

Keen: Kotlin Genetic Algorithms Framework

*Thesis for the degrees of
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and
Master of Science in Computing*



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Abstract

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Chapter 1

Theoretical Framework

1.1 Evolutionary Algorithms

In the field of computational intelligence, evolutionary algorithms (EA) [5] are a family of algorithms inspired by the process of natural selection. They are part of the larger field of evolutionary computation,¹ which is a subfield of metaheuristics.²

EAs are algorithms that perform optimization or learning tasks by evolving solutions to a given problem. These tasks may range from function optimization to machine learning or game AI development. EAs have three main characteristics:

- **Population-based:** These algorithms work with a population of solutions, allowing them to explore the search space in parallel.³
- **Fitness-oriented:** The solutions in the population are evaluated using a fitness function, which is a problem-dependent function that assigns a value to each solution based on its quality. The goal of the algorithm is to find the solution with the highest⁴ fitness.
- **Variation-driven:** The candidate solutions are modified using genetic operators, such as mutation, crossover, and selection, to create new solutions. These operators are usually based on the biological processes of mutation and recombination.

While these principles serve as the foundation for most EAs, it's important to note that some variants may prioritize some principles over others, or introduce new principles. This diversity allows EAs to be adapted to a wide range of problems and scenarios.

1.2 Genetic Algorithms

Genetic Algorithms (GA)⁵ [3, 4, 5, 6] are a kind of EA where a *population of individuals*⁶ representing candidate solutions to an optimization problem evolves towards better solutions. Each individual is defined by its location in the search space, which is called its *genotype*⁷, and its fitness value, which is calculated with a *fitness function*.

¹See definition A.4 on page 51

²See definition A.9 on page 52

³Not to be confused with parallelization, which is a technique used to speed up the execution of an algorithm by running it in parallel on multiple processors. “Parallel” in this context means that the algorithm is exploring multiple points in the search space (definition A.13 on page 52) simultaneously.

⁴In some cases, the goal is to minimize the fitness function, in which case the algorithm will aim to find the solution with the lowest fitness.

⁵Also known as Simple Genetic Algorithms (SGA) [5], or Traditional Genetic Algorithms (TGA) [6].

⁶See definition A.8 on page 52.

⁷See definition A.7 on page 51

A classical GA works as follows:

Algorithm 1 Genetic Algorithm

```

 $population \leftarrow \text{initializePopulation}()$ 
 $\text{evaluate}(population)$ 
repeat
   $parents \leftarrow \text{selectParents}(population)$ 
   $\text{alter}(offspring)$ 
   $population \leftarrow \text{selectSurvivors}(population, offspring)$ 
until termination condition is met
return fittest( $population$ )

```

Where $\text{initializePopulation}()$ creates a random population of individuals, and $\text{evaluate}(population)$ calculates the fitness of each individual in the population.

The algorithm then repeats the following steps until a termination condition is met:

1. $\text{selectParents}(population)$ selects a subset of individuals from the population to be the parents of the next generation.
2. $\text{alter}(offspring)$ alters the offspring to introduce new genetic material into the population.
3. $\text{evaluate}(offspring)$ calculates the fitness of each individual in the offspring.
4. $\text{selectSurvivors}(population, offspring)$ selects the individuals that will survive to the next generation.

Finally, the algorithm returns the fittest individual in the population.

The actual implementation of each of these steps depends on the problem being solved, and there are many different ways to implement each of them.

1.2.1 Representation and Evaluation

One of the most important aspects of a GA is the representation of the individuals. The representation is the encoding of potential solutions to the problem into a form that can be manipulated by the algorithm. This defines the search space of the algorithm, and it is one of the main factors that determines the performance of the algorithm.

The most general representation of an individual is a matrix of genes⁸ called the *genotype*⁹ of the individual, where each column of the matrix is called a *chromosome*¹⁰.

Definition 1.1 (Cardinality of the search space). The *cardinality of the search space* is the number of different individuals that can be represented by the encoding.

Formally, given a vector of alphabets $(\mathcal{A}_1, \mathcal{A}_2, \dots, \mathcal{A}_n)$, and a representation \mathbf{G} with n chromosomes of length (m_1, m_2, \dots, m_n) where each chromosome is encoded using the alphabet \mathcal{A}_i , the cardinality of the search space S is defined as:

$$|S| = \prod_{i=1}^n |\mathcal{A}_i|^{m_i} \quad (1.1)$$

Note that this definition assumes that the chromosomes are independent, which may not be the same for all evolutionary algorithms.

Remark. In the original publication of the GA [3], the genotype was known as the environment (E) and the search space was defined as a class \mathcal{E} of all possible environments.

⁸See definition A.5 on page 51.

⁹See [20].

¹⁰See definition A.3 on page 51.

To illustrate this concept, consider the following problem: given a binary string of length n , find the string that has the most ones.¹¹ In this case, we can use a single column matrix \mathbf{G} to represent the individual, where each gene $g_i \in \mathcal{A}$ represents the i -th bit of the string, where $\mathcal{A} = \{0, 1\}$ is the alphabet containing the two possible values of a bit.

Then,

$$|S| = \prod_{i=1}^n |\mathcal{A}|^n = 2^n$$

Knowing this, we can conclude that an exhaustive search of the search space would require evaluating 2^n individuals, and thus the algorithm would have a time complexity of $\mathcal{O}(2^n)$.

This is a very simple example, but we can see how a naive search algorithm would have a very high time complexity. This would be of the utmost importance in a real world problem, where the search space would be much larger.

With a representation defined, we can now define an evaluation method for the individuals, which is done using a *fitness function*.

Definition 1.2 (Fitness function). A *fitness function* is a function $\phi : S \rightarrow \mathbb{R}^n$, where S is the search space and n is the number of objectives of the optimization problem, that takes a genotype as input and returns a vector of real numbers representing how close the individual is to the global optimum of each objective.

The fitness function is usually defined by the user of the algorithm, and it is problem dependent.

Definition 1.3 (Batch fitness function). A *batch fitness function* $\Phi : \mathbb{P} \rightarrow \mathbb{R}^{m \times n}$ is a function that maps a population to a matrix of real numbers, where m is the number of individuals in the population and n is the number of objectives of the optimization problem.

The one max problem is a maximization problem with a single objective, so the fitness function would be defined as follows:

$$\phi_{\mathbf{G}} = \sum_{i=1}^n g_i \tag{1.2}$$

In the *Representation and Evaluation* section, we examined the key aspect of a genetic algorithm (GA) — the representation of individuals, their encoding and search space. The performance of a GA significantly depends on how solutions are encoded to form individuals. We use the concepts of genotype, chromosome, and gene to describe the individual’s representation. The cardinality of the search space, defined as the total number of different individuals that can be represented, is crucial as it impacts the algorithm’s complexity. We introduced the “One Max” problem as an example, using a binary string representation. The fitness function, which evaluates individuals’ fitness, plays a critical role in navigating the search for optimal solutions. In the “One Max” problem, the fitness function sums the binary string elements, representing the number of ones in the string.

1.2.2 Initialization

GA operates on a group of individuals called a *population*. The algorithm designer must define the size of the population, and how to initialize it. The initialization process is usually random, but it can also be guided by some prior knowledge about the problem being solved. For example, if the problem is to find a solution to a maze, the population could be initialized with individuals that represent paths from the start to the end of the maze. This would speed up the search process, since the algorithm would not have to start from scratch.

Once the population is initialized, the algorithm performs an evaluation of each individual in the population, and assigns a *fitness value* to each individual. This is done in an effort to learn something about the problem, and to guide the search process towards better solutions.

¹¹This is known as the *One Max* problem [17] or *Ones Counting* problem [20].

In the case of the *One Max* problem, there is no prior knowledge about the problem, so the population via a blind search of the search space (in other words, the initialization is random). This is done by generating a random binary string of length n for each individual in the population.

Let's assume that we have a population of size 4, and that the length of the binary strings is $n = 4$.

The initialization process could generate the following individuals:¹²

Generation 0		
Individual	Binary string	Fitness
I_1	1100	2
I_2	0001	1
I_3	0000	0
I_4	0100	1

Table 1.1: Population of individuals in generation 0

	Fitness	Individual
Best	2	I_1
Worst	0	I_3
Average	1	

Table 1.2: Fitness of the individuals in generation 0

In the initialization phase of a genetic algorithm, we define and setup the population of individuals to be used in the search process. This population can be randomly generated or informed by some prior knowledge about the problem at hand. Each individual is evaluated to determine its fitness, guiding the algorithm's search for optimal solutions. In our "One Max" problem example, we initialized a population of four individuals with binary strings of length $n = 4$ and evaluated their fitness. This setup marks the beginning of the evolutionary process, setting the stage for the subsequent stages of selection (section 1.2.3), crossover (section 1.2.4 on page 8), and mutation (section 1.2.4 on page 9).

1.2.3 Selection

Once initialization is complete, the Genetic Algorithm (GA) enters its main loop, where the core evolutionary processes take place. In the GA, a mechanism that simulates natural selection operates, providing fitter individuals with higher chances of survival and breeding opportunities.

Suppose that we have a population P of N individuals, each with a fitness value f_i , where $i \in \{1, \dots, N\}$. Let σ be the survival rate, a parameter controlling the degree of elitism. This is the proportion of individuals that will survive (unmodified) to the next generation. The GA will then select $\lfloor \sigma N \rfloor$ individuals to survive to the next generation, and $\lceil (1 - \sigma)N \rceil$ individuals to be replaced by the offspring.¹³

Definition 1.4 (Selection operator). An operator used to select individuals from a population.

Formally, a selection operator is a function

$$\Sigma : \mathbb{P} \times \mathbb{N} \times \dots \rightarrow \mathbb{P}; (P, n, \dots) \mapsto \Sigma(P, n, \dots)$$

where:

- \mathbb{P} is the set of populations;

¹²Since the nature of genetic algorithms is stochastic, the initialization process could generate different individuals each time the algorithm is run. For this example, we selected a specific set of individuals in a way that makes it easier to get a grasp of the algorithm.

¹³The sole purpose of employing both *floor* and *ceiling* functions is to guarantee that the total number of individuals chosen for survival and replacement equals N , which makes these functions interchangeable in this context.

- \mathbb{N} is the set of positive natural numbers;
- P is a population;
- n is the number of individuals to select from P ;
- $\Sigma(P, n)$ is the population of n individuals selected from P .

The selection operator is typically implemented as a *stochastic* operator, introducing some randomness into the selection process.

As an illustration, consider a *roulette wheel* selection operator¹⁴ applied to a population of four individuals with a survival rate of 0.25. In this selection scheme, each individual is assigned a selection probability proportional to its fitness value (assuming higher fitness is better). The selection probability of an individual i is calculated as follows:

$$p_i = \frac{f_i}{\sum_{j=1}^N f_j} \quad (1.3)$$

In our example, the selection probabilities are detailed in table 1.3.

Individual	Fitness	Selection Probability
I_1	2	0.5
I_2	1	0.25
I_3	0	0.0
I_4	1	0.25

Table 1.3: Selection probabilities for the individuals in the example population.

The selection operator then selects individuals at random, each with a probability equal to their selection probability. Suppose I_2 is selected to survive to the next generation, then I_1 , I_3 , and I_4 will be replaced by the offspring.

This section has introduced the concept of selection in GAs, which will be explored further in section 4.3.1 on page 22. Next, we will delve into variation operators responsible for generating the offspring that will replace the individuals not selected to survive to the next generation.

1.2.4 Variation

Variation is the process of creating new individuals from existing ones in the pursuit of exploring the solution space. This is crucial in a Genetic Algorithm (GA) to avoid premature convergence to sub-optimal solutions. In a GA, variation is achieved by applying *variation operators* to the individuals in the population. The most common variation operators are *crossover* and *mutation*, which will be explored in this section.

Definition 1.5 (Variation operator). A variation operator is used to create new individuals from existing ones. Formally, it is a variadic function represented as

$$\varphi : \mathbb{P} \times \mathbb{R} \times \cdots \rightarrow \mathbb{P}; (P, \rho, \dots) \mapsto \varphi(P, \rho, \dots)$$

where:

- \mathbb{P} is the set of all possible populations,
- \mathbb{R} is the set of real numbers,
- P is the population to be varied,
- ρ is the probability of applying the operator to an individual in the population.

¹⁴See section 4.3.1 on page 23 for a detailed description of the roulette wheel selection operator.

The additional arguments depend on the specific implementation of the variation operator. The role of these arguments will be clarified in section 4.3 on page 22.

Crossover

The variation operator in genetic algorithms often involves a procedure known as *crossover*, which emulates the process of genetic recombination observed in nature.¹⁵ This process involves the exchange of genetic material between two individuals to create a new generation.

Definition 1.6 (Crossover operator). A crossover operator is a variation operator that is used to create new individuals from existing ones by performing a recombination of their genetic material.

Formally, it is a variadic function represented as

$$\Xi : \mathbb{P} \times \mathbb{R} \times \cdots \rightarrow \mathbb{P}; (P, \rho, \dots) \mapsto \Xi(P, \rho, \dots)$$

where:

- \mathbb{P} is the set of all possible populations,
- \mathbb{R} is the set of real numbers,
- P is the population to be varied,
- $\rho \in [0, 1]$ is the probability of applying the operator to an individual in the population.

For the problem under consideration, we utilize a simplified form of the *single-point crossover*¹⁶ operator. This operator selects the first half of the genes from two parent individuals and generates two new offspring by interchanging these selected genes.

For instance, consider two parent individuals selected via the *roulette wheel* selector described earlier: $I_1 = 1100$ and $I_2 = 0001$. The single-point crossover operator selects the first half of the genes from each parent, i.e., 11 from I_1 and 00 from I_2 , and produces a pair of new chromosomes with the first half, and produces two new offspring by exchanging these selected parts: $O_1 = 1101$ and $O_2 = 0000$ (as illustrated in fig. 1.1).

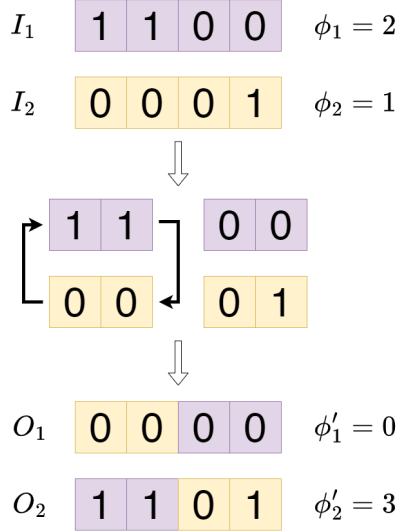


Figure 1.1: Single-point crossover

¹⁵This is referred to as *crossing-over* in [3].

¹⁶See section 4.3.3 on page 30.

Following another iteration of the single-point crossover operator, we can generate a result as shown in table 1.4, leading to a new population $\mathbf{O} = \{(0000, 0), (1101, 3), (0101, 2)\}$.

Generation 0 \rightarrow Generation 1			
\mathbf{I}	$\Phi_{\mathbf{I}}$	\mathbf{O}	$\Phi_{\mathbf{O}}$
$\begin{bmatrix} 1100 \\ 0001 \end{bmatrix}$	$\begin{bmatrix} 2 \\ 1 \end{bmatrix}$	$\begin{bmatrix} 0000 \\ 1101 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 3 \end{bmatrix}$
$\begin{bmatrix} 0001 \\ 0100 \end{bmatrix}$	$\begin{bmatrix} 1 \\ 1 \end{bmatrix}$	$\begin{bmatrix} 0101 \\ \cdot \end{bmatrix}$	$\begin{bmatrix} 2 \\ \cdot \end{bmatrix}$

Table 1.4: Illustration of the single-point crossover operation. In this procedure, two parent individuals are selected and a cut point is chosen. Each offspring is then formed by combining the genes from the parents: one gets the genes from the first part of the first parent and the second part of the second parent, while the other gets the genes from the first part of the second parent and the second part of the first parent. Here, \cdot represents a “discarded” value (since according to the survival rate, only three offspring need to be produced).

If we now use these offspring as-is to create the next generation, we would obtain the population shown in table 1.5:

Generation 1		
Individual	Binary String	Fitness
I_2	0001	1
O_1	0000	0
O_2	1101	3
O_3	0101	2

Table 1.5: Population after applying the single-point crossover operator. Note that I_2 is the survivor of the previous generation picked in section 1.2.3 on page 6.

	Fitness	Individual
Best	3	O_2
Worst	0	O_1
Average	1.25	

Table 1.6: Fitness of the population after applying the single-point crossover operator. “Best” refers to the individual with the highest fitness, and “Worst” refers to the individual with the lowest fitness

As observed from table 1.6, the average fitness of the population has increased from 1 to 1.25, and the fitness of the best individual has improved from 2 to 3. This improvement showcases how the crossover operator helps guide the search towards superior solutions.

While the crossover operation has indeed enhanced the average fitness of the population, to further augment genetic diversity within the population and prevent premature convergence to suboptimal solutions (local optima), the introduction of a *mutation* operator is often beneficial. This operation will be discussed in the next section.

Mutation

One limitation of the crossover operator is its reliance on existing genetic material in the population.

This constraint can lead to premature convergence, particularly for problems with numerous local optima such as the *Rastrigin function* optimization.¹⁷

To counteract this and introduce *diversity* in the population, we use the *mutation* operator.

¹⁷See appendix B.1 on page 53.

This operator alters the genetic material of an individual within the population according to a specific probability.

Definition 1.7 (Mutation operator). A mutation operator is a function that alters the genetic material of individuals within a population based on a certain probability, thereby producing a new population.

Formally, a mutation operator is a variadic function

$$M : \mathbb{P} \times \mathbb{R} \times \cdots \rightarrow \mathbb{P}; (P, \mu, \dots) \mapsto M(P, \mu, \dots)$$

where:

- \mathbb{P} represents the set of all possible populations;
- \mathbb{R} represents the set of real numbers;
- P is the current population;
- μ represents the *mutation rate*—the probability that an individual in the population will undergo mutation.

The other arguments are specific to the mutation operator being used.

For instance, in the “One Max” problem, we can use a *bit-flip* mutation.¹⁸ This operator scans each gene in an individual and substitutes it with its complement according to a predetermined probability.

Suppose we set the *mutation rate* $\mu = 1$, and apply the mutation operator to the population resulting from the crossover operation described in section 1.2.4 on page 8. As shown in ?? on page ??, the resulting population would be $\mathbf{O} = \{(1111, 4), (0010, 1), (1010, 3)\}$.

Generation 0 → Generation 1			
I	$\Phi_{\mathbf{I}}$	O	$\Phi_{\mathbf{O}}$
$\begin{bmatrix} 0000 \\ 1101 \\ 0101 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 3 \\ 2 \end{bmatrix}$	$\begin{bmatrix} 1111 \\ 0010 \\ 1010 \end{bmatrix}$	$\begin{bmatrix} 4 \\ 1 \\ 2 \end{bmatrix}$

Table 1.7: Illustration of the *bit-flip* mutation operator applied to the population resulting from the crossover operation in section 1.2.4 on page 8.

If the mutated offspring were used to generate the next population, as shown in table 1.8, you can observe the increased diversity.

Generation 1		
Individual	Binary String	Fitness
I_2	0001	1
O'_1	1111	4
O'_2	0010	1
O'_3	1010	2

Table 1.8: Population after applying the *bit-flip* mutation operator to the population resulting from the crossover operation in section 1.2.4 on page 8.

¹⁸See section 4.3.2 on page 24.

	Fitness	Individual
Best	4	O'_1
Worst	0	(I_2, O'_2)
Average	2	

Table 1.9: Fitness of the population after applying the *bit-flip* mutation operator to the population resulting from the crossover operation in section 1.2.4 on page 8.

Clearly, the mutation operator has introduced diversity into the population. In the original population, no individual had a 1¹⁹ in the third position. Therefore, the crossover operator could never produce an individual with a 1 in that position. But the mutation operator has introduced three individuals with a 1 in the third position.²⁰

In conclusion, the mutation operator plays a crucial role in genetic algorithms by introducing diversity into the population and preventing premature convergence to local optima. It facilitates a more thorough exploration of the search space, allowing new and potentially beneficial traits to emerge. However, it's essential to note that a high mutation rate might disrupt advantageous traits, while a low rate might not sufficiently prevent premature convergence. The specific mutation operator and the mutation rate used are crucial factors in shaping the genetic algorithm's search process.

With this, the variation process is complete, and we can proceed to the next step of the genetic algorithm.

1.3 Genetic Programming

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¹⁹ $P = \{11\mathbf{00}, 00\mathbf{01}, 00\mathbf{00}, 01\mathbf{00}\}$

²⁰ $P' = \{0001, 11\mathbf{11}, 00\mathbf{10}, 10\mathbf{10}\}$

Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

Chapter 2

Relevant Work (State of the Art)

2.1 Agile Artificial Intelligence in Pharo

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2.5 *GeneticSharp*

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Chapter 3

Introduction

3.1 Motivation

The notion of learning machines has been around since the 1950s, when Alan Turing [1] asked a simple question: “Can machines think?”. Since then, the field of artificial intelligence has grown exponentially, with new applications being developed every day.

The first ideas on programs that simulate natural evolution were proposed by Nils Aall Barricelli [2] in 1954, but was formalized (and popularized) by John Holland [3] in 1975 on his book about genetic algorithms.

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3.2 Hypothesis and Research Questions

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Chapter 4

Keen: Kotlin Evolutionary Algorithms Framework

4.1 Introduction

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4.3 Genetic Operators

4.3.1 Selection

Random Selector

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Roulette Wheel Selector

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Tournament Selector

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4.3.2 Mutation

Bit Flip Mutator

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Random Mutator

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Swap Mutator

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Inversion Mutator

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4.3.3 Crossover

Combine Crossover

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Mean Crossover

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Ordered Crossover (OX)

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Partially Mapped Crossover (PMX)

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Position Based Crossover (PBX)

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Single-Point Crossover

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Single-Node Crossover

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4.4 Genetic Algorithms

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4.5 Genetic Programming

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4.6 Parallelism

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4.7 Extensibility

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4.8 Conclusion

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Chapter 5

Case Study: Real Function Optimization

5.1 Introduction

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5.2 Problem Description

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5.3 Solution

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5.5 Conclusion

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Chapter 6

Case Study: Knapsack Problem

6.1 Introduction

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6.4 Results

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6.5 Conclusion

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Chapter 7

Case Study: Crash Reproduction

7.1 Introduction

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7.3 Solution

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7.4 Results

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7.5 Conclusion

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Chapter 8

Conclusions

8.1 Summary

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8.2 Contributions

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8.3 Future Work

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Appendix A

Glossary

In this appendix we present a glossary of terms used throughout this document as a reference for the reader.

A

Definition A.1 (Alteration). See section 1.2.4 on page 7

Definition A.2 (Alterer). See definition 1.5 on page 7.

C

Definition A.3 (Chromosome). Representation of a single column of genetic information of a candidate solution to a given optimization problem.

Formally, a chromosome is a vector $\mathbf{c} = (g_1, g_2, \dots, g_n)$, where g_i is a gene (see definition A.5).

E

Definition A.4 (Evolutionary computation). Family of algorithms for global optimization inspired by the process of natural selection.

This typically involves processes mimicking natural selection, mutation, recombination, and survival of the fittest. The solutions to a problem are encoded as a set of “individuals” in a “population”. Over multiple generations, these individuals are selected and modified (via genetic operators like crossover and mutation) in order to find better solutions.

G

Definition A.5 (Gene). Representation of a single component of a candidate solution to a given optimization problem.

Formally, for a multi-dimensional function f , a gene is an element g in the domain of f .

Definition A.6 (Generation). Number of iterations performed by an evolutionary algorithm.

Definition A.7 (Genotype). Representation of the full genetic information of a candidate solution to a given optimization problem.

Formally, a genotype is a matrix $\mathbf{G} = (\mathbf{c}_1, \mathbf{c}_2, \dots, \mathbf{c}_n)$, where \mathbf{c}_i is a chromosome (see definition A.3).

I

Definition A.8 (Individual). A candidate solution to a given optimization problem.

Formally, an individual is a pair (\mathbf{G}, \mathbf{f}) , where \mathbf{G} is the genotype (see definition A.7 on the preceding page) and \mathbf{f} is the fitness value of the individual.

M

Definition A.9 (Metaheuristics). Problem-independent algorithmic method that yields a sufficiently good solution within reasonable time for an optimization problem, especially for complex problems where an exact solution is not crucial.

Definition A.10 (Mutator). See definition 1.7 on page 10.

P

Definition A.11 (Phenotype). Same as definition A.8.

Definition A.12 (Population). Set of candidate solutions to a given optimization problem.

S

Definition A.13 (Search space). Set of all candidate solutions to a given optimization problem.

Definition A.14 (Selector). See definition 1.4 on page 6.

V

Definition A.15 (Variadic function). Function that accepts a variable number of arguments.

Appendix B

Test Functions for Optimization

This appendix contains the test functions used in the numerical experiments in chapter 5 on page 36.

B.1 Rastrigin Function

The Rastrigin function is a non-convex function used as a performance test problem for optimization algorithms. It is a typical example of non-linear multimodal function. It was first proposed by Rastrigin in 1974.¹

Definition B.1 (Rastrigin Function). The *Rastrigin function*, $f : \mathbb{R}^n \rightarrow \mathbb{R}$, is defined as:

$$f(\mathbf{x}) = An + \sum_{i=1}^n [\mathbf{x}_i^2 - A \cos(2\pi\mathbf{x}_i)] \quad (\text{B.1})$$

where:

- n is the number of dimensions.
- \mathbf{x} is a vector of n real values.

The global minimum of the Rastrigin function is $f(\mathbf{x}^*) = 0$ at $\mathbf{x}^* = (0, \dots, 0)$. The function has many local minima, which are regularly distributed. The A parameter controls the depth of the local minima. The function is usually evaluated on the hypercube $\mathbf{x} \in [-5.12, 5.12]^n$. A contour plot and a surface plot of the Rastrigin function for $n = 2$ are shown in fig. B.1.

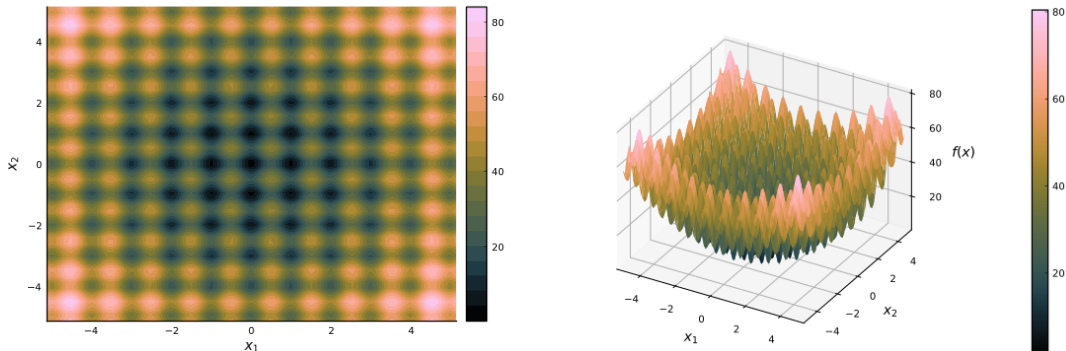


Figure B.1: Rastrigin Function for $n = 2$

¹Rastrigin, L. A. “Systems of extremal control.” Mir, Moscow (1974).

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