Keen: Kotlin Genetic Algorithms Framework

Thesis for the degrees of

Civil Engineer in Computer Science

and

Master of Science in Computing

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Abstract

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Contents

Chapter 1

Theoretical Background

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 highest[4] 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*.
A classical GA works as follows:

[1] See definition A.2
[2] See definition A.7
[3] Not 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 (Def. A.10) simultaneously.
[4] In 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.
[5] Also known as Simple Genetic Algorithms (SGA) [5], or Traditional Genetic Algorithms (TGA) [6].
[6] See definition A.6.
[7] See definition A.5

Algorithm 1 Genetic Algorithm

```
population ← initializePopulation()
evaluate(population)
repeat
    parents ← selectParents(population)
    offspring ← crossover(parents)
    mutate(offspring)
    evaluate(offspring)
    population ← selectSurvivors(population, offspring)
until termination condition is met
return fittest(population)
```

Where initializePopulation() creates a random population of individuals, and 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. selectParents(*population*) selects a subset of individuals from the population to be the parents of the next generation.

2. crossover(*parents*) creates a new population of individuals by combining the parents.

3. mutate(*offspring*) mutates the offspring to introduce new genetic material into the population.

4. evaluate(*offspring*) calculates the fitness of each individual in the offspring.

5. 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 genes[8] called the *genotype* of the individual, where each column of the matrix is called a *chromosome*[9].

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

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

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

[8] See definition A.3.
[9] See definition A.1.

To illustrate this concept, consider the following problem: given a binary string of length n, find the string that has the most ones.[10] 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,

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

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 $f : S \to \mathbb{R}^n$, 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.

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

$$f(\mathbf{G}) = \sum_{i=1}^{n} g_i \tag{1.2}$$

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.
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:[11]

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

Generation 0

Individual	Binary string	Fitness
I_1	0010	1
I_2	0110	2
I_3	0000	0
I_4	1000	1

Table 1.1: Population of individuals in generation 0

	Fitness	Individual
Best	2	I_2
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 (**??** on page ??), crossover (**??** on page ??), and mutation (**??** on page ??).

1.3 Genetic Programming

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Chapter 2

Relevant Work (State of the Art)

2.1 Agile Artificial Intelligence in Pharo

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2.2 *DEAP*

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2.3 *Jenetics*

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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 Nills 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 Hyphotesis and Research Questions

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3.3 Objectives

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3.4 Methodology

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3.5 Structure

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Chapter 4

Keen: Kotlin Evolutionary Algorithms Framework

4.1 Introduction

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4.2 Architecture

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4.3 Genetic Algorithms

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4.5 Parallelism

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4.6 Extensibility

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4.7 Conclusion

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Chapter 5

Case Study: OneMax

5.1 Introduction

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5.5 Conclusion

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Chapter 6

Case Study: Knapsack Problem

6.1 Introduction

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Chapter 7

Case Study: Crash Reproduction

7.1 Introduction

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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 that may not be familiar to the reader, but are not explained in the main text due to their common use in the field.

C

Definition A.1 (Chromosome)**.** Representation of a single column of genetic information of a candidate solution to a given optimization problem.
Formally, a chromosome is a vector $\mathbf{c} = (g_1, g_2, \ldots, g_n)$, where g_i is a gene (see definition A.3).

E

Definition A.2 (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.3 (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.4 (Generation)**.** Number of iterations performed by an evolutionary algorithm.

Definition A.5 (Genotype)**.** Representation of the full genetic information of a candidate solution to a given optimization problem.
Formally, a genotype is a matrix $\mathbf{G} = (\mathbf{c}_1, \mathbf{c}_2, \ldots, \mathbf{c}_n)$, where $\mathbf{c}_i$ is a chromosome (see definition A.1).

I

Definition A.6 (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.5) and $\mathbf{f}$ is the fitness value of the individual.

M

Definition A.7 (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.

P

Definition A.8 (Phenotype)**.** Same as definition A.6.

Definition A.9 (Population)**.** Set of candidate solutions to a given optimization problem.

S

Definition A.10 (Search space)**.** Set of all candidate solutions to a given optimization problem.

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