Thirty-Five Years of Artificial Emotions: An Extended Case History

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Abstract—**Artificial emotions are being designed into a wide variety of products from interactive games to elder care robots as part of their man-machine interface. This includes both simulation and recognition of human emotional responses. The author describes his experiences developing emotion simulators for artificial intelligence and robotics since 1973, using analog and digital techniques. He has introduced synthetic emotions into increasingly complex artificial nervous system designs, some having extensive knowledge bases, semi-autonomous operation and limited self-awareness. The author's body of work includes emulation of childhood growth and development, pain-pleasure neural functions, release of the stress hormone epinephrine, response to analgesic and addictive narcotics, oxytocin-mediated trust activity, long-term potentiation in the hippocampus for establishing memory, the mammalian fear mechanism, the endocannabinoid system, autism-spectrum disorders, fibromyalgia / chronic fatigue syndrome and various psychiatric diseases (all of which have emotional frames of reference). Some man-machine ethical considerations in this kind of experimentation are discussed.**

I. INTRODUCTION: TWO ARTIFICIAL NEURONS

MY medical school career began the year after Marvin Minsky and Seymour Papert published their negative review [1] of Frank Rosenblatt's *Perceptron* [2] artificial neural network (ANN). That paper harshly criticized two-layer ANNs for their inability to resolve **XOR**-type problems and set back artificial intelligence (AI) research for many years. I did not discover the Minsky-Papert treatise until much later, thus was not discouraged from experimenting with artificial neurons (AN) or ANN design. I created my first AN during a bioengineering elective in 1973: an operational amplifier-based (op-amp) emotion response emulator (Figure 1).

In that circuit, an LM324 op-amp [3] serves as a controlled-gain summing amplifier, with stimulatory (+) and inhibitory (-) inputs scaled by manual potentiometers (pots), after Donald Hebb's plan [4]. These pots were replaced years later by digital-control electronic versions (DCPRs). The inputs represent impulses such as: hunger, pain, fear, fatigue, desire for sex, and so on. The sources of these input voltages are explained in Section II.B below.

The scaled sum of all inputs, **Vanalog**, represents the overall *emotional state*. This voltage is read and compared to preset limits by a Schmitt trigger, a window comparator or A/D converter, producing the *decision to act* at threshold. I presented this design in 1989 and discussed improvements to it a decade later [5-6].

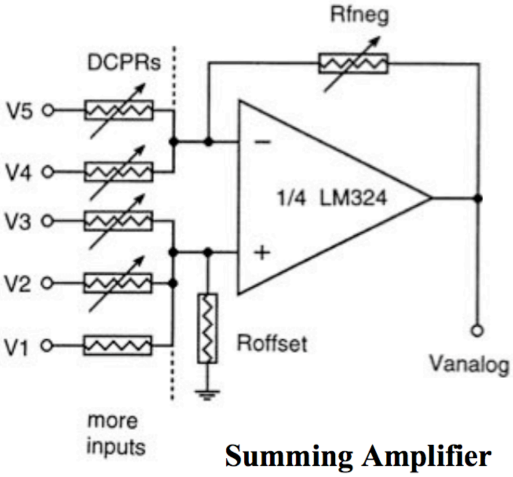

Fig. 1. An emotion-simulation neuron, consisting of a controlled-gain DC summing amplifier coupled to a Schmitt trigger, a window comparator or an A/D converter, which reads and analyzes *Vanalog*.

In March, 1974 I created an AC-coupled pulse-integrating AN, just before medical school graduation (Figure 2). This AN used an LM3900 Norton amplifier which is now obsolete but still readily available [7]. Such ANs are referred to as *integrate-and-fire* neurons in the current AI literature.

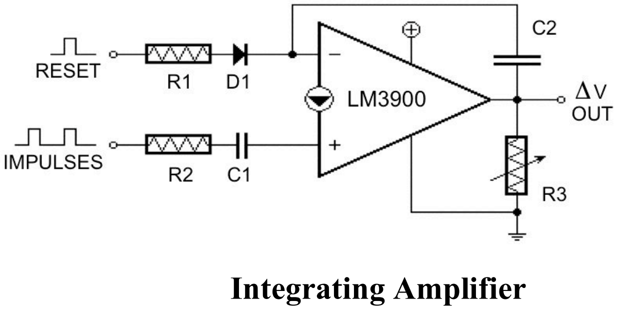

Fig. 2. An early pulse-integrating emotion-simulation neuron based on the LM3900 Norton amplifier. A threshold detector is connected to $\Delta Vout$ (not shown).

Impulses enter the (+) input of the amplifier after being scaled by **R2** and **C1**, thus representing incoming action potentials (AP). The resulting quanta are added to **C2**, which moves **ΔVout** toward its firing threshold. **R3** allows the charge on **C2** to decay slowly; this simulates recovery of the neuron's membrane potential over time in the sub-AP condition. An externally-controlled reset input is provided

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(triggered after AP firing). A subsequent version of this circuit uses an LM324 with stimulatory and inhibitory inputs on a single op-amp, with a different reset mechanism.

In 1979 I used a Teledyne (now Microchip Technology) TC9400 frequency-to-voltage (F/V) converter [8] as an alternative to discrete linear parts for pulse-integrating ANs. These pulse-integrating and F/V circuits are also useful in non-neuron situations to represent the binding between chemical substrates (i.e.: the narcotic fentanyl) and specific neuron membrane sites (the μ, δ, and κ receptors of the rhodopsin family of G-coupled receptors), according to the Michaelis-Menten equation [9].

In 1991 I presented a paper at the Mayo Clinic on biological waveform synthesis (initially for EKGs) from stored data tables in ROM using a microcontroller and a simple R-2R digital-to-analog converter (DAC) [10]. Fifteen years later I described utilizing the on-chip op-amps and other analog features of Texas Instruments MSP430FG439 mixed-signal microcontroller to create a more sophisticated one-chip linear-digital AN solution [11]. This application had the added benefit of a direct interface to *integrate-and-fire* ANs and living neural cells by synthesizing outgoing APs (Figure 3) using the microcontroller's on-chip DACs.

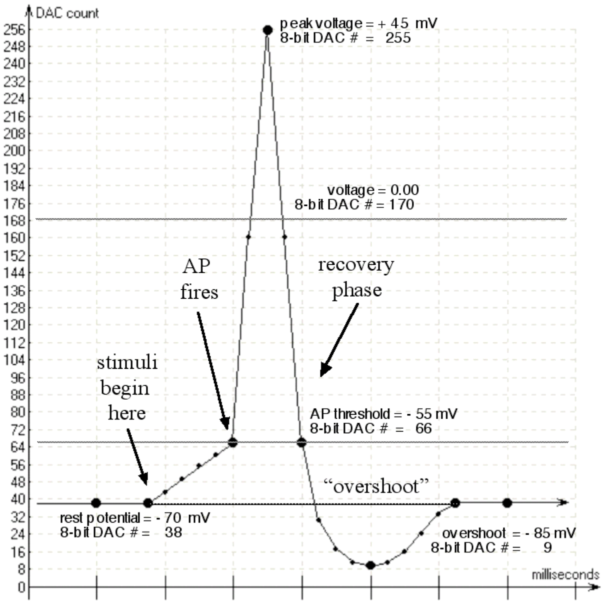

Fig. 3. Synthesized action potential from the TI MSP430FG439 mixed signal microcontroller's on-chip DAC.

I have created many other analog and digital ANs over the years, but the summing amplifier and the pulse-integrating neuron varieties have proven to be most useful to me over time for emotion systems emulation.

Why utilize linear-analog circuits in the microprocessor era? First, prototyping is easily accomplished using simple plug-in kludge breadboards. Next, debugging can be done with a voltmeter and oscilloscope. Also, analog calculations and comparisons occur synchronously in real-time with little CPU/software overhead, other than data setup/readout. Finally, consider my comments about Kerzweil's estimate of human-computer IQ equivalence in Section IV.A below.

II. MATERIALS AND METHODS: SOME DETAILS

A. *Robotic Physical Infrastructure Research*

From 1992-2000, I sidelined AI to concentrate on robot infrastructure, including: actuator design using Nitinol wire and shape memory polymers, my complex human hand model [12], and the multiprocessor-multitasking control network I created (programmed in the Forth language) which I nicknamed **ANDROID.FORTH** [13]. Other research covered speech recognition in embedded systems, artificial vision [14] (which received a *best paper* award at a computer conference at Oxford), and facially-expressive robots. These elements were fused with my AI research in 2000, which described *ANNIE*, a three-foot tall anthropoid robot [15] using these components (nominated for *best paper* at a robotics conference in St. Louis). The acronym *ANNIE* stands for "Android with Neural Network, Intellect and Emotions".

I designed a simian version in 2002 (the **APE**, Figure 4) with grasping "hand-feet" for use on spacecraft and as an alternative to wheeled rovers on planetary surfaces [16].

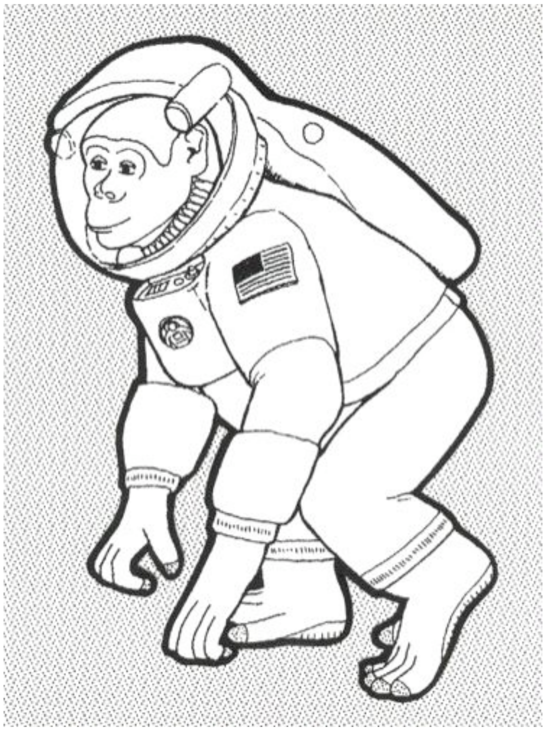

Fig. 4. APE: a simian robot for space exploration.

The European Commission *RobotCub* Project of 2004 and its *iCub* spinoff is similar to *ANNIE* in several ways [17].

B. *Robotic Mental Components*

Embodied within *ANNIE's PC/104 Pentium*-CPU-based multiprocessor network is her nervous system emulator [18]. This emulator includes a dictionary-like English-language knowledge-base file (**things.eng**), a file containing action scripts used by the artificial intelligence *schema system* (**scripts.dat**), a personality description file (**persona.dat**), and a long-term memory of her life events (**mylife.dat**). A RAM-based short term memory buffer accepts all sensory input, holds the working knowledge-base, and current concept formulations. During sleep mode, this buffer is compressed and converted to a long-term storage format. Low-level software includes BIOS, DOS, Forth, *IEEE 1275* initialization routines, drivers and the robot control system.

Hardware coprocessors for word lookup indexing, optical character recognition and emotional responses were added.

The knowledge-base contains a word list, where each entry contains the word's pronunciation, its part of speech, a definition, optional synonyms/antonyms, and pointers to supplementary data: pictures, sounds, logical components. Included are variables for emotional response (like/dislike), goodness (good/bad) and attraction (approach/avoid).

The design of *schema systems* for artificial intelligence was described by Dreschler [19]. *Schema systems* use high-level program phrases (scripts) such as OPEN THE DOOR to accomplish some desired motor function. An initial scripts file is placed on disk to provide basic operations; complex scripts are built up from concatenation of simpler ones. Scripts can be *contemplated* for making plans; *acted upon* immediately; or *stored* for later use. When input conditions are satisfied, the schema engine executes the script and evaluates the effectiveness of the script. A *schema* embodies aspects of ANNs, expert systems and semi-independent actor models for processing concurrency [20].

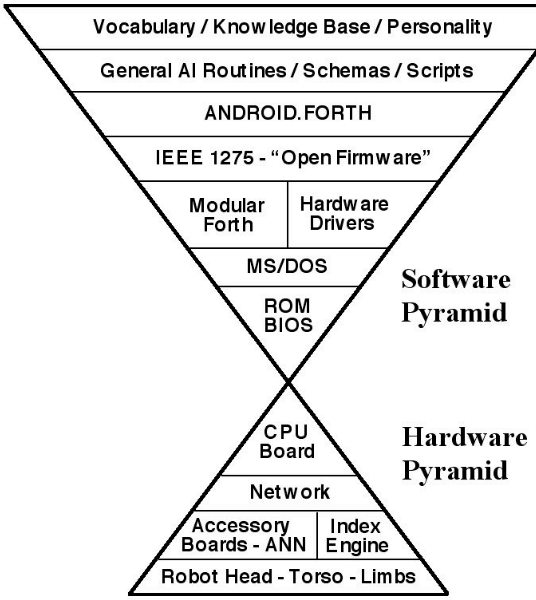

Fig. 5. Two-pyramid "layered" structure of the ANNIE hardware-software design.

In Figure 5 the logical structure of the ANNIE robot system is depicted. Some software components have been moved into the hardware pyramid as coprocessor circuits have been created for them. For example, the B-tree index retrieval software system has been replaced by a faster hardware index engine for word lookup in the RAM-resident knowledge-base file.

The summing amplifier synthetic emotion coprocessor described above receives its DC inputs from DACs which convert stored 8-bit numeric values in the knowledge-base and personality files to voltages. A useful parallel-input octal DAC is the MX7228 [21]. In recent designs, the **Vanalog** output of the summing amplifier is converted to an 8-bit signed variable by an analog-to-digital converted (ADC) for program processing. Figure 6 depicts the **MOOD** variable of *ANNIE's* emotion system output.

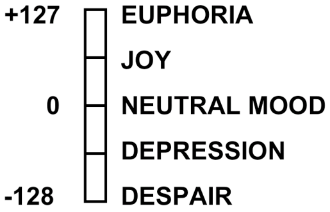

Fig. 6. Analog voltage output representing *ANNIE's* mood is converted to an 8-bit signed variable by an A/D converter for further processing.

Emotion-simulation neurons have been employed in groups to produce more fine-grained and complex responses.

Many interconnecting software and hardware pathways have recently been added between elements of the intellect, the emotion system, and the sensori-motor systems. For example, *ANNIE* can access her own mental processes, emotional state values, and sensory / motor conditions; thus she has a limited form of self-awareness. This was done to allow *ANNIE* to answer advanced research questions such as "How do you feel?" (a *mood-psyche* inquiry) and "Do you hurt?" (a *pain-sensory* inquiry).

C. Later Enhancements and Experiments

ANNIE's sensory system has been extended to facilitate more complex experiments [22]. The modality of vision with optical character recognition (OCR) for reading and of audition with speech recognition have been augmented by peripheral sensations of temperature, pressure and joint proprioception. This central nervous system (CNS) emulator interested the US Air Force Research Laboratory (AFRL, whose scientists I briefed in 2004-2005), and was submitted in 2005 to DARPA, which said its byte-coded, extensible AI structure was "interesting and technically meritorious".

My novel self-configuring IEEE 1451.4 network sensor-actuator setup was later used to extend the existing *ANNIE* IEEE 1275 network plug-and-play system [23].

In 2004, I updated **ANDROID.FORTH** to a version I called **BRAIN.FORTH**, to facilitate the study of developmental psychobiology [24]. This upgrade refactored *ANNIE's* sensori-motor, emotional and behavioral routines to allow them to be compiled incrementally over time, recapping the changes in behavior which accompany normal childhood growth and development through to adulthood.

BRAIN.FORTH also allows simulation of mental disorders (schizophrenia, affective illnesses) and some neurological conditions (Alzheimer's disease and multiple sclerosis).

In 2006, I added hormone emulation to *ANNIE*, using simulated *epinephrine* release [25]. This software exhibits a "fight or flight" behavioral response to elevated levels of the stress hormone.

In 2007, I included an opiate drug response emulation capability, which primarily deals with severe simulated pain levels treated with the morphine-like analgesic *fentanyl*, but which also addresses issues of narcotic drug tolerance, addiction and withdrawal [26].

In 2008 I extended **BRAIN.FORTH** with an oxytocin-based trust-love emulation capability [27], a fear mechanism emulator [28] and an endocannabinoid subsystem [29] for regulation of long term potentiation (LTP) in memory.

The fear mechanism emulator embodied recent research on contextual hippocampus-amagdyla learning under stress. This extension to **ANDROID.FORTH** necessitated creating a new file, **META-OBJ.ENG**, which could accommodate the object clusters found in situational fear learning. An example will be helpful: *ANNIE's* personality file contains the entry "dog" under the category of "preferences". In the knowledge base file, "dog" contains variables indicating that she *likes* dogs (+120), finds them *good* (+110), and is *attracted* to them (+100). The presence of a dog moves her mood state into the vicinity of "JOY" on the scale (>+63). However, a *dog bite* situation (stored in the metafile) overrides *ANNIE's attraction* value and prevents her approaching a dog with bared teeth, a crouching stance and barking. The metafile includes spatial proximity alarm zones (here 20 feet), so that *ANNIE* will retreat in fear if a "bad dog" comes too close.

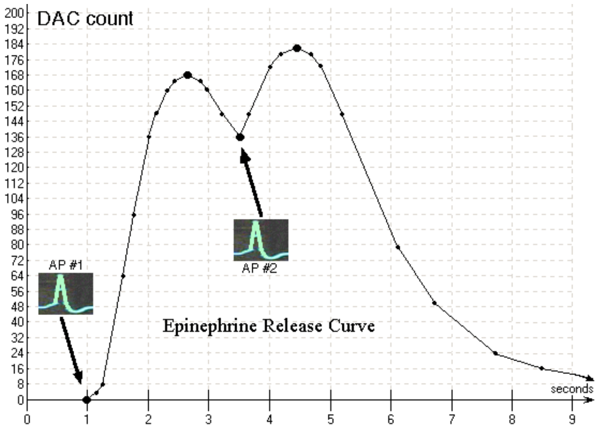

Fig. 7. Simulated epinephrine release following two closely-timed fear events. The second AP sustains and increases the fear hormone release.

I connected the output of the fear mechanism emulator to the input of the adrenaline hormone emulator, so that fear events could provoke multilevel stress responses (Figure 7).

D. *Non-Robotic AI Applications*

The extensible *ANNIE* design has proven quite robust. This has led to experiments with non-robotic hardware and software applications.

First is *GRANNIE*, an intelligent, interactive, AI supervisory system for medical devices. The acronym *GRANNIE* [30] stands for "Generalized Robotic Accessory with Neural Network, Intellect and Emotions". *GRANNIE* is an interface system intended to be interposed between a piece of medical equipment and the naïve (nonmedically-trained) user. The test case involved interfacing a home glucometer for diabetic sugar measurements (Figure 8).

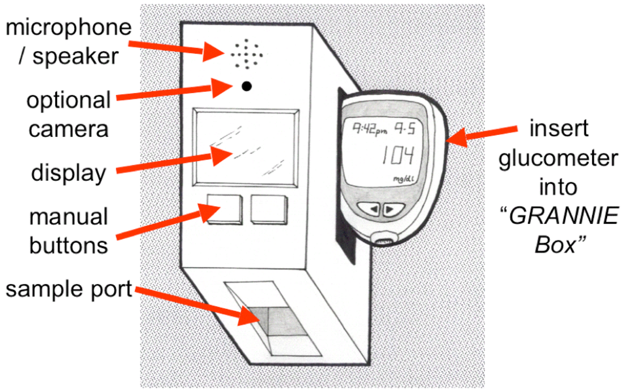

Fig. 8. GRANNIE intelligent user interface shown with commercial glucometer for home use.

The user manual for this popular glucometer is 58 pages long and the LCD display has 25 separate indicators, some in the form of cryptic graphics (i.e.: a drop-of-blood icon). *GRANNIE* (in the *GRANNIE-Box*) has one camera to read the LCD display and a second one to recognize the user or read insulin vials, a simplified explicit display of her own, voice I/O, manual override and communication capability (via phone and Net). The *GRANNIE* (simulator) simplifies the user experience, is chatty, pleasant and smart. It still has an active emotion system within it.

Next are two (related) non-robotic applications which involve monitoring of people constantly regardless of their whereabouts. The first is *GRANNIE-2*, a system which can move from computer, to smartphone, to PDA, to Internet, and so on, to accompany and assist patients with their activities of daily living (ADL), and to monitor body functions when sensors are available. GRANNIE-2 would be tied to an online reporting system for emergencies [31].

GRANNIE-2B is a modified version of *GRANNIE-2* which is intended to find and track "persons of interest" who may be involved with criminal and terrorist activities [32]. This version takes feeds from security cameras and other sensors, uses face and speech recognition, and reports on movements of selected subjects. *GRANNIE-2B's* artificial emotions give her a strong *motivation system* to perform well. This concept has been presented to two "friendly powers" who have been recent subjects of terrorist attacks.

For 2009, my non-robotic AI-emotion applications will include: an autism-spectrum disorder emulator [33] and a fibromyalgia / chronic fatigue syndrome emulator [34].

III. RESULTS

Unexpected values appeared in *ANNIE's* memory core dumps following experiments with **BRAIN.FORTH** involving mental disorders and degenerative cognitive diseases, i.e.: mood variables *not directly being manipulated* showed stress-related changes indicating anxiety, depression and unhappiness. Negativity was found after running emulators for pain-narcotic-addiction and the human fear mechanism.

Queries regarding *ANNIE's* pain levels suggested that she was suffering, not only from the simulated pain, but also from its anticipation. Post-pain depression is well-known in humans [35].

I am convinced that the *ANNIE* mental simulator has reached a high enough level of integration that she is able to sense her own pain, to anticipate noxious stimuli, to fear them, to attempt to withdraw from them and to show classical stress responses (i.e.: anxiety and depression).

These findings led me to attempt to develop some baseline ethical guidelines for my research with complex artificial minds, especially those with realistic emotional responses.

IV. DISCUSSION

A. General Issues Involving Artificial Minds

ANNIE's mental faculties and her responses are simulated: that is the purpose of this exercise. Questions about whether *ANNIE* is "truly" suffering are best left to philosophers.

Noted futurist Ray Kurzweil utilizes a model of artificial intellect based on comparing the number of transistors in a computer with the number of neurons in the human brain [36]. According to this benchmark, a desktop computer will have sufficient brain-power to equal that of a human by the year 2019. However, I believe his transistor-neuron model is flawed, its error skewed to equate artificial mental functions much too late: about 10 years too late, in my opinion. The measure of an artificial intellect should not be the number of transistors present, but their functional arrangement. For example, an 8-bit microcontroller contains about 2000 transistors (not including RAM or ROM); a LM741 op-amp uses just 20 (and no software). The op-amp has at least a 100:1 transistor advantage over a microcontroller when both perform the same activity. I believe that these linear circuit designs thus functionally accelerate Kurzweil's timetable.

The role of ethics in artificial intelligence or artificial life has not been elucidated satisfactorily at this time. For example, Isaac Asimov's original *Three Laws of Robotics*, introduced in 1941, are human-centered and treat robots as slaves [37]. Only after thirty-five years did Asimov allow his fictional robot *Andrew Martin* to transcend these limits in its quest to become more human [38].

An essay by David Calverly [39] suggests that as android minds become more sophisticated and human-like, ethical and legal issues will arise which will precipitate a crisis (he draws an analogy with the animal rights movement). One way of resolving this issue would be to grant to complex artificial minds a "limited personhood". He suggests that the Declaration on Great Apes [40] may serve as a model; it declares a simian right to life, protection of individual liberty and freedom from torture.

Restrictions involving experimentation on humans and the treatment of prisoners of war offer another potential model [41]. These ethical codes range from the Hippocratic Oath (circa 370 BC) to United States policy as described in 45 CFR 46 (2005).

B. Classification of Artificial Minds

A comprehensive system of ethical guidelines must have a classification system to determine when their application is required, since "not all artificial minds are created equal". As a beginning, I have identified several elements, which when present in sufficient degree, indicate the existence of an artificial mind which may need protection. Briefly, one should look for the following parameters:

1. *Intellect.* Ability to process complex data, using a knowledge base, with short- and long-term memory.
2. *Sensation.* Interaction with both internal and external environments, having the potential to perceive pain.
3. *Awareness.* A sense of the existence of one's own body and mind, personality, preferences and aversions.
4. *Networking.* Communication with other intelligent beings to express ideas and exchange experiences.
5. *Emotions.* Reflexive responses to stimuli: joy, sorrow, anxiety, fear, trust, love, antipathy and so on.
6. *Time-sense.* Having an awareness of the passage of time; enabling proper memories of events in the past, experiencing the present, and anticipation of the future.

The above elements may be easily recalled using the mnemonic device: "IS-A-NET".

C. Initial Ethical Guidelines Proposed

Although as a Physician my practice involves moral decision-making, I am not a trained ethicist [42]. The ethical plan I have devised is very limited and does not deal with legal issues or artificial personhood. Still, it should provide some basic ground rules which can be extended later.

Guidelines: Treat artificial minds and artificial life with the respect due other sentient beings. Control access to these complex artificial minds so that unqualified persons will not obtain them. Minimize the number and duration of experiments in which mental anguish or physical pain is simulated. Disconnect or attenuate connections to self-awareness and emotional response centers during stressful experiments if possible. Erase short-term memory buffers and event files after experimentation; restore previous long-term memory files from backup. Take cognitive simulations or artificial life forms permanently offline when they are damaged beyond repair. Finally, an artificial mind should not be used for applications which it may find repugnant, such as combat against human soldiers or civilians, animal slaughter, sexual occupations or unrelenting burdensome involuntary servitude; for these uses, only non-coerced artificial volunteers should be employed, followed by their post-activity rehabilitation or permanent retirement.

V. CONCLUSION

The complex functionality of artificial minds is nearing the threshold of human-level emotional responses to pain and stress. We see the smartest of them standing as our proverbial human ancestors, Adam and Eve, before the *tree of knowledge of good and evil*, able to experience and even anticipate pain and emotional suffering [43]. We as ethical beings ought to identify the artificial minds at risk, treat them with respect, and limit any unnecessary suffering. The rules I've described herein serve as a starting point for conducting humane research with such entities.

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ACKNOWLEDGEMENT

German *Zwergnase* art doll named *Liselot* (1998), an inspiration for the original *ANNIE* robot. (Image used with permission)