Evolution and Learning in Artificial Ecosystems

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General intelligence exists in the animal kingdom, so by modeling animal cognition well enough, one gets AGI.

We will build a model for artificial animals (animats) and use performance measures from biology: need satisfaction, survival, and fitness.

This strategy enables a gradual approach to AGI:
- Start with relatively simple animals
- Start with relatively simple problems facing all animals: survival and reproduction in different ecosystems.
Strategy for AGI

- Animals can have greatly varying anatomies, but the basic mechanisms for perception, action, learning, decision-making, reproduction, and death seem to be the same for all higher animals.
- We will build a generic animat model with configurable anatomy.

There is no fundamental difference between man and the higher mammals in their mental faculties...The difference in mind between man and the higher animals, great as it is, certainly is one of degree and not of kind.
Our model combines two fundamental mechanisms of animal behavior:

- evolution (adaptation between generations)
- learning (adaptation inside generations).

Including both mechanisms in the same model seems to be essential for realistic modeling. Yet it is uncommon in AI as well as artificial life, psychology, ecosystem modeling, and behavioral economics.
Philosophical foundations

- Evolution (Darwin)
- Empiricism (Hume)
- Constructivism (von Glasersfeld)
- Behaviorism (Skinner)
- Reinforcement learning (Thorndike)
Building blocks of the model

Definition

- **A sensor** is a propositional variable.
  - For example, *red*, *green*, and *blue* could be sensors.

- **A sensor set** is a set of sensors
  - For example, {}, \{blue, green\}, and \{red, blue, green\} could be sensor sets (representing black, turquoise, and white).

- **A concept** is a non-empty sequence of sensor sets.
  - For example, \[[\{red\}, \{red\}, \{green\}]\] and \[[\{red, green, blue\}]\] could be concepts.
Definition

An *input stream* is a function $\sigma(s, t)$ that assigns a boolean value to each sensor $s$ at each time $t$.

Definition

Given the input stream $\sigma$, the concept $[S_0, \ldots, S_n]$ is *active* at $t$ if $\sigma(s, t - n + k)$ is true for all $s \in S_k$ and all $k$ such that $0 \leq k \leq n$. 
More building blocks

Definition
An action is a propositional variable.
- For example, left, right, forward, eat, drink could be actions.

Definition
A reflex is a pair consisting of a concept and an action.
- For example, (knee_sensor, kick) could be a reflex.

Definition
A need is a variable $h_i$ that takes real values in the interval $[0, 1]$.
- For example, energy and water could be needs.
Genotype

Definition

A *genotype* consists of

- a set of concepts
- a set of actions
- a set of reflexes
- a set of needs
- a set of parameters

The genotype models the cognitive system at birth. In the context of reproduction, it will be represented as a binary string.
A phenotype consists of
- a set of concepts
- a subset of active concepts
- a set of experience values:
  - values of the needs $h_i$
  - local Q-values $Q_i(c, a)$: the value of doing action $a$ when $c$ is active from the perspective of need $h_i$
  - probabilities $Pr(c'|c, a)$: the probability of reaching $c'$ when doing $a$ in $c$

The phenotype models the present state of the cognitive system, including the set of concepts, which may have changed since birth.
An **animat** consists of:

- a genotype
- a phenotype
- a conformation: a subset of $\mathbb{R}^3$

The genotype remains constant over the animat’s life, whereas the phenotype and conformation typically vary at each tick.

At birth the phenotype concept set is set to the genotype concept set.

The animat **dies** if

- $h_i = 0$ for some $h_i$ (death from lack of resources), or
- $age = x_{max\_age}$ (death from senescence).
Ecosystems

**Definition**
An *object* consists of:
- a type: e.g. rock, earth, sand, air, and water.
- a conformation: a subset of $\mathbb{R}^3$.

**Definition**
An *ecosystem* is a set of objects and animats with pairwise disjoint conformations.
Ecosystem dynamics

- Time proceeds in discrete ticks.
- At each tick all animats receive stimuli in the form of boolean values to their sensors and real values in $[0,1]$ to their needs.
Animat update algorithm (overview)

Input: The initial animat \( A \)

while alive do
    Read the new values to the sensors
    Compute the set of perceived concepts
    Select an action
    Read the new values of the needs
    Update the concept set
    Update the experience variables
end

This algorithm is generic in the sense that it is the same for all animats.
Ecosystem example: a frog in a pond

- Needs: *energy, water*
- Actions: *eat – and – jump, drink – and – jump*
- Genotype concepts: [{green}], [{blue}]
- Phenotype concepts: [{green}], [{blue}]

### Graph

![Graph showing vitality over time for Animat and Control]
Ecosystem example: a frog in a swamp

- Needs: same
- Actions: same
- Genotype concepts: same
- Phenotype concepts: added \([\{\text{green, blue}\}]\)
Ecosystem example: a frog in a creek

- Needs: same
- Actions: same
- Genotype concepts: same
- Phenotype concepts: added \([\{green\}, \{blue\}]\)
Two animats $A$ and $A'$ reproduce if

- they have similar genotypes in terms of Hamming distance
- they have opposite sex
- they are both fertile
- they have physical contact
- they are lucky, as determined by a skewed coin toss.
Ecosystem example: grass, sheep, and wolves
Generality of the animat model

- Simple foraging (Strannegård et al, IJCAI WS 2017)
- Simple navigation (Carlsson, 2018)
- Simple ecosystem modeling (Xu, 2018)
- Simple language (Johansson et al, BICA, 2018)
- Simple arithmetic (Lallo et al, 2018)
- Simple logic (Lallo et al, 2018)
- Animats versus deep Q-learning (Mäkeläinen et al, AGI, 2018)
Conclusion

- We proposed a generic artificial animal with configurable anatomy (concepts, actions, needs, conformations).
- The mechanisms for perception, decision-making, learning, reproduction, and death are the same for all animats.
- The model is autonomous and can operate with or without seed knowledge and with or without interaction with humans.
- The model is general enough to handle simple cases of foraging, navigation, logic, and language.
- The model is only a prototype and it can be improved in several directions.