nce .e. e n e. <u>_</u>___ е o n of nfo. e o, y nd -e peed of nfo, on n ed n •-e , n on , n on eq en nfo. cn e on y, e, red f, o on е 0 е ce 💁 🌢 fnc on ♣-e dd.e of ♣-e nfo. ♣-e, efo, e nfo, on e n e o,y on e ♣-o d e dd.e en eo, y A 4-o 4o of een fo nd o ppo, 📭e en ♣-e e o,v n♣-e , n o♣- dd.e e nd con en dd.e e 4-e.e.4no ve ny e on e 4-eo, yo, ode 4-e-c n nfy 4-e e-, ce, c of dd.e e nd con en dd.e e o,y e no ed e 00, e

▲ → e dereopenofne.oooyndn. oy.ee.e → e een .ynore e → e e.nnnde o.yee n .c.y on the of the ne, ce (ne, on "n the y he, e h, o h h e M P ode h e ♣-e cydec, e♣-efncono, ♣-, , o, of ne on ⁶ sen e popo ed e nn p po 1- 1-e en 1- of e cency of 1-e yn pe e een one on nce e A-en A-ev oAc∉ e ♣-e e e ♣- ♠- no no n #e ne,nn, e⁷ Ande, onf, #-e, p, opo ed pene, ne o, 🎩 🖉 cn ene, e n n e, cre e o,y⁸ Mo,erre, pre, ne, ne o, ode of con en dd.e e o. oc 🛹 e 🧳 o, y e, e e e e ef pec y 📫 op edp.opo ed .ec ..en ne . ne o. 斗 💁 e efe. ed o pop e d ne o ¹²⁴ nde 4-e e,nn & e e of of o e, p,od c ,o p of pep e, n c n e o, ed n 4-e 📫 op ed ne. o, ♣-fnconof oc y e o,y . een een y 11-o n 11- 11-e y e.co. en e. zed ⊯op ed ne o. ♣- . ♣-√ o. of oc \checkmark e e o, y \checkmark op e d ne o, $^{13-15}$

Bed on Al-epyeloo c f c Al- Al-e e . o.y o.ed n le n y op nd y ♣-e ♣-o,♣- p,opo ed oo c ne, ne o, c ed pe e o,y ne, ne o, fdMNN ¹⁶ A- e- c n e , n nd e o, ze (o, e n e n, y pen sconen dd.e e e o.yfnc on Mo, ere, cn e con, ced n - e, n -差 ne,nn, e nce, nene 📭 ne o, cneconde,ed cnof -eeo, yn ♣-e, n [~]n ♣-e ♣- of ♣- de eno e ♣ e ♣ e of nfo, on (n.yp e, n o.ed n £12MNN n +-e , n +-en +-e e . o, y of -e , n e con de, ed film NN n One MNN y e connec on e o e e e und MNN n the faid MNN n the statement of the second seco **≜**-е ,е , 🛩 of one p e, n y c e 4-e, e, y of 4-e o4-e, "e ed p e"n 🏨 e e o oc 🛩 e e o y "n • y n e. of film NN y connec o e¹-e, n ce, n o, de, o e, n nd e o, ze p o e po, p e, n eq ence Ce, ny 4-e nfo, on oc on on the effdMNN 🛩 e, y po, n o 🏎 n n nfe, ence dec on ec₄o∉e, fo, pcy e ne ec₄ee ♣-ee,o. oc 🛩e eo,y connec on on ♣-ee £MMNN n +-e c ... en p pe.

A e $e - p e_n$ o ed n f MNN ncon en dd e e y nd c n e e f e d o n yf o o n f MNN $- e o - e_n f MNN$ one p e e - n of $- e_n e_n f$ of p e n on $- e_n e_n$ £1dMNN n o, n 4-e np p e, n o ♣-e.£MMNN n f p, e y Ce, ny ♣-e co...epondn p e.ncn e .e . red f.o o e £MMNN f. et a ne on n e e , n o, o ell-e, ll-en e ee o, l-e, o e ♪-n B ♪- ncon en ♪- ♪-e oo c ndn 4- 4-ene, on , e creonyn o e oc e on of M-e, n M-en e ee o, M-e, o eM-n Mo, ere, o ncon en 4-4-e, e of pyde-oocepe, en 📭 📭 e o,y e. . red o₄ dd.e y nd con en dd.e y 🚧 doe 📲 e , n , e , 🍞 e pece of nfo. on (penn•effdMNN n dde y •ec conyeofoo n "yye ce ecn ne 🏎 🗣 e nfo, on e o, zed noce ceecn⁴-e, n⁻nfc ♣-en e e o e ne nfo, on e y♣-n ♣-o _e e o ♣-e o♣-e, e o, zed nfo, on "n 🏎 y 🏎 e ne nfo, on e e o, zed y c c e c e con en ♣-en e.e., re n e of nfo. on f.o ♣-e np e y e 💁 c c e c nd n y.e. y ce. nfdMNN n -efdMNN n Al-e, efo, e Al-e e e, Al-p of Al-e c c ecof♣-enfo, on y errendd.e fo, 4-e nfo, on 4- e n dd, e e y .e. e he nfo. on q c y nd co..ec y n ♣-e ♣- of ♣- de e p.opo e ♣-y .d ne . , ne o, of dd, e e nd con en dd, e е e o,yon 4-e,falMNN n y 4-6-n e of nfo, on (n, yp e, n e o, zed nd e e dd e ynd con en dd e V Con eq en y 4-4-y, d ode e po e ♣ ♣ e con en dd.e e e o.y co p е ♣-♣-e dd.e e e o.y

"n eq e e p.opo e \bullet - e^{\bullet} - y, d ne, ne o, of dd, e e nd con en dd, e e e o, y n filec 2 e f \bullet - \bullet - \bullet - \bullet - e e , n n , e of \bullet - e \bullet - y, d ne , ne o, n filec "n filec ... p e on e pe, en cond c ed o de on , e o , p.opo ed ne o, n y e - e, ef conc on n filec

e e n - , ef de c. p on of pe e , o, y ne , ne o, $fdMNN^{16}$, ene, y nfdMNN con of n connec ed n , y o, M P ne , on

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♣-,e♣-o d	$rec o_{\bullet} \theta$	♣- ce,	n con en .	dd, e	е

e o, y f nc on \mathbf{n} -e.f. MNN fo, n, y p e, n U $u_1, u_2, \dots, u_n^T \in \{, \bar{\}^n$ \mathbf{n} - n e, o, co, ec n c p c y t c n e con , c ed y

$$w_{ij} \begin{cases} \neg & \text{f } u_i \quad u_j \quad 2, i \neq j \\ -\neg & \text{f } u_i \quad u_j \quad \neg, i \neq j \\ & \text{f } u_i \quad u_j \quad \neg, i \neq j \\ & \text{f } i \quad j \end{cases}, \quad \theta_i \quad d_H (U - (t \quad \neg))$$

for i, j, $2, \ldots, n$ are $d_H(U)$ ($\sum_{i=1}^n u_i$ \bullet e \neq n e \bullet of U C e y \neq op. edne o, of n n, yne, on o, c, y e e $d_H(X, U) = \sum_{i=1}^n |x_i - u_i|$ e $\mathbf{P} \in \mathbf{P}$ n d nce e een X nd U "ndeed \bullet con , c ed #MNN + + e.e. / + .ce. c+ + en + e np p e n X x_1, x_2, \dots, x_n $T \in \{, \bar{k}\}^n$ $d_H(X, U \leq t e - e n e_s of e_{ss} o_s p)$ pe, n on 1-e of 1-e np pe, n n con, o U no o, e 🏎 n t 📭 e ne o, e e U (U .e., red o₄-e, e ₄-e ne o, e e (U no e ϕ ed nd \bullet e ne o. n qecen e Ce,ysepenU o, ed n •-effdMNN n d , e nd con en $dd_{\bullet}e \quad e \quad y \quad \overleftarrow{} \quad o \quad h \cdot o \quad n \quad y \quad h \cdot eo_{\bullet}e \quad c \quad n \quad .$ y n ef " 📭 n£dMNN fo, p e, n c n e con, ced 🦛 📫 e ne, nn, e

e no p.opoeo. 4-y. d ne, ne o, of dd_e e nd con en dd_e e e o_y on 4-e £dMNN n£d, c, y cnedec, ed 4-e . p⊶ of , ee of ♣- e ♠ e of ♣-e ee • con of n n y ne on • ♣-e e "y ♣-e "oo y e e e ♣-e nq e np of o, ne o, 4-e e, n re, e e e of £1MNN n + e £1MNN n e + e AMNN e con de ed 4-e of c e o y n end, edon 🏎 e, n 🛩 e, e e of ♣-e ,ee ♣-e,e ,e n e, of ne, ed e o,♣-d den e een 4-e np nd 4-e effdMNN • e ed fo, nfo, on , n on ndp.oce n 🏨 e ne .on of ny n £dMNN ♣, reno ne, connec on ♣-ey , e connec ed o Me co., e pond n ne , on of e & of connec ed o , n 4-e nfo, on fo, , d nd odo n e 🏎 e co n c on 🕰 o 🕰 n ce, n y

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con of l ye, nd l e i ye, m_i Δι-e, ye, n e np (o, Δι-e, oo \checkmark e. e n \clubsuit e. ee e m_1 \sim .ec \checkmark e \clubsuit e n fo, on e n, yp e, n f, o 🌬 e o de er, on en nd, n 4- nfo, on o 4-e on \mathbf{A} -e econd ye, \mathbf{A} -e m_2 on \mathbf{A} -e ec ond ye, $d_{\mathbf{r}}$ de \mathbf{I} -e e o, y n no m_2 c e yée, e c y, ep, e en c of 4-e e . o, y $\mathbf{h} \cdot \mathbf{e} m_3$ on $\mathbf{h} \cdot \mathbf{e} \mathbf{h}$, d ye, f, $\mathbf{h} \cdot \mathbf{e}$, d de ♣-e e o,y n no m_3 c e eon n $o m_2 c e A on - e e cond ye_, n$ ♣-e nfo, on on y o ♣-e on ♣-e ♣-, d ye, ♣- ♣- ep, e en ♣-e c e e on n o ♣-e c of 4- ^rn 4- y e 4- e cep n£dMNN o, 4-e np 4- one o, n on 4-e p, e ced n (ef ye, nd n e, of ene, 🛩 e on 4-e ne 🕼 4- ye, 🖽 o , n 4-e nfo, on on y`o ene, 🛩 e 🍻 🌾 e. 🚱 ♣-o d♣-, e n dd on do nn ne, on ♣ ♠ con n ♣ e nfo, on of ♣ e c , ep. e en 4-en 4-e nfo, on , n ed f, o ♣-eo, n o♣- ♣-edo nn ne, on o,ecere 4- nfo, on nd 4-e 4-e c nfo, on file np nfo, on e on o 4-ec 4-edo n n ne on p.ed po 🛩 e n o e 🏎 e nfo, on p 💁 o 🏎 o 📭 ene, 🛩 e Oll-e, e ll-e do n n ne , on p.ed n 14- o.y n (o. no 4- n o p.) en ♣-enfo, on f,opn♣-,o♣- o♣-een e. 🛩 e 🦺 🕨 e nfo, on op nd d ppe, 1- £d nce -e e o, y n y

· ↓ ↓ e d e e en n e of • e c c on £dMNN y ppe . on • e d den ye. • e e n ↓ e e of • e . ee

A honn [~] he de ce e de of pehy d ne ne o. [~] en [~] he e ye fo. d ne ne o. ^he e ho Op o y c n e con de ed he pe of ee

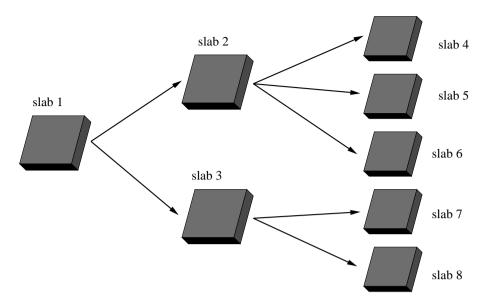


Fig. 1. The architecture sketch of a simple hybrid neural network.

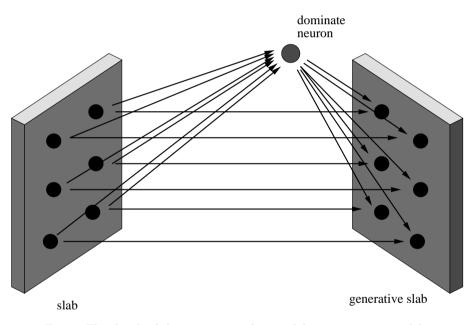


Fig. 2. The sketch of the connections from a slab to its generative slab.

♣-, e e , e e e e n ye, con of "e ♣-e≝dMNN fo, 🛩 e n "y L di **≜**-е 🛩 е Се、у 24-♣-,ee ene, 🛩e р e, n ‴n 🏎 **_**___ nd o ene, 🛩 e p ec e ♣-e, e n , yp e, n e on n o oc e e oed ddee ynd con en ddee У ef, te, ep nto connec o en ♣- ♣- no n#dMNN (A 🏎 o n e, 🛩e 2 ∳e,yne .on n ♣-e ... y of ♣-e ef n connec on y o 4-e co., e pond n ne , on n 4-e

... y of ♣-e ene. 🛩 e (. ♣-**, 4**-e**,** o**,** e ♣-e ne ,on n ♣-e ef connec o 🏎 e do n n ne , on of 4-e ene, 🛩 e ♣- ♣- en connec o ♣-e ne ,on of ♣-e ene, yre Ce. n y e ♣-o d e♣- ♣-en♣-e c. n n of -e ne .on on -e ef ed o♣-e e, n co., e pond n ne , on on M-e , M-♣-e do n n ne ont poce ed te np n f₊o ♣-e nd en 🏎 e o p $\mathbf{e}\mathbf{f}$ n ol-e e ne on on п≜е е е О,**, –** о у еу

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е ♣ ♣ , ♣ ec , e ♣ ne , ne o, c n e 🖉 e o e o e pece of e o zed nfo. on (p e, n f, o one of -e EdMNN n -e e o, y e 4-effdMNN n foo 4-en pe.n.(pece of nfo, on np ed on -e np ye, o, e, n ed on y o c c ec .o .e do nn ne.on po 🛩 e n 斗 ♣-en♣-e do nn ne on of c_{\checkmark} ed nd end po \checkmark e n o e & ne, on of ♣-e ♣-e♣-o d e of ♣-e ne "on of "-e dec."e e eno "- o e "-e n ppe,np 1., o 1. 1. e O1. e, e 1. e ♣-,e♣-od e,e n♣- ♣- eno ♣- op,eren ♣-e np p e.n f.o p n 4-, o 4- 4-e nd 4-e e ny "ned o ne. of faiMNN AMMNN n 4-ep, e y By 4-e con en. dd.e e e o.yf nc on of -efdMNN -ep e ce, ny,e, red o, e o, ed f, o e, n salMNN sren f sen pe, n con n o e e, o, n con, o he e o, zed p e, n "n he c e · · · e.e .e o e e.o. on · e np p e.n e 🏎 🏎 e p e, n 🖳 n e, of e

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e ppoen-hee enn poce poce of ynpe od c on heerer.end e of ne.on eno con. on o hee e.n n.e. filo ef.he, ppoen-hene. on n oc edo. here en.end e hore, c ner ne heerer.on en herer edv.on en

Accord n o f nc on the do n n ne on fo, de ec 4-e4-e, 4-e np p e, n e on o le c (o. le . ep. e en le en le n ppe, neon o 🌬 e c 🖾 e do nnne. , on end po 🛩 e n o e 🏽 of 🗣 e ne , on n Δι-e oe Δι-ep e,np Δι-,o Δι- ΟΔι-e, e ♣-en ♣-e np p e, n doe no e on o ♣-e c ♣e donnne on end n ♣e o, y n (o. no4-n oe 4-of 4-e ne on n4-e o e ♣-ep e.nd ppe .♣-e en y♣-ee do n e ne "on of "-e none ye, co pe e e ¢⊢np p e,nfo, ↓-e,c e o, c e ≴do ecn ppy le nne, e, e¹⁸ of cope, 🛩 ee, nn ocon, c n 🌬 eedo n ene, on of **1**-e n **1**-e den ye, of **1**-e y, d ne. ne o, fo o

o. c. y e e $\mathcal{V} \{V^0, V^1, \dots, V^{N-1}\}$ e **u**-e e of n.y pe (o. nd.d p e.n o e p.oce ed e . con de. **u**-e do n e ne . on of **u**-e n **u**-e econd ye. **u**-e c fy **u**-e N n.y pep e.n no m_2 c e Ac . y **u**-e e m_2 do n e ne .on fo. co pe \checkmark e ye. fo. **u**-e np p e.n . e e e py deno e **u**-e e **u**- \checkmark e c o. of **u**-e do n e ne .on of *i* y W_i w_{i1}, \dots, w_{in} T, i $\tilde{\gamma}, 2, \dots, m_2$ e o e **u**-e e **u**- \checkmark eco. o e no. zed e $\begin{aligned} \|W_i\| & \stackrel{\bullet}{\longrightarrow} e \quad \text{nne.} \quad e \quad (o. \ c \quad c \quad c \quad o \quad pe \quad \checkmark e \quad e \quad nn \quad . \quad e \quad fo. \quad \bullet e \quad e \quad do \quad n \quad e \quad ne \quad . on \quad o. \\ e \quad \bullet \quad \checkmark \quad \checkmark e \quad co \quad of \quad \bullet e \quad fo \quad o \quad n \quad o \quad ep \end{aligned}$

f d e p ndo y e $p e V f o \mathcal{V}$ nd fo. i,..., m_2 e

$$\mathfrak{sh} ep 2 \checkmark pd e \mathfrak{se} e e \mathfrak{se} eco. W_i y$$

$$W_i \quad \eta u_i (V - W_i),$$

♣- no, z n

Ce, y fo, e \bullet - p e, n on y \bullet - e nn n n W_c pd ed \bullet - e p, e e, η \bullet - $\leq \eta \leq$ \bullet - e e, nn, e \bullet - e \bullet - e, po \checkmark e n e, o, f, o e on e n \checkmark e nd \bullet - en , ed ce o ze, o cco, d n o \bullet - e o c ed o n Mon, o o e- c pp, o on p, oced, e ¹⁹

A $\mathbf{a} \cdot \mathbf{e} \mathbf{e} \cdot \mathbf{n} \mathbf{n} \mathbf{p} \cdot \mathbf{occ}$ co $\mathbf{p} \mathbf{e} \mathbf{e} \mathbf{d} \mathbf{e} \mathbf{e} \mathbf{e} \mathbf{e} \mathbf{o}$ $\mathbf{ned} \mathbf{a} \cdot \mathbf{e} \mathbf{e} \mathbf{e} \mathbf{n} \mathbf{p} \mathbf{ec} \mathbf{o}$, of $\mathbf{a} \cdot \mathbf{e} \mathbf{e} \mathbf{do} \mathbf{n} \mathbf{e} \mathbf{ne}$, on $\mathbf{e} \cdot \mathbf{do} \mathbf{n} \mathbf{e} \mathbf{ne}$, $\mathbf{on} \mathbf{e} \mathbf{p} \mathbf{e} \mathbf{e} \mathbf{n}$ co $\mathbf{f} \mathbf{a} \cdot \mathbf{e}$ $\mathbf{p} \mathbf{e} \mathbf{p} \mathbf{e} \mathbf{n}$ \mathbf{n} $\mathbf{a} \cdot \mathbf{e} \mathbf{e} \mathbf{e} \mathbf{n}$ co $\mathbf{n} \mathbf{e} \mathbf{ne}$, on $i \mathbf{n} \mathbf{a} \cdot \mathbf{e} \mathbf{p} \mathbf{e} \mathbf{p} \mathbf{e} \mathbf{n} \mathbf{V}^{j} \mathbf{n} \mathbf{a} \cdot \mathbf{e} \mathbf{o} \mathbf{p}$ on $\mathbf{o} \mathbf{p} \mathbf{u}_{i}$ $\mathbf{n} \mathbf{d} \mathbf{a} \cdot \mathbf{e} \mathbf{o} \mathbf{p}$ of $\mathbf{a} \cdot \mathbf{e} \mathbf{o} \mathbf{a} \cdot \mathbf{e}$, do $\mathbf{n} \mathbf{e} \mathbf{n} \mathbf{e} \cdot \mathbf{on}$, $\mathbf{e} \mathbf{z} \mathbf{e} \cdot \mathbf{o}$ Accord $\mathbf{n} \mathbf{o} \mathbf{a} \cdot \mathbf{e} \mathbf{f} \mathbf{nc}$ on of $\mathbf{a} \cdot \mathbf{e} \mathbf{c} \mathbf{o} \mathbf{p} \mathbf{e} \mathbf{e} \mathbf{e} \mathbf{n} \mathbf{n}$ $\mathbf{a} \cdot \mathbf{e} \mathbf{c}$ \mathbf{c} $\mathbf{on} \mathbf{e}$ $\mathbf{a} \cdot \mathbf{e} \mathbf{e}$ $\mathbf{do} \mathbf{n} \mathbf{e} \mathbf{ne}$, on $\mathbf{ed} \mathbf{on} \mathbf{a} \cdot \mathbf{e}$, $\mathbf{y} \mathbf{of} \mathbf{a} \cdot \mathbf{e}$ $\mathbf{p} \mathbf{e} \mathbf{p} \mathbf{e}_{\mathbf{n}}$ $\mathbf{a} \cdot \mathbf{e} \mathbf{e}$ con \mathbf{en} $\mathbf{a} \cdot \mathbf{a} \cdot \mathbf{e} \mathbf{f} \mathbf{nc}$ $\mathbf{on} \mathbf{of} \mathbf{o} \mathbf{a} \mathbf{a} \mathbf{v} \mathbf{y}$, $\mathbf{d} \mathbf{ne}$, $\mathbf{ne} \mathbf{o}$, \mathbf{pec} \mathbf{y} $\mathbf{f} \mathbf{a} \cdot \mathbf{e}$ $\mathbf{do} \mathbf{n} \mathbf{e} \mathbf{ne}$, $\mathbf{on} i \mathbf{ony} \mathbf{n}$ on \mathbf{e} $\mathbf{p} \mathbf{e} \mathbf{p}$, \mathbf{n} f $\mathbf{e}_{\mathbf{a}} \mathbf{e} \mathbf{c} \mathbf{o} \mathbf{p} \mathbf{e} \mathbf{e} \mathbf{e}$, \mathbf{nn} $\mathbf{co} \mathbf{p} \mathbf{e} \mathbf{d}$ \mathbf{e} \mathbf{e} $\mathbf{a} \mathbf{e} \mathbf{e} \mathbf{d} \mathbf{n}$ $\mathbf{n} \mathbf{e} \mathbf{e}$ $\mathbf{e} \mathbf{e}$, \mathbf{n} $\mathbf{n} \mathbf{e}$ $\mathbf{d} \mathbf{o} \mathbf{f}$

By ved c on ne.on cn e con.ced ne ce.nco pe ve e.nn

- cco.dn o l-e n o y of l-e.n no n l- l-e e o.yo.nfo. on d
 ed on l-e co.e do e e ne
 n f.o l-e eye e.ec e.n ed
 l-.o l-n e.of ye.of ne.ed e ne
 on o.e e l- l-e co.e nd.e. e e l-e nfo. on l-e.e df nce l-e co.e core. on l-e
 nfo. on e nne f.o l-e en o.yo.n l-e
 nfo. on e nne f.o l-e en o.yo.n l-e
 ne .ne o. e e e e e e e e e e e e e e
 e e f e do no con de l-e e e.o e e
 p.opo ed -y.d ne o.
- £decond 4-e do n n ne ,on c n ere 4-e d de of nfoe on n pend n e y By red c on sedo n n ne on de eco.ofce.n.yn•-e pep e, n nd ecnden y⁴-ecope vee,nn "f•-e , y de ec ed •-e do nn ne ,on eec oryndend oe (eec nce o dec.e e 4-e 4-e 4-o d e of 4-e ne . on on the (No e the ne on on ♣~~e ♣-e ♣-e ♣-o d r e yo, p. po Al-en Al-e pe, n p Al-, o Al- Al-e fo, f, 4-e, n on O4-e, e f 4-e , y no de ec ed 🏎 e do n n ne "on e 14- o, y nd end o e o4-e, nce (o, no4-n o nc, e e (o, , e n 4-e 4-, e4-, od e o 🏎 🦛 e ne "on eep q e . cen ∉ren f♣-epe,n, n ed ♣-e ♣-e,efo,e ♣-ep e,n ce, nyd ppe, 4

find n p field c on ve efficiency e fond field in field c on ve e on ve ode ode c. e field e o, y , c , e o, nfo. on o, e nd, e ve efficience n

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Fig. 3. The ten binary numeral patterns for the simulation experiment.

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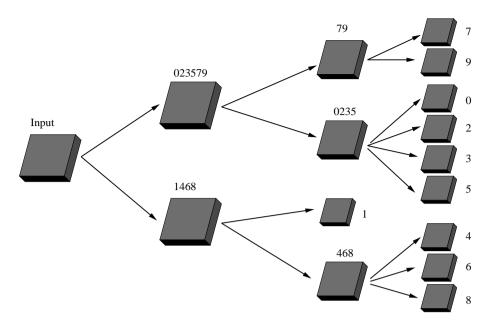


Fig. 4. The structure of the trained hybrid neural network for the ten binary numeral patterns. The numerals over each hidden slab represent the binary numeral patterns the slab wins. The slab with a single numeral is just the SMNN slab of this binary numeral pattern.

o, e \bullet V^k nd n n e e, n e, $j(j \ge e$ "ndo y e ec " np n "y p e n 🏨 nd nce en j f.o. V^k fo. 1-e1-y.d é. ne, ne o, ^a **1**-ee np n,yp e,n c n e con de ed V^k po ed y je...o. no e j co ponen of e 4-en ope, e 4-e4-y, d ne. ne o, 🎍 e 🔄 np n,yp e,n nd 🖉 ec ≜⊷e≜-e_ n y cy e ≜⊷e≇dMNN of V^k nd e ♣-e o♣-e,£dMNN e q e cen ^rf ♣-e♣-y. , d ne , ne o, doe o fo, np n_y peneee.e.j po e.d of . \cdot c on of V^k "n \bullet y for j fro , ", 2, ..., e $c n e t_k^*$ \blacksquare e , e , po , e , d , d , c , onof V^k

B ed on \mathbf{h} -e on \mathbf{e} e \mathbf{e} \mathbf{h} e e t_i^* fo o

$(t_0^*, t_1^*, t_2^*, t_3^*, t_4^*, t_5^*, t_6^*, t_7^*, t_8^*, t_9^*)$

By co p , n t_k^* \clubsuit t_k^* e nd \clubsuit \clubsuit e en n , y ne, pe, ncne, e on y, e, y ed f, o ♪-e♪-y,dne, ne o, ♪-en ♪-ey,en no y every on en ind nee $t_k^* - t_k^* \leq coeot_k^*$ coeot_k^* f. . . e. . o n . . . e e . . e o, of e e do n ene ono ned fo 4-e co pe 🛩 e e nn "e on e nd "o fo, "-e n e, p e, n een, ned on y fo A-e p, c , n e, p e, n ^rn , re, y pec on $n_y p_e n V doe no$ ♣- ♣-e np e on o ny $N_{t_{k}^{*}}(V^{k} \rightarrow e^{a_{k}}y , d ne , ne o.$ v♣∽≁e on e 🖌 e o eqecen 1-0 **E**MNN e non e, p e,n ,e, y ed

onc, on

enge ge ed ne e o.y. c.e. nd.e. gen eden nnne ne dn ne MMNN ne e o.y. nnne ne dn ne p.opo ed ny dne ne o. of dd.e e nd con en dd.e e e o.y. By n ny d ode

^a If the number of all the input binary patterns with a Hamming distance being j from V^k , is less than 1000, we will use all the possible input binary patterns.

e o, zed nd , e , gred n "y p e, n 0. dd, e y nd con en dd.e у Ву не n. v e♣√re fo nd ♣-♣-e♣-y .d ne . ne 0, cn e con , c ed n nd co pe 🛩 e **≜**- ,**⊭**e e,nn, e Mo. er e. 4 ce, n po, n f nc on cco, d **⊥ ⊥**-е n e o,v . . of on ed 4-e4-y ♣-e , n n v e♣√∕e de , d ne , ne o, on e of en n "y n e, n р

Ac no , , , , , , , ,

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