Proceedings of International Joint Conference on Neural Networks, Atlanta, Georgia, USA, June 14-19, 2009

Cognitive Memory: Human and Machine

Bernard Widrow, *Life Fellow, IEEE,* Mozziyar Etemadi, *Student Member, IEEE*

***Abstract*— This paper addresses three questions: how does human memory work? How could I build a memory like that? How could I use it to solve practical problems?**

I. INTRODUCTION

Pattern recognition remains an elusive art, even after decades of work by thousands of people in the field worldwide. Some progress has been made. You can now phone an airline company, talk to a computer, and make a flight reservation. There are other examples of practical applications of current methodology, but they all exhibit far from human-like capability.

What is it about humans and animals that gives them such an amazing ability to recognize objects and patterns? Why after all these years are we not able to approximate animal capability for pattern recognition by artificial means? Is there something magical or supernatural about humans and animals? Or are they simply machines of great complexity? What is it?

We believe that humans and animals are superbly capable complex machines, not possessing supernatural powers. Believing that, we try to understand the mechanism, the action that takes place when we are seeing and hearing, and in particular, how we recognize patterns.

Fundamentally, human and animal pattern recognition involves matching an unknown incoming pattern with a pattern seen before and currently stored in memory. Not everyone will accept this, but this is what we believe.

During a visit when an interesting subject is being discussed, the "mental tape recorder" is recording in memory the sights, sounds, etc. of the visit. In a half hour of discussion, perhaps 100,000 images of the visitor's face are recorded. These images are retinal views that capture the visitor's face with different translations, rotations, light levels, perspectives, etc. These images are stored permanently in memory, wherever there is an empty place. Unlike a digital computer with numbered memory registers where data storage locations are program controlled, and data is retrieved when needed by calling for it by register number, human memory has no numbered registers. Data is stored in human memory wherever there is an empty place and once stored, the memory has no idea where the data has been stored.

We contemplate a memory of enormous, almost unbelievable capacity, enough to hold many lifetimes of stored visual, auditory, tactile, olfactory, vestibular, etc. patterns of interest. Data and patterns are retrieved in response to an input pattern, whether visual, auditory, tactile, etc. or a combination. The input pattern serves as a prompt to initiate retrieval of data patterns related to the prompt, if they are stored in the memory. If data patterns are retrieved and if they contain an identification, the input pattern is thereby identified.

It is surprising that many aspects of human mental activity can be explained by such a simple idea of memory. Some of these aspects will be described below. On the engineering side, we will introduce new approaches to computer memory, to pattern recognition, and to control systems.

Pattern matching is complicated by the fact that unknown incoming prompt patterns may be different from stored patterns in perspective, translation, rotation, scale, etc. Simple pattern matching may not be adequate, but this will be addressed.

The memory capacity must be enormous, and it should be implemented with a parallel architecture so that search time would be independent of memory size. There are many ways to structure a content-addressable memory. The "cognitive memory" proposed herein is of a unique design that could be physically built to give a computer a "human-like" memory, and furthermore, it is intended to serve as a behavioral model for human and animal memory.

A simplified block diagram of a cognitive memory system is shown in Fig. 1.

The memory of Fig. 1 is divided into segments. Each segment has a set of memory folders capable of storing visual auditory, tactile, olfactory, etc. patterns and if the system were artificial, it could store radar, sonar, and other

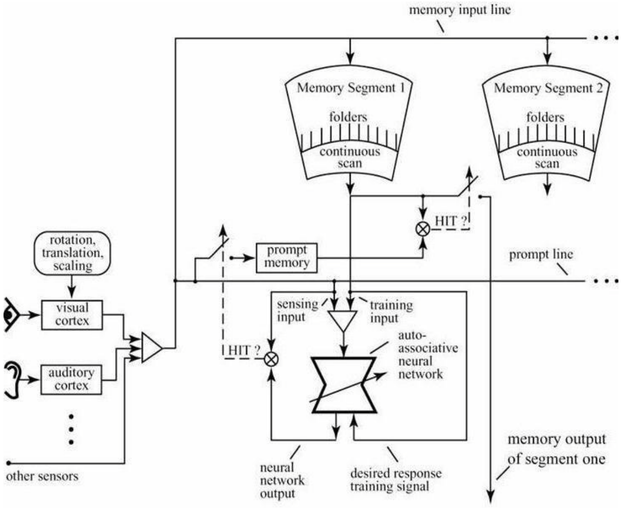

Fig 1. Cognitive Memory System

Manuscript received March 22, 2009.

B. Widrow and M. Etemadi are with the Department of Electrical Engineering, Stanford University, Stanford, CA 94305. (e-mail: metemadi@stanford.edu).

978-1-4244-3553-1/09/$25.00 ©2009 IEEE

sensory patterns. Each segment has its own autoassociative neural network.

During a visit, images of the visitor's face, voice sounds, tactile images, olfactory patterns, etc. are stored together in one of the empty folders. These patterns arrive on the memory input line of Fig. 1. They come from visual, auditory, etc. sensors, having gone through the visual, auditory, etc. cortexes respectively.

The various sensory patterns, having been recorded simultaneously in the same folder, are permanently associated with each other. The result is that, when the contents of a folder are retrieved in response to a visual prompt which may be the image of a singer, in one's mind, the sound of the person singing can be "heard." If the prompt is the sound of singing, the image of the singer's face can be "seen" in one's mind. If the prompt is a certain smell of cooking, the image of the kitchen or restaurant can be "seen" in one's mind.

Since the various sensory input patterns are stored together, it is likely that they are not stored in separate cortexes. The likely purpose of the cortexes is pre-processing the sensory inputs before they are sent to the storage folders. When we computer simulate the cognitive memory system, pre-processing is done with the input patterns. For example, a photograph of a person's face is rotated, translated, scaled, etc. Hundreds of images are made from a single photograph, using MATLAB. In a paper by Widrow and Winter [1], it is shown how neural networks can perform this kind of pre-processing in a parallel operation, resembling the processing done in living cortexes.

Offline, when the memory system is idle, the autoassociative neural networks in all the segments are trained. For humans and animals, offline training occurs during non-REM sleep. In the simulated system, a continuous scanning process extracts all the patterns one-by-one from all the folders in a segment, and trains these patterns into the segment's autoassociative neural network. This occurs simultaneously and separately in all the segments.

In the simulated system, the autoassociative neural networks were three-layer perceptrons. The backpropagation algorithm was used for training. Input patterns came from the memory folders. For each training pattern, the desired response pattern was identical to the training pattern. After training, unknown prompt patterns were presented to the neural networks via the prompt line. If a prompt pattern were identical or close to identical to one of the patterns in one of the folders, the output pattern from the corresponding neural network would match the prompt pattern. This is determined by subtracting the output pattern from the prompt pattern. The difference is the error pattern. The mean square error (MSE), the normalized square of the magnitude of the error pattern, was measured. If the MSE was below a set threshold, there was a "hit." This indicated that there is a pattern in one or more of the folders that matches the prompt pattern. Now knowing exactly what to look for, an exhaustive search is made, checking the hit prompt against all of the patterns in the folders. The contents of the "hit folder," the folder containing the pattern that matches the "hit prompt," are delivered as the memory output. The hit folder would deliver everything recorded in it, visual auditory, tactile, etc. as outputs.

When a prompt input pattern does not have a hit, all other versions of the pattern serve as prompts that try to make a hit with a neural network. With visual patterns, rotated, translated, scaled, etc. versions are tried. If there is no hit, the prompt fails and the memory delivers no output.

The neural networks are not trained to identify a prompt pattern, only to say hit or no hit, i.e. "I have seen that pattern before, or not." Déjà vu, yes or no? Use of the neural network speeds up the search process. Every pattern in every folder does not need to be tested against every variation of the prompt pattern. The number of combinations would be horrendous. Every pattern in every folder only needs to be tested against a single "hit prompt pattern." Hits can be determined very quickly by the parallel neural networks.

In our simulations, the neural networks were trained by backpropagation, a supervised learning algorithm. However, since the desired response patterns were in fact the same as the training patterns, the training process was not supervised learning. There was no external supervisor, and the cognitive memory system was completely self organizing!

One day while walking down the street, you see a familiar face at a great distance. You know that you know this person. Déjà vu! You come closer and start a nice conversation. But you keep asking yourself, what is his name? What is his name? You keep talking and looking for ten minutes or so, when suddenly his name, Jim Jones, pops into your head and you say to him, "well Jim, …" He thinks that all the while you knew his name. What happened? How did this work?

You have many Jim Jones folders in various memory segments, recorded from a number of Jim Jones visits. The folders contain many images of his face, recordings of two-way conversations, etc. One of the folders has a recording of your first meeting with him when he was introduced by a mutual friend, who said "this is Jim Jones." When you first saw him at a distance, the contents of one of the Jim Jones folders was retrieved, but that folder did not contain the sound of his name. The facial images and voice sounds of that folder are used in turn as prompt patterns. This causes more Jim Jones folders to be tapped. This works like feedback. Also, the images of his face and sounds of his voice from the current conversation act as further prompts. You keep pulling more Jim Jones folders until you come upon the one containing his name. Bingo!

II. SALIENT FEATURES OF COGNITIVE MEMORY

- Stores memory patterns (visual, auditory, tactile, radar, sonar, etc.)
- Stores patterns wherever place is available, not in specified memory locations.
- Stores simultaneously sensed input patterns in the same folder (e.g., simultaneous visual and auditory patterns are stored together).

- Data recovery is in response to “prompt” input patterns (e.g., a visual or auditory input pattern would trigger recall).
- Autoassociative neural networks are used in the data retrieval system.

III. Application of Cognitive Memory to Face Detection and Recognition

Detection of human faces in a complicated scene is done by scanning with a low-resolution 20x20 pixel window over the scene. Different window sizes, window rotations, and various brightness and contrasts were used to create images of different rotations, translations, scale, brightness, and contrast. These images or patterns were fed to a 20x20 input autoassociative neural network. The network was trained on many versions (rotated, translated, scaled, etc.) of an arbitrary person’s face. When there is a hit, a face is detected.

Once a face is detected, the system switches to a high resolution (50x50 pixels) window. The window’s images were fed to a 50x50 input autoassociative neural network. This high resolution network was trained with 50x50 pixel facial images of many people. Each person had a separate folder, and the folders contained hundreds of images of the individual with different perspectives, rotations, translations, etc., plus the person’s name. When the unknown 50x50 pixel images were fed to the autoassociative network, if there were a hit, the unknown hit image must be stored in one of the folders. Making an exhaustive search, the folder is found and the hit face is identified.

*A. Face **Detection** Training*

- One image of a person’s face was trained in
- The image was then adjusted by
  - ➢ Rotation (2° increments, 7 angles)
  - ➢ Translation (left/right, up/down, 1 pixel increments, 9 positions)
  - ➢ Brightness (5 levels of intensity)
- Total number of training patterns = 315
- Training time 1.2 minutes on AMD 64 bit Athlon 2.6 GHz computer for 0.25% MSE

*B. Face **Detection** Sensing*

- Each input pattern was adjusted by
  - ➢ Scaling (6 window sizes)
  - ➢ Translation (90 pixel increments)
- Errors with background were ~8X greater than with a person’s face
- 600 patterns per second through neural network
- Autoassociative neural network has total of 1100 neurons distributed over 3 layers
  - ➢ 400 neurons, 400 weights/neuron, 1st layer
  - ➢ 300 neurons, 400 weights/neuron, 2nd layer
  - ➢ 400 neurons, 300 weights/neuron, 3rd layer

Fig 2. a) Photos of B. Widrow used for training, b) Photos of J.C. Aragon, V. Eliashberg, and B. Widrow used for sensing

*C. Face **Recognition** Training*

- Three images of Widrow’s face were trained in
- Each image was adjusted by
  - ➢ Rotation (2° increments, 7 angles)
  - ➢ Translation (left/right, up/down, 1 pixel increments, 25 positions)
  - ➢ Scaling (3 window sizes)
- Total number of training patterns = 1575
- Training time 15.6 minutes in AMD 64 bit Athlon 2.6 GHz computer for 0.25% MSE

*D. Face **Recognition** Sensing*

- Each input pattern was adjusted by
  - ➢ Brightness (6 levels of intensity)
  - ➢ Translation (2 pixel increments, 25 positions)
  - ➢ Scaling (6 window sizes)
- Optimization was done for each detected face
- Errors with unidentified faces were ~4X greater than with Widrow’s face
- 5 patterns per second through neural network
- Autoassociative neural network
  - ➢ 1800 neurons, 2500 weights/neuron, 1st layer
  - ➢ 1500 neurons, 1800 weights/neuron, 2nd layer
  - ➢ 2500 neurons, 1500 weights/neuron, 3rd layer
  - ➢ Total 5800 neurons, 10,950,000 weights

Figure 2 shows the three photos of B. Widrow that were trained into the 50x50 input autoassociative neural network. The photo of Aragon, Eliashberg, and Widrow was scanned with the 20x20 window and the faces were detected. The faces were checked with the 50x50 network, and the faces of Aragon and Eliashberg were called “unknown,” and the face of Widrow was identified as “Dr. Widrow.”

IV. Cognitive Memory Challenged

We used the Cognitive Memory system to identify faces from the NIST Face Recognition Challenge version 1:

- Photographs of 75 persons were selected for training.
- 75 other photographs of the above persons were selected for sensing purposes.
- 300 photographs of persons NOT trained-in were selected for sensing.
- In total, 75 photos were used for training and 375 different photos were used for sensing.
- Autoassociative neural network had 3 layers distributed as follows:
  - ➢ 2000 neurons in the first layer
  - ➢ 1500 neurons in the second layer
  - ➢ 10000 neurons in the last layer

- Total number of weights: 38 million. Retina size: 100 × 100 pixels.
- Results: The 75 people trained-in were recognized and identified without error, while the 300 people not trained-in were rejected by the Cognitive Memory system.

V. THE BIOLOGICAL VIEW

Between both of the authors of this paper, we have experienced almost 100 years of living with human memory. Observations from everyday life have given us insight into the workings and the behavior of human memory. Knowledge of electronics and computer memory also colors our view.

A. Memory patterns are probably not stored in the brain's synapses. Why?
   - Synapses do have memory capability, but this is analog memory. For stability, long-term memory requires digital memory.
   - Neurons, dendrites, and synapses change over time as circuitry is added during childhood brain growth, and later, circuitry dies out with aging and disease. Constant training of the brain's neural networks is needed in order to maintain stability of response.
   - Training of neural networks requires training patterns that must be stored somewhere.
   - Why would nature provide storage for training patterns in order to train neural networks to store the training patterns? Catch 22!
   - Loss of neurons, dendrites, and synapses does cause loss of memory. We theorize that neurons, dendrites, and synapses are used in the data retrieval process, not in the data storage process, but in that way, are associated with memory loss as neural networks deteriorate.

B. Human memory is capable of storing patterns in great detail.

Thirty or so years ago, Béla Julesz, who at that time was a researcher on 3-dimensional vision at Bell Telephone Laboratories, gave a fascinating lecture at Stanford on his research on what he called random-dot stereograms. Computer-generated random dot patterns were presented to the eyes from which 3-dimensional objects could be perceived. Using polarized light projected on a screen, the left pattern was addressed to the left eye, the right pattern was addressed to the right eye. Looking with one eye, one sees random dots. Looking with both eyes, dramatic 3-dimensional objects emerged. He wrote a book on this subject [2].

Dr. Julesz described memory experiments that he did with an eidetic subject, a woman with a "photographic" memory. In the lab one day, he covered her right eye and let her stare at the left-eye random dot pattern. A week later, she returned to the lab where he covered her left eye and let her stare at the right-eye pattern. All she was seeing with her right eye was a page of random dots, but she was able to perceive the embossed characters and she read: "now is the time for all good men to come to the aid of the party." She was able to remember in exquisite detail the left-eye pattern and compare it with what she was seeing with her right eye to get the 3-D effect.

He gave her a book to read. A week later she returned the book. He opened it at random to one of the pages, say page 373. He said to her, what do you see on page 373? She was able to tell him exactly what was on that page, word for word. He said that she was very bright, but a very unhappy person. He said that the number of people with this kind of memory would probably be several in a billion. He was asked if she had a head as big as North America. He said no, she looks like a normal young woman.

If this young woman could have such a memory, it is reasonable to assume that everyone has such a memory capability but nature somehow protects us from it. She wasn't so lucky.

C. Sensory Input Pattern Storage

Sensory patterns that are "interesting" are stored in long-term memory. They are stored in short-term memory for a long enough time to decide if they are interesting or not. They are presented on the sensory input line like prompt patterns, and if they make hits with any of the autoassociative neural networks in any of the memory segments, they relate to contents of the memory and they cause the memory's "tape recorder" to turn on, i.e. to cause the memory to start permanent recording of all sensory inputs and thus to add new patterns to the database. New data is learned, and knowledge is expanded when something familiar is observed. The following are some features of the memory system.

- Sensory input patterns come from eyes, ears, tactile, olfactory, vestibular and other sensors.
- Incoming patterns are stored in empty folders, wherever they are located.
- Sequences of patterns, like videos are stored in the same folder.
- Visual, auditory, and other sensory patterns that were received at the same time are stored in the same folder.
- Only "interesting" input patterns are stored in the memory. They remain for the rest of one's life. An eidetic stores everything, interesting or not.
- Sensory input patterns go to short term memory and, if interesting, are transferred to main memory and recorded for life.
- Short term memory (of the order of a few seconds) is used in the determination of what is interesting. The problem solver can also decide what is interesting.
- Autoassociative neural networks are used in the pattern retrieval process.
- Pattern retrieval occurs in response to prompt patterns.
- Prompt patterns may come from sensory inputs.

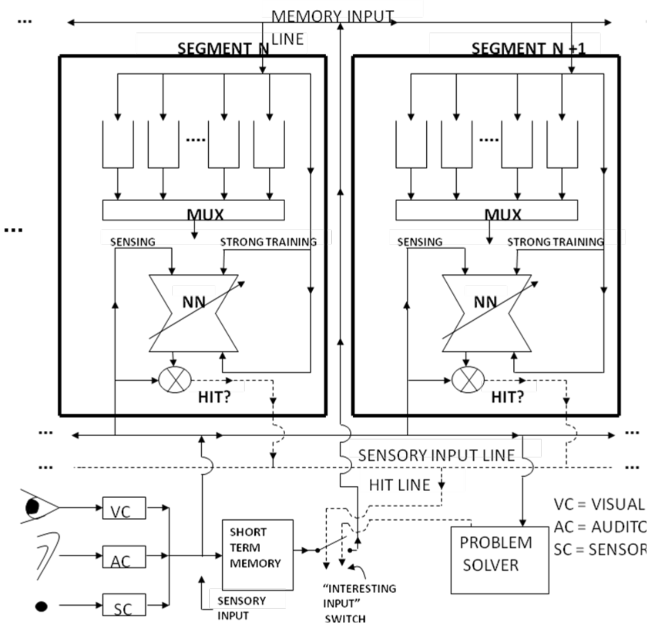

Fig. 3. Sensory Input Pattern Storage

- The memory is organized in the form of independent segments to make possible a very large storage capacity.

Figure 3 is a block diagram of the sensory input pattern system. Notice the block called "problem solver." This is envisioned to embody a deductive reasoning process, perhaps modeled after the checker playing algorithms developed long ago by Arthur Samuel [3]. The problem solver makes use of data drawn from long-term memory, and is the "customer" for memory output. The problem solver could also turn on the memory's "tape recorder" if a loud sound or a bright light or a bright color is seen, or if something about the sensory input excites it. The problem solver is central to the reasonng process. It is not part of this memory study, however.

D. Innate Memory

Inborn knowledge is stored in long-term memory. The following describes some characteristics of innate memory.

- Inborn knowledge in the form of patterns is pre-loaded in the developing brain's memory and remains intact throughout one's lifetime.
- Examples of inborn knowledge :
  (a) A bird building a nest involves complex construction in "safe" places such as roof tops, tree tops, telephone poles, etc.
  (b) Baby horse walking and finding lunch within minutes of birth.
  (c) Human baby sucking, crying, peeing and pooping.
- It is conjectured that the memory storage means for inborn knowledge is the same as for sensory knowledge gained during a lifetime.
- It is conjectured that the memory retrieval means for inborn data is the same as for sensory input data.
- Inborn patterns are stored in folders in "memory segment 0".

Figure 4 is a block diagram for innate memory. This memory is like the memory for sensory input patterns.

E. Activity of a Baby's Memory

A newborn baby starts with innate knowledge in its memory and builds a database from there as it learns. Sensory inputs that correspond to items in memory create curiosity and cause the "tape recorder" to load new inputs into long-term memory. The combination of new memory patterns and innate memory patterns comprise a database for comparison with sensed objects in the real world. The bigger the database, the greater the curiosity and the faster will subsequent learning take place.

There is evidence that newborns have the ability to detect a human face in a complex scene [4]. The earliest faces detected are that of hospital staff and the parents. Seeing each person turns on the tape recorder, and the baby records thousands of images of each person's face. If the baby is breastfed, the folders containing images of the mother's face also contain all the sensory pleasures of being fed. Thus, mother is something special, different from everyone else.

It is believed that human memory is a self-organizing system and its learning is unsupervised. Innate knowledge, the "initial conditions," and real-world exposure seem to determine one's direction in life.

F. Thought Pattern Storage

Thought patterns developed by the problem solver are stored in memory like sensory input patterns. All thought patterns are deemed "interesting." The following are some characteristics of thought storage.

- Thought patterns are stored in long-term memory. Storage means and retrieval means for thought patterns are the same as for sensory input patterns.
- Thought patterns come from the "problem solver".

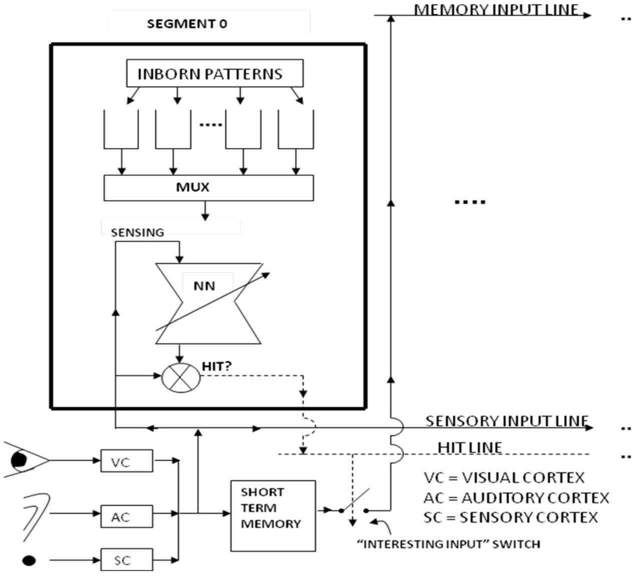

Fig 4. Inborn Pattern Storage

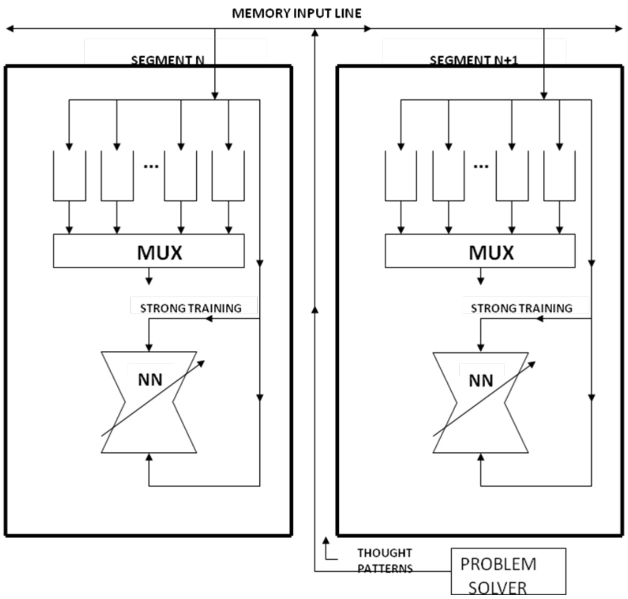

Fig. 5. Thought Pattern Storage

- The design of the problem solver is not yet part of this study, but could be thought of as a mechanism based on Arthur Samuel's checker player [3].
- Thought patterns are always interesting and stored in empty memory locations.
- Storage of thought patterns takes precedence over storage of sensory input patterns.

Why does storage of thought patterns take precedence over storage of sensory input patterns? Do the following experiment. Read a paragraph of an article while your mind is wandering. What sticks is the wandering thoughts. You will retain nothing from the reading. You will need to re-read the paragraph to grasp its contents. Try this and you will see.

A block-diagram for thought pattern storage is shown in Figure 5.

G. Pattern Retrieval System

Sensory input patterns, thought patterns, and patterns of innate knowledge are all retrieved by the same mechanism, some of whose properties are listed as follows.

- Patterns stored in memory can be retrieved without knowledge of their storage location.
- Autoassociative neural networks are part of the retrieval mechanism.
- Autoassociative neural networks are trained by using their input patterns as both input and desired response patterns. They are trained to produce outputs that are reproductions of their inputs.
- Once trained, autoassociative networks produce small input/output differences when presented with patterns that were trained in, but large differences when presented with patterns that were not trained in. Déjà Vu ? Hit or no hit ?
- Autoassociative networks are trained with all the patterns stored in the connected memory folders.
- The autoassociative networks are prompted with sensory input patterns or thought patterns. Visual input patterns for example are rotated, translated, scaled, brightened, contrasted, etc. by the "visual cortex" VC while attempting to make a hit. If there is a hit, the hit pattern is saved and compared with the contents of all the connected memory folders. The patterns of the folder containing the hit pattern are retrieved and sent to the problem solver, which is the memory output "customer".
- These patterns in turn may be used as prompts to retrieve other folders. This type of feedback could cause a "chain reaction" resulting in the retrieval of many interrelated folders. (I have been speaking with someone for ten minutes but what is his name? Oh, now I remember. It's Jim Jones.)

A block diagram for the pattern retrieval system is shown in Figure 6.

H. Training During non-REM Sleep

- It is speculated that the autoassociative neural networks are trained during non-REM sleep.
- Multiplexers (MUX) sense the memory folders, sequentially feeding the pattern contents to the autoassociative networks for training.
- The training process initiates automatically once the brain is in "sleep mode". This continues throughout the night during periods of non-REM sleep.
- The autoassociative neural network in each memory segment is thus trained on all the patterns in all of that segment's folders. A block diagram is shown in Fig 7.

I. Memory Activity during REM Sleep

During non-REM sleep as well as during REM sleep, input sensors such as eyes, ears, tactile, olfactory, etc. are

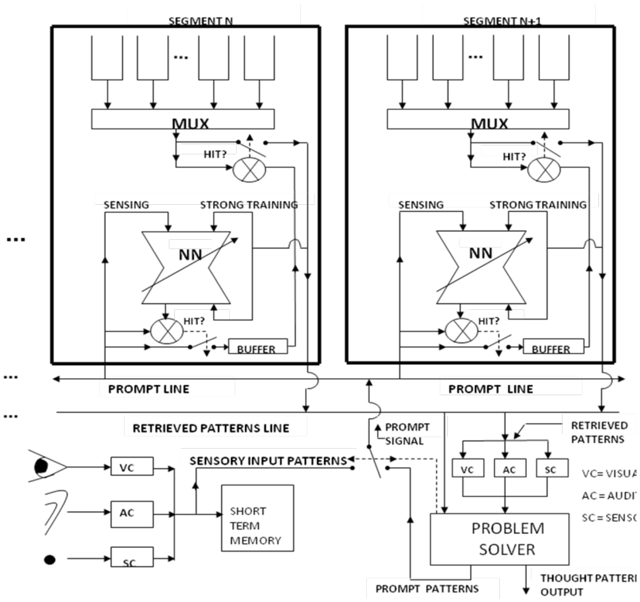

Fig. 6. Pattern Retrieval System

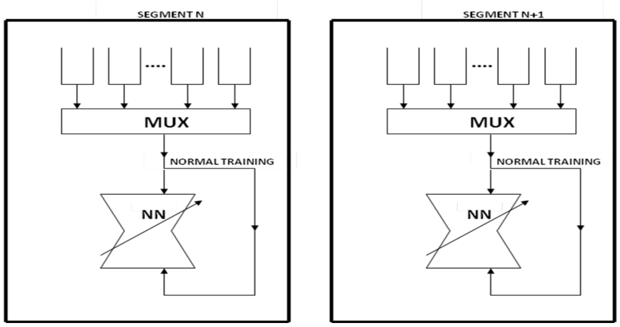

Fig. 7. Training During Non-REM Sleep

turned off. During non-REM sleep, simple training of the neural networks takes place. During REM sleep, the brain is active, almost like during wakefulness. With the sensory inputs off, the memory receives no external prompts. Prompt patterns come from the memory itself. A folder spontaneously delivers its contents to the problem solver, and the contents serve as prompts to cause other folders to deliver their contents to the problem solver, and the problem solver has plenty of inputs to process and play with. Some characteristics of REM sleep are the following:

- Every 90 minutes or so during the night, the brain goes into "REM mode". Each episode of REM lasts for about 20 - 30 minutes, increasing as the night progresses.
- It is generally believed that during REM (Rapid Eye Movement) sleep, the person is dreaming.
- The body is paralyzed during REM sleep, probably to prevent the person from acting out the dream.
- During REM, contents are pulled from memory prompted by thought patterns from the problem solver. Memory contents provide further prompts to retrieve further related contents. This is a "chain reaction". The retrieved memory contents are available to the problem solver.
- The memory contents are juxtaposed and intermingled in strange ways, creating fantasies that are dreams. The dreams themselves are stored in new memory locations.
- During REM, the autoassociative neural networks are trained hard when dream patterns are stored and when patterns are drawn from the memory folders. These networks are both sensed and trained during REM.
- Brain activity during REM is similar to that of wide-awake consciousness, according to EEG and FMRI. The difference is that during REM, the sensory inputs from the eyes, ears, etc. are shut off.

A block diagram for memory activity during REM sleep is shown Figure 8. We speculate the following about the REM state:

- It is speculated that the purpose of REM sleep is **problem solving**. Uninhibited thought can be highly creative.
- During a night's sleep, episodes of REM take place about every 90 minutes or so. Upon awaking one is generally unaware of having dreamt unless waking in the middle of a dream. To retrieve an unaware dream from memory, one needs an appropriate prompt. This is the function of psychoanalysis, on the couch, talking.
- It is speculated that schizophrenia is an abnormal condition under which the subject is awake and conscious and in REM sleep at the same time, with fantasized images superposed on top of real-time visual, auditory, etc. inputs.This is hallucination. The fantasized images are drawn from memory spontaneously, without prompting.

J. *Speculation about Seeing, Hearing, Walking, Etc.*

- Seeing involves processing and recording new visual images and making associations with pre-recorded images stored in memory. Vision and memory are intertwined.
- Hearing and understanding speech involves processing and recording new auditory images and making associations with pre-recorded auditory images stored in memory. Hearing and speech understanding and memory are intertwined.
- While walking, sensory signals from all over the body deliver to the brain information about the mechanical state of the body. These sensory signals acts as prompts to the memory that, in turn, provides muscle control signals that enable walking. This works like a lookup table. Muscle control signals are not computed in real time but are pulled from memory. Control planning is also pulled from memory.
- While speaking, muscle control of the vocal tract is

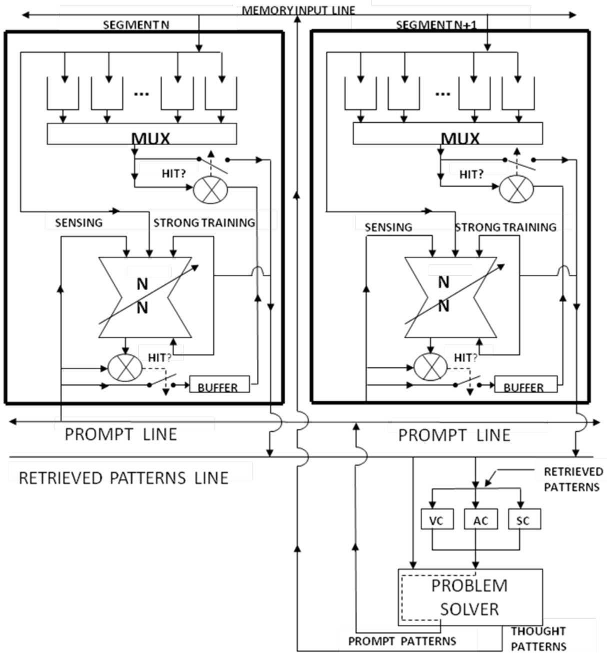

Fig. 8. Memory Activity during REM Sleep

pulled from memory in response to prompts. The brain does not compute these control signals in real time.

K. Speculation about Feature Detection

- Hubel and Wiesel's discovery of cat cortical cells that respond to vertical and horizontal lines suggest importance of feature detection.
- Julesz's work with random dot stereograms and experiments with an eidetic subject suggest that the visual process involves the total image in full detail (not just features) and that pattern association is critical.

L. Speculation about Learning

- Human learning involves storing patterns in memory.
- Supervised learning, unsupervised learning, learning with a critic, Bayesian learning are all useful concepts but probably have little to do with human learning.

M. Speculation about Memory Failure

- Ageing causes slow death of neurons and the dendritic tree, with insufficient rate of replacement. This affects memory retrieval as it becomes more difficult to continue training the brain's neural networks. Old data and newly recorded data gradually become inaccessible. Old data lasts the longest.
- Alzheimer's disease with associated plaques and tangles in the neurons and dendritic tree has an effect like accelerated ageing of these brain structures, makes neural training more difficult, gradually becoming impossible, thereby making old and new memories but especially new memories more and more inaccessible.
- Brain injury like in the movie 'Memento' cuts the link to the "memory input line" and prevents the formation of new memories. Short-term memory still works. Recall of old memories still works, and neural training still works. Everything works except no new memories.

N. Speculation about the Mechanisms of Storage and Retrieval

- At the moment of conception, DNA is taken from the mother and father to form a new cell. That is the start of a new living animal.
- The DNA of the new cell contains the information (the "blue print") needed to construct the living animal.
- The DNA contains the information to construct the body, the internal organs, including the brain. The DNA also contains the inborn information, necessary for survival, that will be pre-loaded in the developing brain.
- Inborn information is stored in DNA.
- The mechanism for storage and retrieval of the information gained during a lifetime is the same as that for storage and retrieval of inborn information.

O. Wild Guesses

- **All information stored in memory is stored in DNA. The DNA that stores this information may be located in the glial cells of the brain or perhaps elsewhere.**
- Stored information is not stored in the neurons and dendritic tree. The neurons and the dendritic tree play a key role in association and retrieval of stored information.

VI. SOME INTERESTING QUESTIONS

- Why do new-born babies sleep so much, and a lot less when they become kids?
- Why do babies cry so much, and less as they grow older? Why do adults cry so little?
- Memory of children and young people is great. Why can't we remember life events that happened in the first few years?
- What is the connection between schizophrenia and sleep walking?
- What did Sigmund Freud do that was right?
- Why does one often not remember performing acts of habit?
- What are habits? How are they related to addiction? How are they related to speech and locomotion? How can you change or break habits?
- How are questions of sexuality, hetero or homo, related to questions about autism?
- What causes subject wandering in the middle of a conversation?

VII. CONCLUSION

The purpose of this paper has been to describe the design of a memory system intended to be as simple as possible, yet able to behave like and emulate certain aspects of human memory. One of our goals was to develop a new kind of memory for computers, adjunct to existing forms of memory, to facilitate solutions to problems in artificial intelligence, pattern recognition, speech recognition, control systems, etc. A second goal was to advance cognitive science with new insight into the working of human memory. We are hoping to give engineers and biologists some new thinking on subjects of great mutual interest.

REFERENCES

[1] B. Widrow and R. Winter, "Neural nets for adaptive filtering and adaptive pattern recognition," Computer, vol. 21, no. 3, pp. 25-39, 1988. [Online]. Available: http://dx.doi.org/10.1109/2.29

[2] B. Julesz, *Foundations of cyclopean perception.* University of Chicago Press, December 1971.

[3] A. Samuel, "Some studies in machine learning using the game of checkers," IBM J. Res. Develop., vol 11, pp. 601–617, 1967.

[1] J. Morton and M. Johnson, "CONSPEC and CONLERN: A Two-Process Theory of Infant Face Recognition," Psychological Review, vol. 98, no 2., pp. 164-181. April 1991.