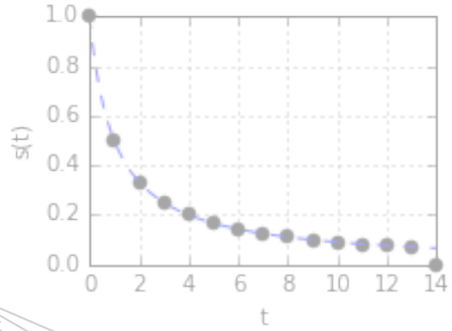
GENETICS

@kaznatcheev



Algorithmic Biology: Evolution is an algorithms; Let us analyze it like one

Artem Kaznatcheev
Department of Computer Science, University of Oxford
Department of Translational Hematology & Oncology Research, Cleveland Clinic
egtheory.wordpress.com

Natural Selection:

Struggle for Existence as the constraint that powers evolution

Machines and Nature:

from Steam Engines to Computers

Algorithmic Biology:

Computational Complexity as the constraint that powers open-ended evolution

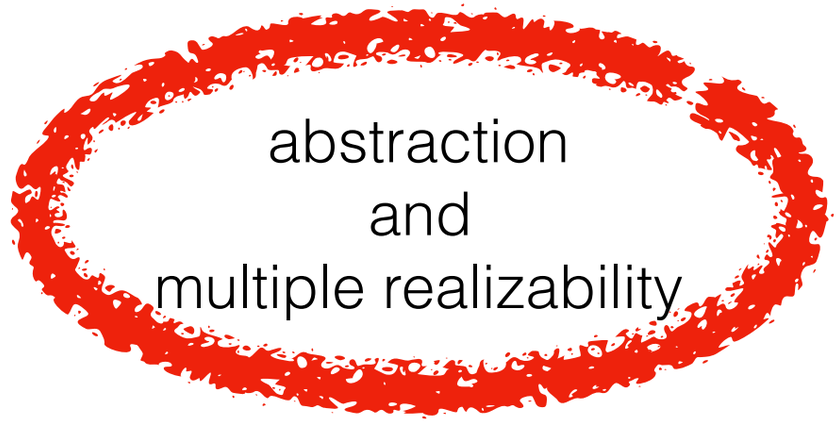
data crunching

Use computer…
… control experiments
… visualize data

simulate experiments

computer programs

genetic algorithms



algorithms

Theorems, lemmas, and proofs

Computational-X ⟷ **Algorithmic-X**

build artificial biologies

bioinformatics

conceptual analysis

Practical skills from CS
applied to the
outputs of field X

Mathematical techniques from CS
applied to the
conceptual grounding of field X

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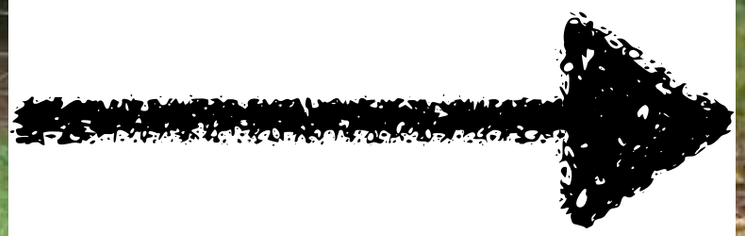
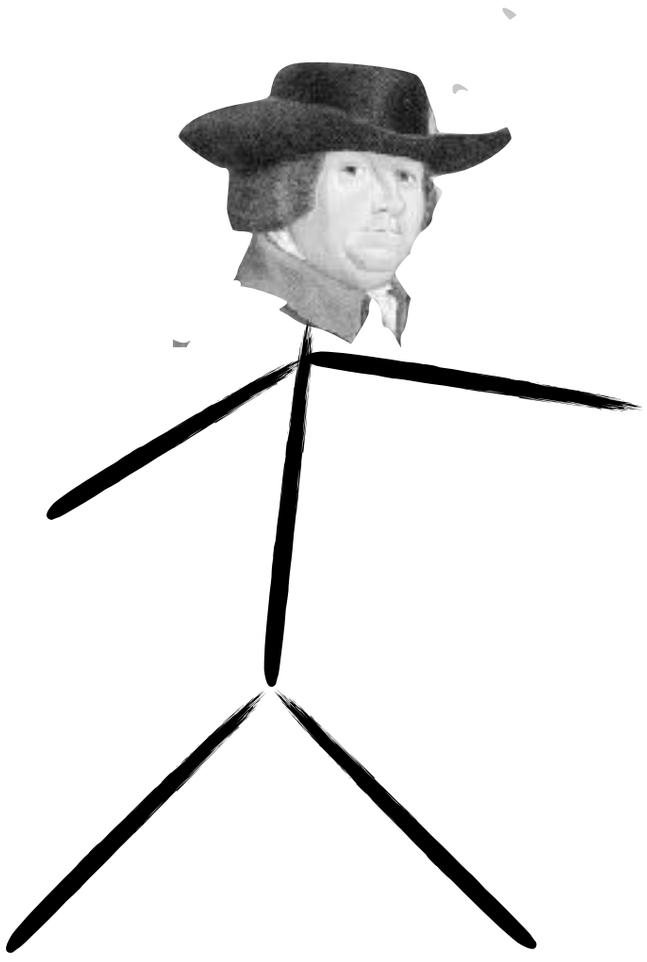
New Technology in the time of Darwin and Wallace



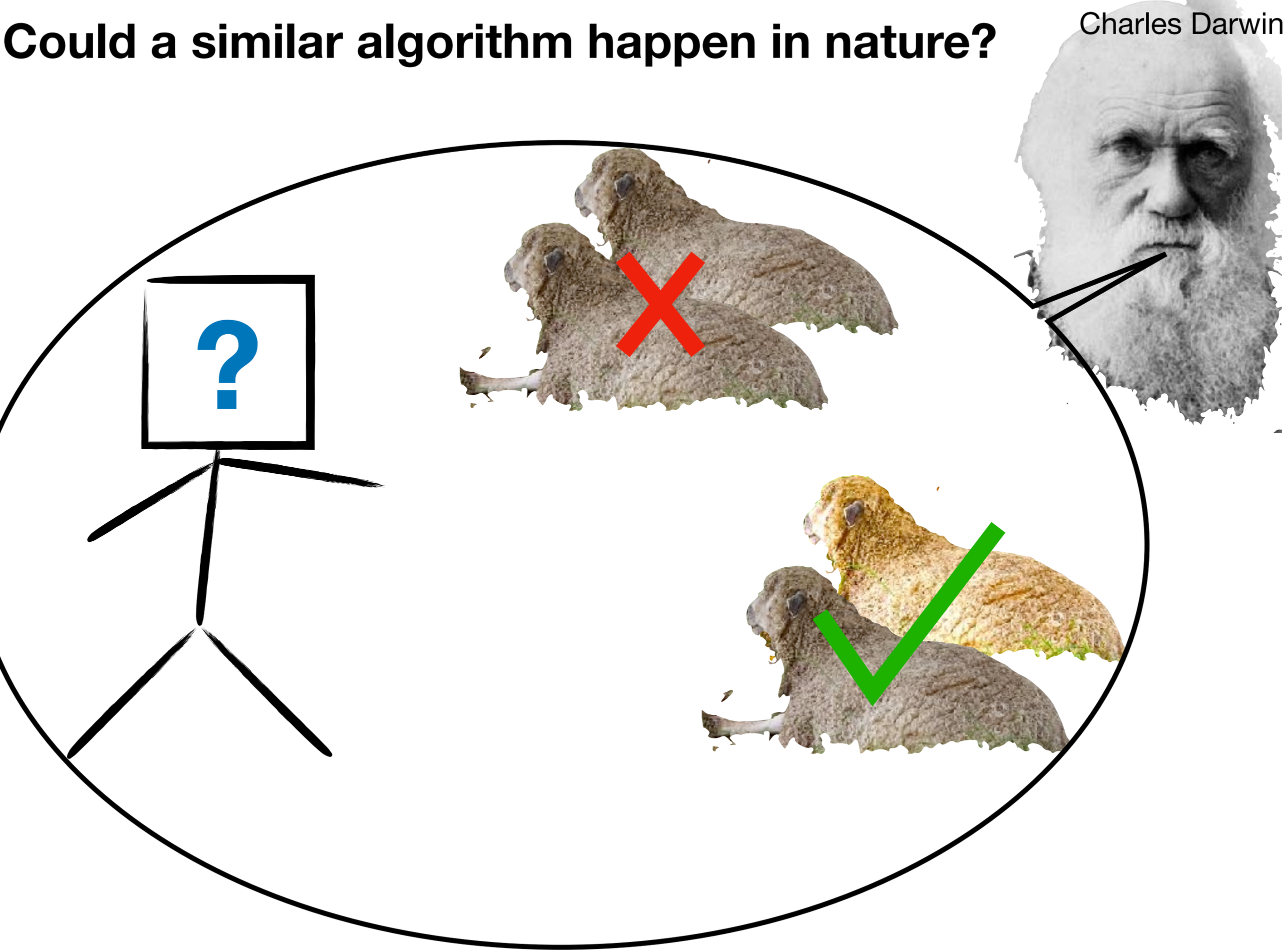
Robert Bakewell

Thomas Coke

Bakewell introduced systematic <u>selective breeding</u>



Could a similar algorithm happen in nature?

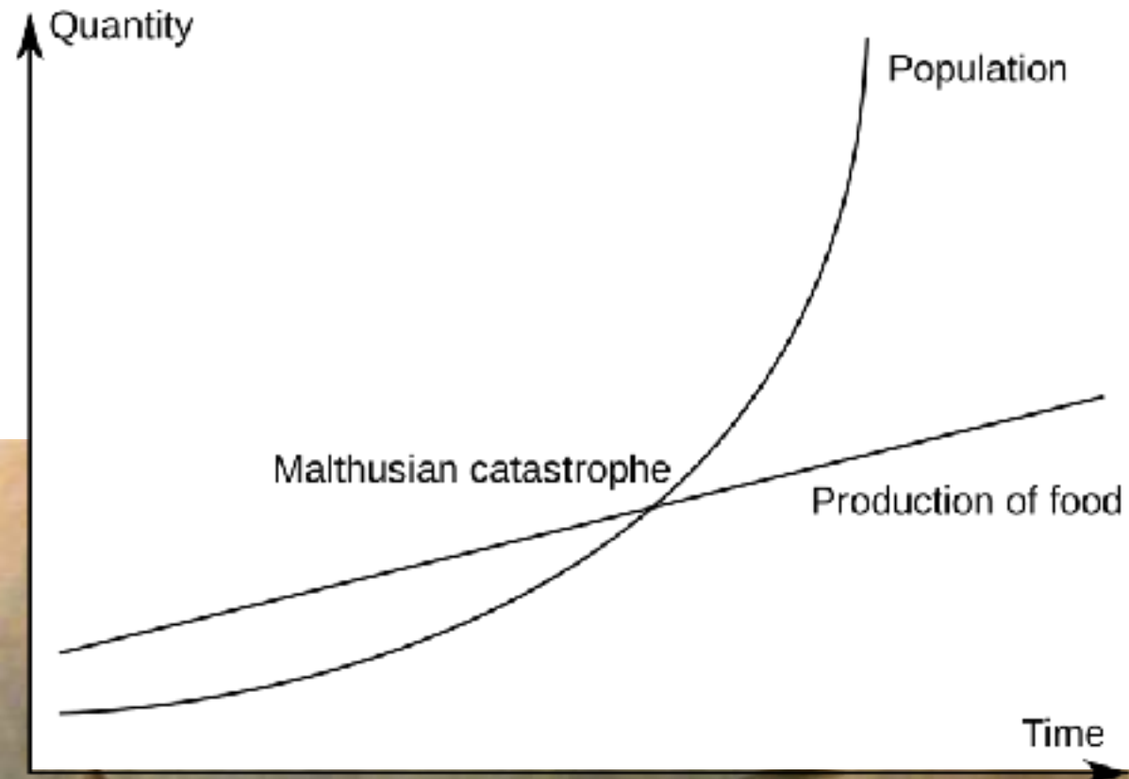


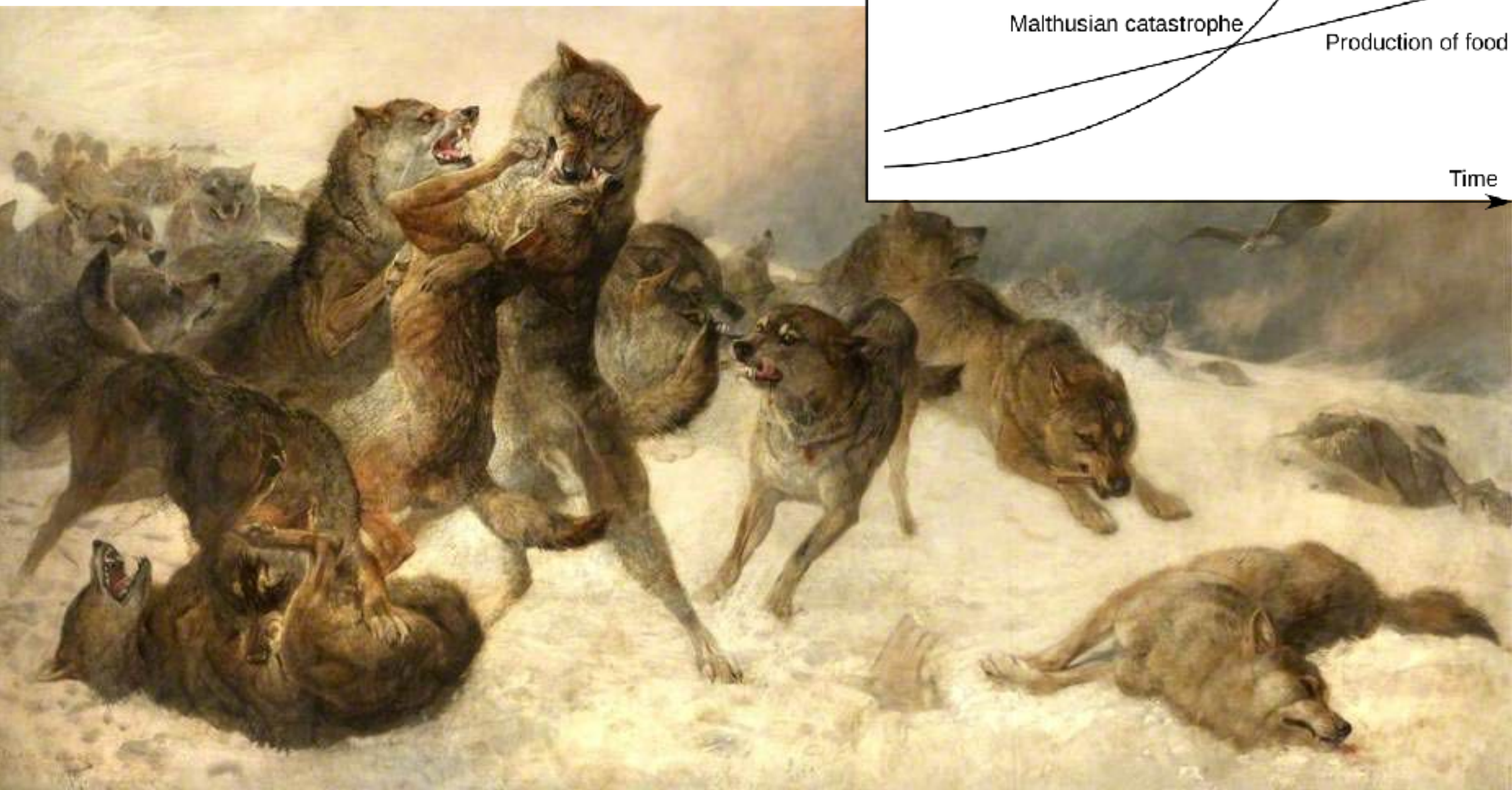
Charles Darwin

Malthus and the *Struggle for Existence*

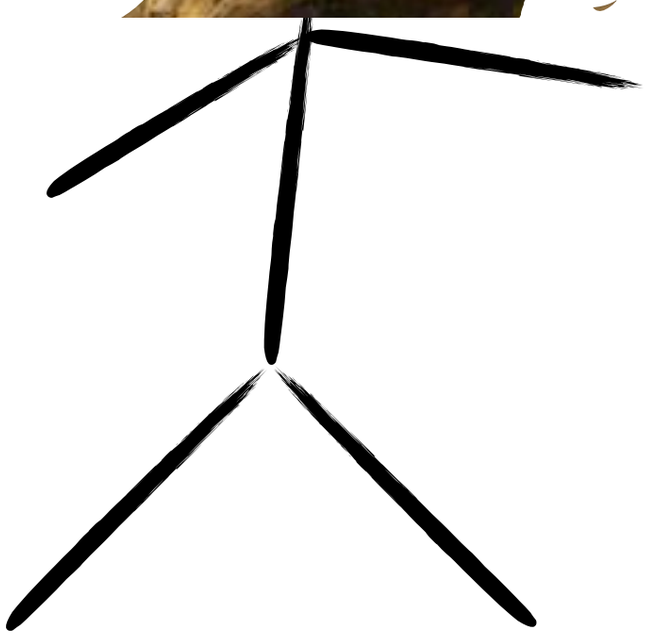
Asymptotic analysis:
big-O of production versus
little-Omega of population

n << 2^n

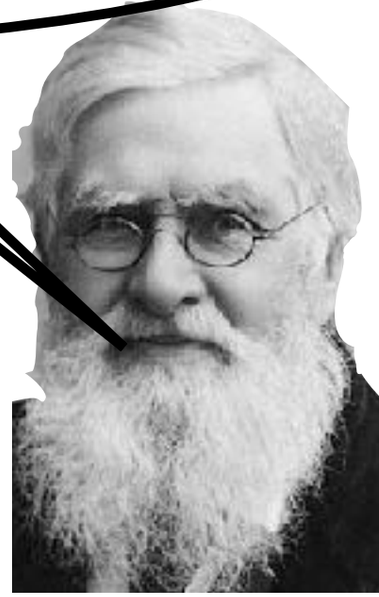




Natural selection

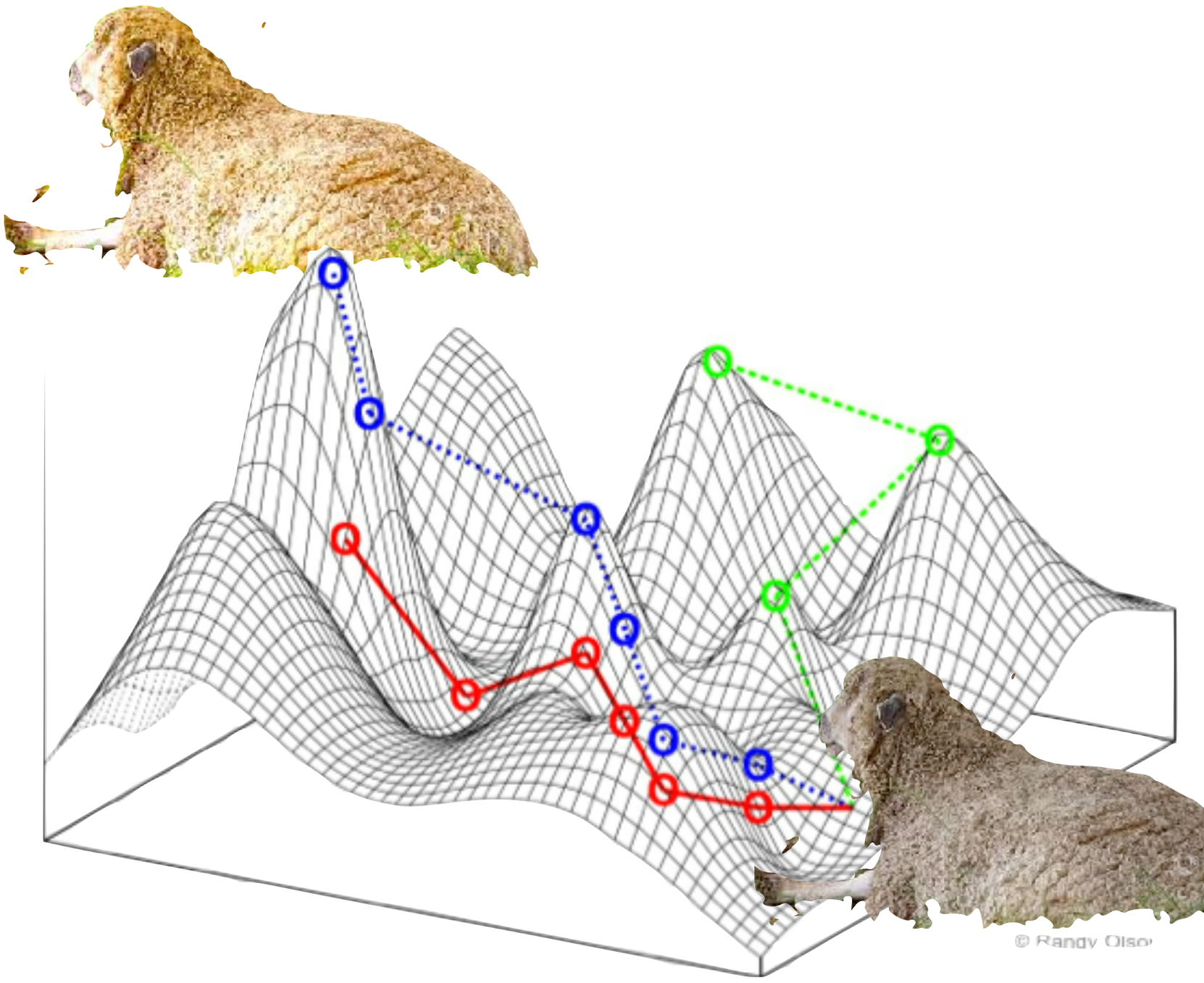


“the action of this principle is exactly like that of the centrifugal governor of the steam engine”



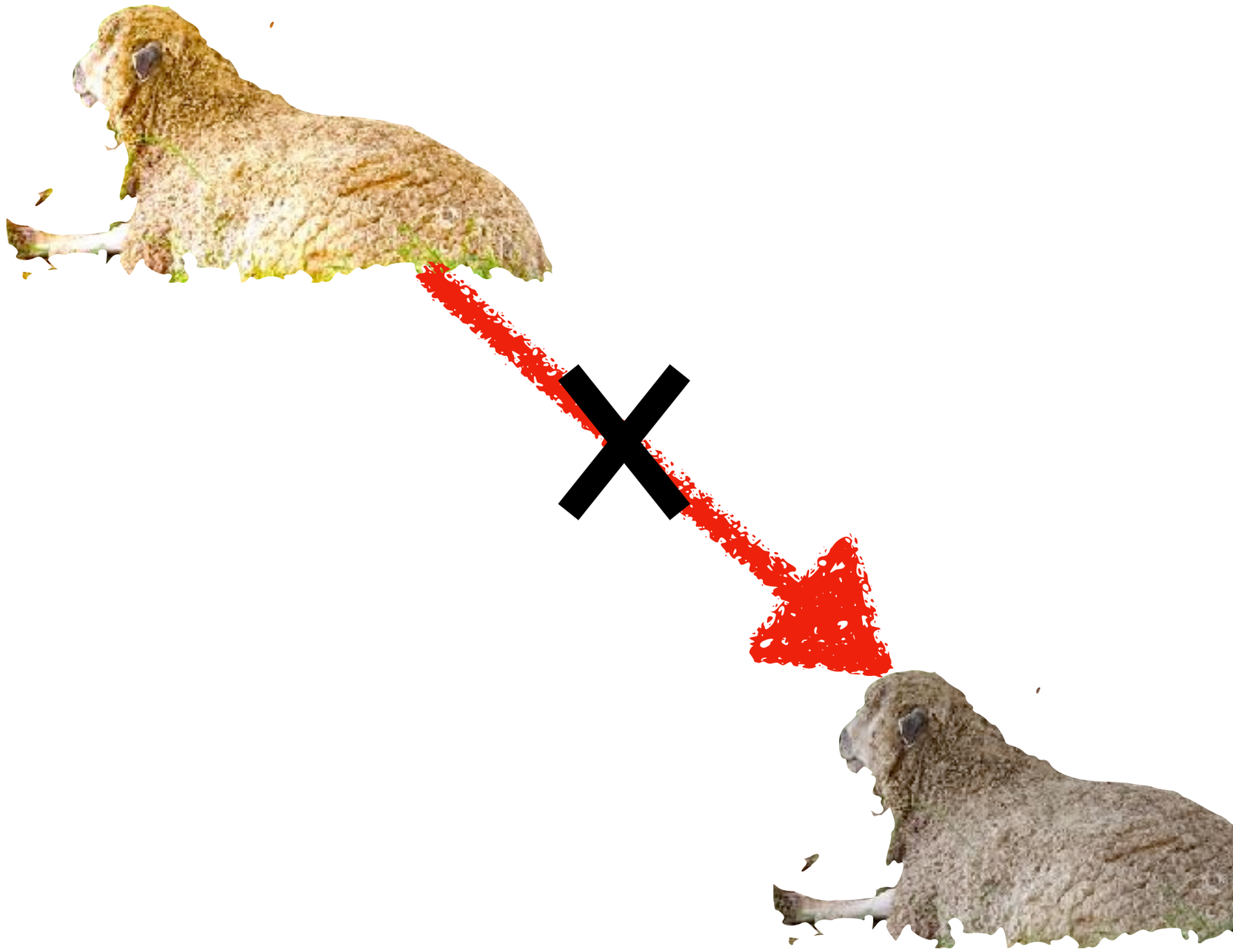
Alfred Russel Wallace

Natural selection: walk up a fitness landscape



Can natural selection produce new species?

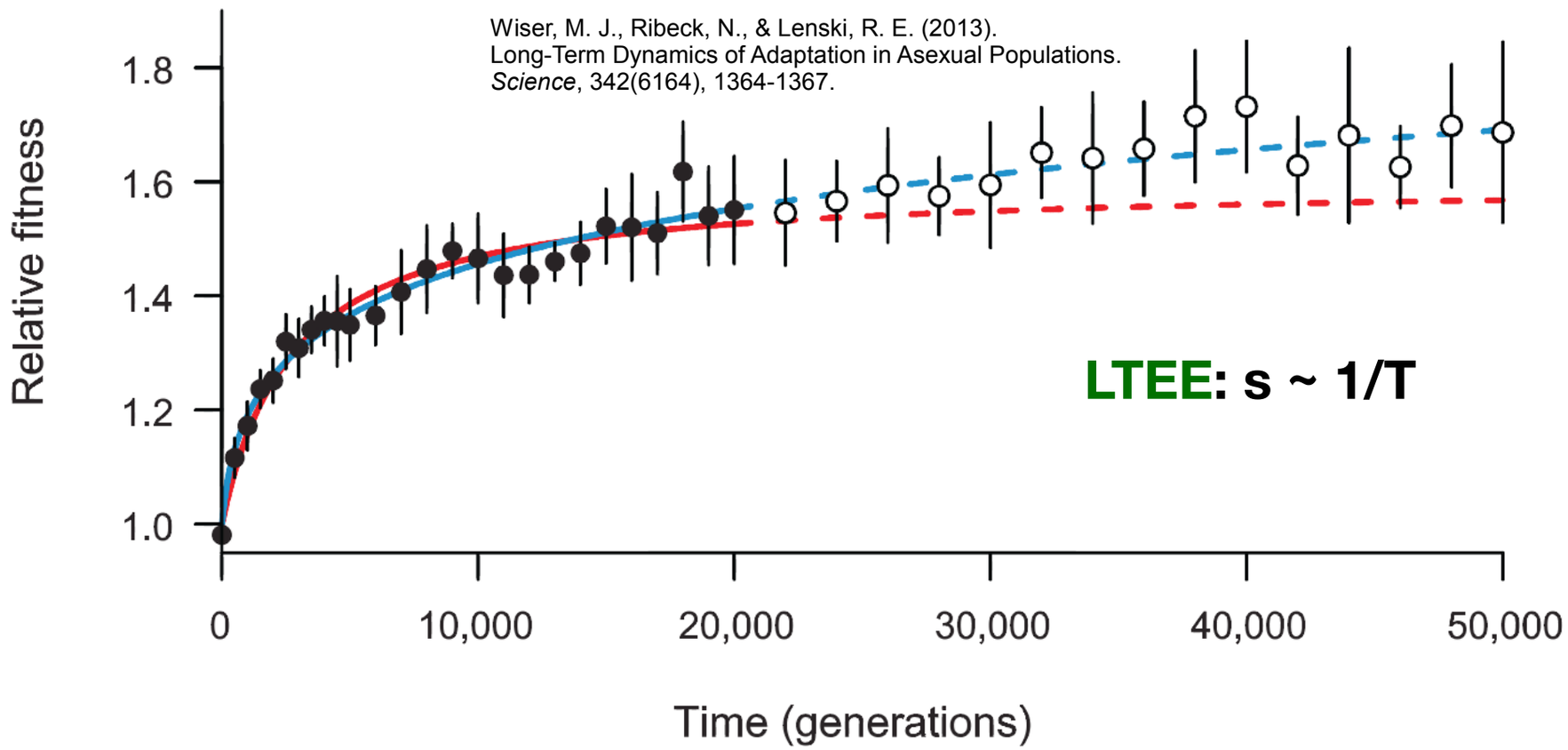
Darwin and Wallace turn to geology:
the world is constantly changing and this geological change gets reflected in biological world



Can natural selection produce new species?

Darwin and Wallace turn to geology:
the world is constantly changing and this geological change gets reflected in biological world

But what about static worlds?



Richard Lenski

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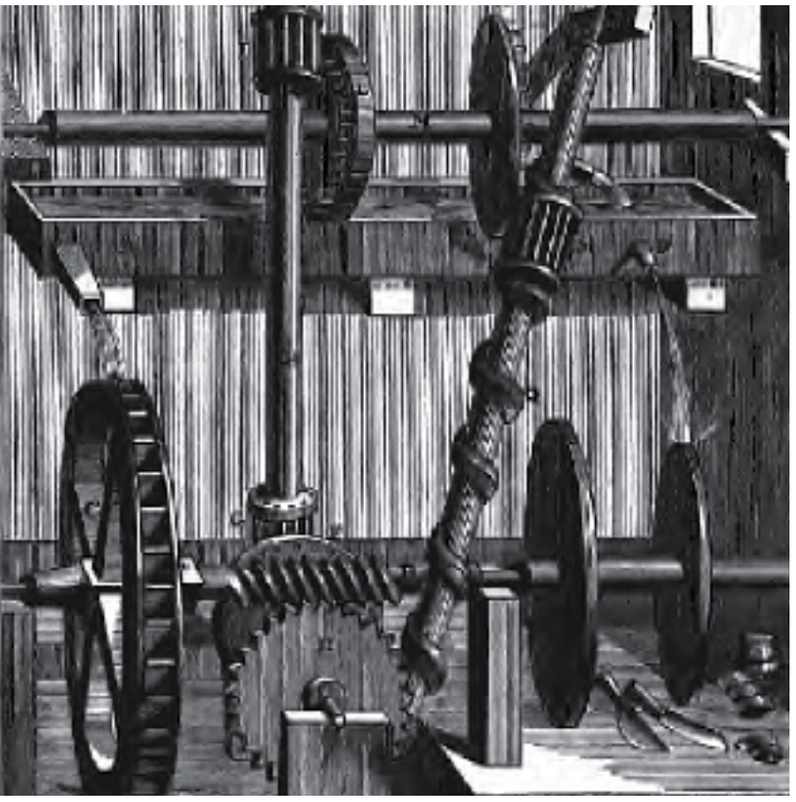
Machines and the Conservation of Energy



Perpetual Motion Machines

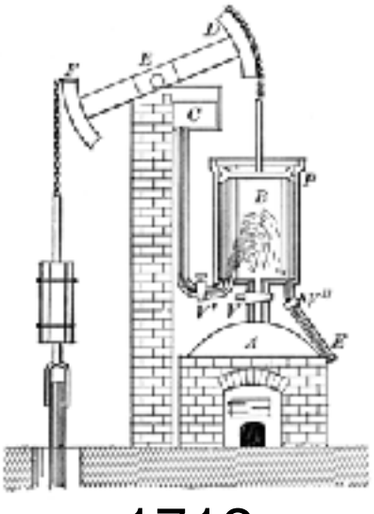
vs.

Conservation of Energy

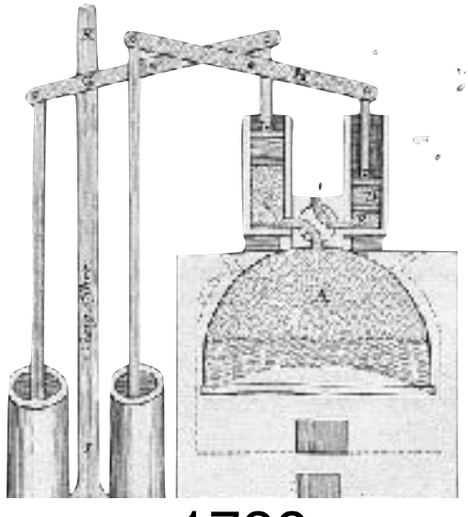
Noether's Theorem (1918)

"What is the design that enables a machine to produce useful work for a perpetual time?"

Is thermodynamics about steam engines?



1712



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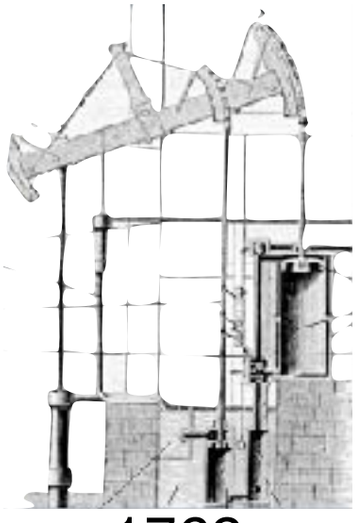
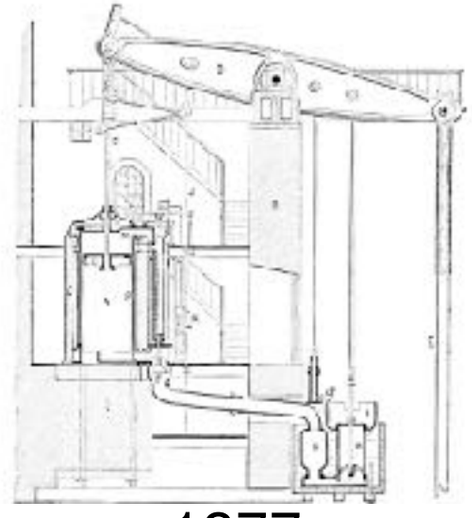
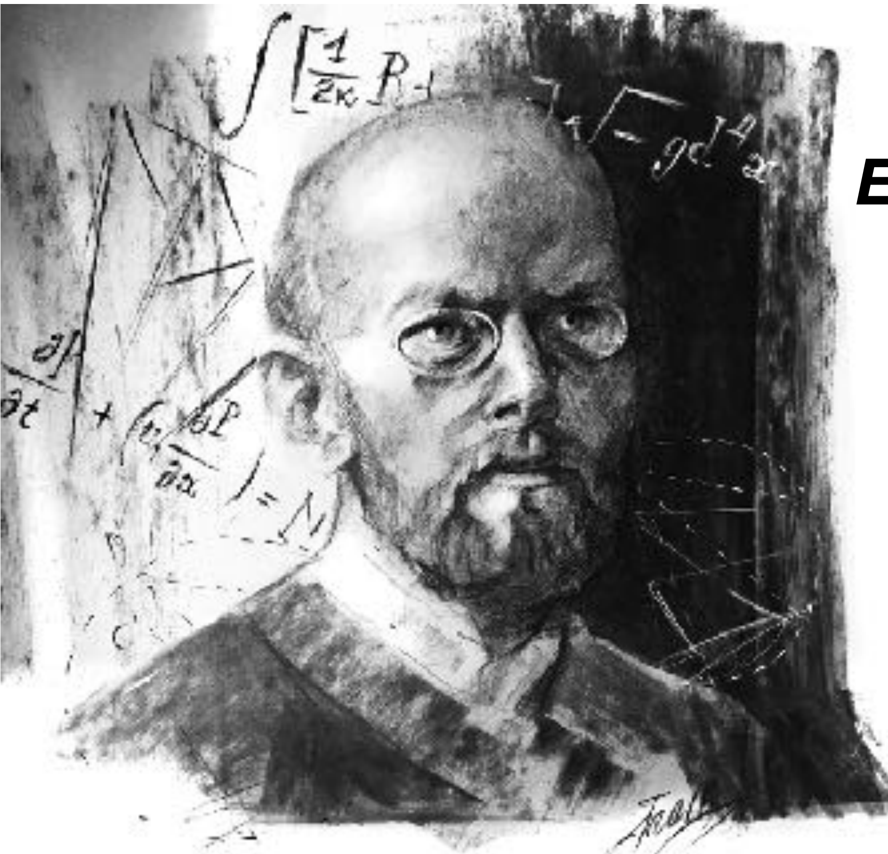


1769



1877

Algorithms and the Complexity of Computation



Entscheidungsproblem

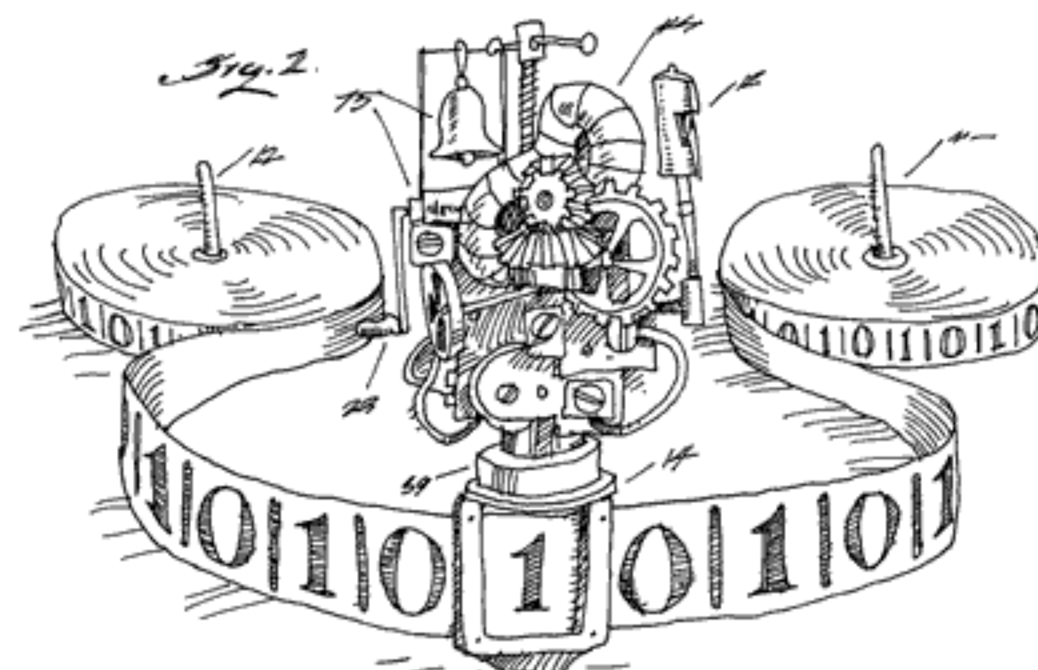
vs.

Complexity of Computation

“What is the procedure that determines for each logical expression for which domains it is valid or satisfiable?”

- Hilbert & Ackermann (1928)

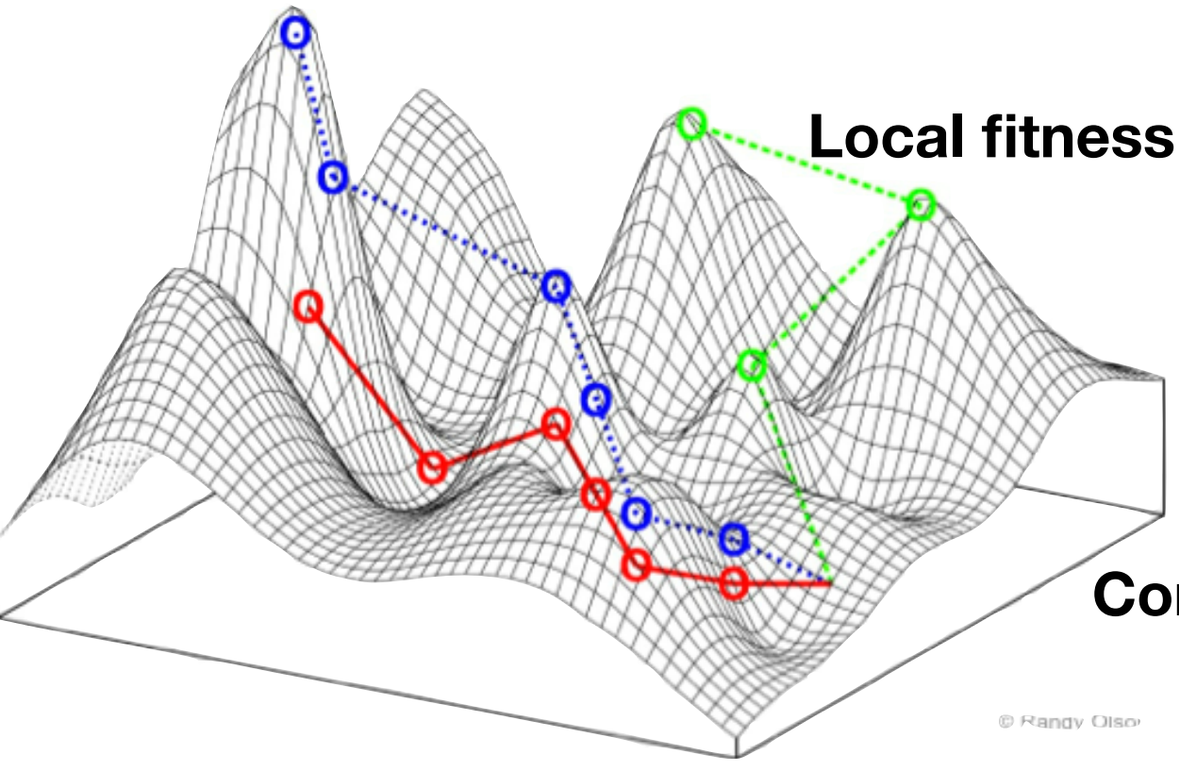
Is theoretical computer science about computers?



Easy: solvable in polynomial time

Hard: general solution requires super-polynomial time

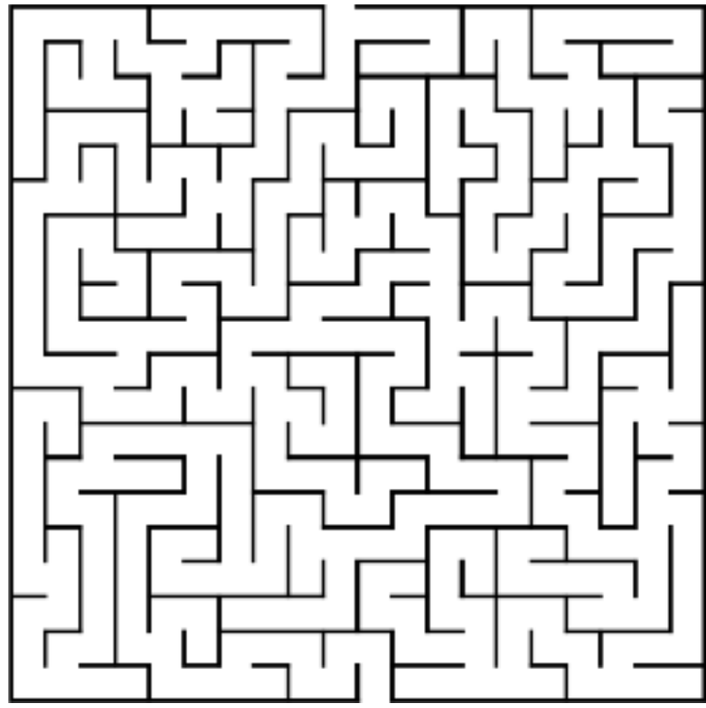
Evolution and the Constraint of Computation



Local fitness peaks

vs.

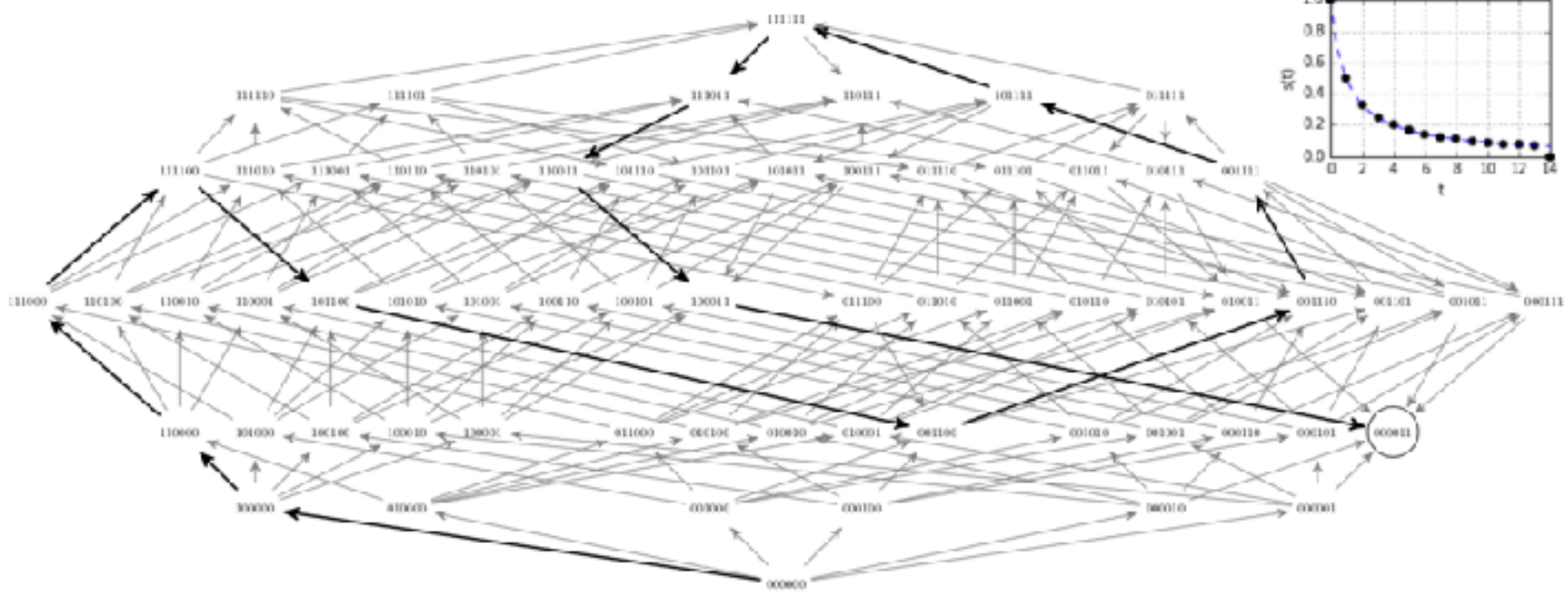
Constraint of Computation



“In a rugged field of this character selection will easily carry the species to the nearest peak”

- Wright (1932)

Kaznatcheev, A. (**2019**)
Computational complexity as an ultimate constraint on evolution
Genetics, 302000.2019



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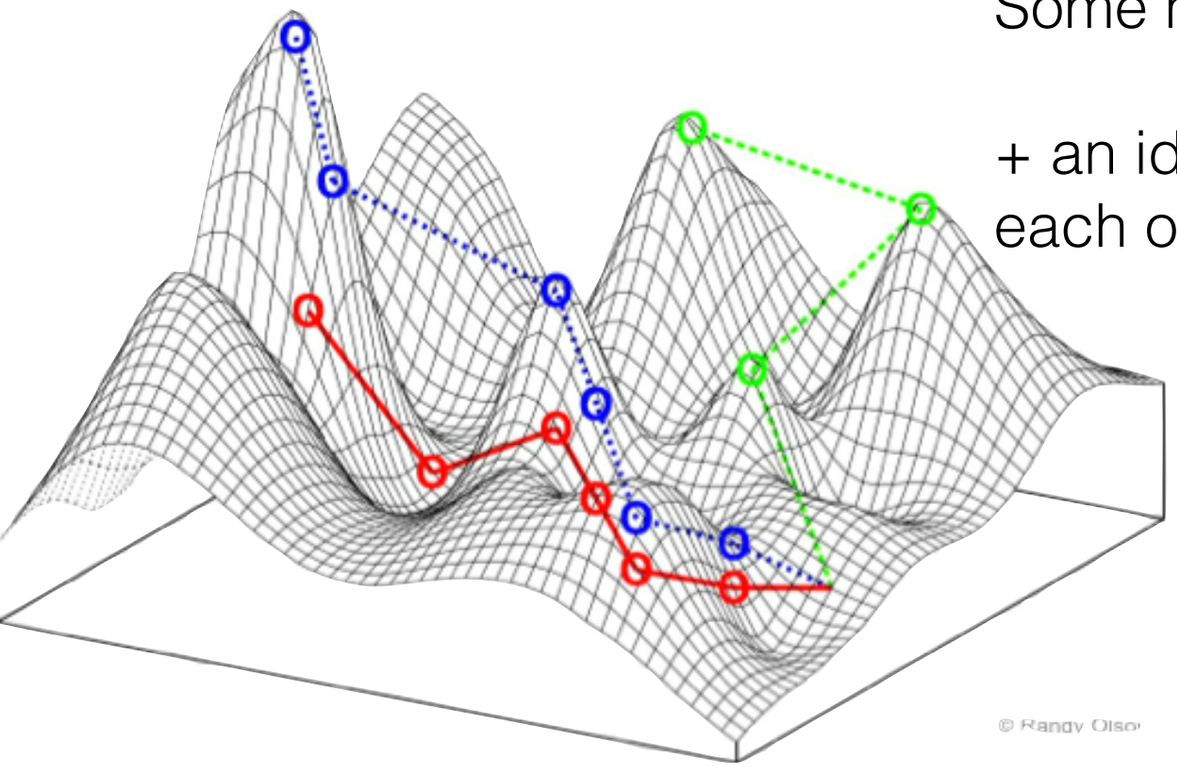
Fitness Landscapes and Constraints



Some mapping from genotypes (or phenotypes) to fitness.

+ an idea of which genotypes (or phenotypes) are near each other and which are not.

A genotype is a **local fitness peak** if all nearby genotypes are of the same or lower fitness

A **constraint** is anything that prevents evolution from finding a local fitness peak

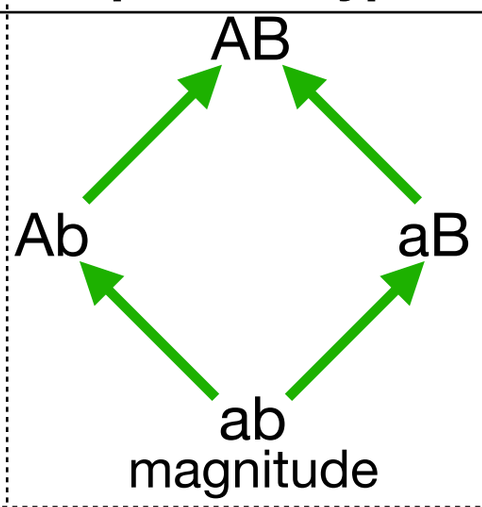
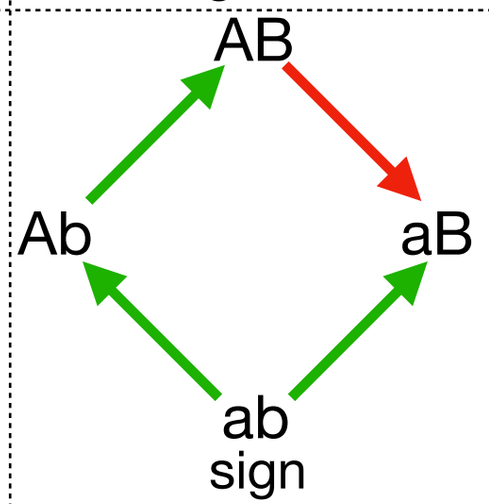
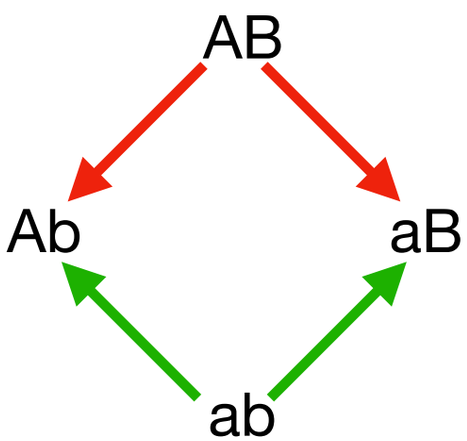
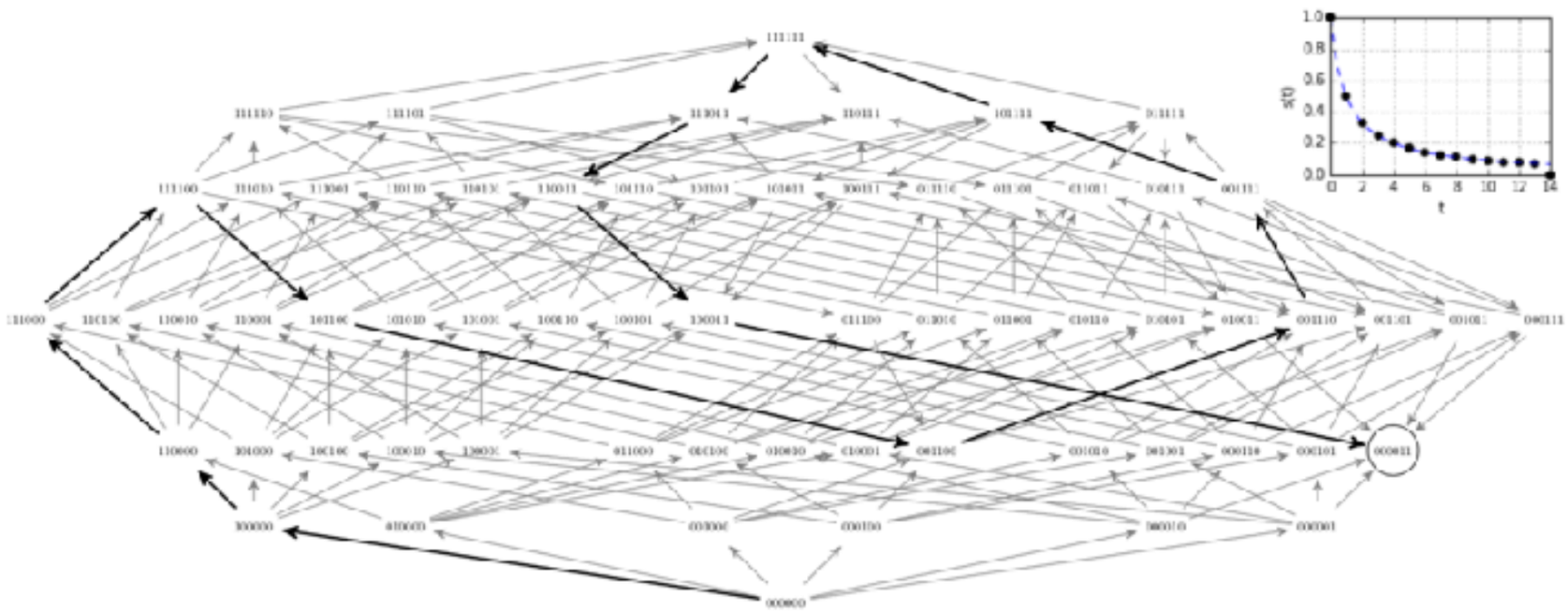
Algorithms and Problems

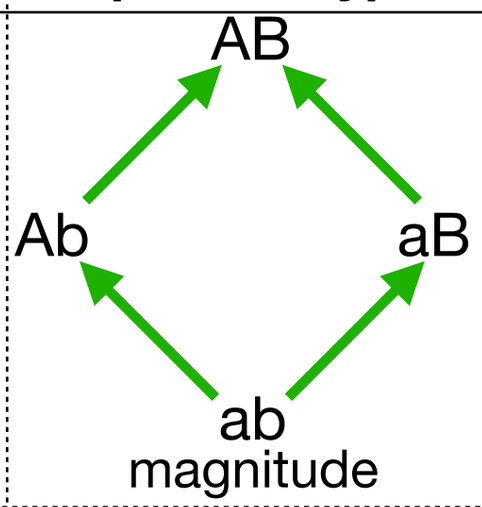
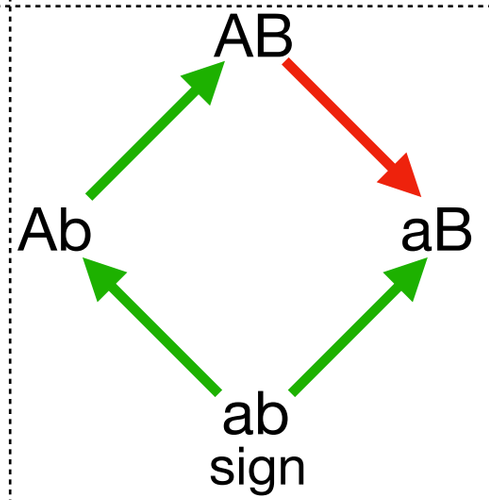
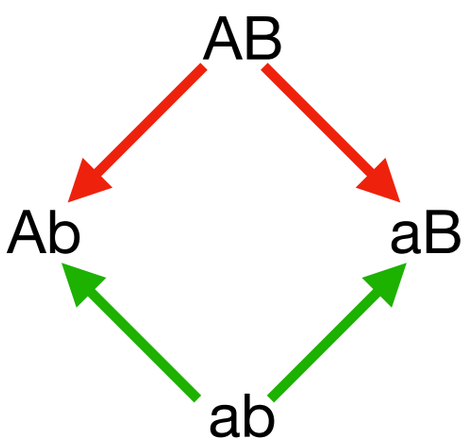
Different population structures, developmental structures, trait co-variants, standing variation, etc…
can produce different evolutionary dynamics and correspond to **different algorithms**

proximal constraints

Families of different fitness landscapes
correspond to **different problems**

ultimate constraints

Landscape type	Max allowed epistasis type	Hardness of reaching local optima
smooth		**Easy** for all strong-selection weak-mutation (SSWM) dynamics
semismooth		**Hard** for SSWM with random fitter mutant or fittest mutant dynamics
rugged	 reciprocal sign	

Landscape type	Max allowed epistasis type	Hardness of reaching local optima
smooth		**Easy** for all strong-selection weak-mutation (SSWM) dynamics
semismooth		**Hard** for SSWM with random fitter mutant or fittest mutant dynamics
rugged	 reciprocal sign	**Hard** for all SSWM dynamics: initial genotypes with all adaptive paths of exponential lengths **Hard** for all evolutionary dynamics (if FP != PLS)

From Constraints to Positive Results: Costly Learning

“Characters individually acquired by members of a group of organisms may eventually, under the influence of selection, be reenforced or replaced by similar hereditary characters”

- Simpson (1958)

Baldwin effect:

1. Organisms adapt to the environment individually.
2. Genetic factors produce hereditary characteristics similar to the ones made available by individual adaptation.
3. These hereditary traits are favoured by natural selection and spread in the population.

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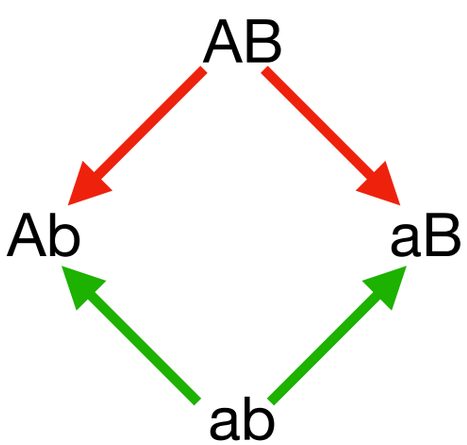
rugged



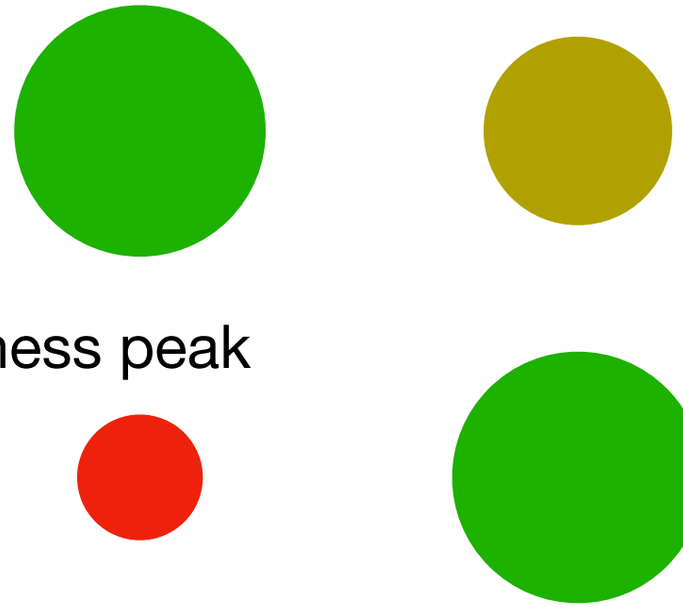
reciprocal sign

Hard for all SSWM dynamics: initial genotypes with all adaptive paths of exponential lengths

Hard for all evolutionary dynamics (if FP != PLS)

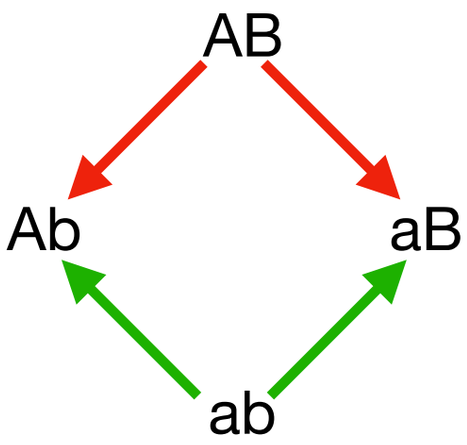
From Constraints to Positive Results: Cooperation

Patch structured population
can maintain cooperation by
hitchhiking on adaptive mutations



… but this effect can only go until we reach a fitness peak

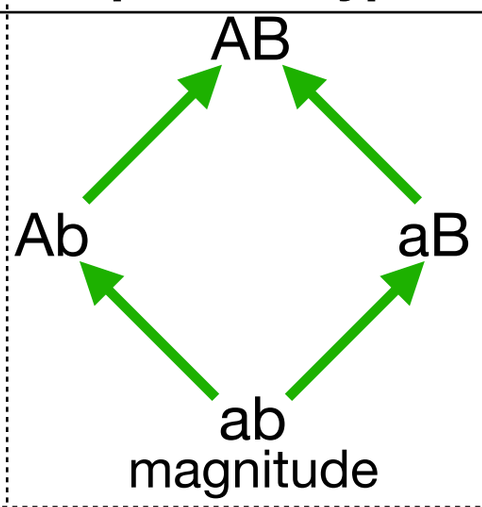
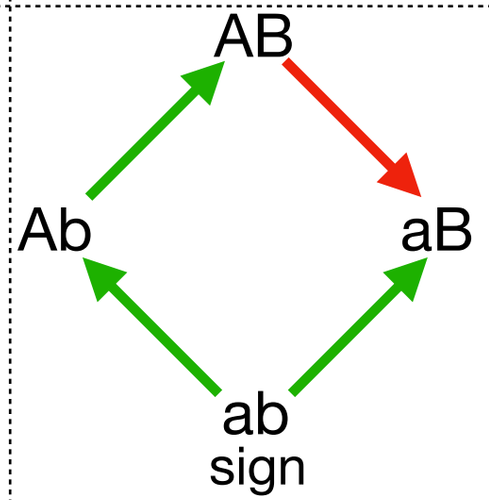
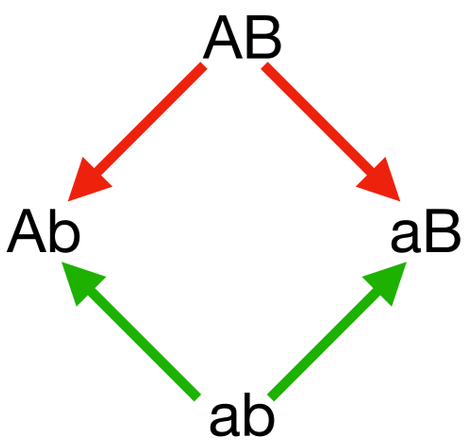
rugged



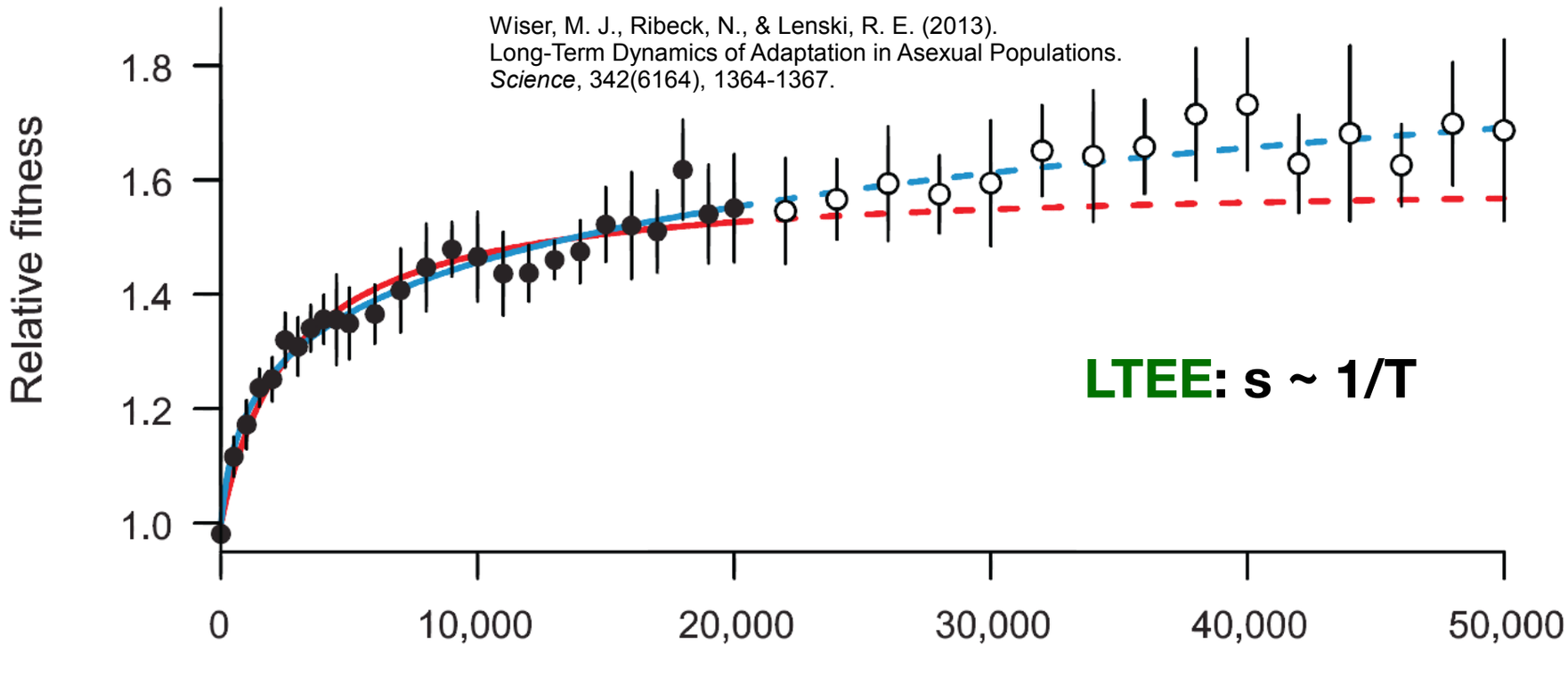
reciprocal sign

Hard for all SSWM dynamics: initial genotypes with all adaptive paths of exponential lengths

Hard for all evolutionary dynamics (if FP != PLS)

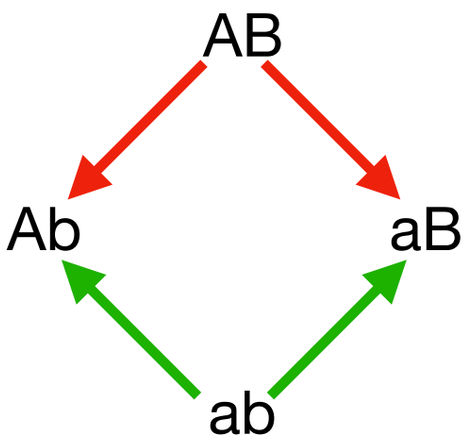
Landscape type	Max allowed epistasis type	Hardness of reaching local optima
smooth		**Easy** for all strong-selection weak-mutation (SSWM) dynamics
semismooth		**Hard** for SSWM with random fitter mutant or fittest mutant dynamics
rugged	 reciprocal sign	**Hard** for all SSWM dynamics: initial genotypes with all adaptive paths of exponential lengths **Hard** for all evolutionary dynamics (if FP != PLS) **Easy** for finding approximate local peaks with moderate optimality gap: selection coefficient **can drop-off as power law** **Hard** for approximate local peaks with small optimality gap: selection coefficient **cannot drop-off exponentially**

Unbounded Growth in Fitness & Open-Ended Evolution



YES: s ~ poly(n,1/T)
NO: s ~ exp(-T)poly(n)

rugged



reciprocal sign

Easy for finding approximate local peaks with moderate optimality gap: selection coefficient **can drop-off as power law**

Hard for approximate local peaks with small optimality gap: selection coefficient **cannot drop-off exponentially**

Thank you!

References

Wright, S. (1932). The roles of mutation, inbreeding, crossbreeding, and selection in evolution. *Proceedings of the Sixth International Congress of Genetics*, 356-366

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