Journal of Theoretical Biology 383 (2015) 28–43

Contents lists available at ScienceDirect

Journal of Theoretical Biology

journal homepage: www.elsevier.com/locate/yjtbi

Toward a unifying framework for evolutionary processes

Tiago Paixão [a,*], Golnaz Badkobeh [c], Nick Barton [a], Doğan Çörüş [b], Duc-Cuong Dang [b], Tobias Friedrich [d], Per Kristian Lehre [b], Dirk Sudholt [c], Andrew M. Sutton [d], Barbora Trubenová [a]

[a] Institute of Science and Technology, Am Campus 1, A3400 Klosterneuburg, Austria
[b] University of Nottingham, UK
[c] University of Sheffield, UK
[d] Hasso Plattner Institute, Potsdam, Germany

HIGHLIGHTS

○Variation operators (mutation and recombination).○Selection operators.
- Formalizing several common examples of these operators in terms of our framework.
- Proving that these common operators respect the properties that we define for their class.
- Casting several classical models and algorithms from both fields into our framework.
- A unifying framework for evolutionary processes.
- Formalizing the defining properties of the different kinds of processes:

ARTICLE INFO

Article history:
Received 27 November 2014
Received in revised form
8 July 2015
Accepted 15 July 2015
Available online 26 July 2015

Keywords:
Population genetics
Evolution
Evolutionary computation
Mathematical modelling

ABSTRACT

The theory of population genetics and evolutionary computation have been evolving separately for nearly 30 years. Many results have been independently obtained in both fields and many others are unique to its respective field. We aim to bridge this gap by developing a unifying framework for evolutionary processes that allows both evolutionary algorithms and population genetics models to be cast in the same formal framework. The framework we present here decomposes the evolutionary process into its several components in order to facilitate the identification of similarities between different models. In particular, we propose a classification of evolutionary operators based on the defining properties of the different components. We cast several commonly used operators from both fields into this common framework. Using this, we map different evolutionary and genetic algorithms to different evolutionary regimes and identify candidates with the most potential for the translation of results between the fields. This provides a unified description of evolutionary processes and represents a stepping stone towards new tools and results to both fields.

1. Introduction

Evolutionary computation and population genetics share a common object of study, the evolutionary process. Population genetics tries to understand the evolution of natural populations while evolutionary computation focuses on designing and understanding artificial evolutionary processes used for solving optimization problems. Both fields have developed independently, with very little interaction between them.

Population genetics (PG) studies how evolution is shaped by basic forces such as mutation, selection, recombination, migration among sub-populations, and stochasticity; it forms the core of the modern understanding of evolution (the so-called “modern synthesis”). PG has a long tradition of mathematical modelling, starting in the 1920s with the pioneering work of Fisher, Wright, Haldane and others, and is now a highly sophisticated field in which mathematical analysis plays a central role. Early work focussed on simple deterministic models with small numbers of loci, aiming

* Corresponding author.
E-mail addresses: tiago.paixao@ist.ac.at (T. Paixão), golnaz.badkobeh@googlemail.com (G. Badkobeh), nick.barton@ist.ac.at (N. Barton), dogan.corus@gmail.com (D. Çörüş), Duc-Cuong.Dang@nottingham.ac.uk (D.-C. Dang), friedrich@hpi.de (T. Friedrich), PerKristian.Lehre@nottingham.ac.uk (P.K. Lehre), d.sudholt@sheffield.ac.uk (D. Sudholt), andrew.sutton@hpi.de (A.M. Sutton), barbora.trubenova@ist.ac.at (B. Trubenová).

http://dx.doi.org/10.1016/j.jtbi.2015.07.011
0022-5193/

at understanding how the change in genotype frequencies in a population was affected by basic evolutionary forces. It has since branched out to investigate topics such as the evolution of sexual reproduction, the role of environmental fluctuations in driving genetic change, and how populations evolve to become independent species. Almost all current PG models are restricted to the simplest fitness landscapes. Since natural fitness landscapes are likely to be far more complicated, indeed too complicated to ever be measured completely, there is a need for a theory that describes the speed of adaptation over a broad range of landscapes in terms of just a few key features.

In evolutionary computation (EC), the *evolutionary algorithm* is the basic object of study. An evolutionary algorithm is a computational process that employs operators inspired by Darwinian principles to search a large state space. The basic scheme of an evolutionary algorithm is depicted in Fig. 1. However, specific concrete evolutionary algorithms differ in the details of each step, for example how elements are selected for reproduction or survival, or which variation operators are used. Evolutionary algorithms typically deal with finite populations and consider classes of fitness functions, in contrast with PG that mostly deals with specific instances. Moreover, these classes can be of arbitrary complexity, such as in the case of combinatorial optimization, again in contrast with PG, where mostly the simplest landscapes are considered.

As can be seen, the questions and approaches both fields take are very different. However, the underlying processes share striking similarities. The basic processes of variation and selection, as proposed by Darwin, seem to be required, though these can appear in many different forms. Is there something general that could be said about evolutionary processes? Can we compare different evolutionary processes in a common framework, so that we can identify similarities that may not be obvious? What are the general features of an evolutionary process? What are the required properties of operations such as mutation or recombination? In fact, what is an evolutionary process?

In order to tackle these questions, we propose a general framework that is able to describe a wide range of evolutionary processes. The purpose of such a framework is to enable comparisons between different evolutionary models. We require this framework to be modular, so that different components of the evolutionary process can be isolated and independently analysed. In nature, this separation between the different processes does not necessarily exist. However, even when the different processes become entangled with each other, if the dynamics are slow enough, as is typical in natural systems, their relative order in the life-cycle becomes largely irrelevant. This will allow us to identify evolutionary regimes and evolutionary algorithms that are similar, allowing translation of results between the two fields. Furthermore, comparing related but different models and algorithms will allow us to disentangle the relative role of different processes or choices of process for the speed of adaptation.

A general framework for evolutionary models that is able to integrate models from both EC and PG in a way suitable for comparison should display the following properties:

- The framework should be able to represent the vast majority of different evolutionary processes in a common mathematical framework.
- The framework should be modular with respect to the different mechanistic processes of evolution (mutation, selection, etc.) and describe evolutionary processes as compositions of these processes.
- It should be able to describe both finite and infinite populations and make it easy to relate infinite population models to their stochastic counterparts.

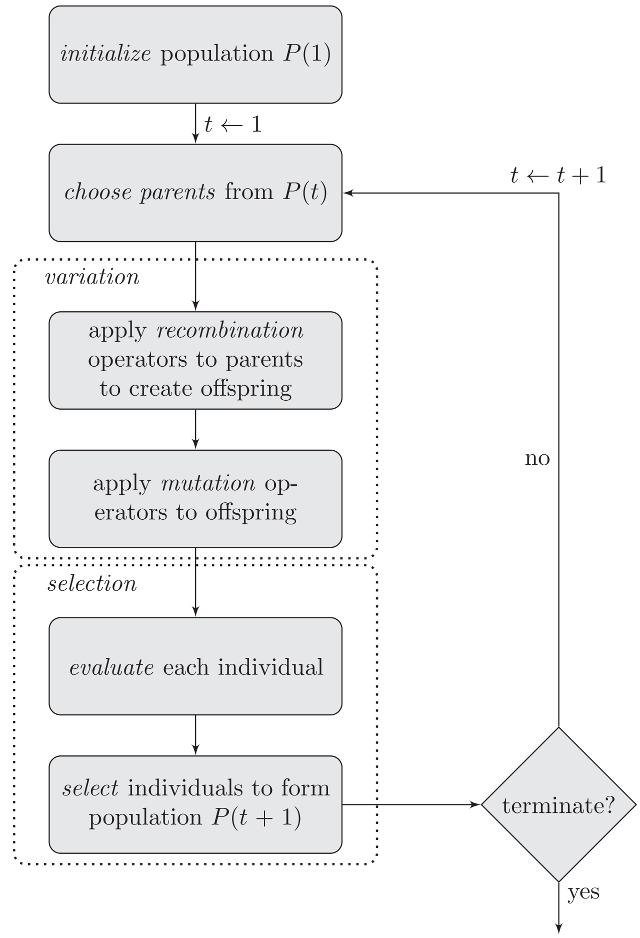

Fig. 1. A basic description of an evolutionary algorithm.

In this report we propose such a framework and we show that by instantiating several evolutionary processes within this framework we can find unsuspected similarities between different evolutionary algorithms and evolutionary regimes.

There have been several attempts at creating a general framework to describe different models in both PG and EC (Altenberg, 1995; Affenzeller, 2005), although none that created a general framework to describe different models in both. In the following section we review some of these other attempts at general models of evolution.

2. Related work

2.1. Population genetics models

In population genetics the dynamics of evolution are typically described in terms of the dynamics of allele or genotype frequencies. In a certain sense, this type of framework is a general model of evolution, albeit not a very useful one, because of its generality. It is akin to saying that the theory of differential equations is a general model of dynamics. However, there have been a few attempts at formalizing this dynamical process into more structured forms, suitable for comparison between different models.

Lewontin (1964) first introduced a general model of evolution for deterministic systems that is cast in terms of frequencies of genotypes. In this model, a basic recursion is defined that describes