A New Model of Artificial Emotions via Virtual Neuromodulators

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How can we make machines actually feel emotions? Is there any option to make AI suffer, feel happiness, love, aggression, contempt, awe? Before we could find proper answer to this question we should be take in account several aspects: philosophical, psychological as overall picture of low level and high level subjective emotions, neurophysiological as low level objective mechanism of brain response and cognitive architecture to put all these approaches in. We propose framework for affective computation implementation in computational spiking neurons based on Lövheim “Cube of emotions” [15] , Plutchik “Wheel of emotions” [22], Tomkins “Theory of affects” [11] and combine this theories in the cognitive architecture environment of “The emotion machine” by Marvin Minsky [18]. We propose mechanisms of emotions influence on computational processes via neuromodulation.
Keywords: AI, Affective Computation, Cognitive Architecture, Cognitive Modeling, Affective Modeling, Machine Thinking, Machine Understanding, Computing Emotions, Affective Computing, Neuromodulation, Neurotransmission, Model of Emotions, Model of Emotional Thinking

1 Introduction

The biggest problem of artificial intelligence is that we don’t know what natural intelligence is. Unfortunately there are no aliens so far who would be able to demonstrate non-human intelligence, and examples on Earth lack certain substance. Rosalind Picard in her article indicated: ”There may exist a kind of alien intelligent living system, something weve never encountered, which achieves its intelligence without having anything like emotion. Although humans are the most marvellous example of intelligence we have, and we wish to build systems that are natural for humans to understand, these reasons for building human-like systems should not limit us to thinking only of human abilities.” [21]

There are several domains that still remain unclear: creativity, intuition, insight and consciousness that prevent us from answering the question: ”How David Lynch could create Mulholland Drive or Picasso could create Guernica?”. One aspect of modern AI is affective computation that become more and more important it is based on several domains: psychology: [22, 23, 24, 25, 27], neuroscience: [4, 5, 9, 15, 22, 25, 1], computer science: [31, 6, 7, 8, 12, 19, 16, 8, 7, 5, 4, 2, 3, 14]. Although there are still only several computational emotions models created [17, 14, 10, 13].

Turing stated in his report “Intelligent Machinery” [31] that idea of intelligent machines ”cannot be wholly ignored, because the idea of ’intelligence’ is itself emotional rather than mathematical”. There is an interconnection between emotions and rational thought. Marvin Minsky in his book ”The emotion machine” proposed that emotions are inseparable from thinking: ”Emotional thinking: A flash of impatience or anger can cut through what seems like a hopelessly tangled knot. Each such ’emotional way to

Submitted to:
MOD* 2014

think' is a different way to deal with things, and some can increase your persistence or courage, while others can help you simplify things. In any case, after each such change, you may still want to pursue some similar goals, but now you'll see them from new points of view because each switch to a new Way to Think may initiate a large-scale cascade. Then, depending on how long those changes persist, you (or your friends) might recognize this as a change in your emotional state".

The other interesting point of view was represented by Ziemke and Lowe [32, 4] "Do robots need emotions? A pragmatic answer would be that robots, as currently conceived and constructed, simply do not haveanyneeds (of their own) in the first placeand thus of course neither need emotions, nor energy, nor sensors, actuators, etc. A more relevant question then may be whether or notwe, the human designers and users of robots, need or want robots to have or at least express emotions."

Good review of computational models of emotions was presented by Jonathan Gratch and Stacy Marsella [10, 17].

This article is dedicated to model of affective computation based on neuroscientific monoamine model of neuromodulation and affects in human brain and derivative possible influence of emotions(affects) [1] on computational processes in Marvin Minsky's cognitive architecture [18]. It could be considered as a base of affective computation framework and we hope could be used in several domains like:

1. Advertisement
2. Emotional behavior simulations
3. Robotics
4. Intellectual assistants
5. Estimating human behaviour
6. Nursing software and robotics

2 Bases

Starting from the top we first reviewed several psychological models of emotions. Then we tried to understand the low level nature of emotions that brought us to neurochemical base of emotions. As we got the picture of human emotional processes we mapped them to cognitive architecture to gain AI basis. This approach is represented on the figure 1.

Firstly we wanted to gain overall picture of human emotional processes. It could be understood as combination of high level processes and model that triggers processes steps. This lead us to the first base: the evolutionary psychology theory of Plutchik "Wheel of emotions" [22]. In comparison to other classifications of emotions it provides complete picture of basic and combination of basics into high level taking in account emotional processes (feedback loops). For extensive description see Emotional Feedback Loops section. We adapted feedback loops into Model of six [18] thinking levels of Marvin Minsky's cognitive architecture.

As we gained overall picture of th human emotions, we faced the problem of low level mechanism that actually triggers the affects (emotional states), this leads us to neurobiological hypothesis of Lövheim: neuromodulatory base of emotions [15]. "Cube of emotions" by it self based on the theory of

[1] In this article we use affects and emotions as notions with the same or close meaning, usually affects is used in sections dedicated to affects theory [28, 29, 30] or derivatives [15], emotions on the other hand is used in context of Plutchik "wheel of emotions" context [22].

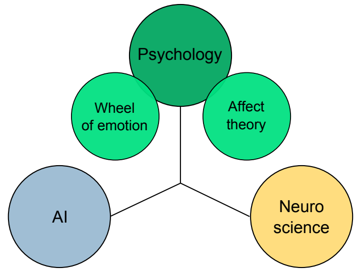

Figure 1: Theoretical bases of current work.

affects by Tomkins [11, 28, 29, 30]. We used Tomkins theory of affects as the base for low level(basic) emotions and appraisal [11, 24, 23, 25].

We gained proper philosophical context by means of Marvin Minsky book "The emotion machine". This book shades the light on really complex phenomena like: consciousness, thinking, levels of mental activities and so on. We mapped all the theories described above on Marvin Minsky's cognitive architecture described in his book ”The emotion machine” [18].

3 Emotional Feedback Loops

Robert Plutchik created the three dimensional model [22] called ”Wheel of emotions”, that we used to describe subjective perception of emotions. There are eight basic emotions grouped in pairs:

1. Joy - sorrow
2. Anger - fear
3. Acceptance - disgust
4. Surprise - expectancy

Model presented above could be understood as the base for the subjective picture of emotions. The other indeed important for understanding the emotions aspect presented by Robert Plutchik is emotional processes or feedback loops. He introduced 8 steps processes:

1. stimulus event
2. inferred cognition
3. feeling state
4. physiological arousal
5. impulses to action
6. overt behaviour
7. effect

Robert Plutchik describes it as: "Overall, emotion is a kind of homeostatic process in which behavior mediates progress toward equilibrium; I call it a behavioral homeostatic, negativefeedback system. Emotion is a chain of events made up of feedback loops. Feelings and behavior can affect cognition, just as cognition can influence feeling." [22]. Actions feeling state and physiological arousal are done in parallel. This is overall hight level template of all emotional processes of animals and humans. We interpreted this processes in four layers of Marvin Minsky's "Model of six" our interpretation is not direct we combined inferred cognition with feeling state and physiological arousal in affective appraisal and neuromodulation, we selected cognitive appraisal as separate step and put it on learned reactions layer. The distinction between affective appraisal and cognitive appraisal was inspired by [4, 9] the potential neuromodulation pathway: from spinal cord, to hypothalamus and nucleus of the solitary tract then to amygdala and septum and then to cingulate cortex and frontal cortex, so firstly every stimulus is been responded by low level: spinal cord, to hypothalamus and nucleus of the solitary tract then to amygdala and septum, non-consciously, and then cingulate cortex and frontal cortex could impact to the whole processing consciously in case of frontal cortex. Mapping of emotional feedback loops to "Model of six" is presented on the figure 2.

We use four of the six layers just for the purpose of this example. Self-conscious reflections layer could influence emotions; for example evaluation of self as not progressing could cause sorrow or even depression, but it was not shown on the diagram.

We correspond instinctive reactions layer with non-conscious, innate, affective responses that mainly takes palace in: hypothalamus and amygdala, only after the frontal cortex is triggered in stimulus processing becomes conscious. This way any stimulus is being processed first unconsciously; this is shown as affective appraisal oval, and then consciously, this is shown as cognitive appraisal oval.

Using a concrete example presented on figure 2: first stimulus triggers affective appraisal and affective appraisal triggers neuromodulation. Neuromodulation triggers an emotional state switch from serenity to fear, depicted by yellow and green rectangle. Emotional states are represented as rounded rectangles on the diagram. Affective appraisal triggers cognitive appraisal and reflective thinking. Actions like appraisals, deliberations, copings and neuromodulations are represented as ovals on the diagram, initiation or triggering are shown on diagram as arrows. Cognitive appraisal in its turn initiates a appraisal deliberation process. Meanwhile second stimulus triggers second affective appraisal and its neuromodulation switches emotional state from fear to terror. Second affective appraisal triggers cognitive appraisal that in its turn initiates second appraisal deliberation. Then reflective thinking process estimating all activities in mind realizes that it's too emotional now and then stop all appraisal related processes and starts new coping oriented deliberation and switches emotional state via neuromodulation from terror to fear. Third appraisal deliberation selects cognitive reappraisal as coping strategy and this coping strategy is executed and switches emotional state back to serenity (via neuromodulation). In parallel to all cognitive and reflective process the second affective appraisal initiates non-conscious instinctive coping strategy and it when applied created an effect over environment and this effect is been appraised again as stimulus.

4 Neuromodulatory Basis of Artificial Emotions

Hugo Lövheim in 2012 published his article "A new three-dimensional model for emotions and monoamine neurotransmitters" [15]. He described three dimensional model of emotions. Axes of the model are neuromodulators (monoamines): serotonin, dopamine, noradrenaline. "As each of these three monoamine systems probably represents a different aspect of emotion, a hypothetical three-dimensional space for possible combinations is formed. It is evolutionarily rational that the monoamine systems are mutually orthogonal as this maximizes the amount of information that can be transmitted, however, although likely, this needs to be further established empirically. It is important to note that as long as none of the monoamines transmit exactly the same information as any other (which seems unlikely), there will still

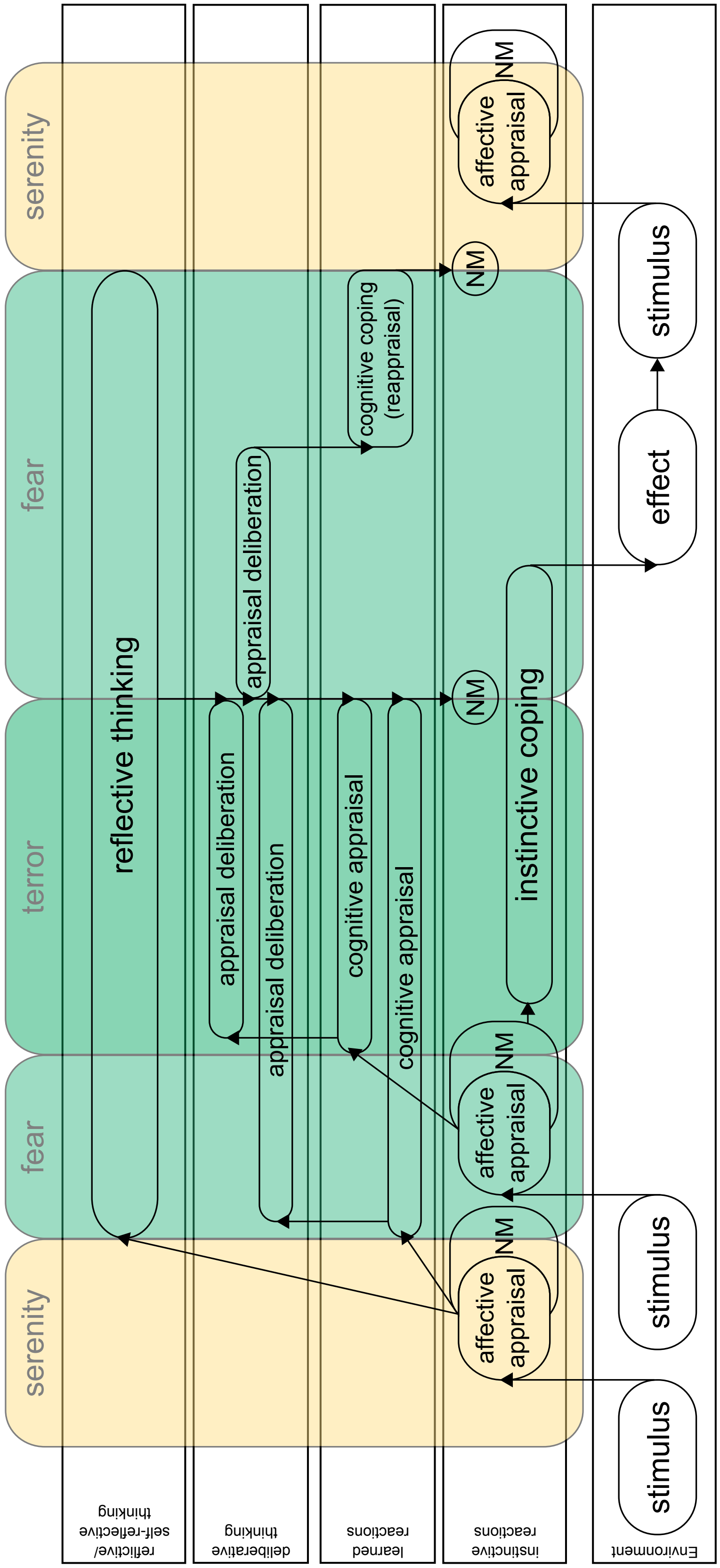

Figure 2: Orchestra of emotions

be a three-dimensional space. For simplicity, in this article the monoamines axes have been depicted as mutually orthogonal."

Vertexes are affects from Tomkins affect theory [11]. "The psychologist Silvan Tomkins devoted his life to the study of emotions and developed an elaborate and comprehensive theory of basic emotions[8587,89]. Tomkins identified eight basic emotions, which he labeled with one word for the emotion when it was of low intensity and another word for the same emotion at a higher intensity[98,99]. Tomkins referred to basic emotions as innate affects where affect, in his theory, stands for the strictly biological portion of emotion[83]. According to his theory, these are the eight basic emotions:"

1. Enjoyment/Joy
2. Interest/Excitement
3. Surprise
4. Anger/Rage
5. Disgust
6. Distress/Anguish
7. Fear/Terror
8. Shame/Humiliation

Hugo Lövheim gives extended explanation of mapping of each neurotransmitter to group of emotions that he inherited from Tomkins "Theory of affects". We placed several quotes form "A new three-dimensional model for emotions and monoamine neurotransmitters" [15] for sake of justification of neurotransmitters choice.

4.1 Fear/terror and anger/range

"Both of the basic emotions, fear/terror and anger/rage, are supposedly high-dopaminergic and therefore coupled to reinforcement[9,101104]. This seems logical when one considers the great evolutionary value of learning about those dangerous situations in which these negative basic emotions are triggered. It has been found that laboratory rats easily learn to avoid various stimuli presented simultaneously as something innately scary (such as a cat)[34]. The rewarding effect of these basic emotions might also possibly explain why certain people continue to seek so-called adrenaline rushes.

...

Both fear/terror and anger/rage are here further assumed to be low-serotonergic, as these emotions are triggered when the individual feels threatened or under pressure, and therefore probably has an inner feeling of weakness. Aggression has also been coupled to serotonergic deficit in many studies, supporting the placement of anger/rage on the low-serotonergic side[10,19,27,28,52,53].

...

High-noradrenergic emotions are supposedly those where the individual is active and aroused, attentive, with a high pulse [5,33,45,47,50]. The basic emotion fear/terror has been placed in the low-serotonergic, low-noradrenergic, high-dopaminergic corner of the cube. This basic emotion should not be confused with the active fight or flight reaction; instead fear/terror is considered here the white, cold fear, when the heart almost stops beating."

4.2 Shame/humiliation and distress/anguish

"Distress/anguish is placed in a corner close to shame/humiliation, as the active (and hence noradrenaline-high) analogue to shame/humiliation, i.e. where noradrenaline is supposedly high and dopamine and serotonin are low. The relation between shame and depression [115117], and anxiety and depression [118] respectively, supports the placing of these two basic emotions on the low-serotonergic side, as do the effect of SSRI antidepressants on anxiety disorders[119], and an increased serotonin transporter binding in generalized social anxiety disorder[120,121]. The association between shame and anxiety supports the decision to place these two basic emotions close to each other[122,123]

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Noradrenergic β - receptors have been found to be critical for the expression of cocaine-induced anxiety in mice [130], and high doses of caffeine might provoke panic attacks in patients with panic disorder or social phobia[131]."

4.3 Interest/excitement and enjoyment/joy

"Interest/excitement has been placed in the corner of the cube where all three monoamines are high. This basic emotion is, therefore, according to this model, active, reinforcing and coupled to a basic feeling of inner strength. One archetypal form of excitement is sexual excitement, but this basic emotion might accompany a wide range of events, perceptions or thoughts.

...

Enjoyment/joy is suggested as the low-noradrenergic analogue to interest/excitement. Another word for this basic emotion might be contentment, and compared to the basic emotion of interest/excitement the individual experiencing enjoyment/joy is calm and relaxed."

4.4 Contempt/disgust

"Disgust might, therefore, be somewhat related to satiety, in its extreme. This points towards disgust being high-serotonergic, as do the reduced ability to recognize disgusted faces found in healthy individuals after tryptophan depletion[160] and among patients with severe depression [161] or social anxiety disorder[162]. ... The relation between shame/humiliation and contempt/disgust has been described as self-contempt versus contempt for an object[86], and therefore, it seems logical that the difference between these basic emotions, according to the model, is the serotonergic state, assumed to be related to inner strength and self-confidence.

Disgust is supposedly low-dopaminergic as it is in many ways the direct opposite of reinforcement. Contempt/disgust is closely related to repulsion and withdrawal; we usually stop eating when we feel disgust."

4.5 Surprise

"Surprise has been placed in the high-serotonergic, low-dopaminergic, high-noradrenergic corner, and might thus be regarded as the non-reinforced analogue to excitement, which seems logical considering that surprise has been described as a neutral basic emotion. At the same time surprise is a highly focused, attentive state, and therefore logically high-noradrenergic. Also, according to the model, the individual experiencing surprise as compared to distress/anguish has a basic feeling of confidence and inner strength."

From our perspective this is the base of objective non-conscious emotional brain reaction to stimulus. On the other hand according to “Emotions: from brain to robot” [4] there are four following neuronal systems involved in emotional processing:

1. Hypothalamus
2. Amygdala
3. Frontal cortex,
4. Cingulate cortex

We roughly correspond non-conscious instinctive reactions layer of ”model of six” [18] with hypothalamus amygdala and cingulate cortex, while conscious processes and learned reactions, deliberative thinking, reflective thinking, self-reflective thinking, self-conscious reflections with frontal. This approach could be understood as subjective emotions to objective brain reaction mapping. This is fundamental for representation of emotional processes on computational system parameters.

5 Neuromodulators to Computing Parameters Mapping

Mostly low level of the influences of the affects on brain we could call it cellular or neuronal is described above and provides fundamental base for the affective computation. Noradrenaline, serotonin, dopamine do not have direct mapping on computational processes, for obvious reasons current computers do not have anything in common with biochemical processes in neurons. Most reasonable way the we observe at the moment is to create indirect mapping based on role of each neuromodulator involved in human emotions in thinking (natural computational process). In other words we draw an analogy between computational processes in computer and neurotransmission in brain and corresponded biochemical influence of neuromodulatory systems on neurons with influence of virtual neuromodulators levels on computational processes of a machine. We used several works to gain proper picture and understanding of neuromodulation and neuromodulatory systems [15, 4, 9, 32].

Role of dopamine, serotonin and their impact is discussed in “Emotions: from brain to robot” [4] that could be considered as one of bases of this work in neuromodulation.

5.1 Dopamine

“In the mammalian brain, dopamine appears to play a major role in motor activation, appetitive motivation, reward processing and cellular plasticity, and might be important in emotion. Dopamine is contained in two main pathways that ascend from the midbrain to innervate many cortical regions. Dopamine neurons in the monkey have been observed to fire to predicted rewards[67,68]. Moreover, dopamine receptors are essential for the ability of prefrontal networks to hold neural representations in memory and use them to guide adaptive behavior. Therefore, dopamine plays essential roles all the way from basic motivational systems to working memory systems essential for linking emotion, cognition and consciousness.”

According to Lövheim [15] dopamine is associated with “Reward, reinforcement, motivation”.

From computational system perspective we interpret dopamine impact like: it plays role in: reward processing thus in decision making, working memory - memory distribution and storage in computing system, motivation - decision making.

5.2 Serotonin

"Serotonin has been implicated in behavioral state regulation and arousal, motor pattern generation, sleep, learning and plasticity, food intake, mood and social behavior [69]. The cell bodies of serotonergic systems are found in midbrain and pontine regions in the mammalian brain and have extensive descending and ascending projections. Serotonin plays a crucial role in the modulation of aggression and in agonistic social interactions in many animals. In crustaceans, serotonin plays a specific role in social status and aggression; in primates, with the systems expansive development and innervation of the cerebral cortex, serotonin has come to play a much broader role in cognitive and emotional regulation, particularly control of negative mood or affect."

Lövheim associates serotonin with "Self confidence, inner strength, satisfaction".

Thus our interpretation of influence of serotonin system looks like: decision making of the system is influenced by serotonin, learning and satisfaction as coloring of the knowledge is impacted by serotonin too, this way serotonin should influence training of machine and storage of the information learned.

5.3 Noradrenaline

Hugo Lövheim [15] used only three monomaines for three-dimensional space model definition. The third monoamine neuromodulator he used is noradrenaline, he emphasises its role in "Attention, vigilance, activity". Then he describes the role of noradrenaline: "while noradrenaline has been coupled to the fight or flight response and to stress and anxiety, and appears to represent an axis of activation, vigilance and attention". Robert D. Hunt describes role of noradrenaline (NE) and its impact on cognitive functions [**?**] : "NE has an emerging role in several essential processes: (1) maintaining and increasing overall arousal, (2) contributing to affect regulation related to excitability and response to danger or opportunity, and (3) contributing to memory storage and retrieval, especially affect-related or emotionally intense events. While NE has a critical role in emergency response, it also assists in maintaining basal or tonic alertness. At a quieter moment, reading a book, studying at night, the effort to remain alert and stay on task partially mediated by NE.[3]"

Noradrenaline or it is better to call virtual adrenaline could influence modern computational system like this: attention and concentration could impact computing power and memory distribution between processes and threads (here we use processes in the meaning of Operating system processes and memory available for operating system), alertness also impact distribution of computing power and memory of a system. Decision making is influenced by alertness effect of noradrenaline reducing number of options in the observation, and possibly making system use more risky choices.

5.4 Computational system parameters

... Add description of two groups of parameters here.

Our understanding of the role of neuromodulators is represented in following mapping of neuromodulators to computing system parameters, the figure 3.

5.5 Computing system parameters

1. Generic:
   (a) Computing power: noradrenaline
   (b) Memory distribution (attention): noradrenaline

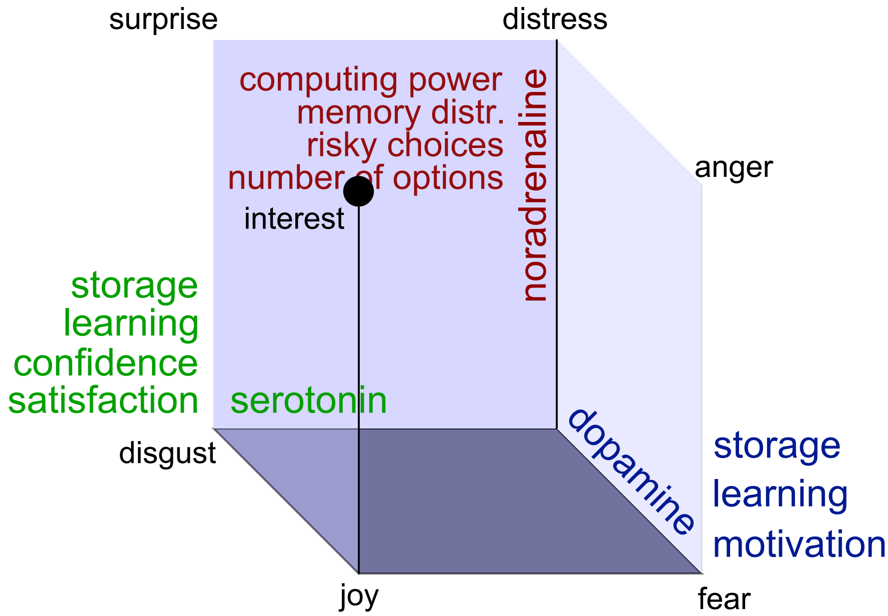

Figure 3: Cube of parameters

   (c) Learning: serotonin, dopamine
   (d) Storage: serotonin, dopamine

2. Decision making/reward processing:
   (a) Confidence: serotonin
   (b) Satisfaction: serotonin
   (c) Motivation, wanting: dopamine
   (d) Risky choices inclination: noradrenaline
   (e) Number of options to process: noradrenaline

5.5.1 Generic

Computing power: distribution and priority of parallel process or load balancing, is impacted by noradrenaline: the higher the level of noradrenaline is the more computing power must be concentrated on current activity (neuromodulator regulating attention).

Working memory(short term) distribution and concentration is impacted by noradrenaline (attention).

Learning is impacted by serotonin and dopamine: dopamine plays major role in activation of previously remembered patterns and serotonin in pattern generation.

Storage management (long term memory) is impacted by both by serotonin and dopamine, higher concentrations of both neuromodulators makes system better remember stimulus. In general, strong emotions generate more persistent memories.

5.5.2 Decision making

This decision making is done mainly in deliberation and learned reaction layers of model of six. Parameters: confidence, satisfaction, risky are used to highlight actions stored(remembered).

Confidence and satisfaction of the system is directly influenced by serotonin.

System is more *motivated* under the influence of dopamine.

System tends to choose *risky* actions under the influence of noradrenaline.

Noradrenaline makes system consider a smaller *number of options* in width and depth to be processed during deliberation.

This mapping is exhaustively described in “Computational emotional thinking and virtual neurotransmitters” [26]. It could be used as a low level (”hard-coded”) model of emotional processes implemented in a spiking neuron model used to build a neural network and could be used as a basic framework for the emotion enabled systems [20].

6 Cognitive Architecture Analysis

... Expand

To understand the current scientific state of affairs, existing models and implementations in actual code, and to find proper a base for our implementation we used the most traditional way: run a comparative analysis. It worth to mention that we don’t want to limit ourselves with the emotion-oriented architectures; we rather want to get a wide view on the current situation in the domain. We analyzed 27 cognitive architectures with following set of criteria:

1. Emotional criteria:
   (a) Cognitive Representation
   (b) Cognition → Emotion
   (c) Emotion Representation
   (d) Emotion → Cognition
   (e) Compatibility with Plutchick wheel of emotion
   (f) Compatibility with Tomkins affects
   (g) Compatibility with Picard criteria
2. Thinking levels:
   (a) Instinctive level
   (b) Learned level
   (c) Deliberative level
   (d) Reflection level
3. AI components:
   (a) Attention
   (b) Planning
   (c) Motivation(implying Emotions)
   (d) Common sense logic
   (e) Reasoning
   (f) Perception/understanding
   (g) Memory:
      i. Constructive memory
      ii. Reconstructive memory

(h) Consciousness:
  i. Awareness
  ii. Learning
  iii. Anticipation
  iv. Subjective experience
(i) Intuition
(j) Creativity(imagination)
(k) Dream/sleep

4. Parallel processing

5. Self-emergent/self-organized

Criteria are organized in three groups: emotional group depicts our interest in emotions implementation in cognitive architecture [14], thinking levels are the compatibility with Marvin Minsky's "The emotion machine", AI components group is used to gain understanding of width of coverage of AI domains by cognitive architecture. We used two additional criteria that seem to play important role and were not in previous groups. Exhaustive analysis is available on-line [2].

We used primitive Boolean approach to measure if component or emotional criteria are in specific cognitive architecture. Cumulative table is available on-line[3], it contains simple summary of the Boolean criteria.

According to our brief overview of the list of architectures most interesting are: ASMO, CLARION, DUAL, *H-CogAff*, LIDA, *Psi-Theory*, Soar, *Society of mind* (*), WASABI, EMA, Hikonen, Shanahan. H-CogAff is more of philosophical framework to build the cognitive architecture, or a meta-architecture that has the most significant potential to be the most advanced at the moment and the least limited. Homeostatic principle of Psi-Theory seems to be ubiquitous in the psychological basis of emotions [22]. Society of mind needs further analysis and possible update of our criteria.

7 Possible implementation and validation

As emotional neuromodulation is connected to reward system [9, 4, 11, 24, 17, 16] first of all we supposed that most appropriate would be the implementation of this affective computation model as realistic neural network (like NEST [4]), put in life threatening situation. Classical example is zapping rat (brain) [5]. Potential disadvantage of this reward oriented implementation and thus validation is that reinforcement learning could be used in the same life threatening situation with similar effect. The attention is one more important phenomena that is heavily influenced by emotions [9, 32, 4], neuromodulation of noradrenaline. Taking in account both effects on reward system and attention we plan to implement neuromodulation mechanism of three monoamines over realistic neural network [6]. In life threatening situation behavioral difference between emotional and non-emotional neural network should be obvious enough to indicate the advantages/disadvantages of emotional reactions. Other way to validate the

[2]Exhaustive analysis address: `https://github.com/development-team/2/blob/master/doc/analysis/cognitive_architecture.md`

[3]Cumulative table address: `https://github.com/development-team/2/blob/master/doc/analysis/cognitive_architecture.md`

[4]NEST project wikipedia page: `https://en.wikipedia.org/wiki/NEST_(software)`

[5]`http://www.nature.com/news/flashes-of-light-show-how-memories-are-made-1.15330`

[6]The list of realistic NNs: `http://home.earthlink.net/~perlewitz/sftwr.html`

emotional framework could be comparative test of non-emotional reinforcement learning with emotional reinforcement learning. The reinforcement learning its self was inspired by behaviorist psychology [7]. Neuromodulation based affective computation model could contribute to it at least distribution resources (attention) and communicating to other agents (is not discussed in this paper) [32]. Thus implementing described above model we should be able to notice behavioral and resources delta impacted by neuromodulation and thus emotions.

8 Conclusion

... Rework.

We created the synthetic theory of emotions based on four starting points: Robert Plutchick "Wheel of emotions" [22, 7] as high level subjective picture of emotions, Tomkins theory of affects [11] as low level objective framework of affects/emotions, Hugo Lövheim "Cube of emotions" [15] as objective neurophysiological mechanism of emotions and Marvin Minsky "The emotion machine" [18] as cognitive architecture as implementation environment for all mechanisms listed above.

Overall, emotional processes have following structure: stimulus non-conscious appraisal, neuromodulation (physiological emotional state switch), conscious appraisal with possible deliberation and possible coping strategy selection, coping strategy application over environment. As soon as coping, or some other behavior is applied over the environment, its state is appraised again as a new stimulus. This process is called feedback loop [22] and creates everlasting spiral process of emotions appraisal $\rightarrow$ neuromodulation (physiological impact) $\rightarrow$ coping. In the similar way high level thinking processes could influence the emotional state: for example reflective thinking could trigger a neuromodulation switching emotional state of a system and start/stop cognitive appraisal, deliberation. Thus neuromodulators are main actors of the objective brain response. We mapped their impact over computational system parameters:

1. Generic:
   - (a) Computing power: noradrenaline
   - (b) Memory distribution (attention): noradrenaline
   - (c) Learning: serotonin, dopamine
   - (d) Storage: serotonin, dopamine
2. Decision making/reward processing:
   - (a) Confidence: serotonin
   - (b) Satisfaction: serotonin
   - (c) Motivation, wanting: dopamine
   - (d) Risky choices inclination: noradrenaline
   - (e) Number of options to process: noradrenaline

This mapping could be used as a main low level mechanism that build a bridge from the neurophysiological framework to the computational system and answers the question: "How emotions could influence computational system parameters?"

... Expand.

It could be used in a spiking neural network to implement emotional thinking phenomena in computational systems. We suppose it could be useful framework in several domains:

[7] Reinforcement learning wikipedia page: `http://en.wikipedia.org/wiki/Reinforcement_learning`

1. Advertisement
2. Emotional behavior simulations
3. Robotics
4. Intellectual assistants
5. Estimating human behaviour
6. Nursing software and robotics

9 Acknowledgment

Tero Keski-Valkama (MSc) for his constant support and review of our work and theories.

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