Outline

1. Evolutionary Fuzzy Systems
   Evolutionary Algorithms
   Optimization of Fuzzy Controllers
   Summary
Evolutionary Algorithms

... are based on biological theory of evolution.

Fundamental principle:

- Beneficial properties created by random variation are chosen by natural selection.
- Differential reproduction: Individuals with beneficial properties have better chances to reproduce themselves.

The theory of evolution describes the diversity and complexity of species.

It allows to unify all disciplines of biology.
## Fundamental Terms and their Meanings I

<table>
<thead>
<tr>
<th>Term</th>
<th>Biology</th>
<th>Computer Science</th>
</tr>
</thead>
<tbody>
<tr>
<td>individual</td>
<td>living creature</td>
<td>candidate solution</td>
</tr>
<tr>
<td>chromosome</td>
<td>DNA histone protein string</td>
<td>character string</td>
</tr>
<tr>
<td></td>
<td>defines “blueprint” and (partly) properties of individual in coded form</td>
<td></td>
</tr>
<tr>
<td></td>
<td>usually several chromosomes per individual</td>
<td>usually one chromosome per individual</td>
</tr>
<tr>
<td>gene</td>
<td>part of chromosome</td>
<td>one character</td>
</tr>
<tr>
<td></td>
<td>fundamental unit of inheritance that (partly) defines property of an individual</td>
<td></td>
</tr>
<tr>
<td>allele (allomorph)</td>
<td>characteristic of a gene</td>
<td>value of a character</td>
</tr>
<tr>
<td></td>
<td>there is only one characteristic of a gene per chromosome</td>
<td></td>
</tr>
<tr>
<td>locus</td>
<td>position of a gene</td>
<td>position of a character</td>
</tr>
<tr>
<td></td>
<td>exactly just one gene on every position in chromosome</td>
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### Fundamental Terms and their Meanings II

<table>
<thead>
<tr>
<th>Term</th>
<th>Biology</th>
<th>Computer Science</th>
</tr>
</thead>
<tbody>
<tr>
<td>phenotype</td>
<td>outer appearance of a living creature</td>
<td>implementation of a candidate solution</td>
</tr>
<tr>
<td>genotype</td>
<td>genetic constitution of a living creature</td>
<td>encoding of a candidate solution</td>
</tr>
<tr>
<td>population</td>
<td>all living creatures</td>
<td>family/multiset of chromosomes</td>
</tr>
<tr>
<td>generation</td>
<td>population at given time</td>
<td>population at given time</td>
</tr>
<tr>
<td>reproduction</td>
<td>creation of offspring from one or two (if, then usually two) creatures</td>
<td>creation of (child) chromosomes from one or more (parent) chromosomes</td>
</tr>
<tr>
<td>fitness</td>
<td>capability/conformity of a living creature</td>
<td>capability/goodness of a candidate solution</td>
</tr>
<tr>
<td></td>
<td>determines chances of both survival and reproduction</td>
<td></td>
</tr>
</tbody>
</table>
Elements of an Evolutionary Algorithm I

An EA consists of

- a **codebook** for the candidate solutions
  - This codebook is problem-specific (*i.e.* no general rules exist).

- a method to generate an **initial population**
  - Usually, it generates random character strings.
  - Depending on the encoding, sophisticated approaches can be necessary.

- a **weighting function** (fitness function) for individuals
  - It acts as an environment and indicates the goodness of the individuals.

- a **technique of sampling** based on the fitness function
  - It defines both which individuals are used to generate offspring and which ones reach the next generation without any change.
Elements of an Evolutionary Algorithm II

Furthermore, an EA consists of

**genetic operators** that change candidate solutions

- *mutation* (random modification of particular genes)
- *crossover* (recombination of chromosomes; actually “crossing over” due to process in meiosis (period of cell division) where chromosomes are divided and then joined crossed-over again)

values for several **parameters**

- *e.g.* population size, mutation probability, etc.

**termination criterion, e.g.**

- fixed number of generations has been processed
- for fixed number of generations, no improvement occurred
- predefined minimal goodness of solution has been reached
Generic Basic EA

Algorithm 1 EA Schema

\[ t ← 0 \]
\[ \text{pop}(t) ← \text{create population of size } \mu \]
\[ \text{evaluate } \text{pop}(t) \]
\[ \text{while } \text{termination criterion not fulfilled} \{ \]
\[ \quad \text{pop}_1 ← \text{select parents for } \lambda \text{ offspring from } \text{pop}(t) \]
\[ \quad \text{pop}_2 ← \text{generate offspring by recombination from } \text{pop}_1 \]
\[ \quad \text{pop}_3 ← \text{variate individuals in } \text{pop}_2 \]
\[ \quad \text{evaluate } \text{pop}_3 \]
\[ \quad t ← t + 1 \]
\[ \quad \text{pop}(t) ← \text{select } \mu \text{ individuals from } \text{pop}_3 \cup \text{pop}(t - 1) \]
\[ \} \]
\[ \text{return } \text{best individual from } \text{pop}(t) \]
Genetic Operators: Crossover

Exchange of one part of chromosome (or subset of selected genes) between two individuals, e.g. so-called one-point crossover:

1. Choose a random point of division between two genes.
2. Exchange the gene sequences of one side of the division point.

\[
\begin{array}{c|c|c}
4 & 3 & 1 \\
3 & 1 & 4 \\
2 & 4 & 3 \\
1 & 0 & 2 \\
\hline
\end{array}
\rightarrow
\begin{array}{c|c|c}
4 & 3 & 1 \\
3 & 1 & 4 \\
2 & 4 & 3 \\
1 & 0 & 2 \\
\hline
\end{array}
\]
Genetic Operators: Mutation

Randomly chosen genes are randomly replaced (alleles change).
The number of replaced genes maybe random, too (should be small).

Most mutations are damaging/harmful (they worsen the fitness).
Initially non-existent alleles can (only) be generated by mutation.
Optimization of Fuzzy Controllers with GAs

Mamdani controller can be induced/optimized as follows:

- rule base (which rules, which outputs)
- fuzzy sets/fuzzy partitions (shape, location, width, number of fuzzy sets)
- \( t \)-norm or \( t \)-conorm for rule evaluation (rarely)
- parameters of defuzzification method (if present, rarely)
- inputs used in the rules (feature selection)

Here we talk about the optimization of the rule base and the fuzzy sets with a fixed choice of input values.

Rule evaluation: minimum and maximum

Defuzzification: center of gravity (COG)
Optimization: Three Possible Approaches

1. Rule base and fuzzy partitions are optimized simultaneously:
   • Disadvantage: Many parameters must be optimized at same time.

2. First, the fuzzy partitions are optimized \textit{w.r.t.} given rule base, then rule base is optimized with best fuzzy partitions:
   • Disadvantage: Expert knowledge needed to create rule base (starting with random rule base is not promising).

3. First, rule base is optimized \textit{w.r.t.} given fuzzy sets, then fuzzy partitions are optimized with best rule base:
   • Fuzzy sets may be distributed, \textit{e.g.} equidistantly.
   • Here, the user must specify the number of fuzzy sets for input and output.
   • We only consider this approach here.
Optimization: Fitness Function

A good controller should exhibit several properties:

• The target value should be reached from any (initial) situation.
• The target value should be reached quickly.
• The target value should be reached with minimal effort (energy).

The controller is applied multiple times to target system:

• Here, simulation of inverted pendulum problem.
• Several randomly chosen starting points.
• A score is assigned to the controller according to its success (number of situations, duration of successful control, energy costs).

Here, the evaluation of individuals is by far the most expensive operation:

• Every individual must be put in control for at least certain number of time steps in order to yield reliable fitness score.
Assessing the Controller Success

If the deviation of the actual value to the target is big, it’s a failure, e.g. inverted pendulum: It must stay within \([-90^\circ, 90^\circ]\).

After some time, the actual value should be close to the target value and remain within its proximity (range of tolerance). Otherwise the process is aborted also (failure).

The range of tolerance is shrinked during generations (towards target).

- During the first generations, it suffices if the pendulum doesn’t topple over.
- Later the pendulum must stand upright within a shrinking angle interval.

The abs. values of adjusting values are added up as penalty value.

In balance, a fast switch betw. large/small forces effects the controller. Thus large forces need to be avoided.
Optimizing the Rule Base: Encoding

We only consider complete rule bases, that is, one rule for every combination of input fuzzy sets.

For every combination of input fuzzy sets, we need to determine a linguistic term of the control variable (by filling a table).

<table>
<thead>
<tr>
<th>$\dot{\theta}$</th>
<th>nb</th>
<th>nm</th>
<th>ns</th>
<th>az</th>
<th>ps</th>
<th>pm</th>
<th>pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>pb</td>
<td>az</td>
<td>ps</td>
<td>ps</td>
<td>pb</td>
<td>pb</td>
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<td>pb</td>
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<tr>
<td>pm</td>
<td>ns</td>
<td>az</td>
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<td>ps</td>
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<td>nb</td>
<td>nb</td>
<td>ns</td>
<td>ns</td>
<td>az</td>
</tr>
</tbody>
</table>

schematic
Representing the Rule Base as Chromosome

*Linearization* (transformation into a vector):

The table is traversed in an arbitrary but fixed order.

Entries are listed in a vector, *e.g.*

- listing row by row.
- So, neighboring relations between cells are lost.

Adjacent entries should contain similar linguistic terms (this is important, *e.g.* during crossover).

*Table* (direct usage of scheme)

for two- or higher dimensional chromosomes.

Thus special genetic operators are needed.
Genetic Operators for Rule Base: Mutation

1. The rule/table entry is chosen randomly.
2. The linguistic term of output is altered randomly.
3. Multiple table entries may be altered.

It might be beneficial to restrict the mutation of the rule base:
An entry is only changed to a linguistic term similar to the current one, e.g.

- “positive small” $\mapsto$ “approximately zero” or “positive medium”,
- “negative big” $\mapsto$ “negative medium” or “negative small”.

This prevents a too fast “depletion” of the collected information.
Also, the rule bases are only modified “carefully”. 
Genetic Operators: One-Point Crossover

Choose both interior grid point and corner randomly.
This defines a subtable that will be exchanged between two parents.

The crossover should exhibit a location-dependent bias.
So, it prefers to inherit adjacent rules.
Genetic Operators: Two-Point Crossover

Choose two grid points randomly (border points allowed). This defines a subtable that will be exchanged between two parents.

Partial solutions can be exchanged in a more flexible way.

The two-point crossover performs better than one-point crossover.
Optimizing Fuzzy Sets

Given: optimized rules with fixed and unchanged equidistant fuzzy sets.

Goal: further improvement of rule behavior by adjusting fuzzy sets with fixed rule base ("fine tuning").

Encoding fuzzy sets (first possibility):
1. Choose the shape of the fuzzy sets (e.g. triangle, trapezoid, Gaussian, parabola, spline, etc.).
2. List the defining parameters of the fuzzy sets (e.g. triangle: left border, center, right border).

Example: controller with triangular fuzzy sets (excerpt)

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>.</td>
<td>.</td>
<td>-45</td>
<td>-30</td>
<td>-15</td>
<td>-30</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>-15</td>
<td>0</td>
<td>-15</td>
<td>0</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>0</td>
<td>15</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>15</td>
<td>0</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
</tbody>
</table>
Optimizing Fuzzy Sets: Disadvantages

In advance one must specify that, e.g. triangles or trapezoids are used.

So, the encoding is quite “rigid” w.r.t. the shape of the fuzzy sets.

Genetic operators can violate the order of parameters, e.g.
- considering triangles $\mu_l, m, r$, $l \leq m \leq r$ must hold.

A possible “overtaking” between fuzzy sets, i.e.
- the meaningful order of the fuzzy sets may be destroyed by mutation/crossover, e.g. it should hold true that $ns$ lies left of $ps$.

The condition $\forall x : \sum_i \mu_i(x) = 1$ might be violated:
- This can be treated by representing identical parameters only once.
Encoding Fuzzy Partitions

Distinct membership degrees of fuzzy sets are specified for a predefined and equidistant set of sampling points:

\[
\begin{align*}
\text{Gene 1:} & \quad \left( \begin{array}{c}
\mu_1(x_1) \\
\vdots \\
\mu_n(x_1)
\end{array} \right) \\
\text{Gene i:} & \quad \left( \begin{array}{c}
\mu_1(x_i) \\
\vdots \\
\mu_n(x_i)
\end{array} \right) \\
\text{Gene m:} & \quad \left( \begin{array}{c}
\mu_1(x_m) \\
\vdots \\
\mu_n(x_m)
\end{array} \right)
\end{align*}
\]

Encoding with \(m \times n\) numbers \(\in [0, 1]\)

| pb  | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | .5 | 1 | 1 | 1 |
|-----|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| pm  | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | .5 | 1 | .5 | 0 | 0 | 0 |
| ps  | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | .5 | 1 | .5 | 0 | 0 | 0 | 0 |
| az  | 0 | 0 | 0 | 0 | 0 | 0 | 0 | .5 | 1 | .5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| ns  | 0 | 0 | 0 | 0 | 0 | .5 | 1 | .5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| nm  | 0 | 0 | .5 | 1 | .5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| nb  | 1 | 1 | .5 | 1 | .5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

-60  -45  -30  -15  0  15  30  45  60
**Genetic Operators**

Mutation (analogous to standard mutation):
- A randomly chosen entry is altered randomly.
- It is reasonable to restrict the magnitude of alteration, e.g. by specifying an interval or by a normal distribution.

*Crossover* (basic one-/two-point crossover):
Note that fuzzy sets may be erased by crossover.
Repairing Fuzzy Sets

Mutation/crossover may violate the unimodality of the fuzzy set,

- *i.e.* the membership function may have \( \geq 1 \) local maximum.
- Multimodal fuzzy sets are harder to interpret than unimodal ones.

Therefore, fuzzy sets are repaired (made unimodal).

Fuzzy sets may be widened or cut off such that the entire domain is covered, but without having too many fuzzy sets covering the same areas.
Summary

Optimization in two steps:

1. Optimize the rule base with fixed fuzzy partitions.
2. Optimize the fuzzy partitions with an induced rule base.

It was possible to generate a working rule set for the inverted pendulum problem with evolutionary algorithms.

The approach of inducing a rule base is quite expensive in time.

However, it does not need any background knowledge.

Additional requirements might be considered for fitness:

- *compactness* (small number of rules and fuzzy sets)
- *completeness* (coverage of relevant areas of input space)
- *consistency* (no rules with similar antecedents and different consequents)
- *interpretability* (limited overlapping of fuzzy sets)