# Promoting Diversity in Evolutionary Optimization: Why and How

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## Instructors

Squillero and Tonda have been working on diversity in EAs since 2008, and in 2015 they published the paper "Divergence of character and premature convergence: A survey of methodologies for promoting diversity in evolutionary optimization". In 2016 and 2014 they gave introductory tutorials about the topic, respectively, at PPSN (Edinburgh) and IEEE WCCI (Beijing); the instructors also co-chaired *MPDEA*, a GECCO workshop on Measuring and Promoting Diversity in Evolutionary Algorithms in 2016 and 2017.

- **Giovanni Squillero** is an associate professor of computer science at Politecnico di Torino, Department of Control and Computer Engineering.
- **Alberto Tonda** is a permanent researcher at the National Institute of Agronomic Research (INRA), Thiverval-Grignon, France.



## Course Agenda


- Divergence of character in natural and artificial evolution
- Background (diversity and similarity, …)
- Mechanisms for promoting diversity
- Hints and tips
- Conclusion



## Real world (Galapagos)

Image by **pen_ash** from **pixbay**

## Darwin's tree of life

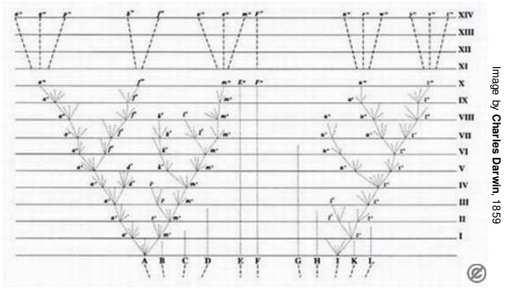



Image by Charles Darwin, 1859

**The only illustration in**
***On the Origin of Species by Natural Selection***



## Divergence of character

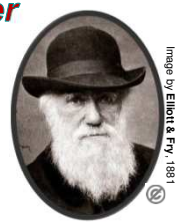


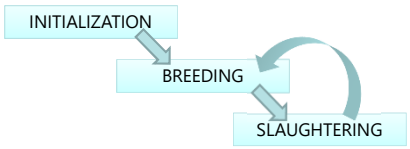
Image by Elliott & Fry, 1881

- "**Great diversity** of forms in nature"
- "The principle, which I have designated by this term, is of **high importance**, and **explains**, as I believe, **several** important **facts**"
  - "The principle of divergence causes differences, at first barely appreciable, to steadily to increase, and the breeds to diverge in character, both from each other and from their common parent"
  - "The varying descendants of each species try to occupy as many and as different places as possible in the economy of nature"



## Evolutionary algorithm

- Oversimplified evolutionary algorithm




- Note: **Optimization**, not artificial life!



## Evolutionary algorithms

## Premature convergence

- I.e., the tendency of an algorithm to converge towards a point where it was not supposed to converge to in the first place
- Probably an oxymoron
- Holland's "Lack of speciation"
- EAs general inability to exploit environmental niches



divergence of character

vs.

premature convergence

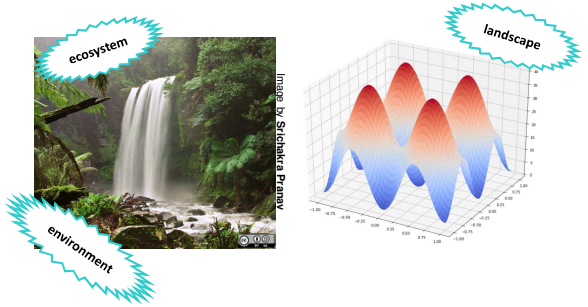


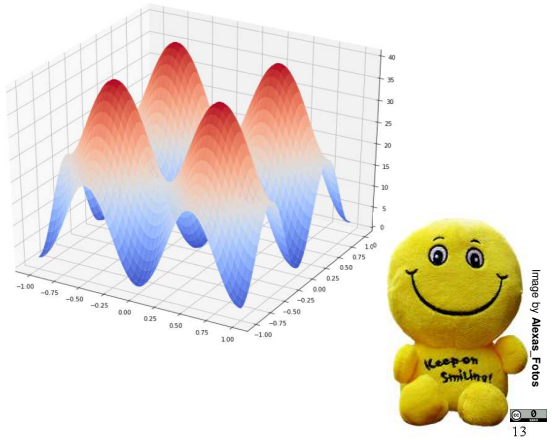
## Divergence of character

- "The basic point of the **principle of divergence is simplicity itself**: the more the coinhabitants of an area differ from each other in their ecological requirements, the less they will compete with each other; therefore natural selection will tend to favor any variation toward greater divergence."




## Environment vs. Fitness function

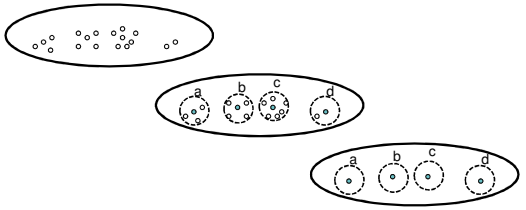







## Niches

- Niche: subspace in the environment with a finite amount of physical resources that can support different types of life



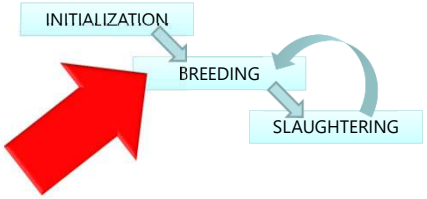



## Niches

- Niches favor the divergence of character
- Niches and speciation
- **How to create** "niches" in EAs since the environment is missing**?**



## Oversimplified Evolutionary Algorithm



## Exploration vs. Exploitation

- Recombination
  - **mixes** together two or more solutions to create the offspring
  - associated with the idea of exploration
- Mutation
  - performs a (usually small) **change** in an individual
  - associated with the idea of exploitation

Image from

## Exploration vs. Exploitation

- When all parents are very similar, the effectiveness of recombination is limited
- The ability to explore remote parts of the search space is impaired
- "**Conventional wisdom** suggests that increasing diversity should be generally beneficial"



## Exploration vs. Exploitation

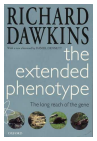
- When all parents are very similar, the effectiv what is the definition of "similar"? limited
- The ability to explore remote parts of the search space is impaired
- "**Conventional wisdom** suggests that increasing diversity should be generally beneficial" and the definition of "diversity"?



## Levels in biology

- **Genotype**: the genetic constitution of an organism
- **Phenotype**: the composite of the organism's observable characteristics or traits
- **Fitness**: individual's ability to propagate its genes (well, almost)

Richard Dawkins
**The Extended Phenotype: The Long Reach of the Gene**
Oxford University Press, 1982 (revised ed. 1999)

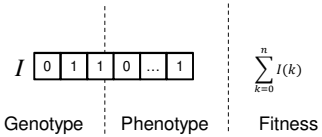


## Levels in EC (a modest proposal)

- **Fitness**: how well the candidate solution is able to solve the target problem
- **Genotype**: the internal representation of the individual, i.e., what is directly manipulated by genetic operators
- **Phenotype**: the candidate solution that is encoded in the genotype
  - the intermediate form in which the genotype needs to be transformed into for evaluating fitness
  - if genotype can be directly evaluated: genotype and phenotype coincide

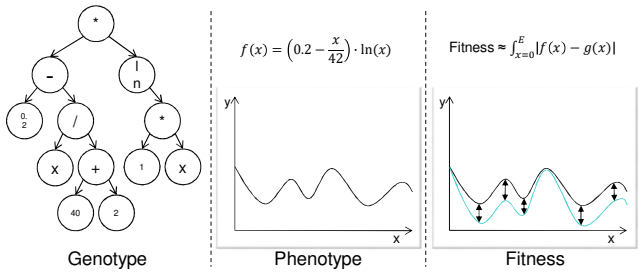


## Levels in EC (GA)





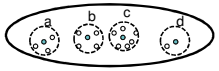

## Levels in EC (GP & LGP)






## Niches in EA

- Niching: grouping **similar** individual
  - similar spatial positions (i.e., islands)
  - similar genotypes (i.e., niching)
  - similar phenotypes
- **Explicit** vs. **implicit** neighborhood
- Several approaches are based on niching



## Detecting clones

- Detecting whether two individuals are clones, i.e., **identical**, is often an easy task at any level




## Measuring diversity

- Diversity ⇒ **distance metric**: how far the individual is
  - from (a subset of) the whole population
  - from a single individual
- Diversity ⇒ **property** of the population
- But, at what level?
  - Phenotype
  - Genotype
  - Fitness



## Measuring diversity

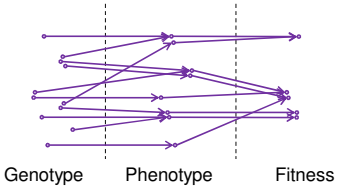
- Different fitness values **imply** different phenotypes,
  different phenotypes **imply** different genotypes

$$F_x \neq F_y \Rightarrow P_x \neq P_y \Rightarrow G_x \neq G_y$$



## Measuring diversity

- What about “diversity”?
- Locality principle
- Rechenberg’s strong causality



## Measuring diversity

- Fitness
  - Usually **trivial**
- Phenotype
  - Usually **ad-hoc**
- Genotype
  - Different genotypes in the population
  - GP subtree frequency
  - Edit distance (a.k.a., Levenshtein distance)
  - Entropy and free energy



## Outline

- Generic EA
- Divergence of character in natural and artificial evolution
- Background (diversity
- Mechanisms for promoting diversity
- Hints and tips
- Conclusion

What has been proposed to alleviate it?



## End goal vs. Means goal

- The **end goal** in optimization is reaching better solutions in less time
- Promoting diversity has often been seen as the key factor to improve performances
- Promoting diversity is a mere **means goal** (yet a quite important one)
- No distinction is made here whether the means goal is
  - **preserve** existing diversity
  - **increase** diversity



## How diversity is promoted (practice)

- Fitness scaling
- Fitness holes
- Tweaking selection mechanism
- Adding selection mechanism
- Multiple populations
- Population topologies
- …

In theory there is no difference between theory and practice

## How diversity is promoted (theory)

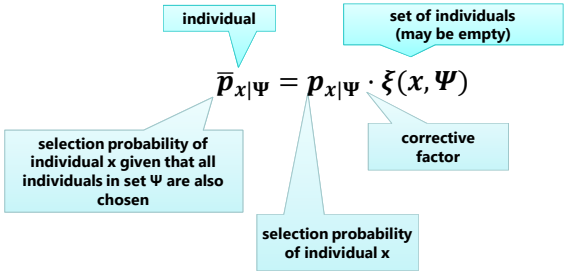
- A methodology for promoting diversity **alters** the selection **probability** of individuals

$$\bar{p}_{x|\Psi} = p_{x|\Psi} \cdot \xi(x, \Psi)$$

- Mere definition: we do not imply that a mechanism operates explicitly on the selection operators
- But the effects on selection probabilities are assessed to classify it



## How diversity is promoted (theory)






## Relevant characteristic

- Lineage (LIN)
- Phenotype (PHE)
- Genotype (GEN)
- Fitness

$\xi(x, \Psi)$



## Relevant characteristic

- Lineage (LIN)
- Phenotype (PHE)
- Genotype (GEN)
- [illegible] (used as a proxy for either phenotype or genotype)

$\xi(x, \Psi)$

## Lineage-based methodologies

- The value of **ξ( ∘ )** does **not depend** on **individual structure** nor **behavior**, but it can be determined considering circumstances of its birth (e.g., time, position)
- LBMs can be applied to **any** kind of **problem**, even in addition to other diversity preservation methods



## Genotype-based methodologies

- Particularly effective when it is possible to define a **sensible distance** between genotypes
- Often used to
  - avoid overexploitation of peaks in the fitness landscape
  - promote the generation of new solutions very far from the most successful ones
  - preserve variability in the gene pool



## Phenotype-based methodologies

- Usually **impractical**
- Sometimes fitness distance can be used as a proxy for phenotype distance (multi objective EAs, or many objective EAs)



## Type of selection

- **Parent** selection (**α**)
  - Usually non-determinstic
- **Survival** selection (**ω**)
  - Usually deterministic

## Diversity Promotion in EA


Divergence of character and premature convergence: A survey of methodologies for promoting diversity in evolutionary optimization ☆

10.1016/j.ins.2015.09.056

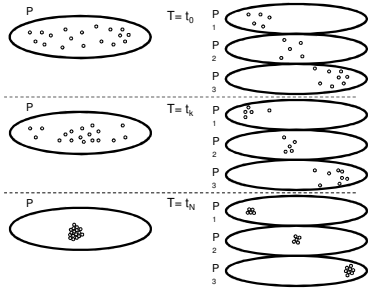



## Island model

- Recipe [LIN αω]
  - The population is partitioned into sub-populations
  - Only local interactions are allowed
  - Periodically, **migrants** are moved between sub-populations
- Rationale
  - Different populations may explore different parts of the search space
  - … but global interactions can be useful

Photo by **Irish Defence Forces** from **flickr.com**

## Island model

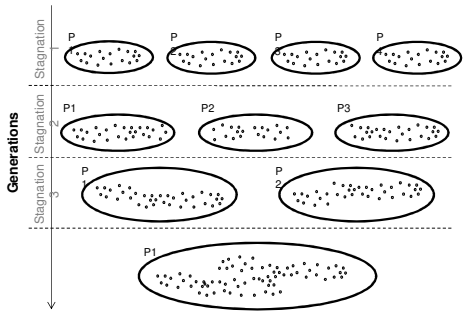





## Segregation

- Recipe [LIN αω]
  - The population is **partitioned** into N sub-populations
  - Only local interactions are allowed
  - Upon stagnation, the *N* sub-populations are merged into *N*-1 sub-populations
- Rationale
  - Same as island models
  - The selective pressure decreases during evolution

## Segregation



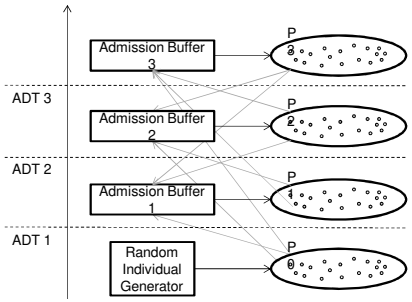



## Hierarchical fair competition

- Recipe [PHE αω]
  - The population is **partitioned** into sub-populations with similar fitness
  - Only **local interactions** are allowed
  - The offspring is promoted or demoted according to fitness
  - New random individuals are constantly generated
- Rationale
  - **Niching** with implicit neighborhood
  - Reduce competition between newborns and already optimized individuals (ladder)



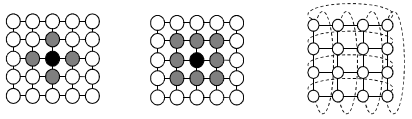
## Hierarchical fair competition






## Cellular EA

- Recipe [LIN αω]
  - Fixed topology (lattice)
  - Only interactions between neighbors are allowed
- Rationale
  - **Limiting interaction** could defer the takeover of the population by clones of the fittest individual



## Deterministic crowding

- Recipe [LIN ω]
  - Offspring compete against parents for survival
- Rationale
  - **Niching** with implicit neighborhood
  - Parents and offspring occupy the same niche
  - No need for evaluating the similarity



## Allopatric selection

- Recipe [LIN ω]
  - The whole offspring compete for survival
- Rationale
  - **Niching** with implicit neighborhood
  - No need for evaluating the similarity
  - Genetic operators that create large offspring can be exploited without the risk for the offspring to invade the population



## Fitness Sharing

- Recipe [GEN αω]
  - Scale down individual fitness
  - $\bar{f}(I_k) = \frac{f(I_k)}{\sum_i sh(I_k, I_i)}$
  - with sh(x, y) depending on the distance between the individuals, and is 0 beyond a fixed radius
- Rationale
  - **Niching** with explicit neighborhood
  - Reduce attractiveness of densely populated area



## Clearing

- Recipe [GEN αω]
  - Inside niches of a certain radius, the best k individuals retain their fitness while the rest are zeroed
- Rationale
  - **Niching** with explicit neighborhood
  - Set a hard limit to population density

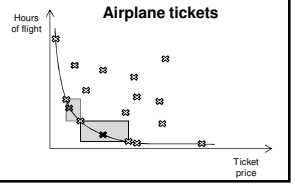
## Standard crowding

- Recipe [GEN ω]
  - New individuals replace the most similar individual in a random niche of size CF
- Rationale
  - **Niching** with explicit neighborhood
  - Favor novelty (generational approach)



## Crowded-comparison operator

- Recipe [PHE α]
  - Estimate the free territory around solutions and favor solutions less crowded regions
- Rationale
  - Smart implementation of **artificial niches**
  - **Requires** a strong **correlation** between phenotype and fitness
  - NSGA-III introduces **ε-domination** (adaptive discretization)




## Reference points partitioning

- Recipe [GEN ω]
  - Population is partitioned using in clusters centered around a set of reference points
  - Reference points are initially chosen by the user, then can be dynamically updated
  - New individuals compete for survival inside their own niche
- Rationale
  - **Niching** with explicit neighborhood



## Vector evaluated genetic algorithm

- Recipe [PHE α]
  - Divide the mating pool in N parts, each one filled with individual selected on their i-th component of the fitness
  - Alternative: select on a weighted sum, but use different weight sets for the different parts
- Rationale
  - Increase the push towards specialization
- Caveats
  - **Only** applicable to **MOEAs**, or when using an **aggregate fitness**

## Lexicase selection

- Recipe [PHE α]
  - Before selection, re-arrange the components of the fitness
  - Compare individual fitnesses lexicographically
- Rationale
  - Increase the push towards specialization
- Caveats
  - **Only** applicable when using an **aggregate fitness**



## Restricted tournament selection

- Recipe [GEN ω]
  - New individuals compete with the most similar individual in a random niche of size CF
- Rationale
  - **Niching** with explicit neighborhood



## Sequential niching

- Recipe [GEN αω]
  - The most promising points in the search space after each run are altered so to become less interesting in further executions
- Rationale
  - Avoid over exploitation



## Gender

- Recipe [LIN/GEN α]
  - Add gender to individual and enforce sexual reproduction
  - More than two sexes are possible, with different mutation probabilities
  - Gender might be part of the genome or not
- Rationale
  - Prevent crossover between clones
  - Limit interactions between related individuals

## Tarpeian method

- Recipe [PHE αω]
  - Randomly kill individual who don't adhere to given standards
- Rationale
  - Note: originally used to prevent bloat
  - Creating dynamic and non-deterministic fitness holes may have several beneficial effects, including to promote diversity



## Diversifiers

- Recipe [GEN αω]
  - Detect less populated areas in the search space and try to generate random inhabitants
- Rationale
  - Increase variability in the gene pool regardless the fitness
  - Require a reliable distance metric



## Random immigrants

- Recipe [PHE αω]
  - Periodically insert random individuals in the population
- Rationale
  - Try to introduce novelty
- Caveats
  - Newborns may need to be artificially kept alive when competing against already optimized individuals

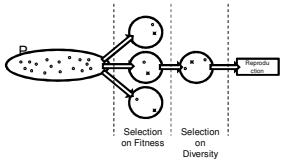


## Extinction

- Recipe [PHE ω]
  - Upon convergence (or periodically) remove a significant part of the population
  - Then fill up the population with the offspring of the survivors and/or random individuals
- Rationale
  - A gust of fresh air: already optimized individuals are not enough to occupy the whole population and newborns may start exploring new regions
- Caveat
  - Fitness variability used as phenotype variability

## Two-level diversity selection

- Recipe [GEN α]
  - Select three individuals using fitness, then pick the two with maximum distance for reproduction
- Rationale
  - Exploit a **reliable distance** metric to increase the efficacy of crossover
  - Not so far from reality (?)






## GDEM – Genetic Diversity Evaluation Method

- Recipe [GEN αω]
  - Add diversity as an explicit goal and go MO
- Rationale
  - Modify the domination criteria
  - Need a reliable diversity metric
- Historical note
  - See: Find Only and Complete Undominated Sets (FOCUS)



## Delta entropy and pseudo entropy

- Recipe [GEN α]
  - With a certain probability select individuals on their ability to increase the global entropy of the population instead of fitness
- Rationale
  - Not-so-fit individual with peculiar traits should be preserved
  - Measuring the entropy of the population is easier than defining a distance function



## Outline

- Generic EA
- Divergence of character in natural and artificial evolution
- Background (diversity and similarity, …)
- Mechanisms for promoting diversity
- Hints and tips
- Conclusion

## Hints and Tips

- Do you really need to promote diversity?
  - Several problems in EA are caused by ill-designed fitness functions
  - Check whether the locality principle holds true
  - Check what happen with multistart

Image from www.clicker.com

## Hints and Tips

- Do you really need to promote diversity?
- Use extinction (20m)
  - Simple n' easy

## Hints and Tips

- Do you really need to promote diversity?
- Use extinction (20m)
- Use lexicase selection (20m)
  - Simple n' easy
  - Only useful for aggregate fitness (combination of several components)

## Hints and Tips

- Do you really need to promote diversity?
- Use extinction (20m)
- Use lexicase selection (20m)
- Use an island model (2h)
  - Far better than multistart (if migrations are properly handled)
  - Only useful if different experiments yield different results

## Hints and Tips

- Do you really need to promote diversity?
- Use extinction (20m)
- Use lexicase selection (20m)
- Use an island model (2h)
- Use fitness holes (20h)
  - Tweak selection operator(s)
  - Only useful if a global (and efficient) diversity measure is available

## Hints and Tips

- Do you really need to promote diversity?
- Use extinction (20m)
- Use lexicase selection (20m)
- Use an island model (2h)
- Use fitness holes (20h)
- Use real niching (2-20d)
  - Only useful if the distance between genotypes is meaningful

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## Conclusion?


Image by Alexas_Fotos