Evolution and Probability

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1. Introduction

2. The mechanisms of evolution

3. Predictability

4. Conclusions
Natural selection is a mechanism for generating an exceedingly high degree of improbability.

R. A. Fisher
Evolution as Progress
Evolution as Progress

- Eohippus
- Oligohippus
- Merychippus
- Pliohippus
- Modern horse
Evolution as Progress
Evolution as Progress

How could the human eye be evolved?

Varifocals
The adaptation paradox

Probability: $2^{-1000} \sim 1/10^{300}$ ???
And yet...

The octopus eye
The devil dwells in the details...

Evolution shaped an eye very similar to the vertebrate one, but via a wholly independent process!
Evolution and tinkering

[...] natural selection does not work as an engineer works. It works like a tinkerer [...] who uses everything at his disposal to produce some kind of workable object.

F. Jacob
Small revealing imperfections...

The recurrent laryngeal nerve

- Superior laryngeal nerve
- Larynx
- Left recurrent laryngeal nerve
- Vagus nerve
- Aortic arch
- Trachea
- Esophagus
The recurrent laryngeal nerve

- Nervus laryngeus inferior
  - Inferior laryngeal nerve
- Nervus vagus
  - Vagus nerve
- Nervus laryngeus recurrens
  - Recurrent laryngeal nerve
  - Arteria corotis
  - Carotid artery
  - Arcus aortae
  - Aortic arch
  - Ductus arteriosus Botalli
  - Botalli’s duct
- Aorta dorsalis
  - Dorsal aorta
- Arteria pulmonalis
  - Pulmonary artery
- Cor
  - Heart

Small revealing imperfections...
The recurrent laryngeal nerve corresponds to the fourth vagus nerve, and turns around the sixth arterial arch which is active in the fetus and is located in the chest.
Evolution as diversification

The Scala naturæ

R. Llull
Evolution as diversification

The tree of life

Ch. Darwin, 1837
Evolution as diversification

The tree of life

E. Haeckel
Evolution as diversification

The tree of life

Bacteria
- Spirochetes
- Proteobacteria
- Cyanobacteria
- Planctomycetes
- Bacteroides
- Cytophaga
- Thermotoga
- Aquifex

Archaea
- Green Filamentous bacteria
- Gram positives
- Methanosarcina
- Methanobacterium
- Methanococcus
- T. celer
- Pyrodicticum

Eukaryota
- Entamoebae
- Slime molds
- Animals
- Fungi
- Plants
- Ciliates
- Flagellates
- Trichomonads
- Microsporidia
- Diplomonads

From Wikipedia
Success probability

- In hindsight, each tree branch appears as the result of a highly improbable process directed towards the present state.
- Looking from the root, there are so many viable choices that the probability of getting “somewhere” is close to one.
- And anyway almost 99% of the species which existed are now extinct...: Most roads led to nowhere!
The mechanisms of evolution

**Reproduction:** Similar begets similar

**Selection:** “Survival of the fittest” (Spencer)

**Mutation:** Selection acts on a population which remains heterogeneous

Describing the evolutionary process requires a probabilistic approach
The Wright-Fisher model: The neutral case
The Wright-Fisher model: The neutral case
The Wright-Fisher model: The neutral case
The Wright-Fisher model: The case with selection
Selecting the improbable
Selecting the improbable
Failures of selection
Wright-Fisher model with selection and mutations

A. Nourmohammad et al., 2013
Yeast cells under clonal evolution for 1,000 generations. Several sets of mutations first increase in frequency but are eventually outcompeted by another lineage.

M. Lässig et al., 2017
Can we predict evolution?

- Details of evolution cannot be predicted
- Some inferences can however be made
- However some aspects can be predicted with present-day techniques
- An example: The choice of influenza vaccines
Darwin’s (and Wallace’s) prediction on the existence of an impollinating insect

‘I have just received such a Box full from Mr Bateman with the astounding Angraecum sesquipedalia [sic] with a nectary a foot long. Good Heavens what insect can suck it’

‘Do you know its marvelous nectary 11 1/2 inches [29.2 cm] long, with nectar only at the extremity. What a proboscis the moth that sucks it, must have! It is a very pretty case.’

Darwin, 1862
Xanthopan morganii praedicta was discovered in 1903, but only in 1992 it was shown sucking A. sesquipedale’s nectar.

Arditti et al., 2012
Angraecum sesquipedale and Xanthopan morganii praedicta

X. morganii praedicta’s giant proboscis

Bar: 10cm

Arditti et al., 2012
The evolution in genotypic space exhibits a large number of paths with equal probability. This process is only partially constrained by selection (red points). Genotypic evolution is neither reproducible nor predictable.

Lässig et al. 2017
Evolution in phenotypic space

The evolution in phenotypic space is more predictable because the number of options is smaller and the options can be distinguished and ranked.

Lässig et al. 2017
Evolution of quantitative traits

Distribution of a quantitative trait in several populations

(a) Stabilizing selection (constant optimum)
(b) Adapting evolution (variable optimum)

A. Nourmohammad et al., 2013
Evolution of quantitative traits

Evolution of a quantitative trait in different modes

The evolution pattern allows to identify the selection mode

A. Nourmohammad et al., 2013
The global circulation of influenza

Bedford et al., 2015
The global circulation of influenza

Lässig et al., 2017
The global genealogy of influenza

Bedford et al., 2015
The selection of influenza vaccines

Process of influenza vaccine virus selection and development

Seasonal

1. Collection of specimens and disease/epidemiological data (all year round)
2. Diagnosis, virus isolation in MDCK, preliminary analysis (hours - 3 weeks)
3. Ferret antisera production (3-5 weeks)
4. Thorough antigenic and genetic analysis
5. Review and selection of candidate viruses for vaccine use (1-3 weeks)
6. Classical reassortment of high-growth viruses for H1N1 & H3N2 (3-4 weeks)
7. Antigenic and genetic characterization of reassortants (4 weeks)
8. Development of standardized reagents for inactivated vaccines (6 weeks)
9. Evaluation of growth property (3 weeks)
10. Development of standardized reagents for inactivated vaccines (6 weeks)
11. Antigenic and genetic characterization of reassortants (4 weeks)

Availability of vaccine viruses and standardized reagents

H5N1

2a. Virus isolation in eggs (1-3 weeks)
4a. Serological studies (3-16 weeks)
6b. Reassortment of high-growth viruses using reverse genetics (and full safety testing) (6 weeks)
Nothing in biology makes sense except in the light of evolution (Dobzhansky)

Nothing in evolution makes sense except in the light of probability

The details of genotypic evolution are neither reproducible nor predictable

The evolution of quantitative traits (e.g., antibody effectiveness, but also antibiotic resistance) can be predicted with present-day techniques
Thank you!
Further reading

• R. A. Fisher, The Genetical Theory of Natural Selection (Oxford: Clarendon Press, 1930)
• F. Jacob, Evolution and tinkering, Science 196 1161–1166 (1977)
• J. Arditti et al., ‘Good Heavens what insect can suck it’ – Charles Darwin, Angraecum sesquipedale and Xanthopan morganii praedicta, Botanical Journal of the Linnean Society 169 403–432 (2012)
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• M. Lässig et al., Predicting evolution, Nature ecology & evolution 1 0077 (2017)
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