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PEGA: probabilistic environmental gradient-driven genetic algorithm considering epigenetic traits to balance global and local optimizations

Key words: Evolutionary algorithm; Epigenetics; Epigenetic algorithm; Probabilistic environmental vector; Variable nucleosome reorganization

Corresponding author: Shunkun YANG
E-mail: ysk@buaa.edu.cn
ORCID: https://orcid.org/0000-0002-2580-4529

Motivation

Epigenetics' flexibility in terms of finer manipulation of genes renders unprecedented levels of refined and diverse evolutionary mechanisms possible. From the epigenetic perspective, the main limitations to improving the stability and accuracy of genetic algorithms are as follows:

- (1) the unchangeable nature of the external environment, which leads to excessive disorders in the changed phenotype after mutation and crossover;
- (2) the premature convergence due to the limited types of epigenetic operators.

Main idea

- Considering the inconsistency of gene weights at different positions on the chromosome, a new operator named multi-dimensional exponential environmental vector (MEEV) is proposed to balance the uneven schema importance by adopting different mutation probabilities for each gene. This operator can make the local suboptimal solution stably converge to the local optimal solution from the perspective of searching scale.
- A probabilistic environmental gradient (PEG) strategy is proposed based on the local gradient information, and a heterogeneous exponential probabilistic distribution is constructed for individual mutation to generate more offspring along the gradient in the solution space. This gradient-oriented offspring generating mechanism can speed up the local optimal convergence from the perspective of searching direction.
- We newly design a variable nucleosome reorganization (VNR) operator for finer-grained recombination control among gene segments in dynamic evolutionary stages. By gradually increasing the nucleosome radius, the global search is gradually transferred to the local search near the suboptimal solution, so that the overall evolution process can evolve to the global optimal solution as much as possible to obtain a fast and stable convergence.

Framework

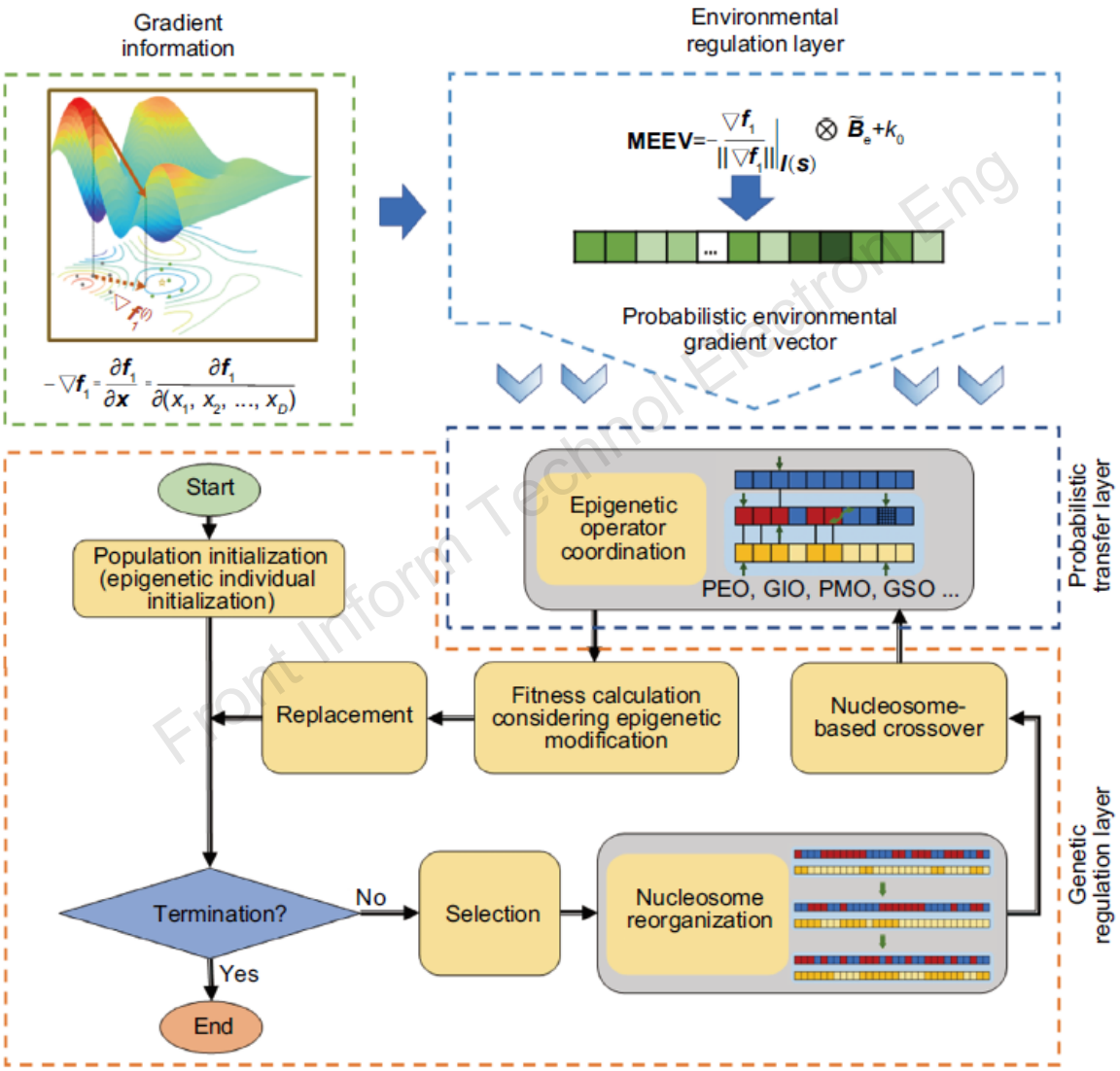
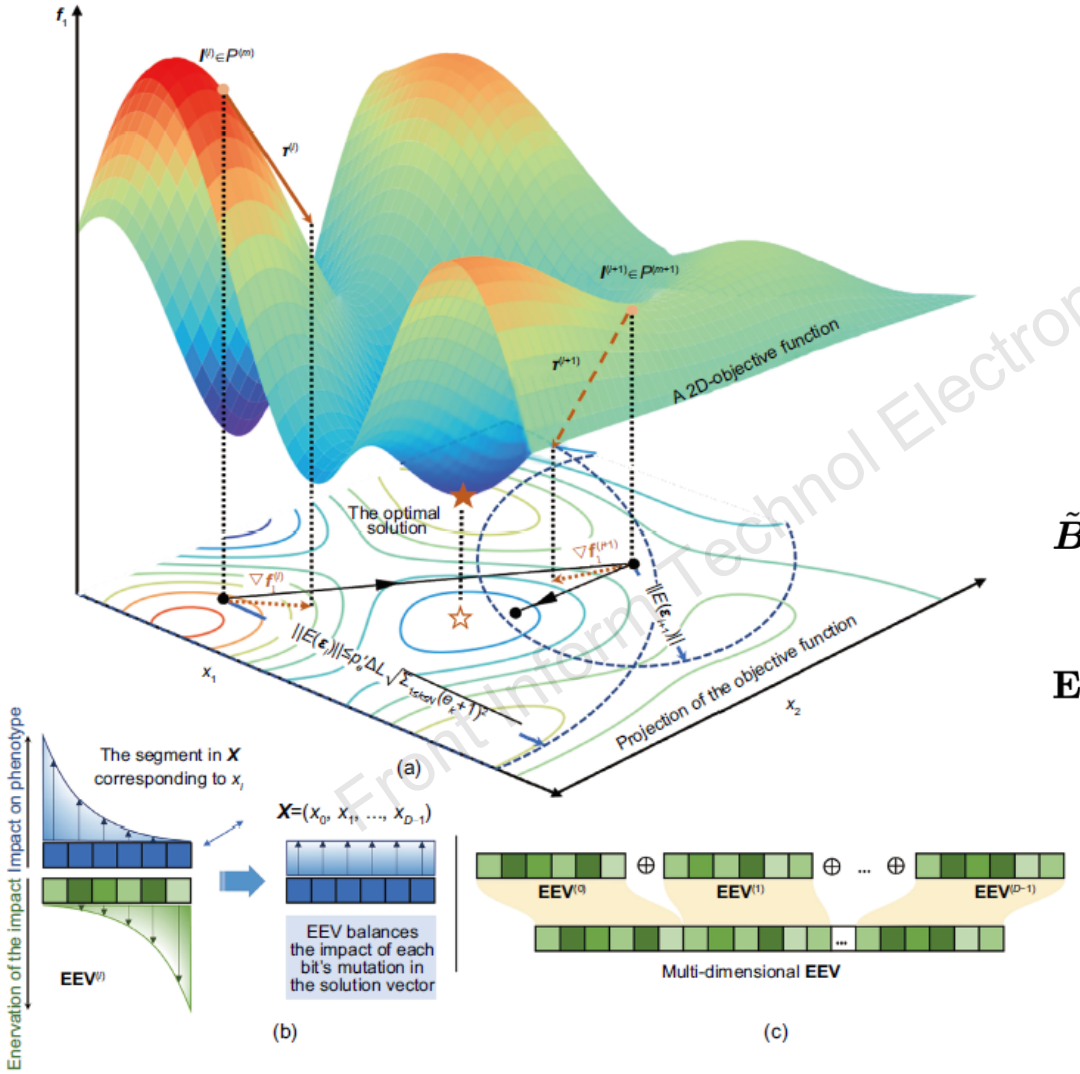


Fig. 2 The proposed probabilistic environmental gradient-driven epigenetic algorithm (PEGA) framework

Method



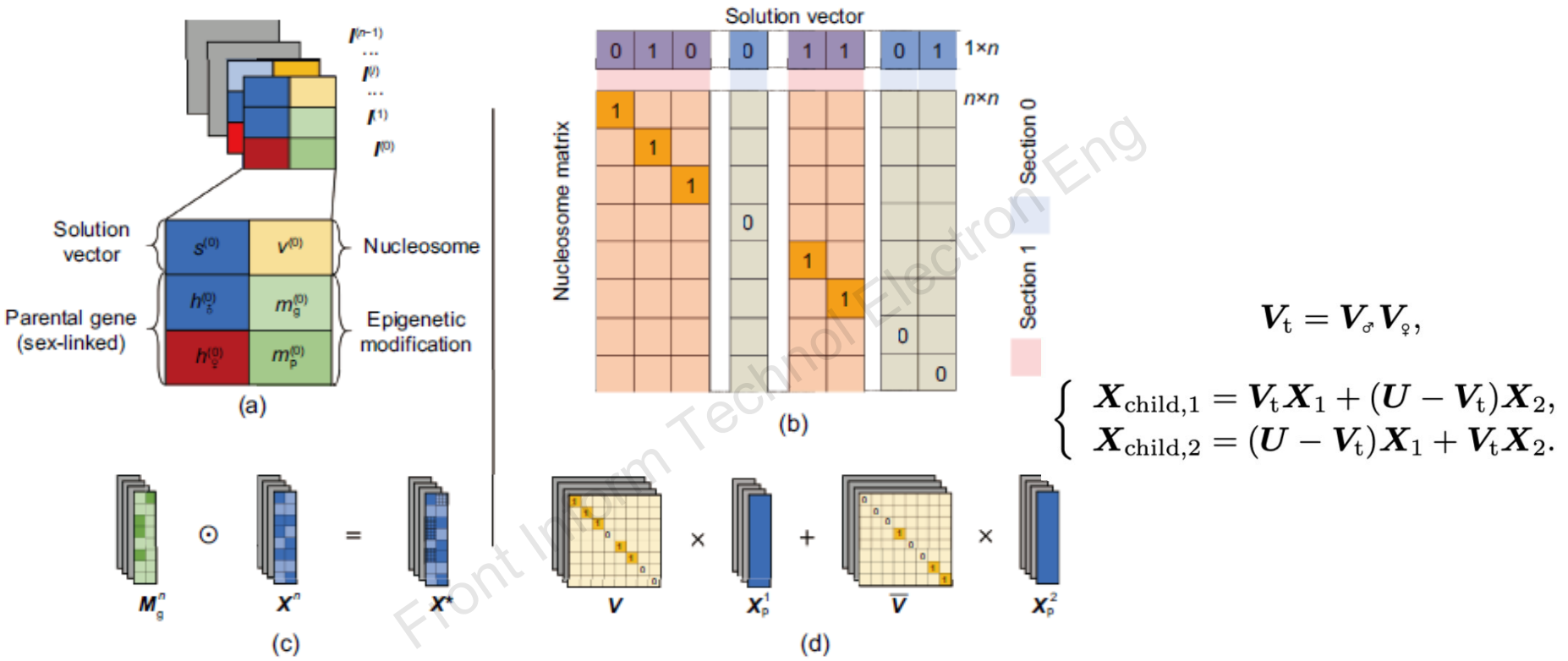
$$\tilde{\boldsymbol{B}}_{\mathrm{e}} = (B_i)_{1\times n},\ B_i = \frac{\kappa_0 \eta^{n-1}}{\eta^{n-1}-1}(1-\eta^i),$$

$$\mathbf{EEV}^{(i)} = -\left(\frac{\nabla \boldsymbol{f}_1}{\|\nabla \boldsymbol{f}_1\|}\bigg|_{\boldsymbol{I}(\boldsymbol{s})}\right)_i \tilde{\boldsymbol{B}}_{\mathrm{e}} + \kappa_0.$$

$$\mathbf{MEEV} = -\frac{\nabla \boldsymbol{f}_1}{\|\nabla \boldsymbol{f}_1\|}\bigg|_{\boldsymbol{I}(\boldsymbol{s})} \otimes \tilde{\boldsymbol{B}}_{\mathrm{e}} + \kappa_0$$

Fig. 3 Three steps for establishing a multi-dimensional environmental vector of probabilistic environmental gradient (PEG) to regulate evolution: (a) compution of gradients for searches based on PEG; (b) establishment of an exponential environmental vector (EEV) with the guidance of PEG; (c) aggregation of the multi-dimensional exponential environmental vector (MEEV) ($P^{(m)}$ denotes the population at the m^{th} generation)

Method



$$\boldsymbol{V}_{\mathrm{t}} = \boldsymbol{V}_{\male}\boldsymbol{V}_{\female},$$

$$\begin{cases} \boldsymbol{X}_{\mathrm{child},1} = \boldsymbol{V}_{\mathrm{t}}\boldsymbol{X}_1 + (\boldsymbol{U} - \boldsymbol{V}_{\mathrm{t}})\boldsymbol{X}_2, \\ \boldsymbol{X}_{\mathrm{child},2} = (\boldsymbol{U} - \boldsymbol{V}_{\mathrm{t}})\boldsymbol{X}_1 + \boldsymbol{V}_{\mathrm{t}}\boldsymbol{X}_2. \end{cases}$$

Fig. 4 Basic data structure and operation relationship in the proposed epigenetic algorithm: (a) epigenetic individual structure; (b) nucleosome matrix based solution vector segmentation; (c) epigenetic modifications; (d) nucleosome-based crossover

Nucleosome-based crossover exceeds traditional crossover process by using a nucleosome matrix. It originally refers to a gene exchange process bounded probabilistically by the nucleosome.

Method

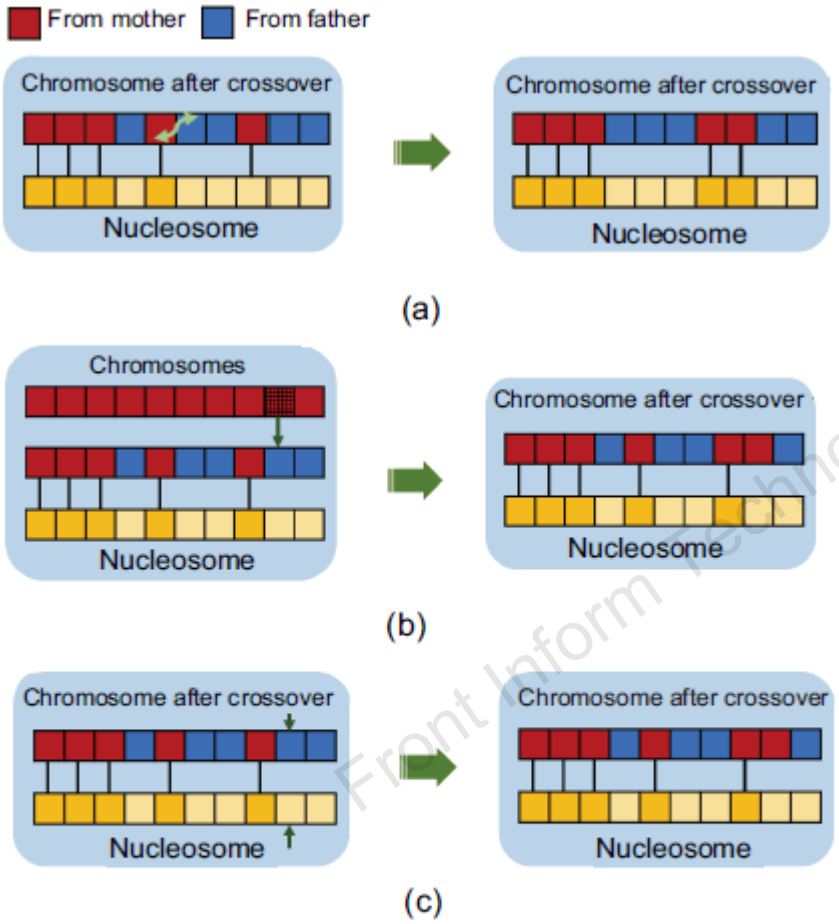


Fig. 5 Three newly introduced different epigenetic operators, i.e., an order-sensitive epigenetic operator (OSEO) and two position-sensitive epigenetic operators (PSEOs): (a) position effect; (b) gene imprinting; (c) paramutation

There are many phenomena in epigenetics that can be used to set different mutation operators. Through the proper selection of operators based on many experiments, a general combination of epigenetic operators is found.

Conclusions

- To address the issue of excessive disorder, an MEEV operator employs varying mutation probabilities for each gene to ensure that the local suboptimal solution converges stably to the local optimal solution. From the search direction perspective, a PEG strategy, using a heterogeneous exponential probabilistic distribution, was designed to accelerate local optimal convergence. Additionally, a VNR operator was implemented to balance exploitation and exploration capabilities, ensuring rapid and stable convergence. To prevent premature convergence, multiple epigenetic operators were organized to generate diverse mutation patterns.
- Experiments on 29 CEC' 17 based benchmark functions were conducted to evaluate the performance of PEGA. The results indicated that the proposed method outperforms 10 state-of-the-art evolutionary algorithms in terms of accuracy and stability on comprehensive performance.