The "Darwinian" and the "Molecular" revolutions in biology

13P035: Introduction à l'histoire et la philosophie des sciences

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Overview

- Scientific revolutions and conceptual change
- The “Darwinian” revolution
- The “Molecular” revolution
- Revolution or … evolution?

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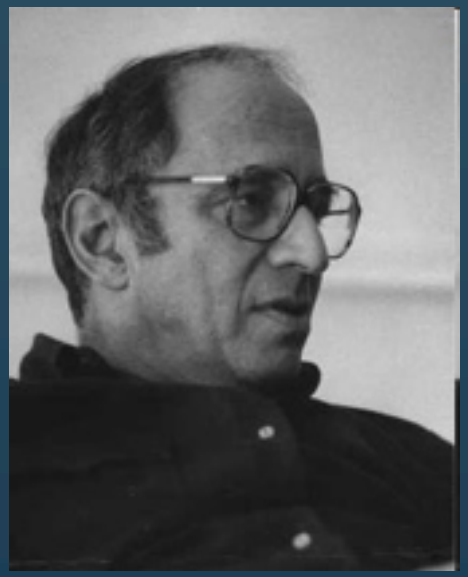
- The “Darwinian” revolution
- The “Molecular” revolution
- Revolution or … evolution?

Scientific revolutions and conceptual change



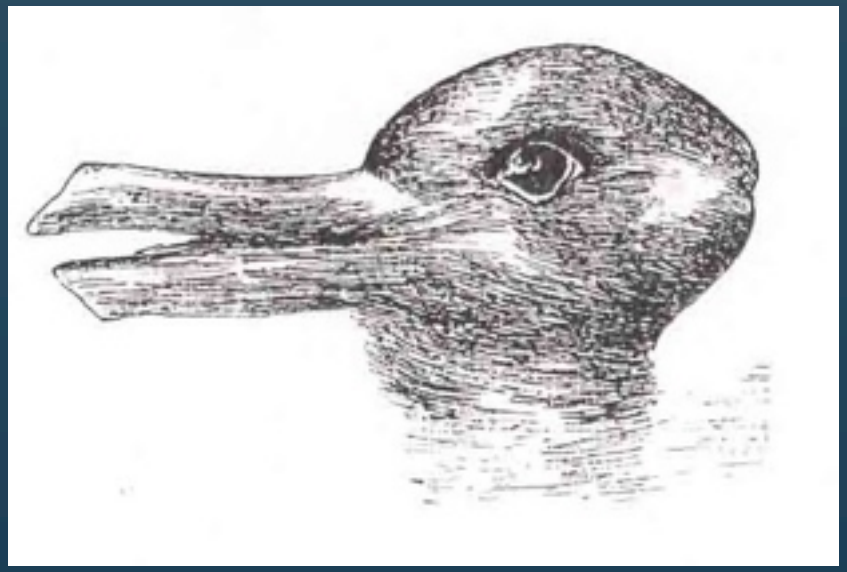
Thomas Kuhn
(1922-1996)

"Equally, it is why, before they can hope to communicate fully, one group or the other must experience the conversion that we have been calling a paradigm shift. Just because it is a transition between incommensurables, the transition between competing paradigms cannot be made a step at a time, forced by logic and neutral experience. Like the gestalt switch, it must occur all at once (though not necessarily in an instant) or not at all."

Kuhn T. S. (1996) *The Structure of Scientific Revolutions.*(3rd edition). University of Chicago Press, Chicago, p.150.

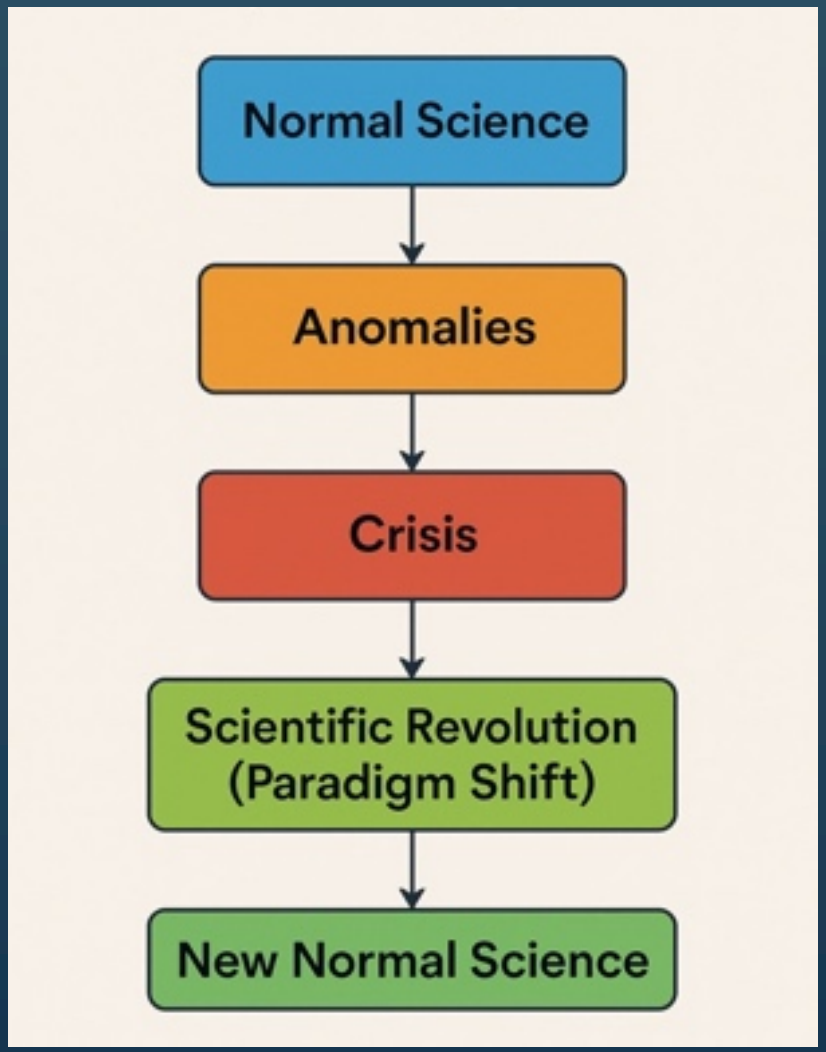
Scientific revolutions and conceptual change

"The subject of a gestalt demonstration knows that his perception has shifted because he can make it shift back and forth repeatedly while he holds the same book or piece of paper in his hands. Aware that nothing in his environment has changed, he directs his attention increasingly not to the figure (duck or rabbit) but to the lines of the paper he is looking at. Ultimately he may even learn to see those lines without seeing either of the figures, and he may then say (what he could not legitimately have said earlier) that it is these lines that he really sees but that he sees them alternately as a duck and as a rabbit."



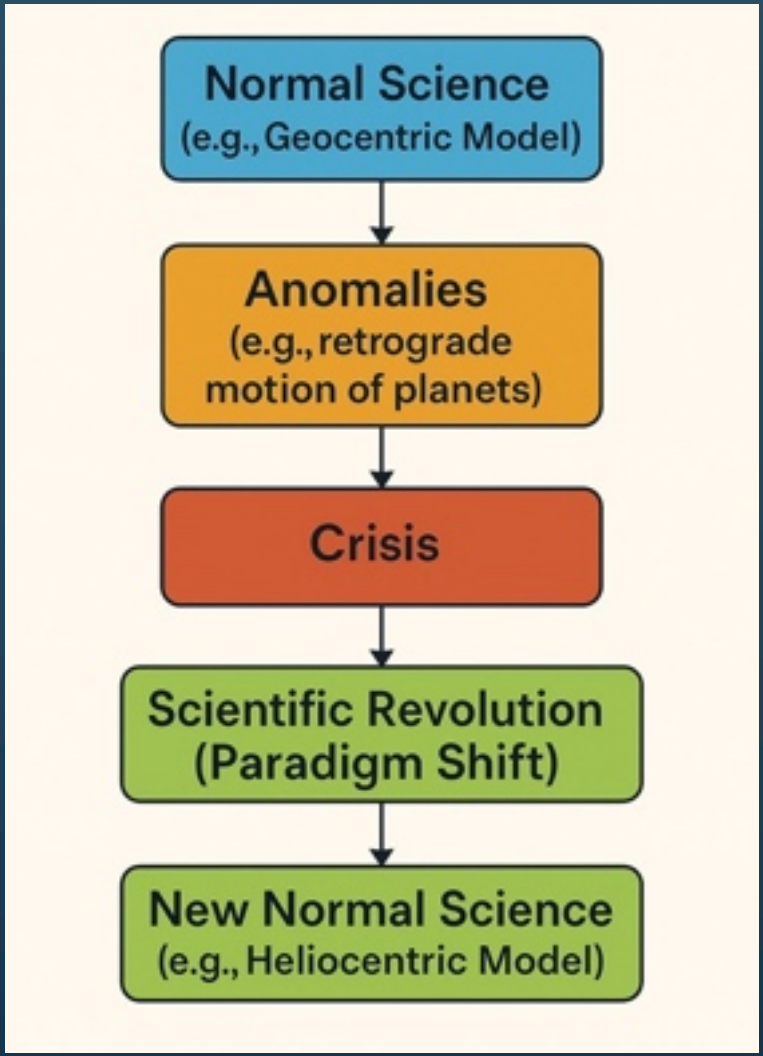
Kuhn T. S. (1996) *The Structure of Scientific Revolutions.*(3rd edition). University of Chicago Press, Chicago, p.114.

Scientific revolutions and conceptual change



Kuhn T. S. (1996) *The Structure of Scientific Revolutions.*(3rd edition). University of Chicago Press, Chicago.

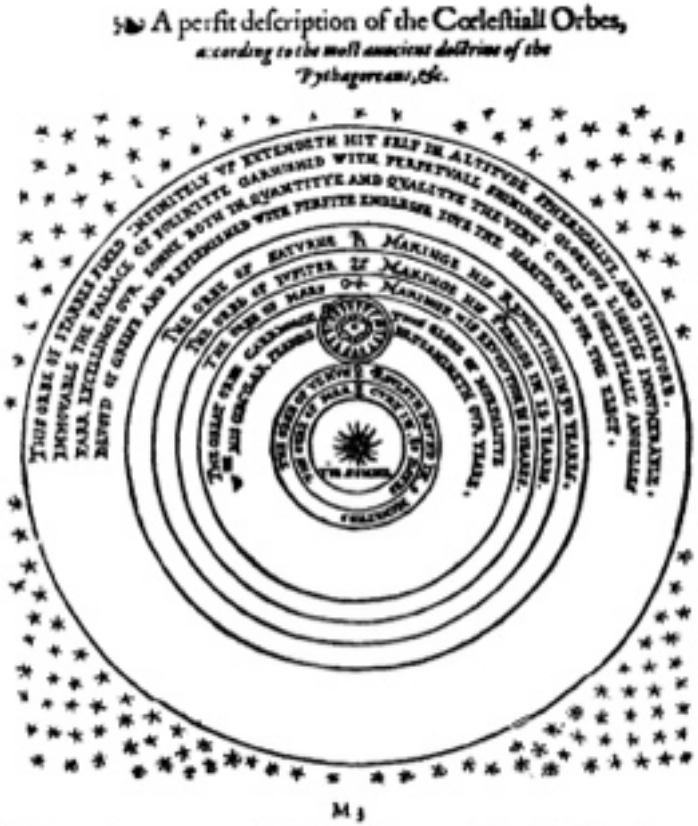
Scientific revolutions and conceptual change



Kuhn T. S. (1996) *The Structure of Scientific Revolutions.*(3rd edition). University of Chicago Press, Chicago.

Scientific revolutions and conceptual change

4. *The Ptolemaic cosmos, as depicted in the middle of the seventeenth century by the eminent German-Polish astronomer Johannes Hevelius (1611–87). Source: Johannes Hevelius,* Selenographia *(1647).*



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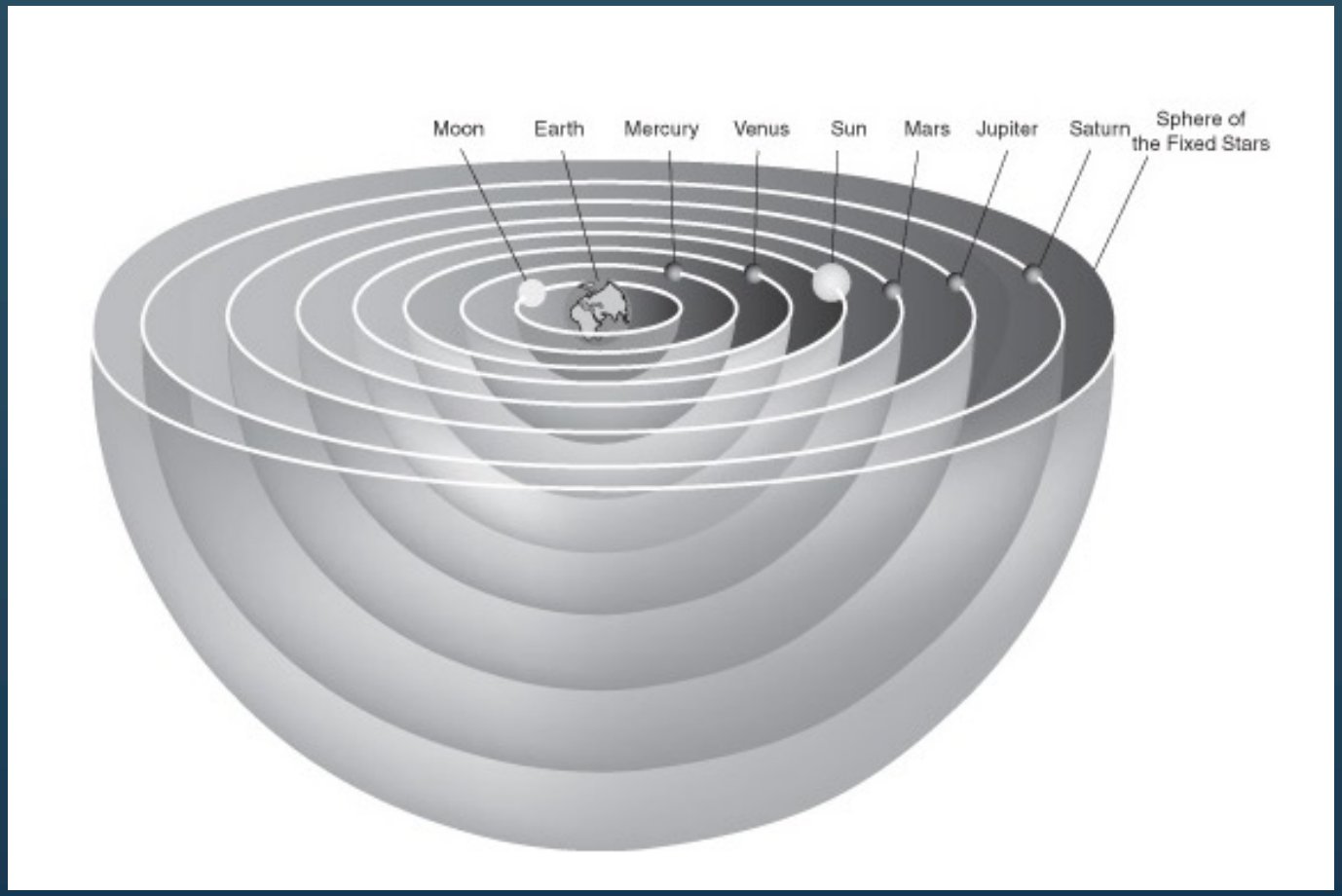
3. *The Copernican system, as depicted in the 1570s by the English mathematician Thomas Digges (ca. 1546–95). Digges modified Copernicus's views by developing a notion of a physical infinite universe in which the stars were placed at different points in that infinite space. Source: Thomas Digges,* A Perfit Description of the Caelestiall Orbes *(1576).*

Shapin, S. (1996) *The Scientific Revolution.* Chicago: University of Chicago Press.

Scientific revolutions and conceptual change



A simplified version of Aristotle's model of concentric spheres.

Principe, L. M. (2011). *The Scientific Revolution: A Very Short Introduction*. Oxford: Oxford University Press.

Scientific revolutions and conceptual change

There are two phenomena that the model of concentric spheres fails to explain:

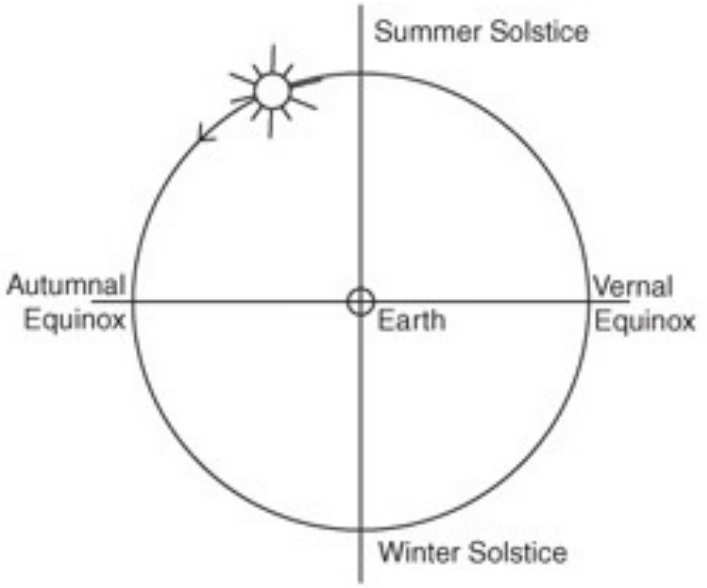
- the unequal length of the seasons
- the variation in the brightness of the planets

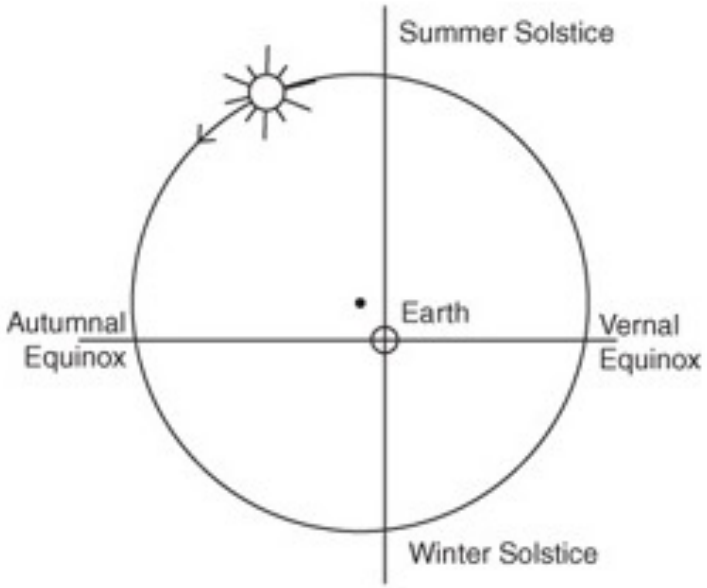
Later astronomers tackled these problems, leading to the system of Claudius Ptolemy.

Claudius Prolemy
(90-168)

Principe, L. M. (2011). *The Scientific Revolution: A Very Short Introduction*. Oxford: Oxford University Press.

Scientific revolutions and conceptual change



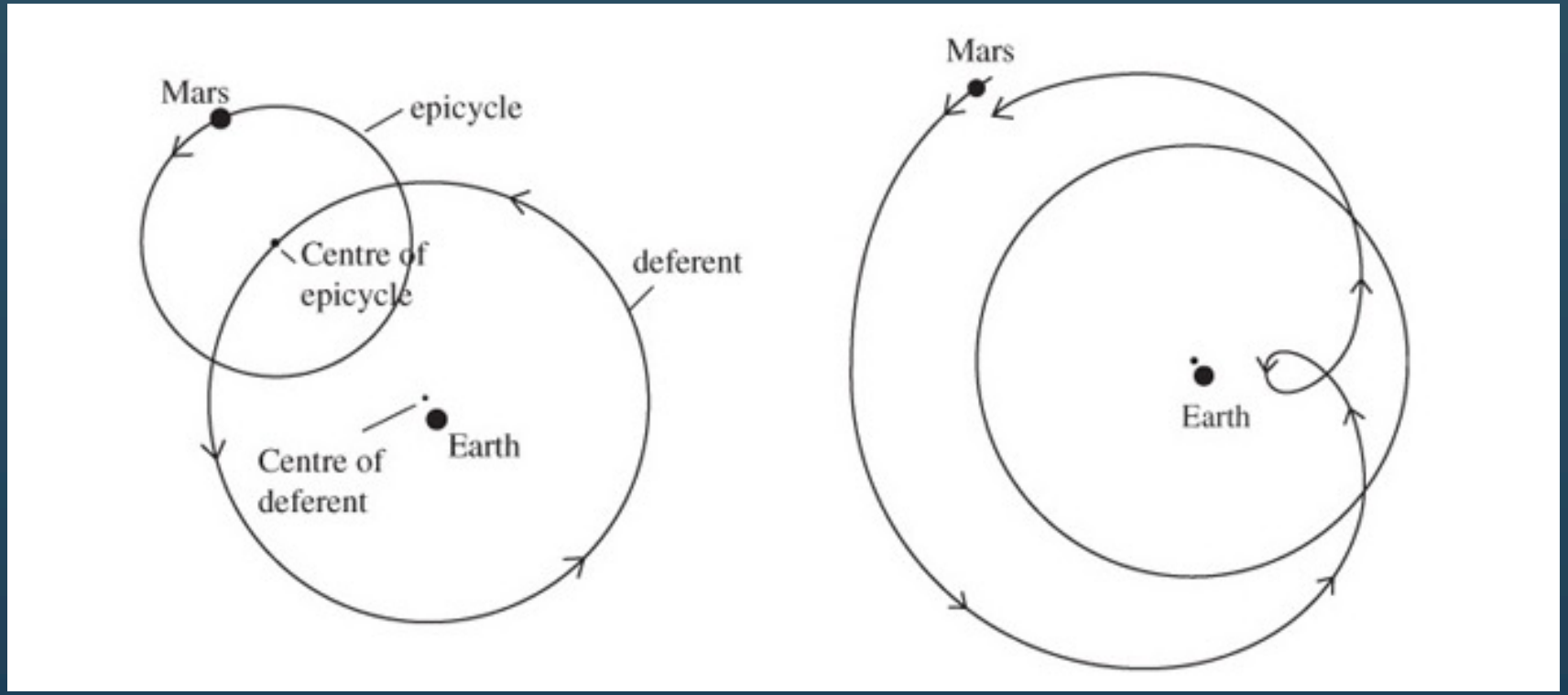


If the Earth were located at the center of the Sun's sphere, the Sun's apparent annual motion would be divided into four equal arcs, which would make the seasons equal in length. But in reality summer is longer than winter.

Ptolemy's off-center Earth divides the Sun's path into four arcs of unequal length, correctly corresponding to the unequal duration of the seasons. This arrangement also explains why the Sun appears to move more slowly in summer: because it is then farther away.

Principe, L. M. (2011). *The Scientific Revolution: A Very Short Introduction*. Oxford: Oxford University Press.

Scientific revolutions and conceptual change



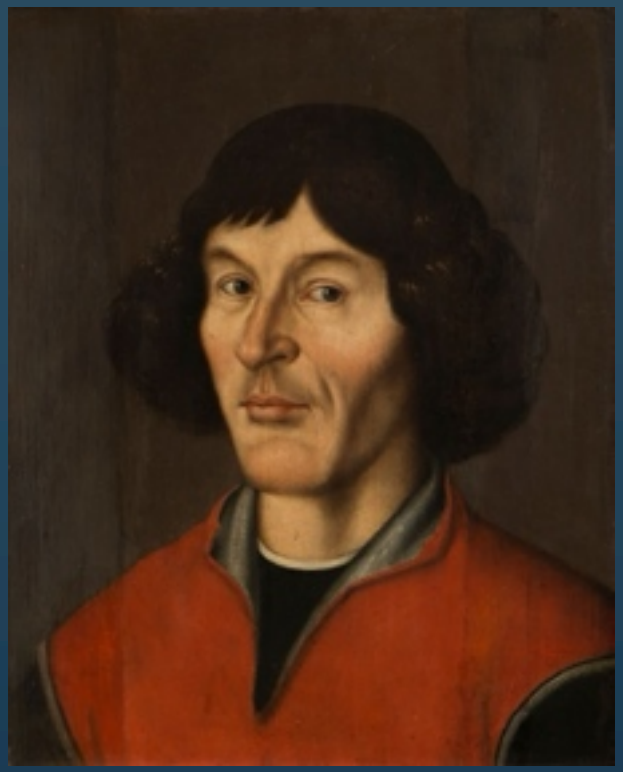
A Ptolemaic epicycle and deferent for a planet. The planet moves counterclockwise (as seen from the Earth's North Pole) on the epicycle, while the epicycle is carried in the same direction along the deferent.

The apparent motion of the planet results from the combination of the motions of the epicycle and the deferent. When the planet is outside the deferent, it appears fainter and moves from west to east; when it is inside, it appears brighter because it is closer, and at its point of greatest approach, it moves from east to west (retrograde motion).

Principe, L. M. (2011). *The Scientific Revolution: A Very Short Introduction*. Oxford: Oxford University Press.

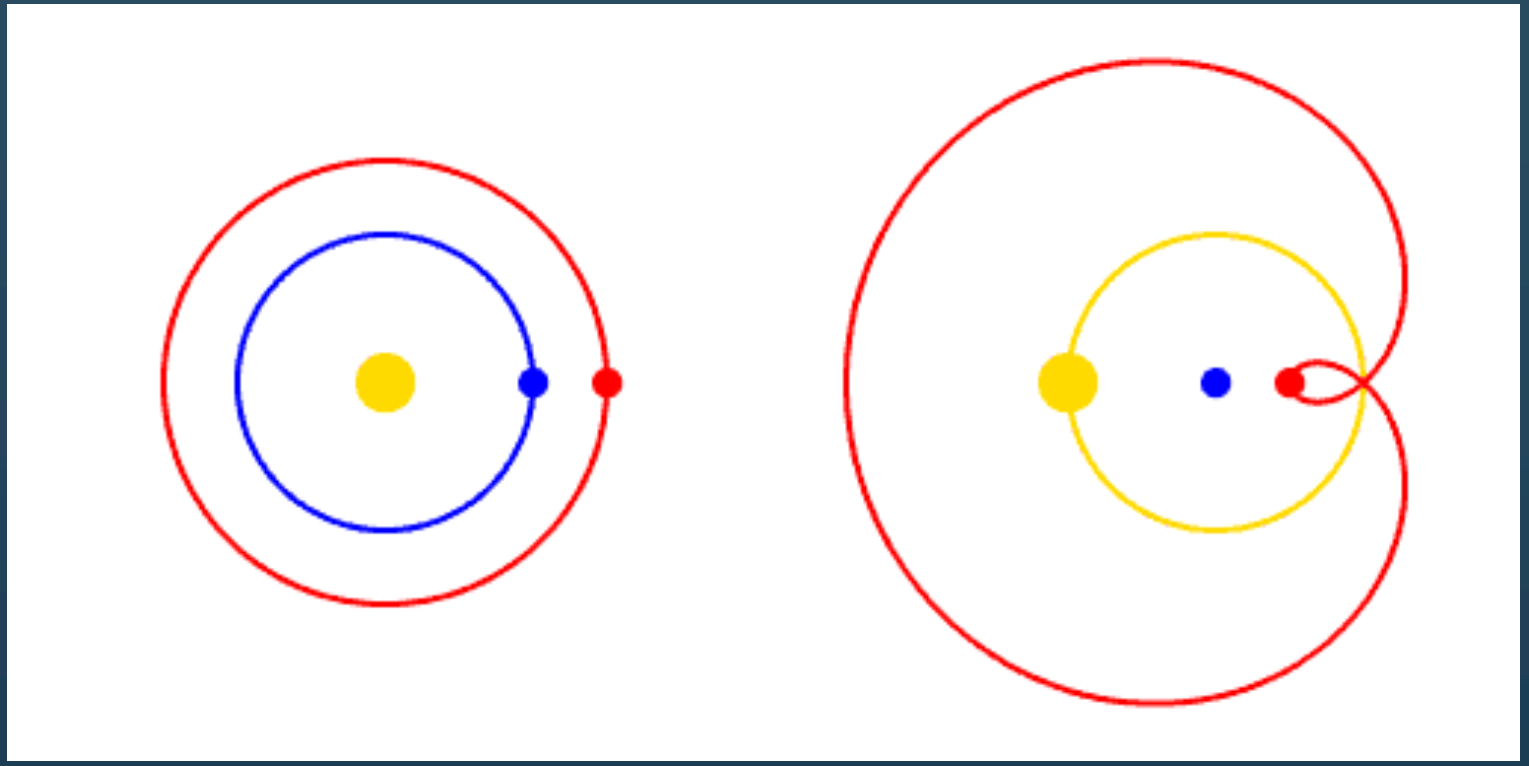
Scientific revolutions and conceptual change

Schematic diagram of the heliocentric theory of the Solar System according to Copernicus, from *De revolutionibus orbium coelestium*.



Nicolaus Copernicus
(1473-1543)

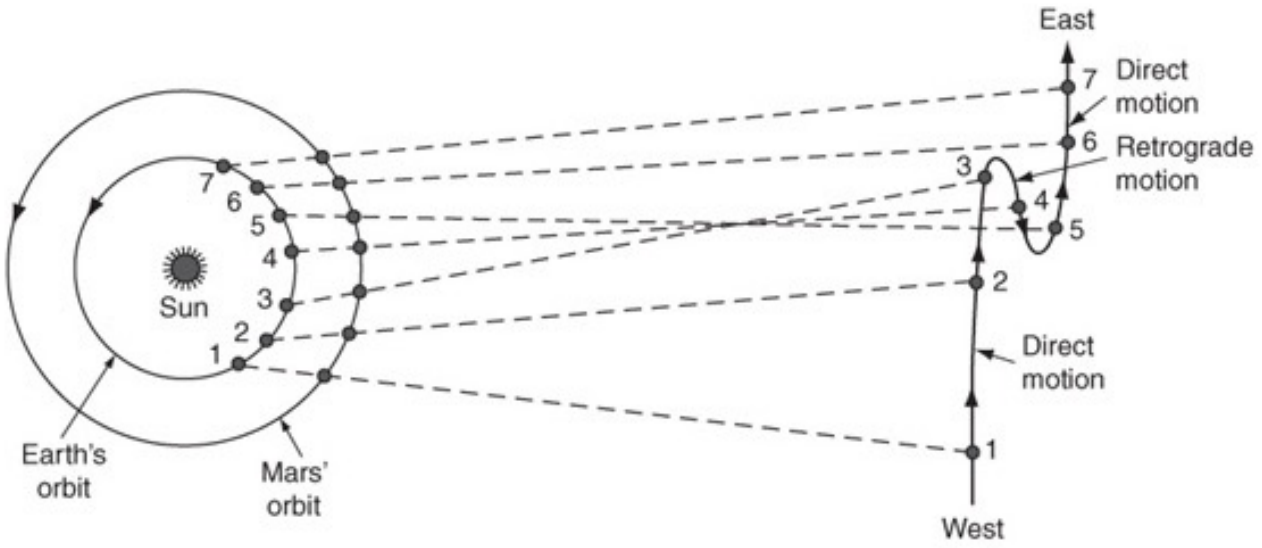
Scientific revolutions and conceptual change



Motion of the Sun, Earth, and Mars. At left, Copernicus's heliocentric motion. At right, traditional geocentric motion, including the retrograde motion of Mars.

https://en.wikipedia.org/wiki/Copernican_Revolution#/media/File:Apparent_retrograde_motion.gif

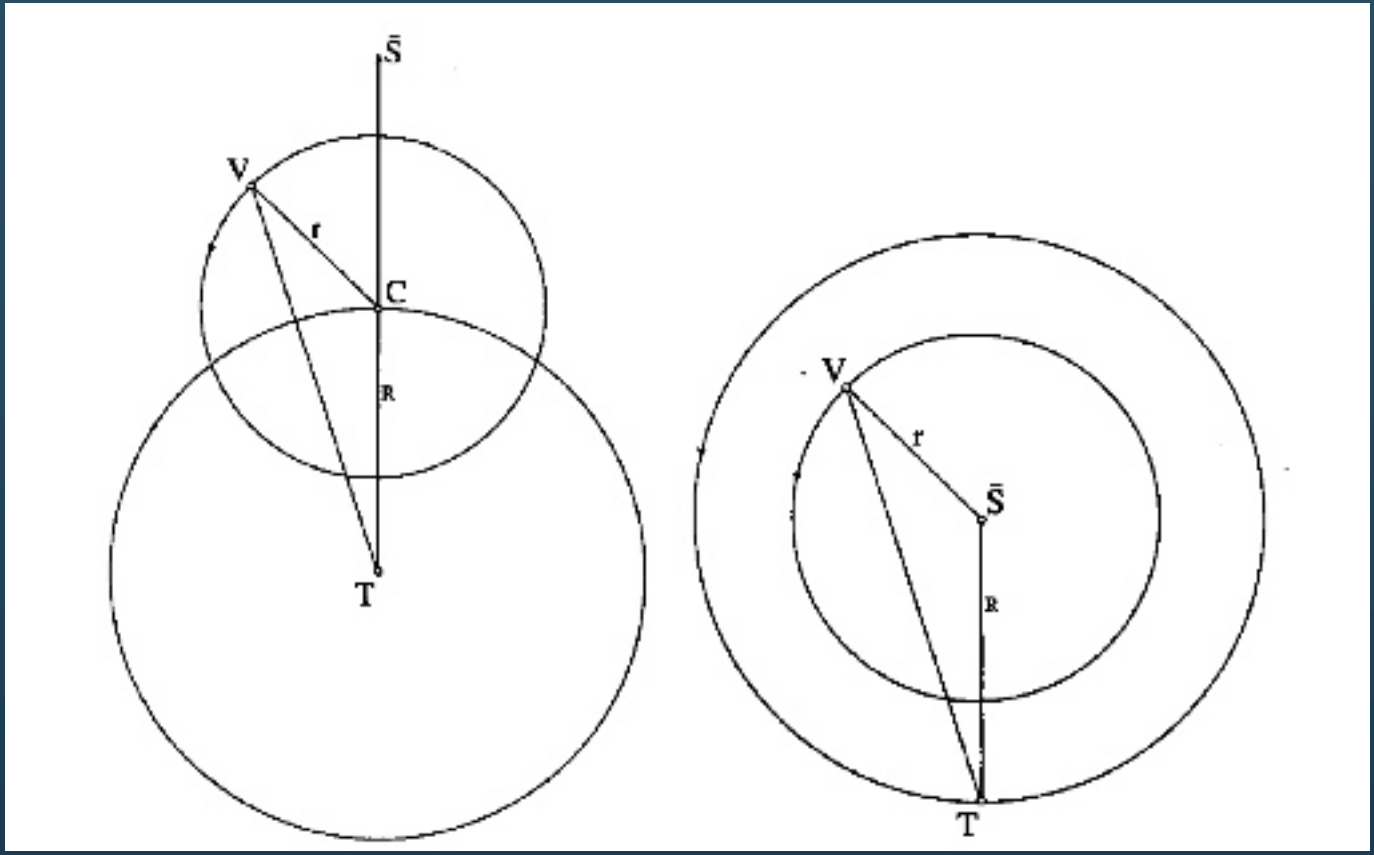
Scientific revolutions and conceptual change



6. Copernicus's explanation of retrograde motion for one of the 'superior', or outer, planets (Mars, Jupiter, or Saturn). The 'loop' is an illusion caused when the Earth moves past one of these planets

Principe, L. M. (2011). *The Scientific Revolution: A Very Short Introduction*. Oxford: Oxford University Press.

Scientific revolutions and conceptual change



(a) A geocentric model for an inferior planet.

(b) A heliocentric model for an inferior planet.

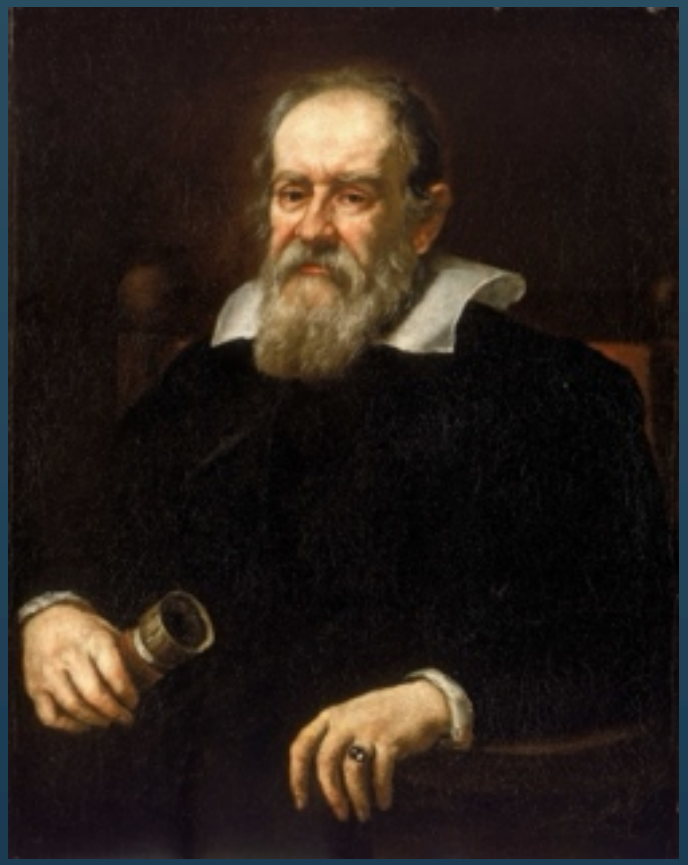
Geocentric model (a): T represents the Earth, V the planet, and S the direction of the mean Sun. The planet moves on an epicycle of radius *r*, centered on a deferent of radius *R* around T. The directions of motion are indicated by arrows.

In the heliocentric model (b), C becomes S: the mean Sun is no longer a direction, but a point at the center of the epicycle, around which the planet revolves. The roles of S and T are then reversed, so that V and T revolve around S. The ratio *r*/*R* remains unchanged.

Goldstein, B. R. (2002). Copernicus and the origins of his heliocentric system. Journal for the History of Astronomy 33, 219–235.

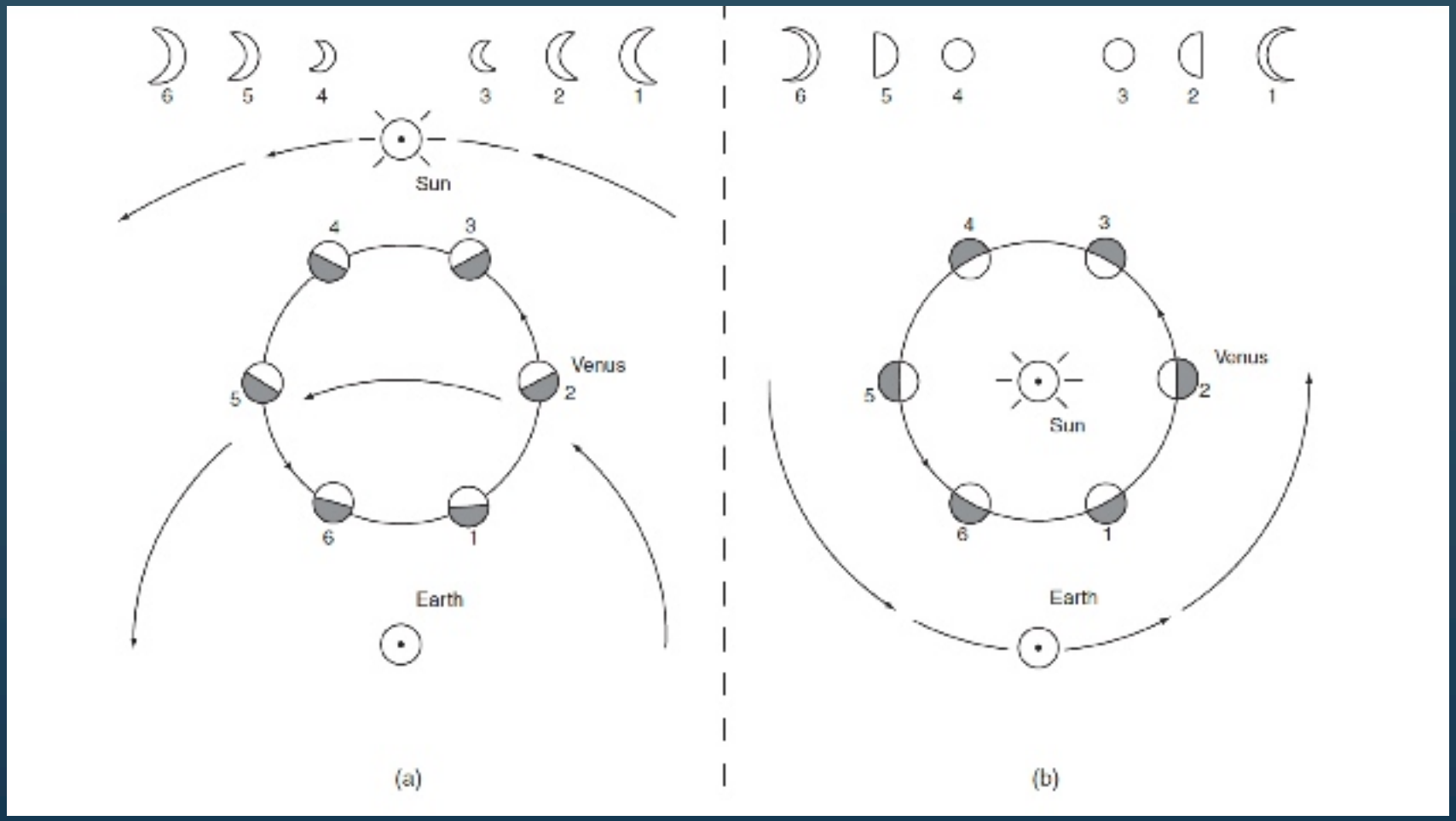
Scientific revolutions and conceptual change

An illustration of the Moon from *Sidereus Nuncius*.



Galileo Galilei
(1564-1642)

Scientific revolutions and conceptual change



The phases of Venus in the Ptolemaic system (a) and the Copernican system (b).

Heilbron, J. L. (2010). *Galileo*. Oxford: Oxford University Press, p.168.

Scientific revolutions and conceptual change

"There was no such thing as the Scientific Revolution, and this is a book about it. Some time ago, when the academic world offered more certainty and more comforts, historians announced the real existence of a coherent, cataclysmic, and climatic event that fundamentally and irrevocably changed what people knew about the natural world and how they secured proper knowledge of that world. It was the moment at which the world became modern, it was a Good Thing, and it happened sometime during the period from the late sixteenth to the early eighteenth century."

Shapin, S. (1996) *The Scientific Revolution.* Chicago: University of Chicago Press.

Scientific revolutions and conceptual change

Kuhn's stages	Shapin's critique
Normal science	Places too much emphasis on internal logic; neglects broader contexts

Shapin, S. (1996) *The Scientific Revolution.* Chicago: University of Chicago Press.

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Shapin, S. (1996) *The Scientific Revolution.* Chicago: University of Chicago Press.

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"Scientfic revolution" (Paradigm shift)	The very notion of "revolution" is mythologized; the change was fragmented and complex

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Scientific revolutions and conceptual change

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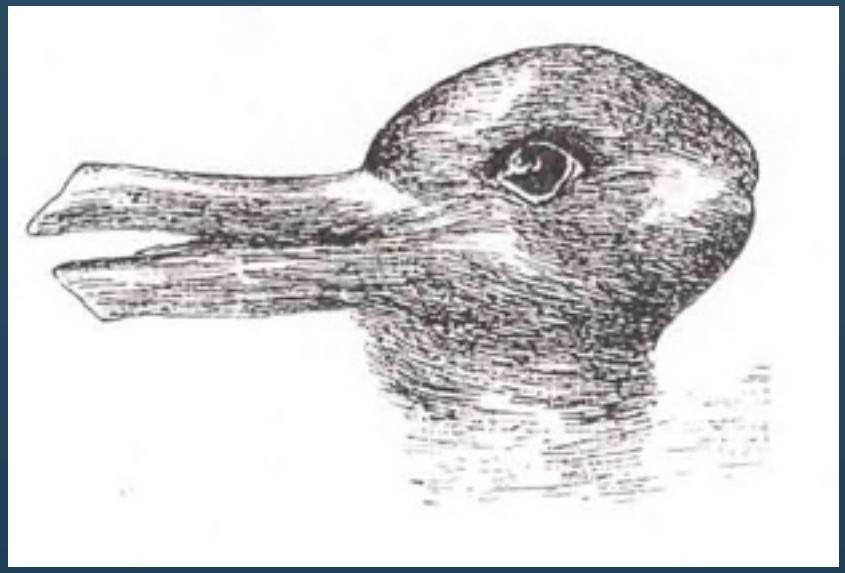
New normal science	There was often no clear new consensus for decades

Shapin, S. (1996) *The Scientific Revolution.* Chicago: University of Chicago Press.

Scientific revolutions and conceptual change

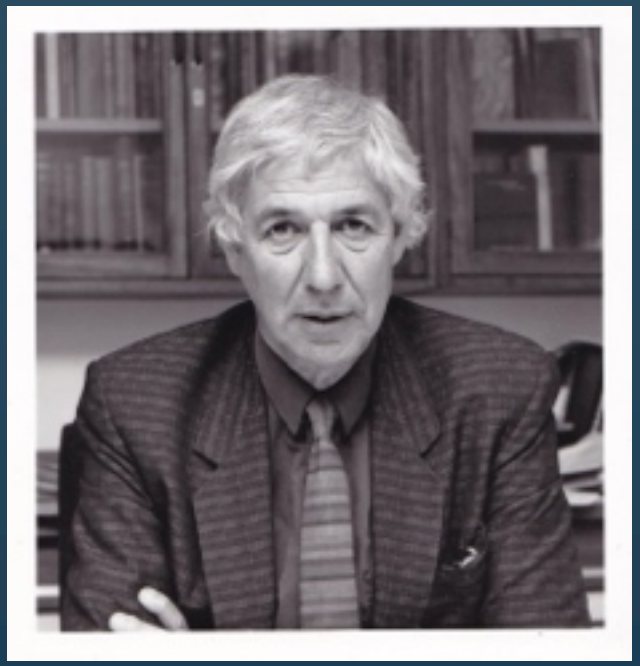
"In a sense I am unable to explicate further, the proponents of competing paradigms practice their trades in different worlds. One contains constrained bodies that fall slowly, the other pendulums that repeat their motions again and again. In one, solutions are compounds, in the other mixtures. One is embedded in a flat, the other in a curved, matrix of space. Practicing in different worlds, the two groups of scientists see different things when they look from the same point in the same direction."



incomensurability

Kuhn T. S. (1996) *The Structure of Scientific Revolutions.*(3rd edition). University of Chicago Press, Chicago, p.150.

Scientific revolutions and conceptual change



Lewis Wolpert
(1929-2021)

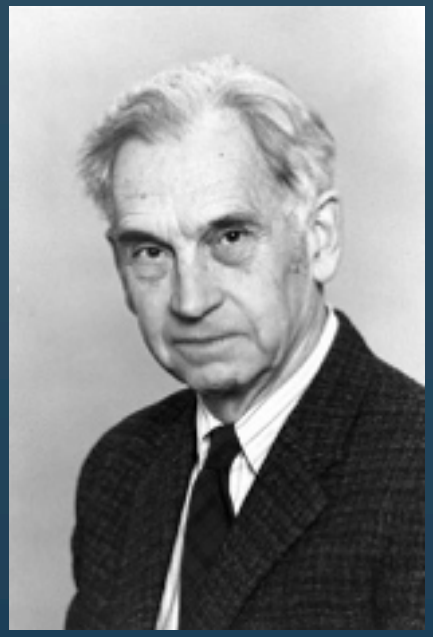
"... The idea of incommensurability forms an important part of Kuhn's image of how science works ... Kuhn characterizes as "normal science" those periods when scientists are working within a shared set of ideas which define the field. He terms the dominant conceptual framework the "paradigm." ... to take two biological examples, there was with Darwin a paradigm shift away from the constancy of species to an evolutionary paradigm in which species change, and, more recently, the revolution in molecular biology changed the paradigm from metabolism to information."

Wolpert, L. (1992). *The unnatural nature of science*. Harvard University Press.

Overview

- Scientific revolutions and conceptual change
- The "Darwinian" revolution
- The "Molecular" revolution
- Revolution or … evolution?

The "Darwinian" revolution

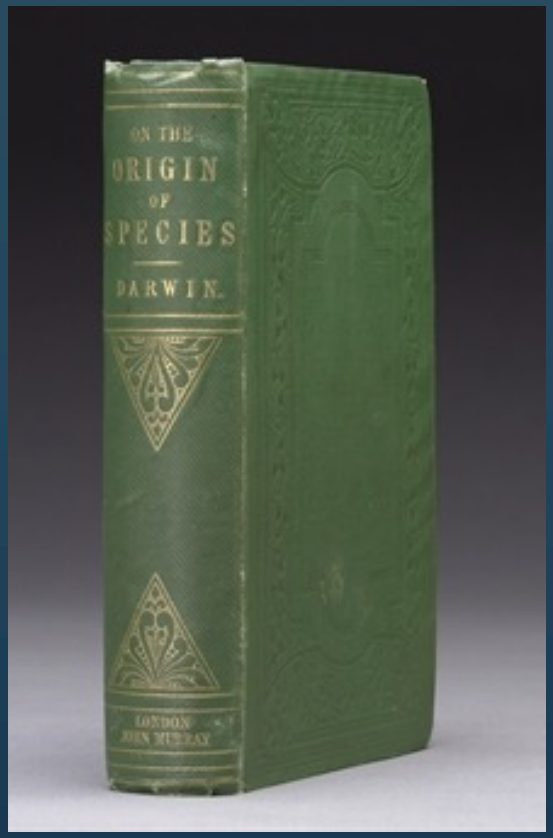


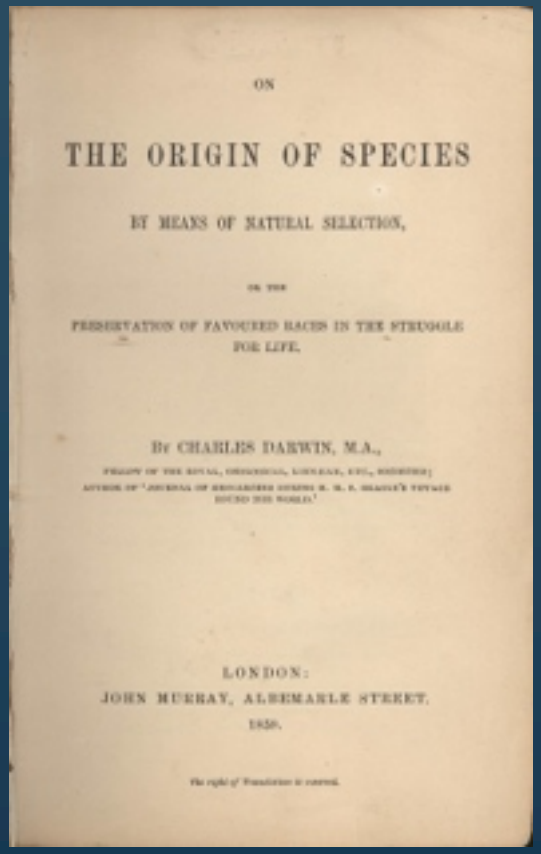
Ernst Mayr
(1904-2005)

"Darwin introduced into the scientific literature a new way of thinking, "population thinking." What is this population thinking, and how does it differ from typological thinking, the then-prevailing mode of thinking? .... According to it, there are a limited number of fixed, unchangeable "ideas" underlying the observed variability, with the eidos (idea) being the only thing that is fixed and real ... The assumptions of population thinking are diametrically opposed to those of the typologist. The populationist stresses the uniqueness of everything in the organic world."

Mayr, E. (1994). Typological versus population thinking. In E. Sober (Ed.), *Conceptual issues in evolutionary biology* (3rd ed., pp. 325–328). MIT Press.

The "Darwinian" revolution




ON

THE ORIGIN OF SPECIES

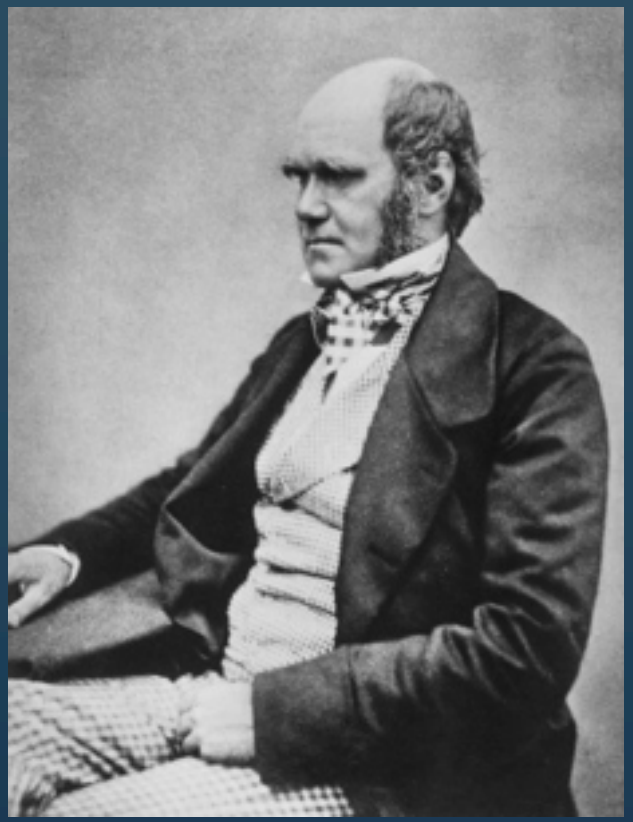
BY MEANS OF NATURAL SELECTION,

OR THE

PRESERVATION OF FAVOURED RACES IN THE STRUGGLE FOR LIFE.

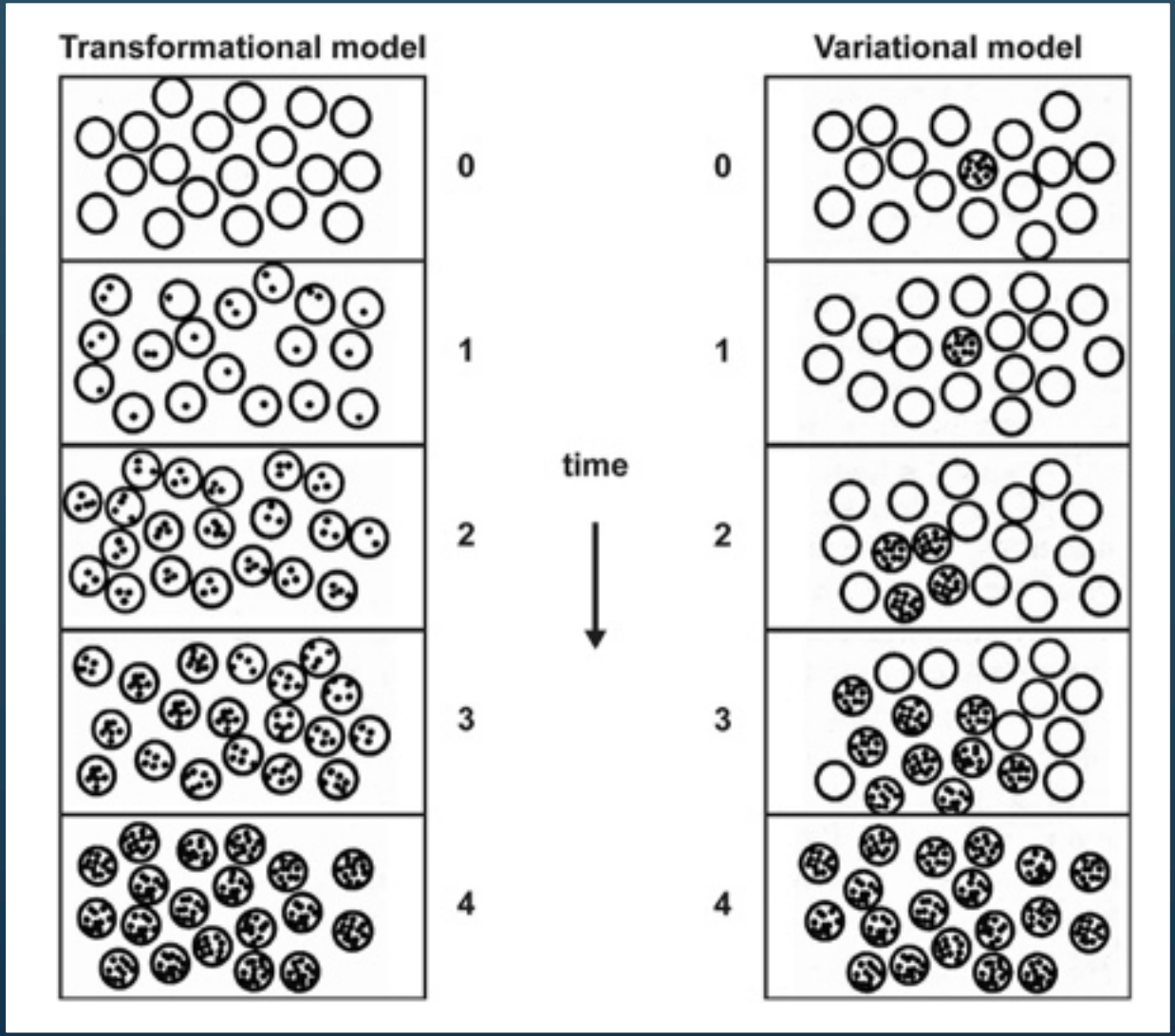
By CHARLES DARWIN, M.A.,

LONDON:
JOHN MURRAY, ALBEMARLE STREET.
1859.



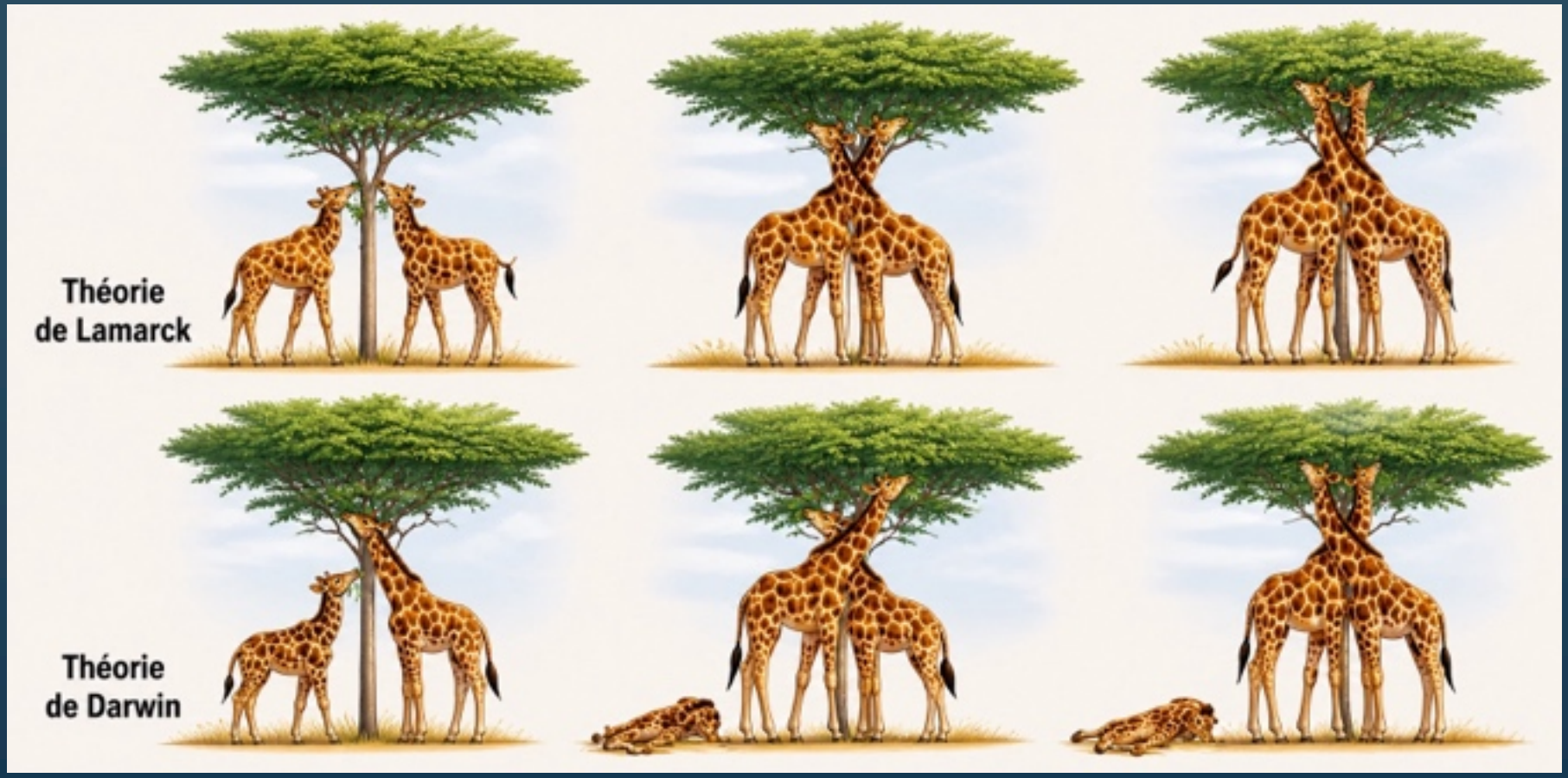
Charles Darwin
(1809-1882)

The "Darwinian" revolution



Nicholson, D. J. (2025). Population thinking and the uniqueness of biological entities. *Acta Biotheoretica*, *73*(1), 8.

The “Darwinian” revolution



The "Darwinian" revolution

Jean Lamarck
(1744-1829)

« *PREMIÈRE LOI.*

Dans tout animal qui n'a point dépassé le terme de ses développemens, l'emploi plus fréquent et soutenu d'un organe quelconque, fortifie peu à peu cet organe, le développe, l'agrandit, et lui donne une puissance proportionnée à la durée de cet emploi ; tandis que le défaut constant d'usage de tel organe, l'affoiblit insensiblement, le détériore, diminue progressivement ses facultés, et finit par le faire disparoître.

DEUXIÈME LOI.

Tout ce que la nature a fait acquérir ou perdre aux individus par l'influence des circonstances où leur race se trouve depuis long-temps exposée, et, par conséquent, par l'influence de l'emploi prédominant de tel organe, ou par celle d'un défaut constant d'usage de telle partie ; elle le conserve par la génération aux nouveaux individus qui en proviennent, pourvu que les changemens acquis soient communs aux deux sexes, ou à ceux qui ont produit ces nouveaux individus. »

Lamarck, J. (1994) [1809]. *Philosophie Zoologique*. GF-Flammarion, Paris.

The "Darwinian" revolution

1. Lamarck presented the idea of the inheritance of acquired characters as self-evident; he never claimed it as his own.
2. Lamarck's innovation with respect to the idea of the inheritance of acquired characters was in his claim that the inheritance of acquired characters was an agent of unlimited change.
3. Lamarck insisted that specific conditions were necessary for acquired changes to be transmitted to the next generation.
4. Lamarck believed that change was slow and incremental. He also maintained (at least for the most part) that change could be expected only if changed circumstances caused animals to adopt new habits.
5. The inheritance of acquired characters was but a tiny item in the broad scheme of Lamarck's theorizing.

Burkhardt, R. W., Jr. (2013). Lamarck, evolution, and the inheritance of acquired characters. *Genetics, 194*(4), 793–805.

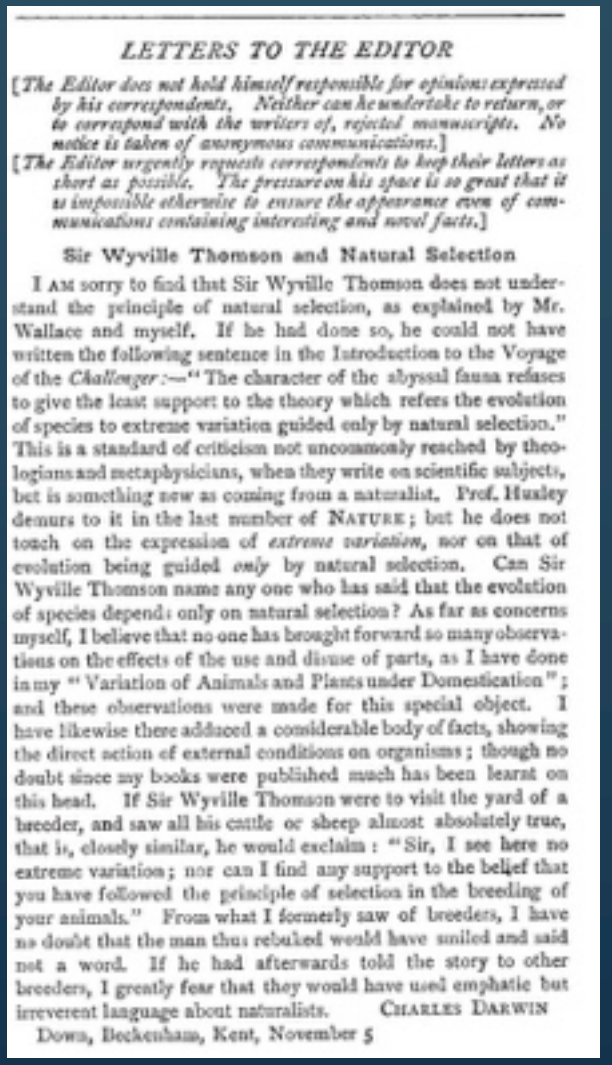
The "Darwinian" revolution

6. Lamarck's thinking has long been characterized (and caricatured) through his examples of the inheritance of acquired characters.
7. Lamarck's examples and his model of species change were about functional, adaptive changes: animals adopt new habits in response to changes in the conditions surrounding them, such changes in habits lead to changes in structures, and the new habits and new structures are passed on to succeeding generations, accumulating to the point of producing new species.
8. Lamarck offered no explanation of the mechanisms by which acquired characters were transmitted from one generation to the next.
9. Lamarck himself never used the phrase "the inheritance of acquired characters," nor for that matter did he ever use the words "heredity" or "hereditary."

Burkhardt, R. W., Jr. (2013). Lamarck, evolution, and the inheritance of acquired characters. *Genetics, 194*(4), 793–805.

The "Darwinian" revolution

"As far as concerns myself, I believe that no one has brought forward so many observations on the effects of the use and disuse of parts, as I have done in my "Variation of Animals and Plants under Domestication"; and these observations were made for this special object. I have likewise there adduced a considerable body of facts, showing the direct action of external conditions on organisms"



LETTERS TO THE EDITOR

[*The Editor does not hold himself responsible for opinions expressed by his correspondents. Neither can he undertake to return, or to correspond with the writers of, rejected manuscripts. No notice is taken of anonymous communications.*]

[*The Editor urgently requests correspondents to keep their Letters as short as possible. The pressure on his space is so great that it is impossible otherwise to ensure the appearance even of communications containing interesting and novel facts.*]

Sir Wyville Thomson and Natural Selection

I AM sorry to find that Sir Wyville Thomson does not understand the principle of natural selection, as explained by Mr. Wallace and myself. If he had done so, he could not have written the following sentence in the Introduction to the Voyage of the *Challenger*:—"The character of the abyssal fauna refuses to give the least support to the theory which refers the evolution of species to extreme variation guided only by natural selection." This is a standard of criticism not uncommonly reached by theologians and metaphysicians, when they write on scientific subjects, but is something new as coming from a naturalist. Prof. Huxley demurs to it in the last number of NATURE; but he does not touch on the expression of *extreme variation*, nor on that of evolution being guided *only* by natural selection. Can Sir Wyville Thomson name any one who has said that the evolution of species depends only on natural selection? As far as concerns myself, I believe that no one has brought forward so many observations on the effects of the use and disuse of parts, as I have done in my "Variation of Animals and Plants under Domestication"; and these observations were made for this special object. I have likewise there adduced a considerable body of facts, showing the direct action of external conditions on organisms; though no doubt since my books were published much has been learnt on this head. If Sir Wyville Thomson were to visit the yard of a breeder, and saw all his cattle or sheep almost absolutely true, that is, closely similar, he would exclaim: "Sir, I see here no extreme variation; nor can I find any support to the belief that you have followed the principle of selection in the breeding of your animals." From what I formerly saw of breeders, I have no doubt that the man thus rebuked would have smiled and said not a word. If he had afterwards told the story to other breeders, I greatly fear that they would have used emphatic but irreverent language about naturalists. CHARLES DARWIN

Down, Bechenham, Kent, November 5

Darwin, C. (1880) Sir Wyville Thomson and Natural Selection. *Nature* **23**, 32.

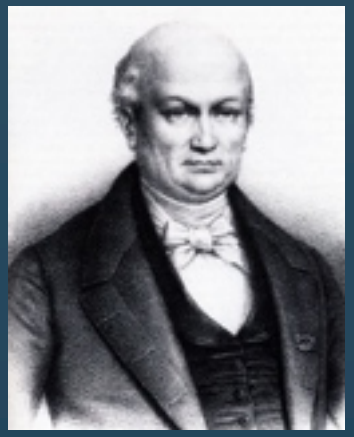
The "Darwinian" revolution

George Louis Leclerc
Compte de Buffon
(1707-1788)

Charles Bonnet
(1720-1793)

Erasmus Darwin
(1731-1802)

Julien-Joseph Virey
(1775–1847)

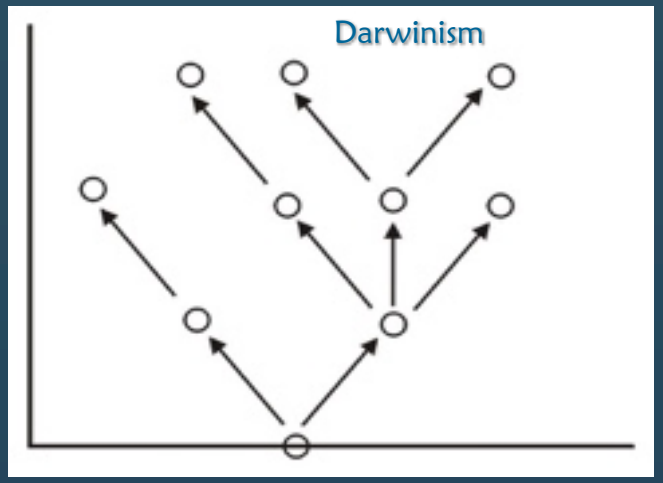


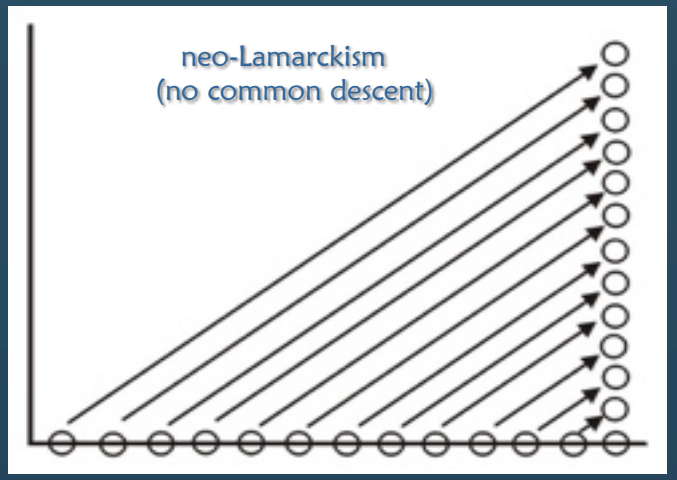
Etienne Geoffroy
Saint-Hilaire
(1772-1844)

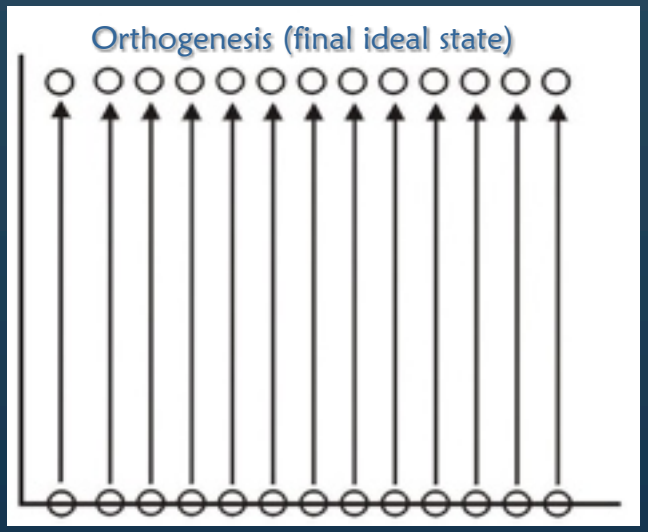
There was a plurality of evolutionary views before Darwin, in the context of European debates on the stability of species.

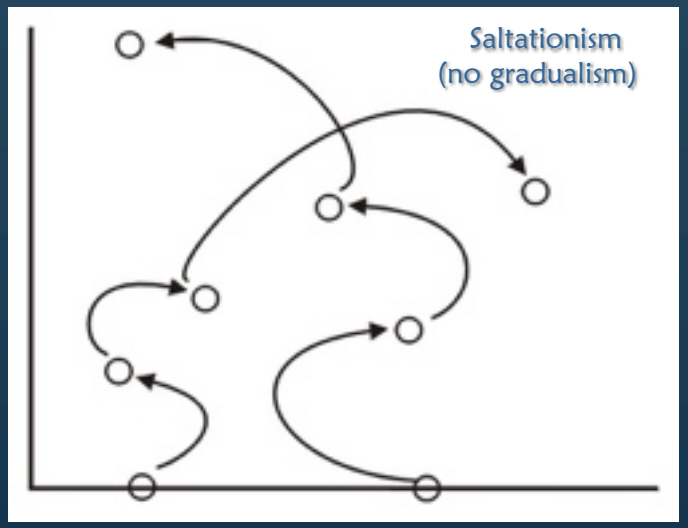
Corsi P. (2005) Before Darwin: transformist concepts in European natural history. *Journal of the History of Biology*, 38, 67-83.

The "Darwinian" revolution



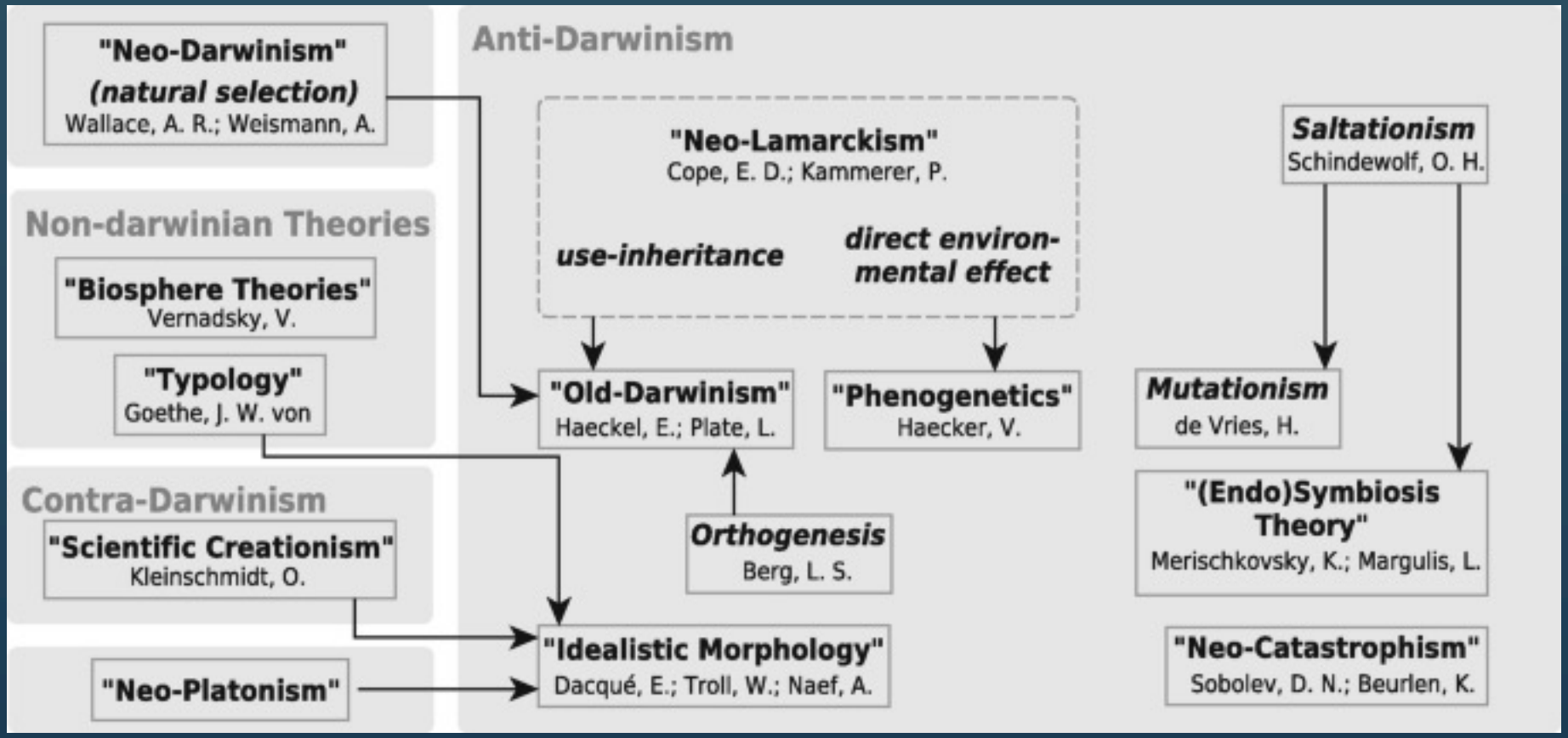






Bowler P.J. (1983) *The Eclipse of Darwinism: Anti-Darwinian Evolution Theories in the Decades around 1900*. Baltimore: Johns Hopkins University Press

The "Darwinian" revolution



Levit, G. S., & Hossfeld, U. (2021). *Natural selection in Ernst Haeckel's legacy*. In R. G. Delisle (Ed.), *Natural selection: Revisiting its explanatory role in evolutionary biology* (pp. 105–133). Springer.

The "Darwinian" revolution

"Darwin's influences have been too many, too deep, too prolonged and too various to fit any such scheme. Far from being less than revolutionary, they have been, in their entirety, more than revolutionary; [...] to say that Darwin's influence has been more than revolutionary [...] is just to say that there is no one transition that can be identified as the shift that replaced a pre-Darwinian with a Darwinian regime in Western thought."

Hodge J. and Radick G. (2009) Darwin's theories in the intellectual long run. In: Hodge J, Radick G (Eds) *The Cambridge Companion to Darwin* (2nd edition). Cambridge University Press, Cambridge, pp. 277-301.

The "Darwinian" revolution

- *1836* return from Beagle voyage
- *1838* selection in Notebooks and reading Malthus

perfect adaptation (strict sense)

- *1839* marriage and first outline of theory
- *1842* *Sketch* of theory
- *1844* *Vestiges* and *Essay* of theory
- *1846* barnacles study begins

perfect adaptation (limited perfection)

- *1851* Annie dies

- *1854* barnacles study completed
- *1857* abstract sent to Gray
- *1858* Wallace's paper received
- *1859* publication of the *Origin*

relative adaptation

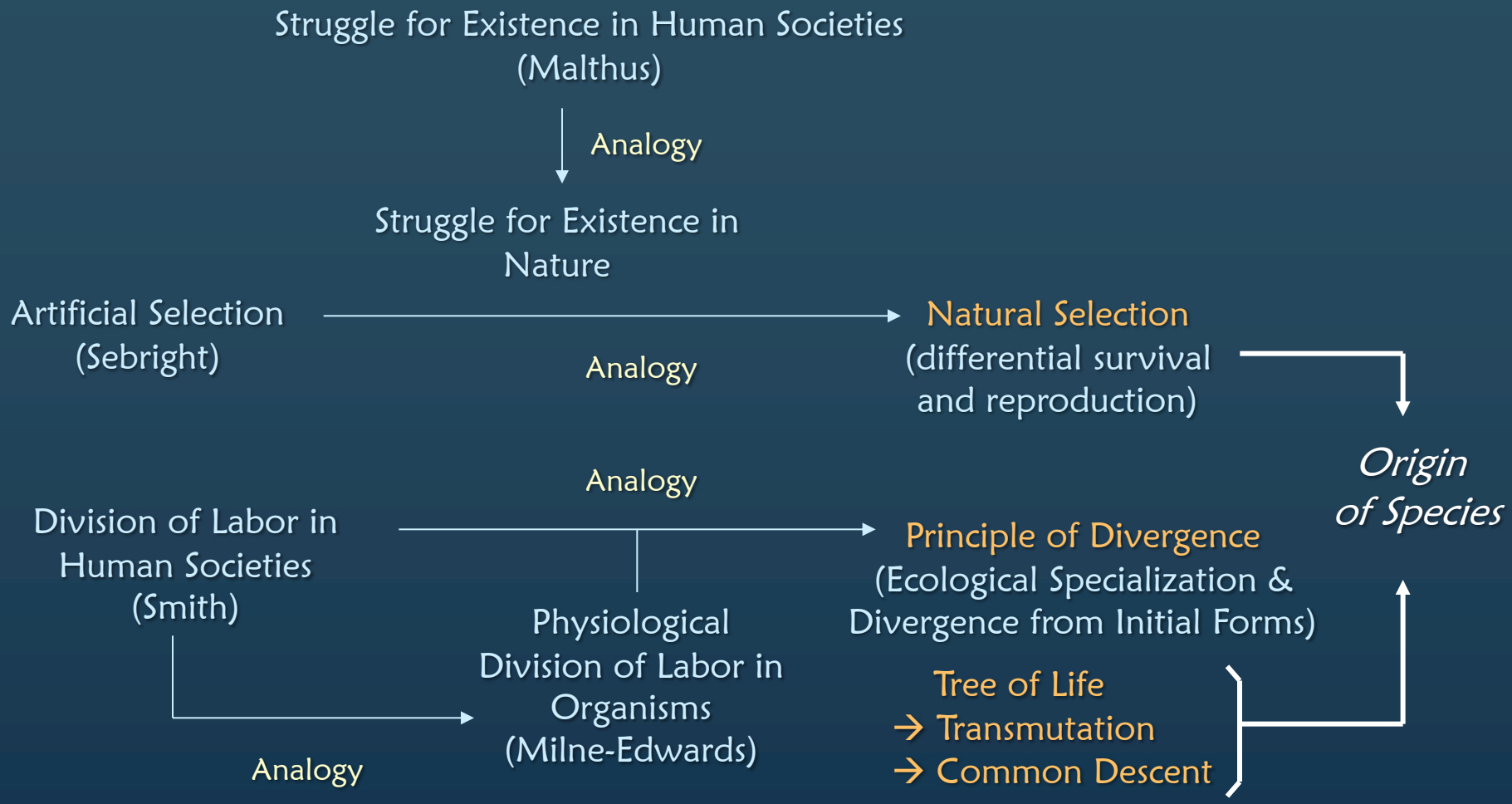
Ospovat D. (1981) *The Development of Darwin's Theory: Natural History, Natural Theology and Natural Selection, 1838-1859*. Cambridge: Cambridge University Press.

The "Darwinian" revolution

"Astronomers might formerly have said that God ordered each planet to move in its particular destiny. – In same manner God orders each animal created with certain form in certain country, but how much more simple & sublime powers let attraction act according to certain law such are inevitable consequen[ces]. Let animals be created, then by the fixed laws of generation, such will be their successors."

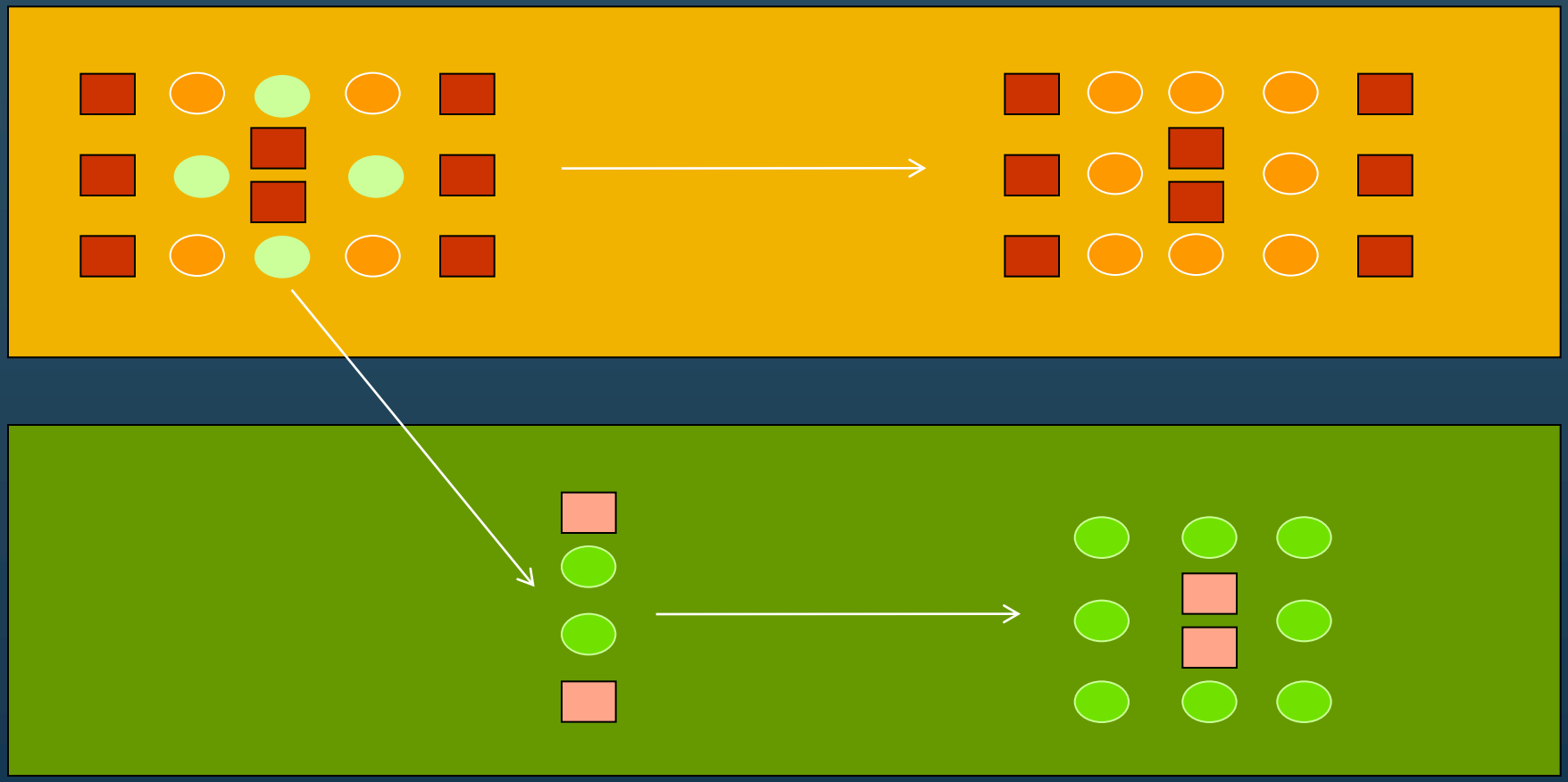
Darwin, C. R. Notebook B: [Transmutation of species (1837-1838)]. CUL-DAR121.- Transcribed by Kees Rookmaaker. (*Darwin Online*, http://darwin-online.org.uk/)

The "Darwinian" revolution



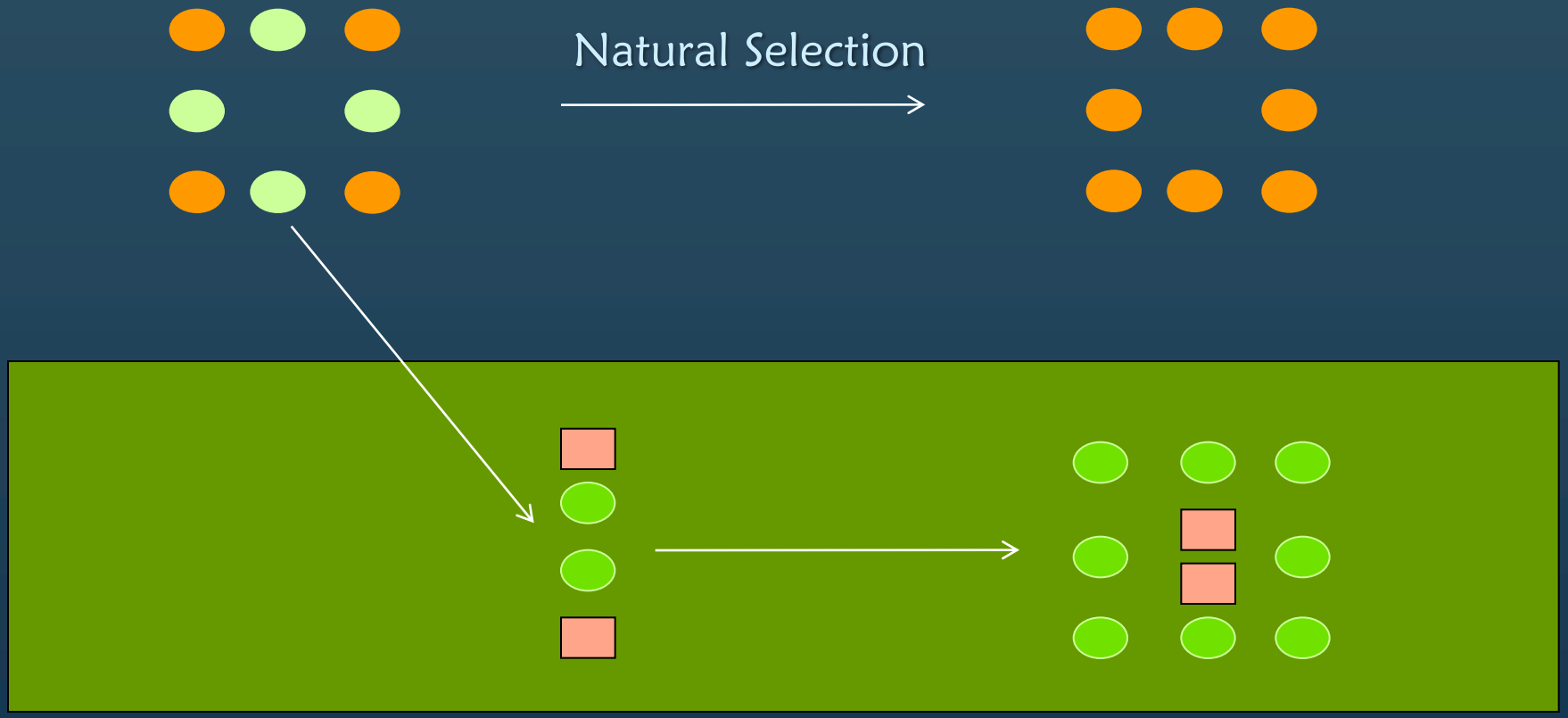
Kampourakis K. (2020) *Understanding Evolution*. Cambridge University Press, Cambridge.

The "Darwinian" revolution



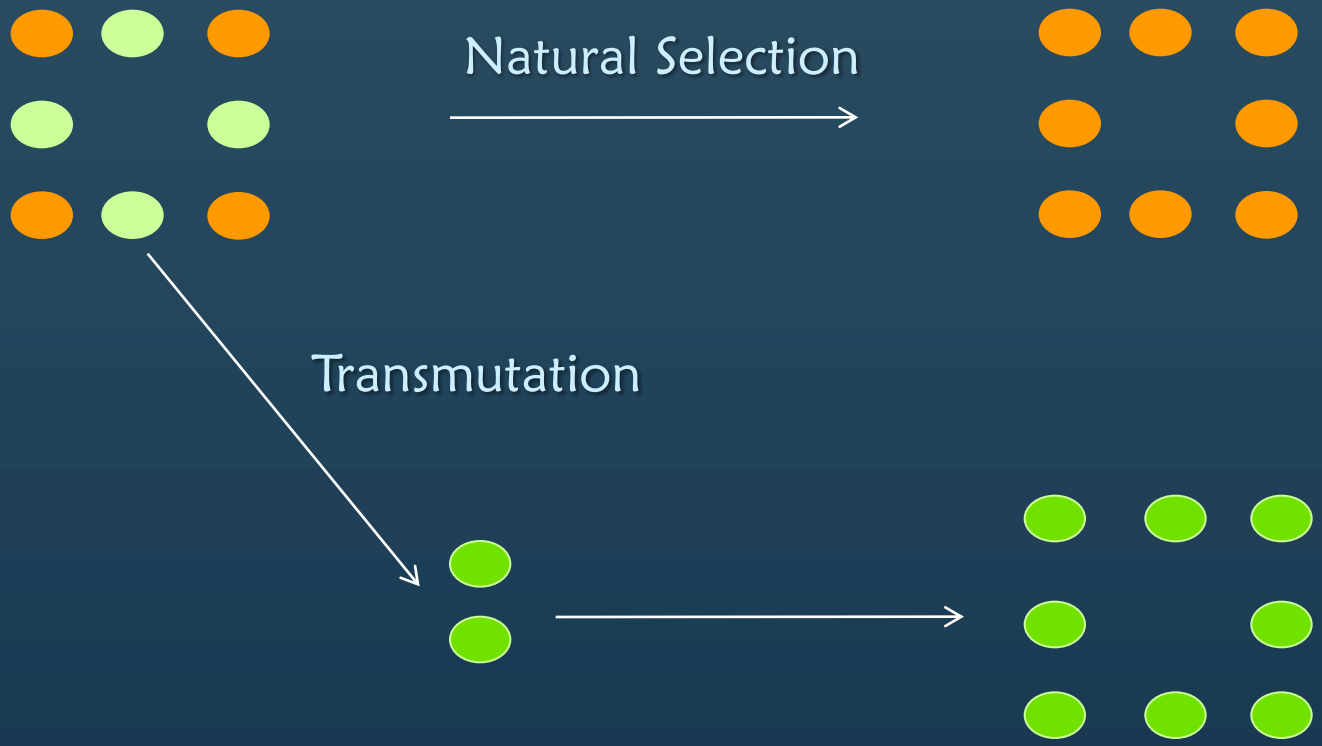
Waters C.K. (2009) The arguments in *The Origin of Species*. In Hodge J., Radick G. (Eds) *The Cambridge Companion to Darwin (2nd edition)*. Cambridge University Press, Cambridge.

The "Darwinian" revolution



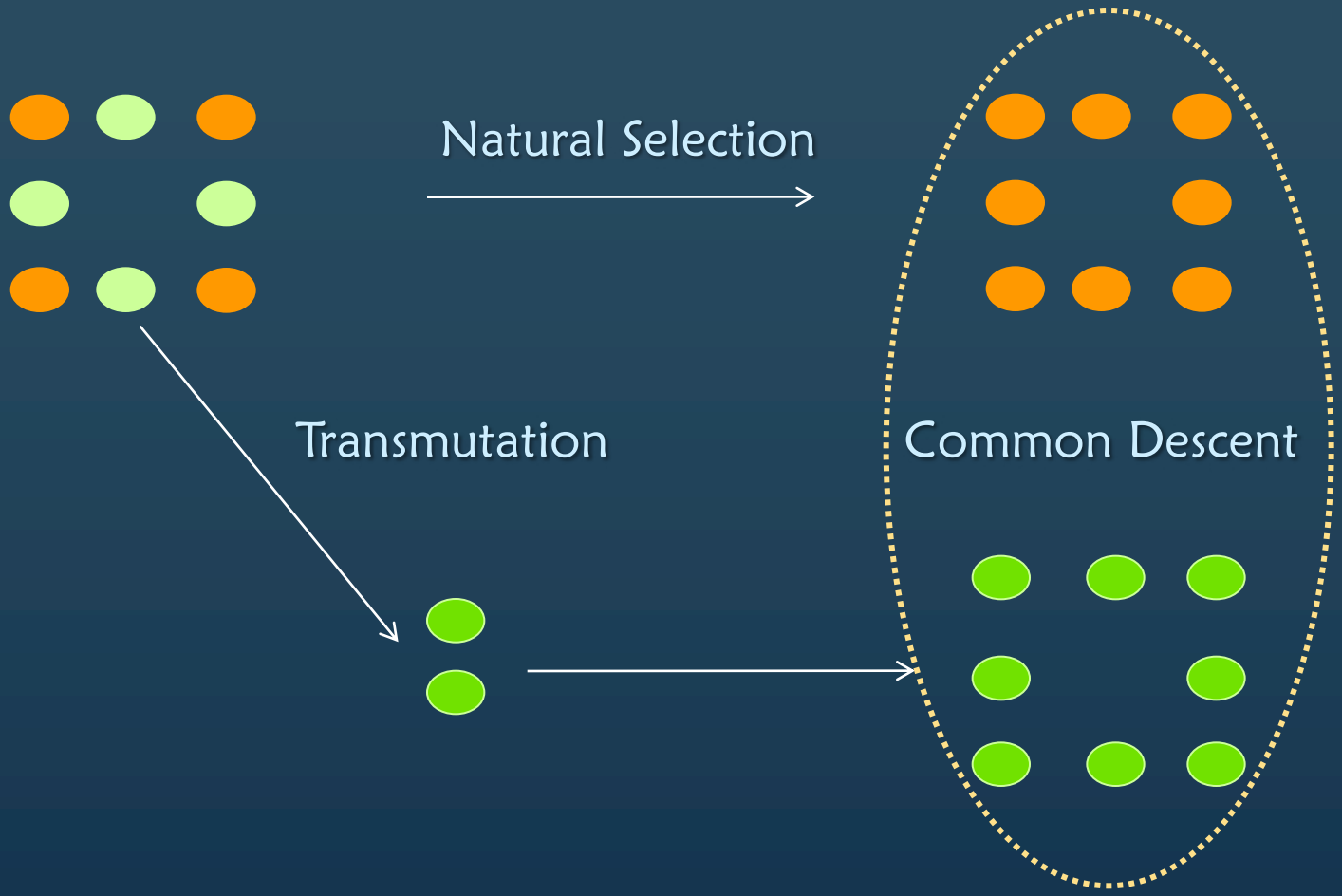
Waters C.K. (2009) The arguments in *The Origin of Species*. In Hodge J., Radick G. (Eds) *The Cambridge Companion to Darwin (2nd edition)*. Cambridge University Press, Cambridge.

The "Darwinian" revolution



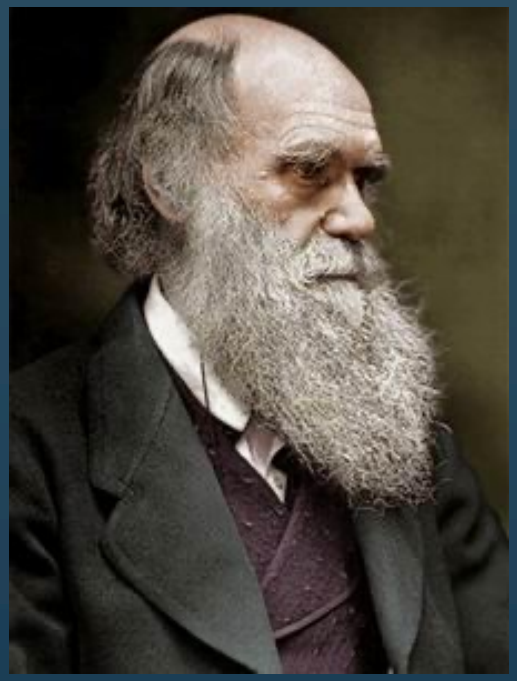
Waters C.K. (2009) The arguments in *The Origin of Species*. In Hodge J., Radick G. (Eds) *The Cambridge Companion to Darwin (2nd edition)*. Cambridge University Press, Cambridge.

The "Darwinian" revolution



Waters C.K. (2009) The arguments in *The Origin of Species.* In Hodge J., Radick G. (Eds) *The Cambridge Companion to Darwin (2nd edition).* Cambridge University Press, Cambridge.

The "Darwinian" revolution



Charles Darwin
(1809-1882)

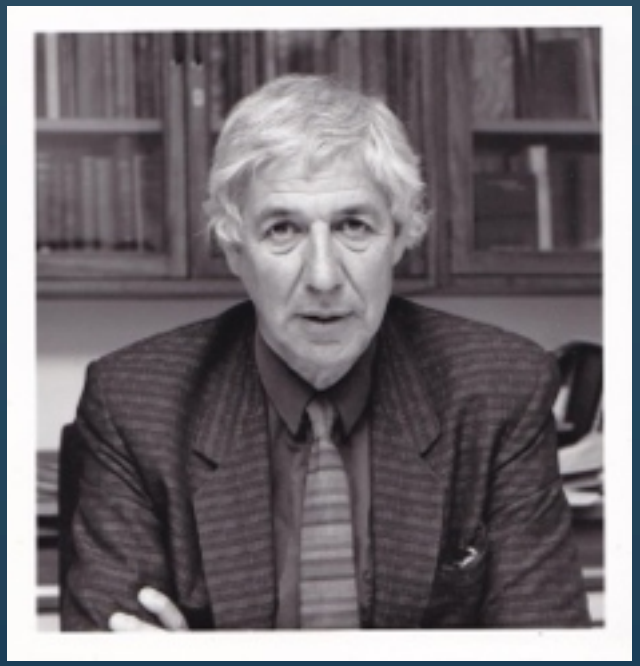
"The old argument of design in nature, as given by Paley, which formerly seemed to me so conclusive, fails, now that the law of natural selection has been discovered. We can no longer argue that, for instance, the beautiful hinge of a bivalve shell must have been made by an intelligent being, like the hinge of a door by man. There seems to be no more design in the variability of organic beings and in the action of natural selection, than in the course which the wind blows. Everything in nature is the result of fixed laws."

Barlow N (Ed) (2005) [1958] The autobiography of Charles Darwin 1809–1882. W.W. Norton, New York

Overview

- Scientific revolutions and conceptual change
- The "Darwinian" revolution
- The "Molecular" revolution
- Revolution or … evolution?

The "Darwinian" revolution

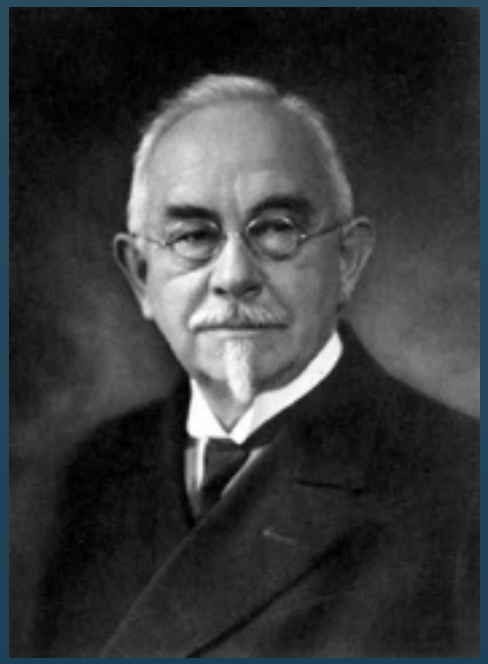


Lewis Wolpert
(1929-2021)

"... the revolution in molecular biology changed the paradigm from metabolism to information. Before the role of DNA was understood, most attention was focused on where the energy for making proteins came from; modern molecular biology introduced the idea that this was not the important issue and that the problem was what information determined the sequence of amino acids in the protein. DNA as we have seen contains the necessary information."

Wolpert, L. (1992). *The unnatural nature of science*. Harvard University Press.

The "Molecular" revolution

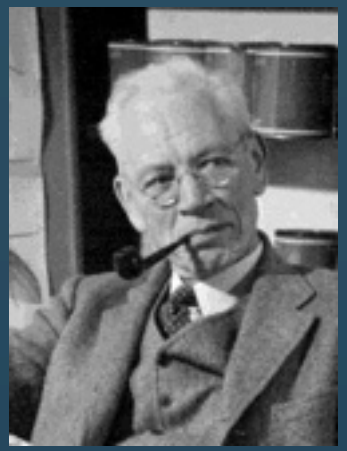


Wilhelm Johannsen
(1857-1927)

"The word 'gene' is completely free from any hypotheses; it expresses only the evident fact that, in any case, many characteristics of the organism are specified in the gametes by means of special conditions, foundations, and determiners which are present in unique, separate, and thereby independent ways—in short, precisely what we wish to call genes."

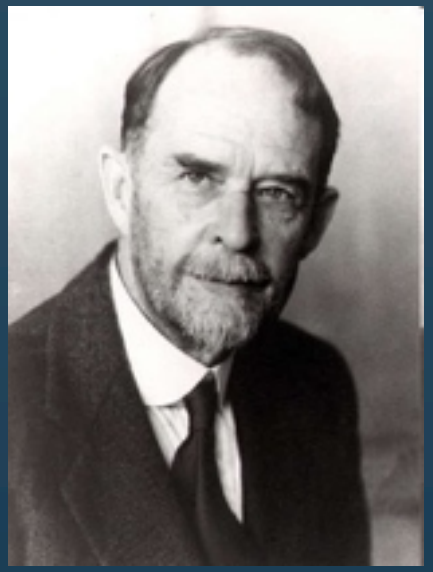
Roll-Hansen, N. (2014). Commentary: Wilhelm Johannsen and the problem of heredity at the turn of the 19th century. *International Journal of Epidemiology*, 43 (4), 1007-1013.

The "Molecular" revolution

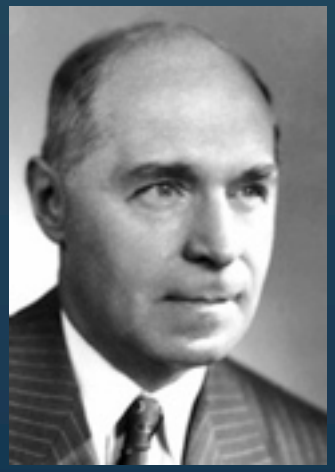


Alfred Sturtevant
(1891-1970)

Calvin Bridges
(1889-1938)



Thomas Hunt Morgan
(1866-1945)

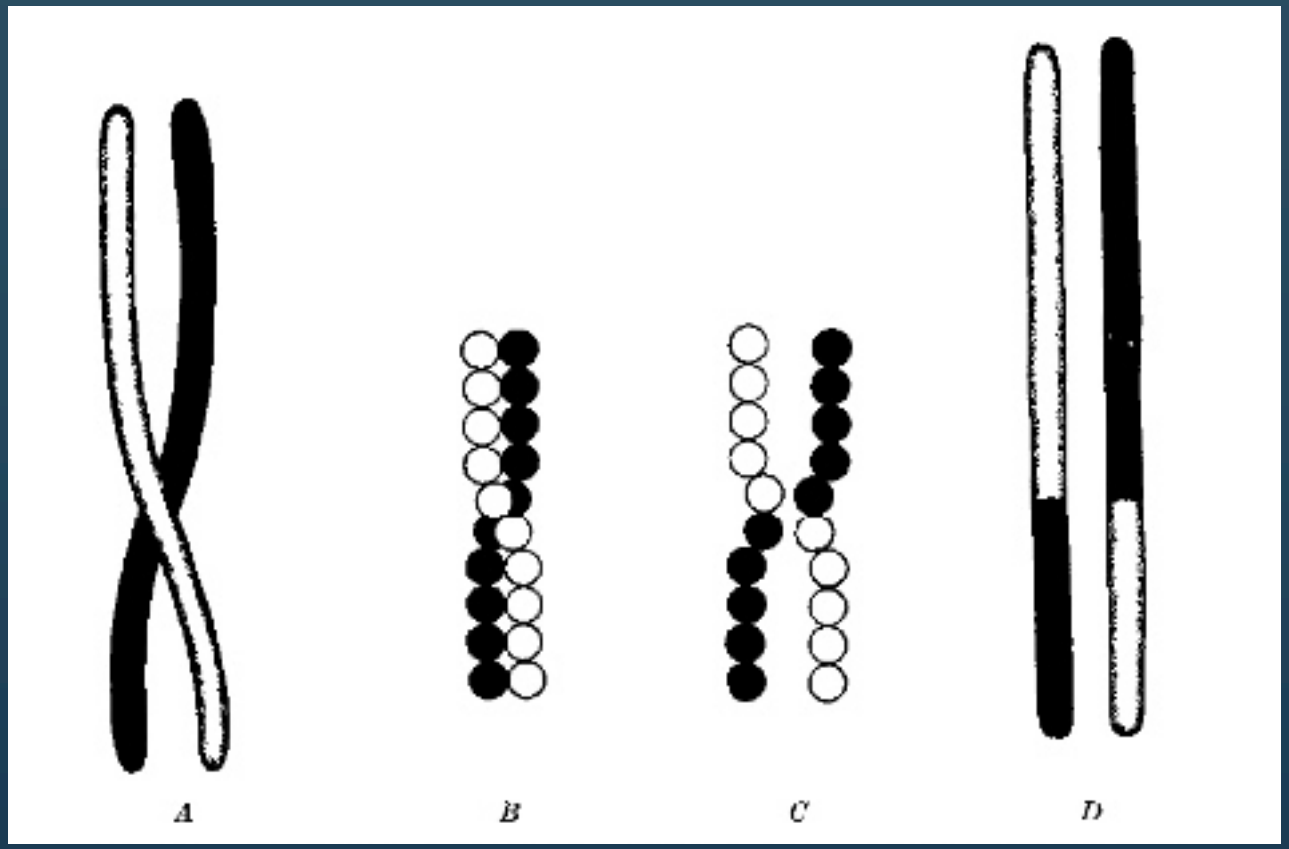


Hermann Muller
(1890-1967)

Theodosius Dobzhansky
(1900-1975)

Kohler R. E. (1994). *Lords of the Fly: Drosophila Genetics and the Experimental Life.* University of Chicago Press, Chicago.

The "Molecular" revolution



"beads on a string"

Morgan, T.H., Sturtevant, A. H., Muller, H. J., & Bridges, C. B. (1915). *The Mechanism of Mendelian Heredity*. New York: Henry Holt and Company.

The "Molecular" revolution

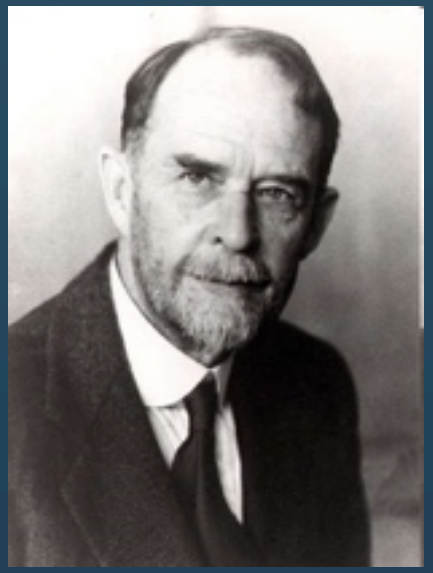
gene 1 →
gene 2 →
gene 3 →
gene 4 →
… →
gene 25 →

gene 1 →
gene 2 →
gene 3* →
gene 4 →
… →
gene 25 →

Waters, C. (2007). Causes that make a difference. *The Journal of Philosophy*, CIV 551 - 579.

The "Molecular" revolution

"There is no consensus of opinion amongst geneticists as to what the genes are - whether they are real or purely fictitious - because at the level at which the genetic experiments lie, it does not make the slightest difference whether the gene is a hypothetical unit, or whether the gene is a material particle."



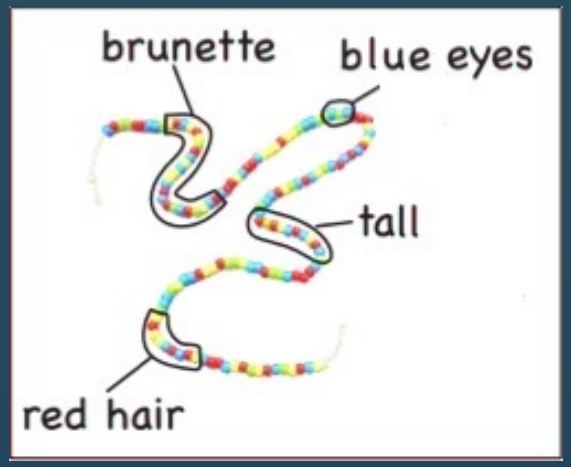
Thomas Hunt Morgan
(1866-1945)

Thomas H. Morgan - Nobel Lecture: The Relation of Genetics to Physiology and Medicine".
http://www.nobelprize.org/nobelprizes/medicine/laureates/1933/morgan-lecture.html

What are genes?

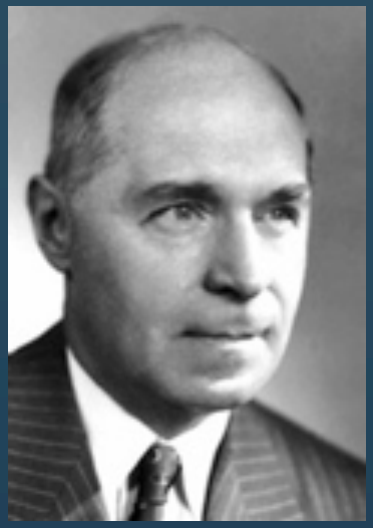
Major gene concepts:

1. "*A factor that controls a trait*" – not specific about what is referred to by the term "gene" (classical gene concept)

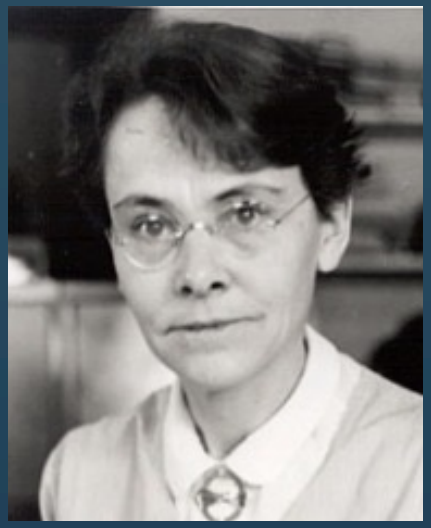


Kampourakis, K. (2021) *Understanding Genes.* Cambridge: Cambridge University Press.

The "Molecular" revolution



Hermann Muller
(1890-1967)



Barbara McClintock
(1902-1992)

genes are material entities

Muller, H. J. (1927). Artificial transmutation of the gene. *Science*, 46, 84-87.

Creighton, H. B., & McClintock, B. (1931). A correlation of cytological and genetical crossing-over in Zea mays. *Proceedings of the National Academy of Sciences*, 17(8), 492-497.

The "Molecular" revolution

Martha Chase
(1927-2003)

Alfred Hershey
(1908-1997)

genes are made of DNA

Hershey, A. D. & Chase, M. (1952). Independent functions of viral proteins and nucleic acid in growth of bacteriophage. *Journal of General Physiology*, 36, 39–56.

The "Molecular" revolution

James Watson
(1928 -)

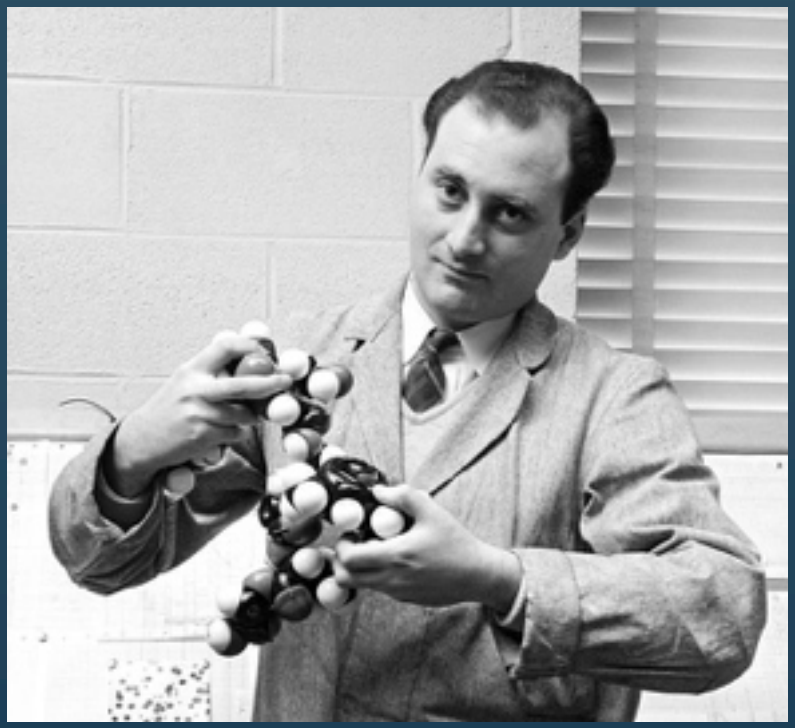
Francis Crick
(1916-2004)

DNA is a double helix

Watson J. D. & Crick F.H.C. (1953). Molecular structure of nucleic acids. *Nature* ,171, 737-738.

Watson J. D. & Crick F.H.C. (1953). Genetical implications of the structure of deoxyribonucleic acid. *Nature* 171, 964-967.

The "Molecular" revolution



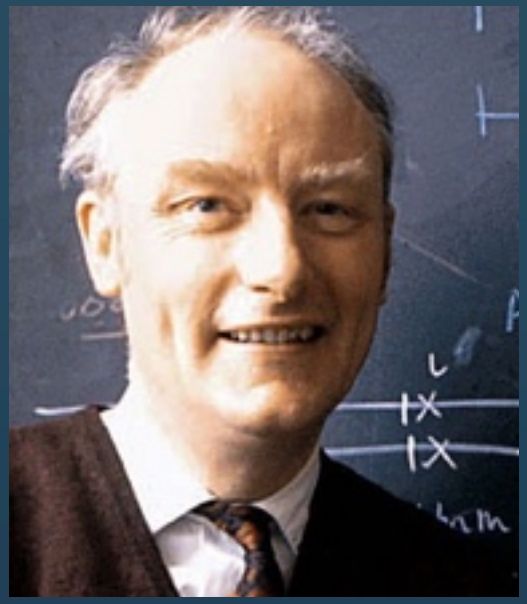
Seymour Benzer
(1908-1997)

genes are divisible, consisting of nucleotides

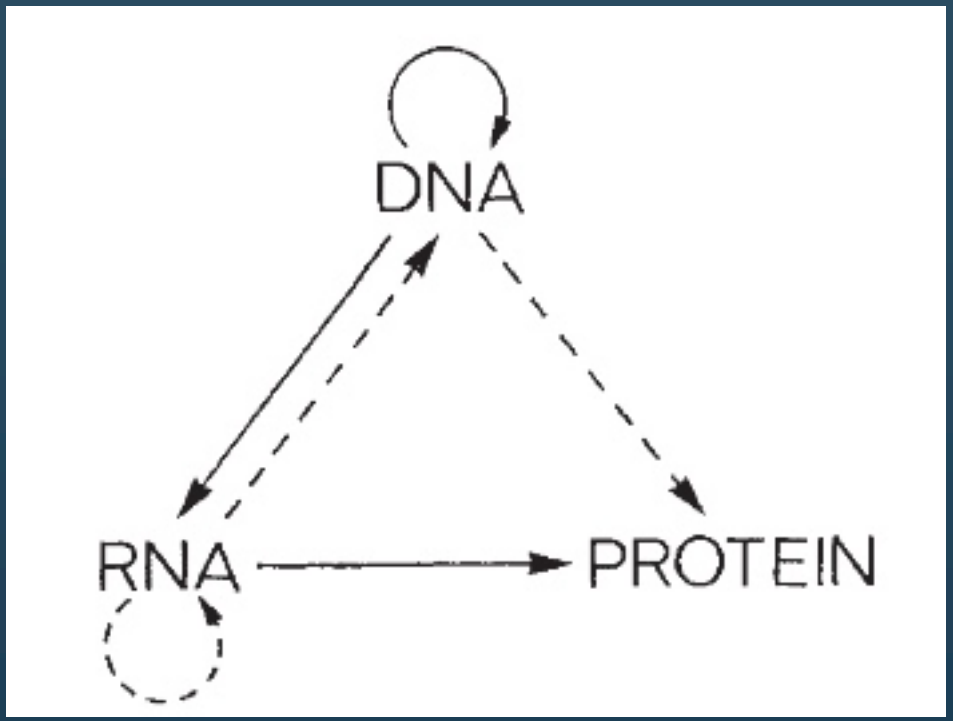
Benzer, S. (1955). Fine structure of a genetic region in bacteriophage. *Proceedings of the National Academies of Science USA* , 41, 344-354.

Benzer, S. (1957). The elementary units of heredity. In *Symposium on the Chemical Basis of Heredity* pp. 70–93. Johns Hopkins University Press.

The "Molecular" revolution



Francis Crick
(1916-2004)

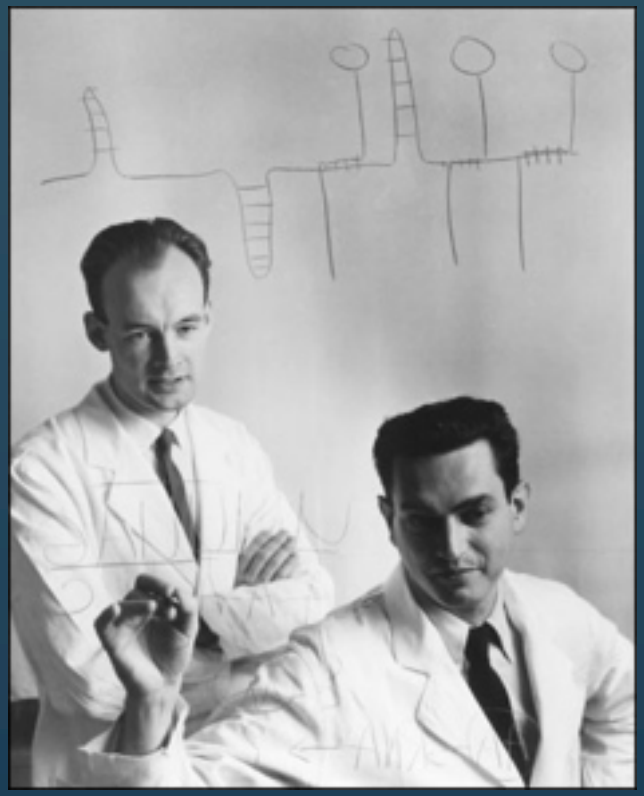


sequence information

Crick, F. (1958). On protein synthesis. *Symposium of the Society of Experimental Biology*, 12, 138–163.

Crick, F. (1970). Central dogma of molecular biology. *Nature*, 227(5258), 561-563.

The "Molecular" revolution



Heinrich Matthaei (1929 -)

Marshall Nirenberg (1927-2010)

genes encode information for protein synthesis

(3 bases – 1 amino acid)

Nirenberg, M.W. & Matthaei, H.J. (1961). The dependence of cell-free protein synthesis in E. coli upon naturally occurring or synthetic polyribonucleotides. *Proceedings of the National Academy of Sciences* USA, 47 (10), 1588–1602.

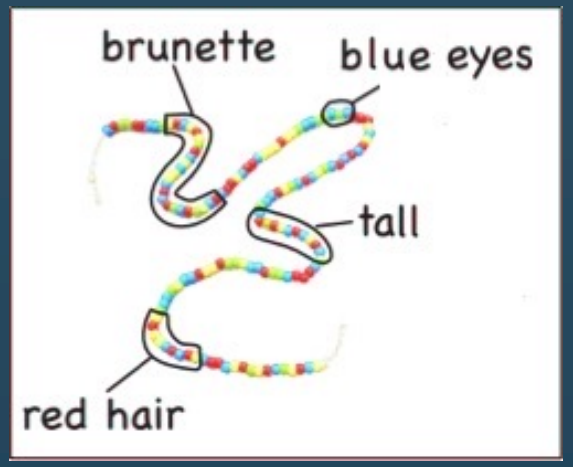
Nirenberg, M., Leder, P., Bernfield, M., Brimacombe, R., Trupin, J., Rottman, F., and O'Neal, C. (1965). RNA codewords and protein synthesis, VII. On the general nature of the RNA code. *Proceedings of the National Academy of Sciences*, USA. 53, 1161–1168.

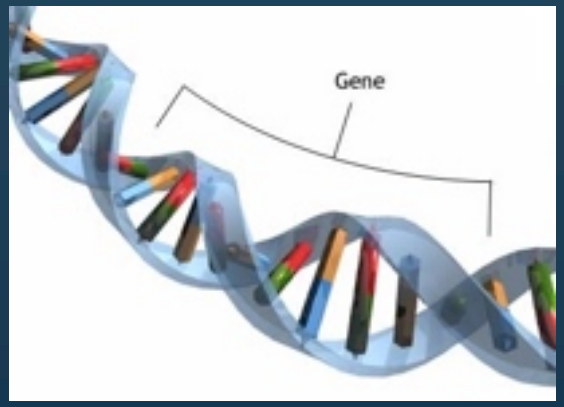
The "Molecular" revolution

Major gene concepts:

1. "*A factor that controls a trait*" – not specific about what is referred to by the term "gene" (classical gene concept)

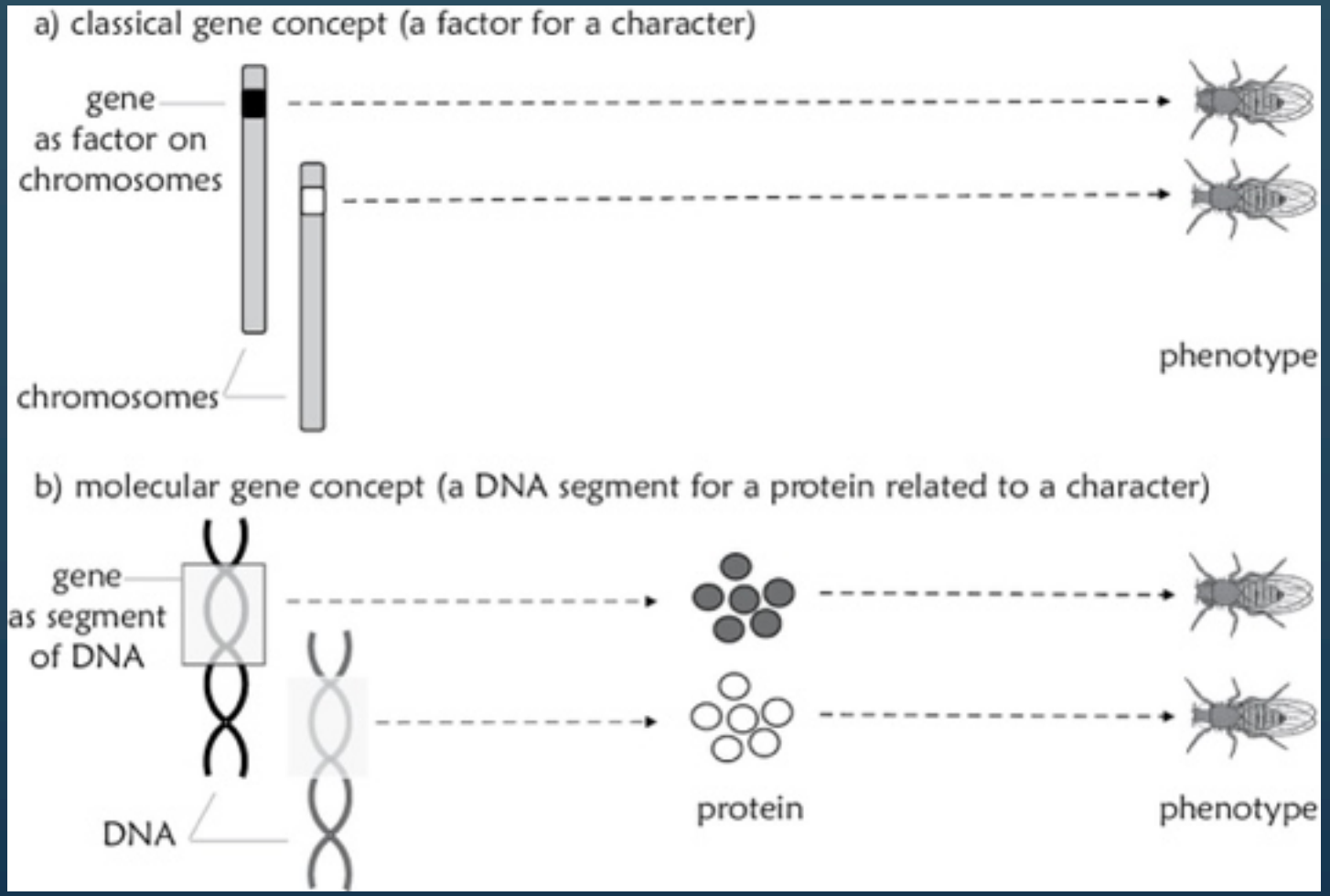
2. "*A DNA segment carrying information for a protein*" – specific about what is referred to by the term "gene" (molecular gene concept)





Kampourakis, K. (2021) *Understanding Genes.* Cambridge: Cambridge University Press.

The "Molecular" revolution



Kampourakis, K. (2021) *Understanding Genes.* Cambridge: Cambridge University Press.

The “Molecular” revolution

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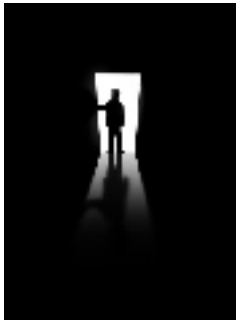

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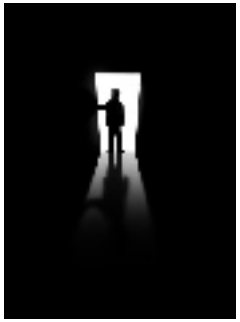
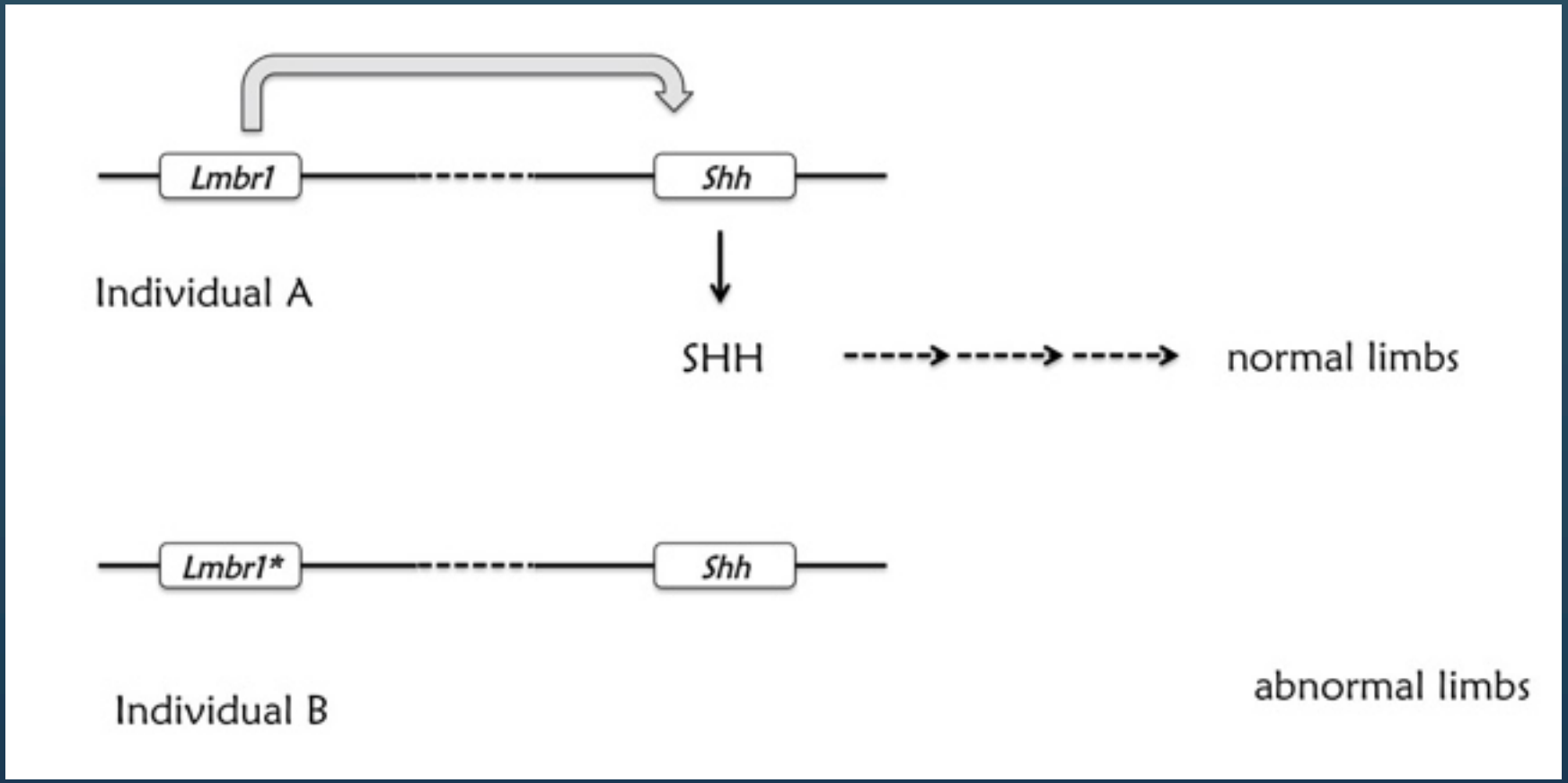


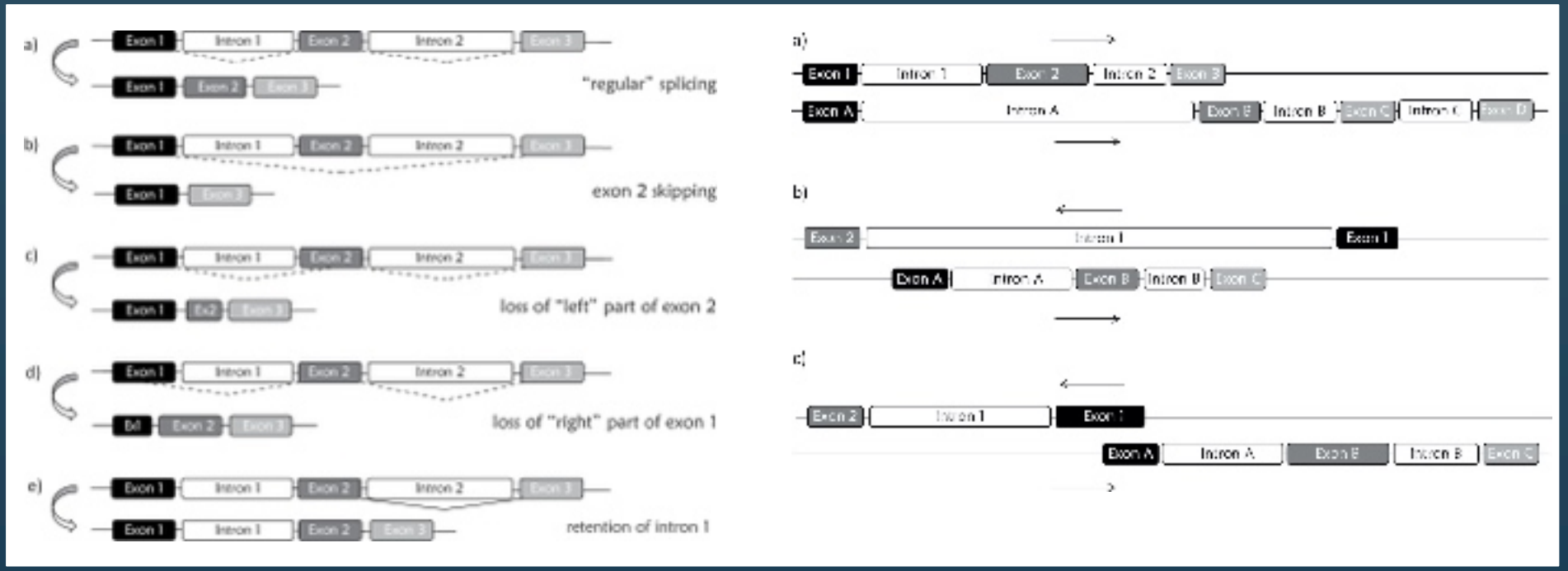
The "Molecular" revolution



Griffiths, P. & Stotz, K. (2013). *Genetics and Philosophy: An Introduction*. Cambridge: Cambridge University Press.

Kampourakis K. (2021). *Understanding Genes.* Cambridge: Cambridge University Press.

The “Molecular” revolution



alternative splicing

overlapping genes

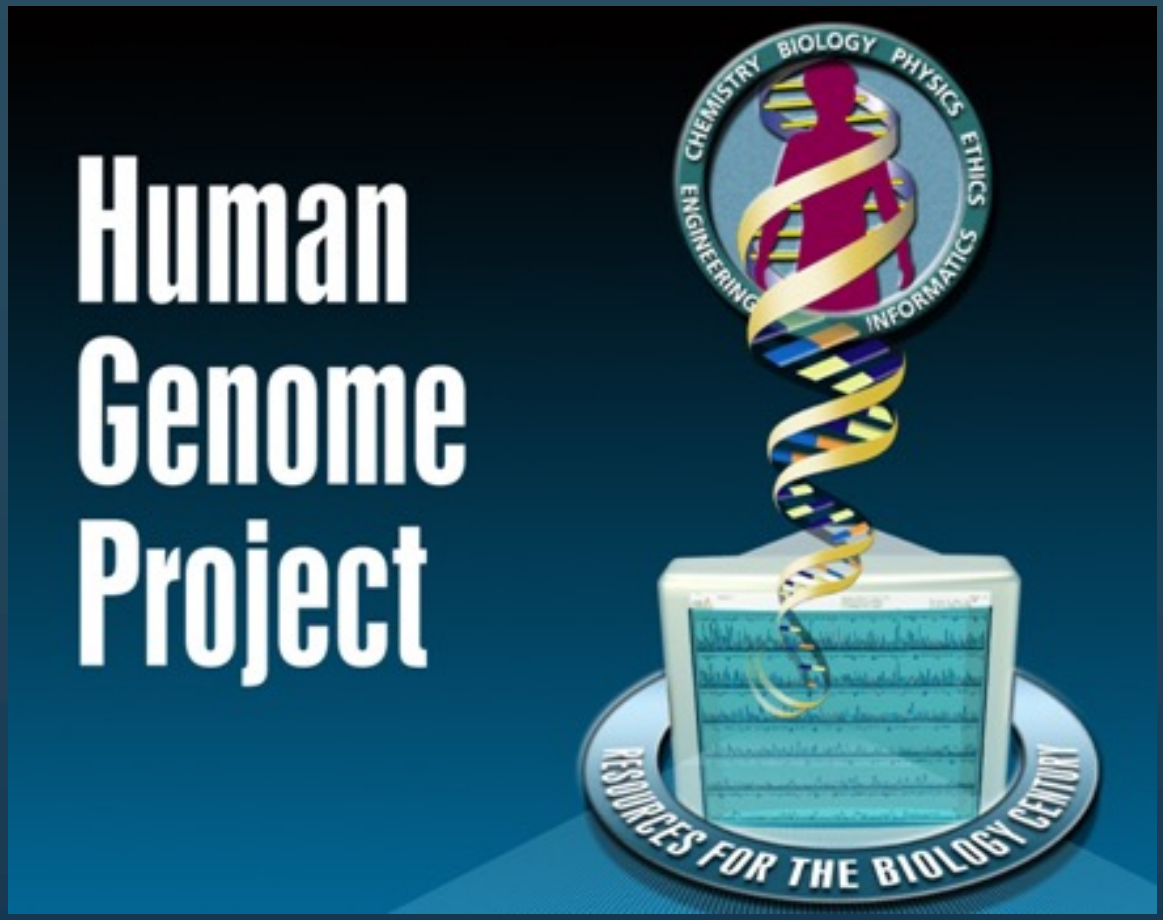
Kampourakis K. (2021). *Understanding Genes.* Cambridge: Cambridge University Press.

The "Molecular" revolution

"A full-scale Kuhnian analysis would seek to demonstrate the existence of an articulated paradigm in the pre-1950s incommensurable with the paradigm of modem molecular biology. There is little support in the literature for the existence of such incommensurable views. Thus the pre-1950s did not differ from the modem period in terms of the fundamental explanatory approach adopted. Save for the paradox-hunters inspired by Bohr, the founders of modem molecular biology were at one with their forebears in seeking straightforward chemical and physical explanations of biological phenomena. The notion of copying a sequence of 'residues' on a template was introduced in the 1930s, 'likewith-like' and 'complementary' schemes of replication were discussed in the 1940s, while hydrogen' bridges' (bonds) and salt-linkages were invoked as the mechanisms for holding polypeptide chains in particular conformations in both the 30S and 40s. Finally, the specificity of large molecules was attributed to their three-dimensional shape and the presence in them of 'active groups'.

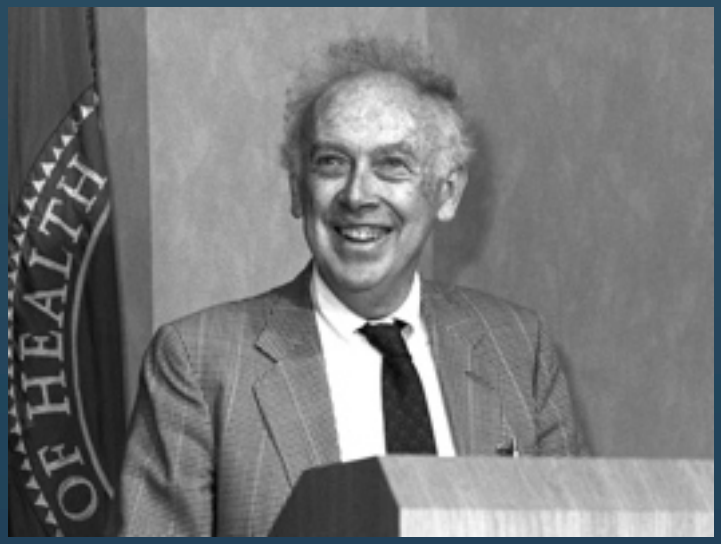
Olby, R. C. (1990). The molecular revolution in biology. In R. C. Olby, G. N. Cantor, J. R. R. Christie, & M. J. S. Hodge (Eds.), *Companion to the history of modern science* (pp. 503-520). Routledge.

The "Molecular" revolution



The "Molecular" revolution

"Since we can now produce good genetic maps that allow us to locate culprit chromosomes and then actually find the genes for disease (as Francis Collins found the gene for cystic fibrosis), genetics should be a very high priority on the agenda of NIH research"

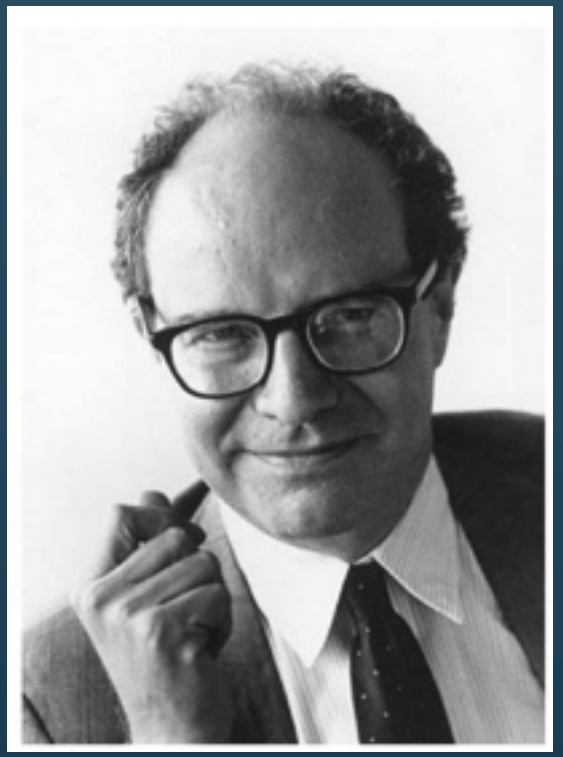


James Watson
(1928 -)

Watson, J. D. (1992). A personal view of the project. In Daniel J. Kevles and Leroy Hood, eds. *The Code of Codes: Scientific and Social Issues in the Human Genome Project.* Cambridge, MA: Harvard University Press, 164-173.

The "Molecular" revolution

"Three billion bases of sequence can be put on a single compact disk (CD), and one will be able to pull a CD out of one's pocket and say, 'Here is a human being; it's me!' But this will be difficult for humans. ... To recognize that we are determined, in a certain sense, by a finite collection of information that is knowable will change our view of ourselves."

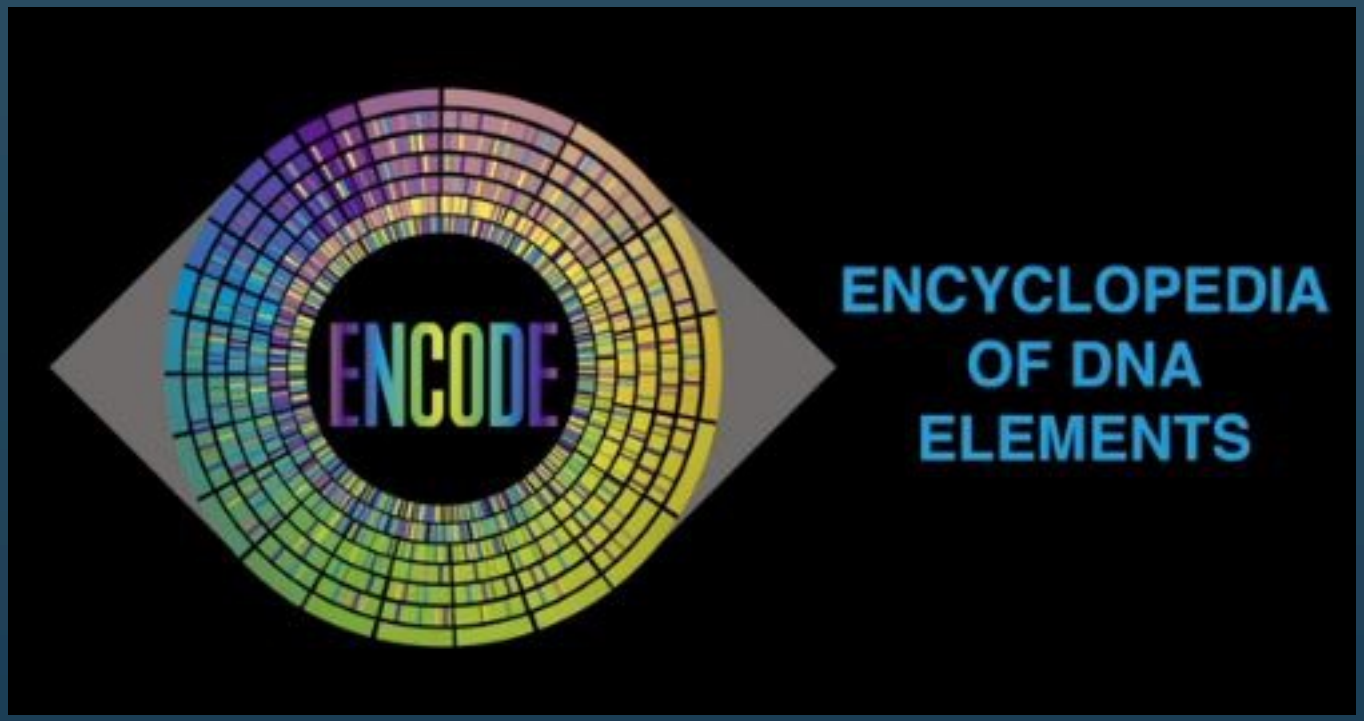


Walter Gilbert
(1932 -)

Gilbert, W. (1992). A vision of the grail. In In Daniel J. Kevles and Leroy Hood, eds. *The Code of Codes: Scientific and Social Issues in the Human Genome Project.* Cambridge, MA: Harvard University Press, 83-97.

The “Molecular” revolution

The “Molecular” revolution



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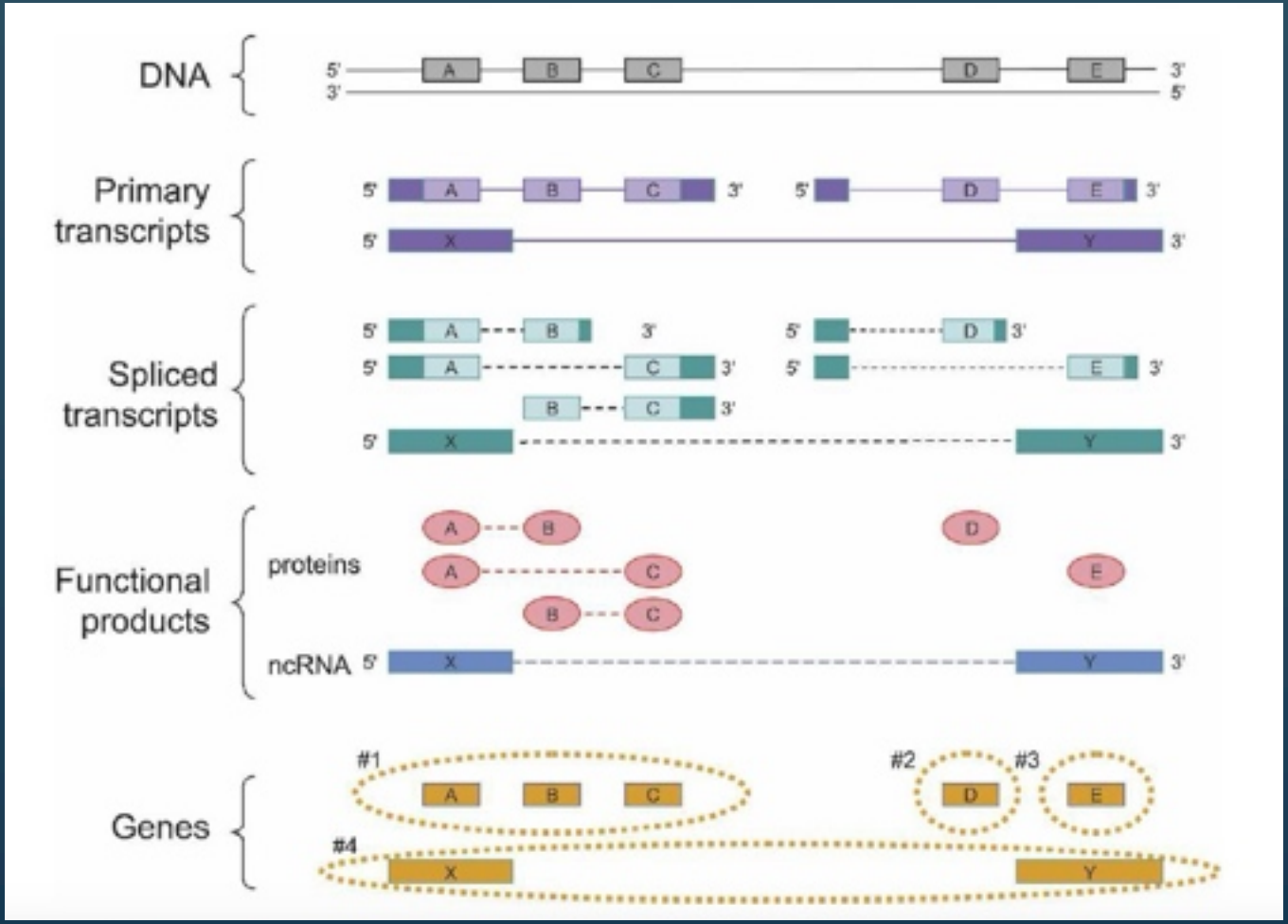

"The gene is a union of genomic sequences encoding a coherent set of potentially overlapping functional products."

Gerstein, M. B., Bruce, C., Rozowsky, J. S., Zheng, D., Du, J., Korbel, J. O., et al. (2007). What is a gene, post-ENCODE? History and updated definition. *Genome Research*, *17*(6), 669-681.

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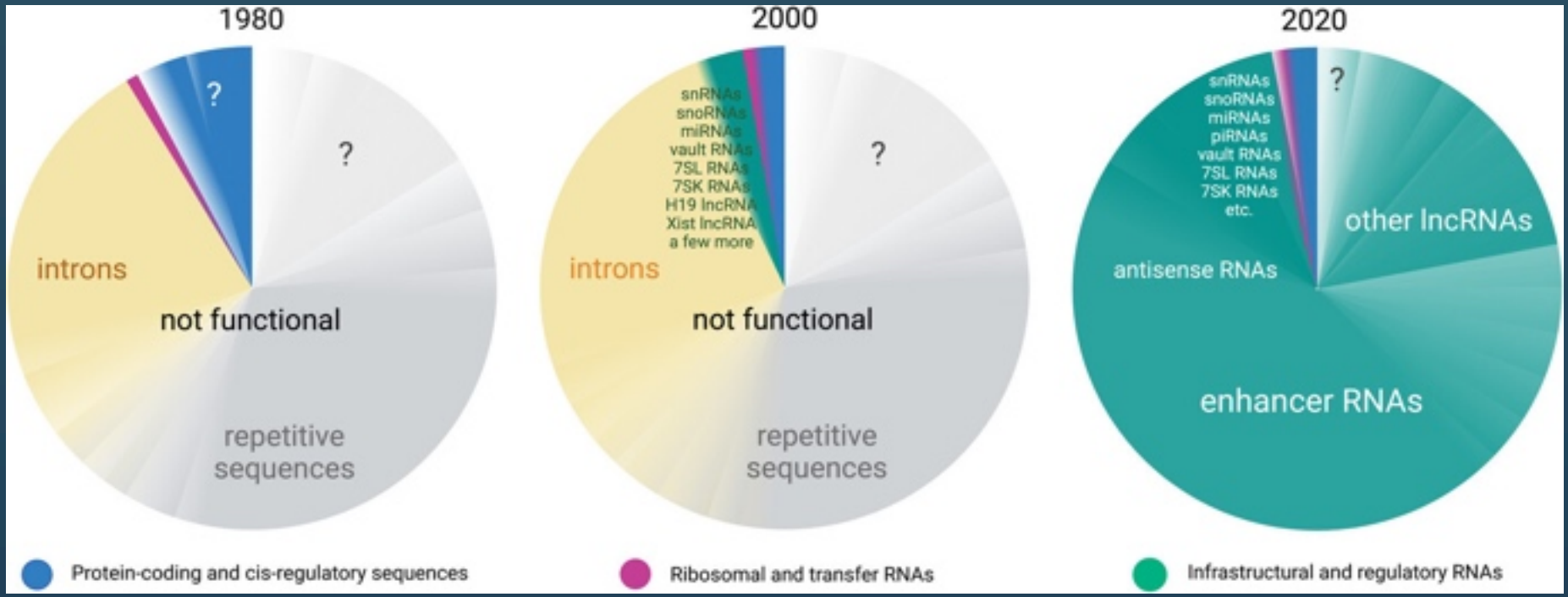

“Thus, in simplified Kuhnian terms, the dominant paradigm in molecular biology since its foundation that “genes encode proteins and sequences that do not are mainly junk” should be replaced by “genes encode proteins and regulatory RNAs, the latter required for the epigenetic control of developmental trajectories”. RNA is not simply an intermediate between gene and protein, but a major player in gene regulation and a contributor to inheritance.”

Mattick, J. S. (2023). A Kuhnian revolution in molecular biology: Most genes in complex organisms express regulatory RNAs. *BioEssays, 45*(9), e2300080

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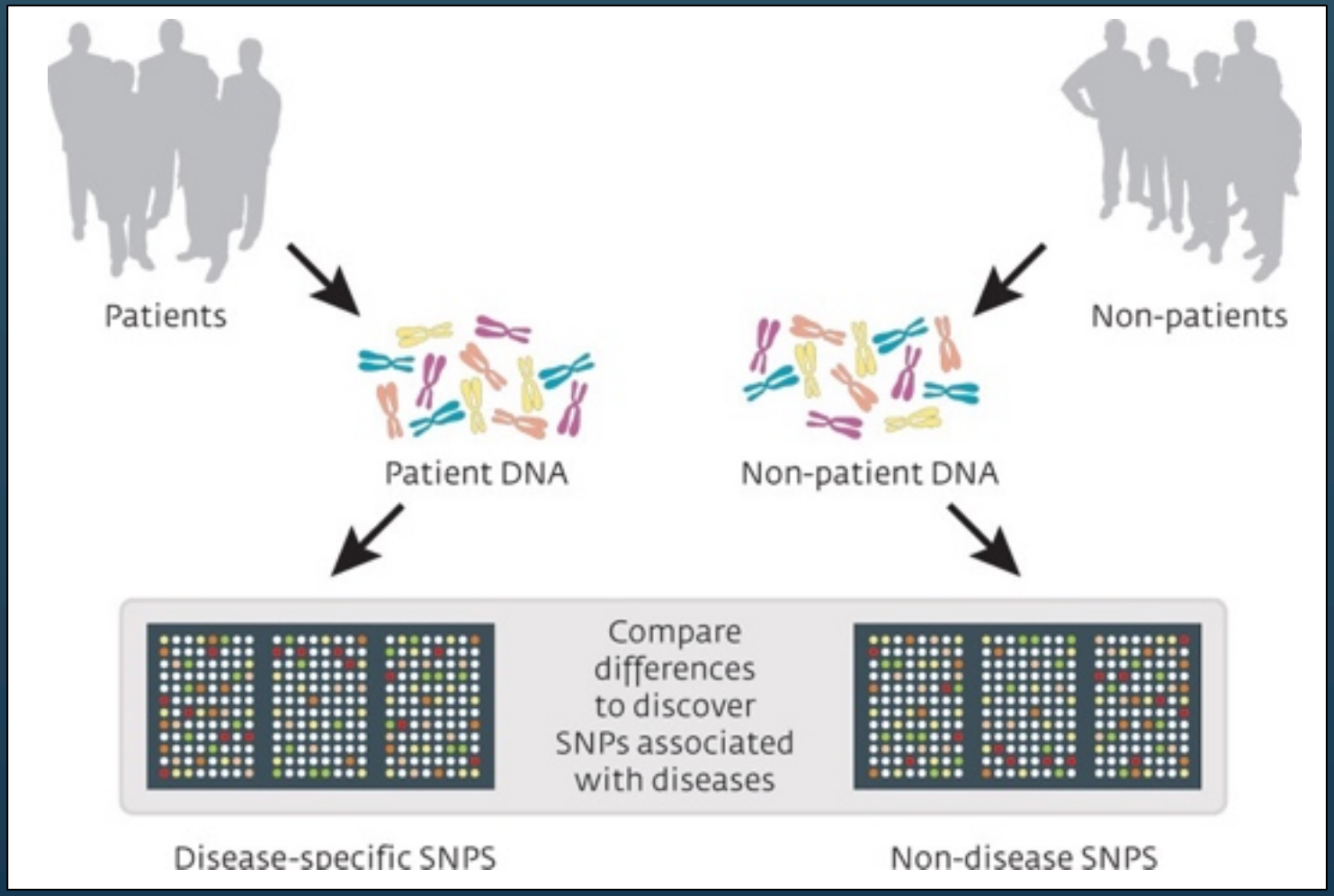


Kruglyak, L. (2008). The road to genome-wide association studies. *Nature Reviews Genetics*, 9(4), 314-318.

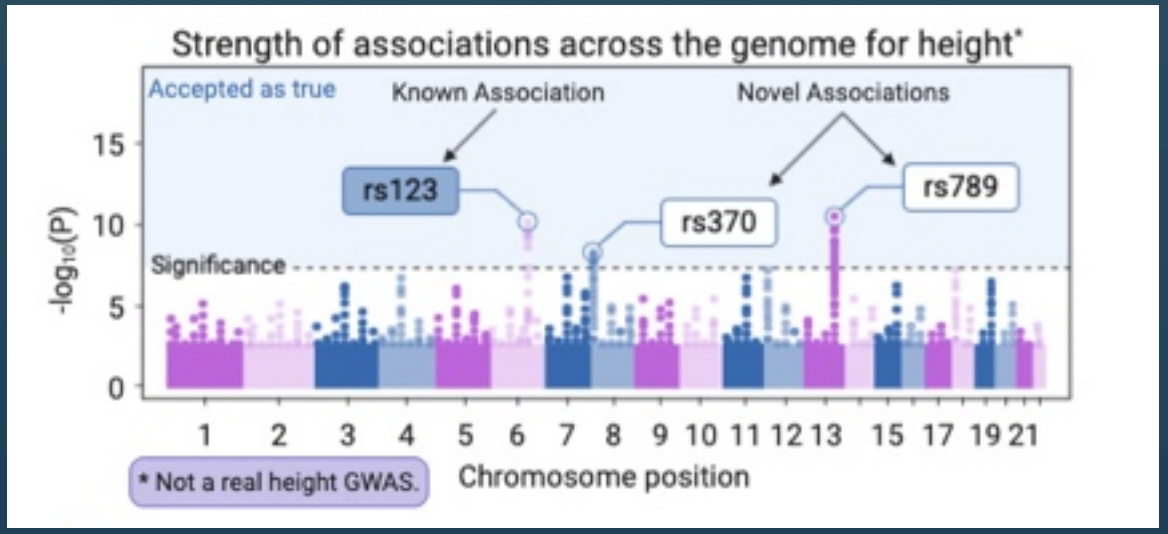
Visscher, P. M., Brown, M. A., McCarthy, M. I., & Yang, J. (2012). Five years of GWAS discovery. *The American Journal of Human Genetics*, 90(1), 7-24.

The "Molecular" revolution

A 21st century gene concept:

the "associated gene"

An allele (gene, DNA segment, or SNP) that has been found to have a statistically significant association with a trait or condition.



Kampourakis, K. (2021) *Understanding Genes.* Cambridge: Cambridge University Press.

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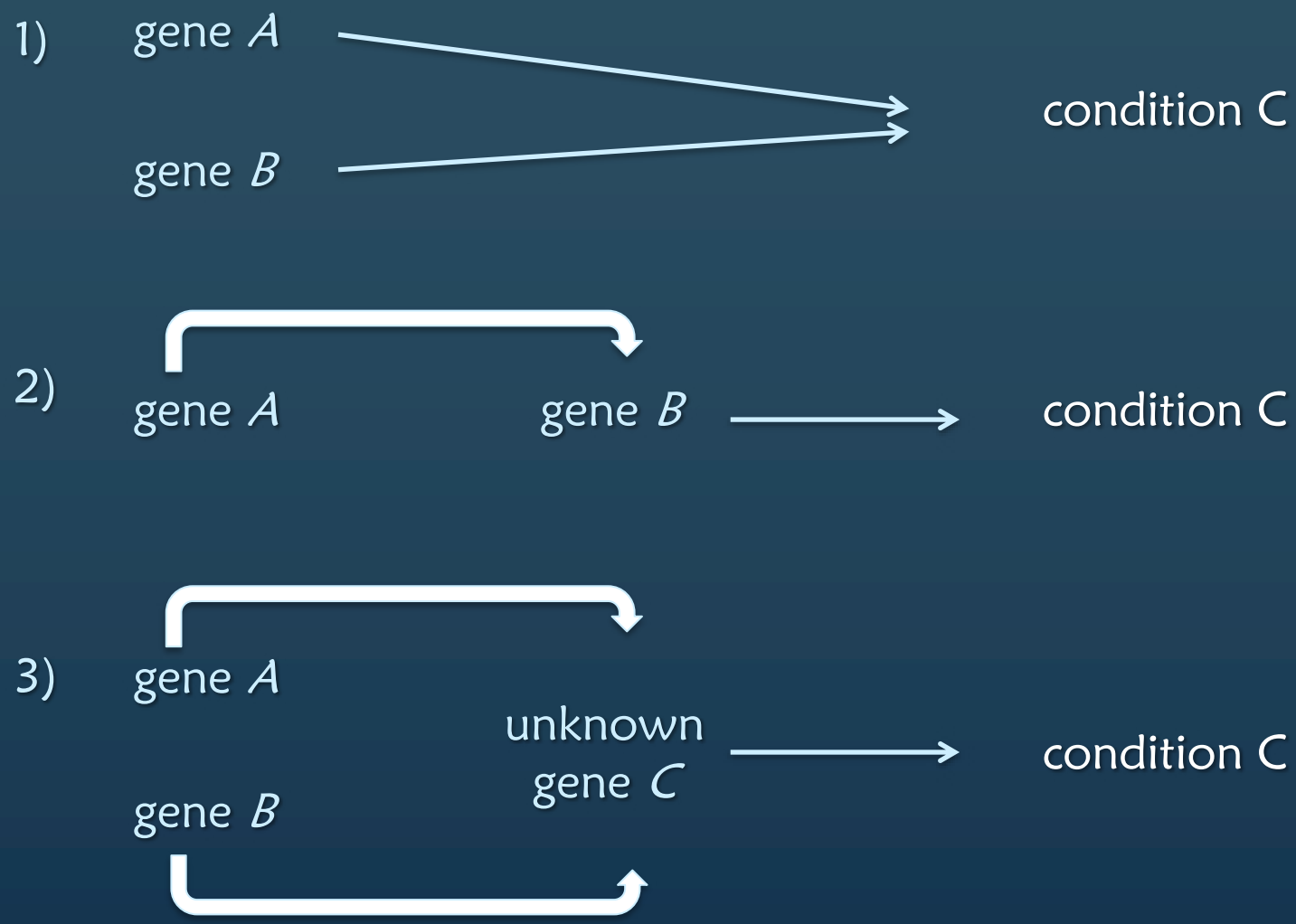

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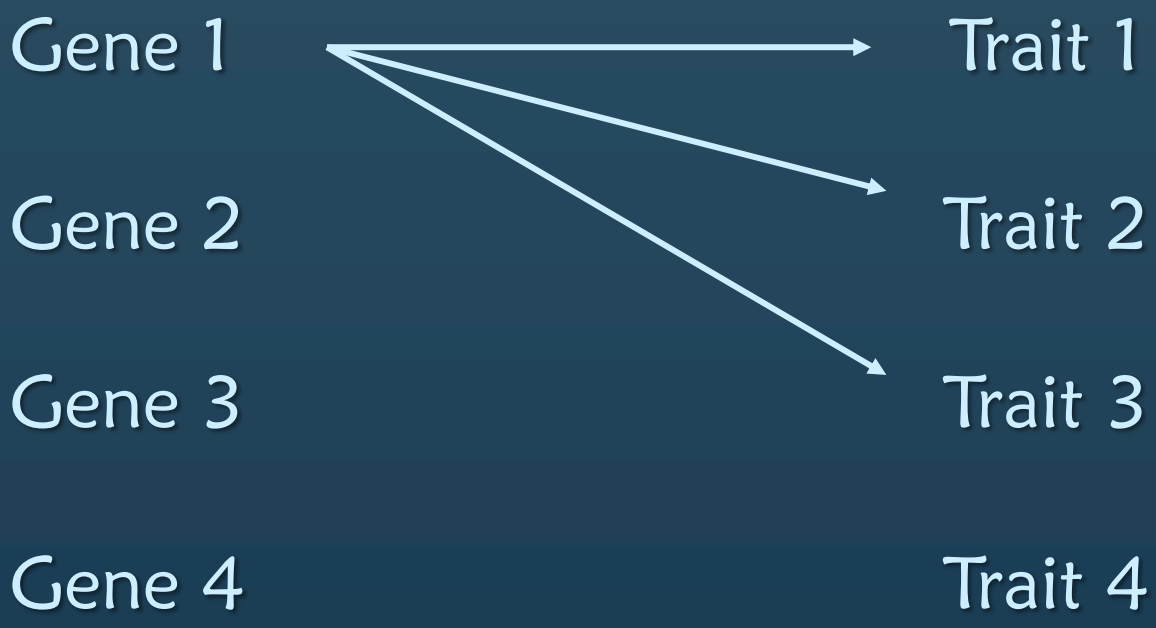
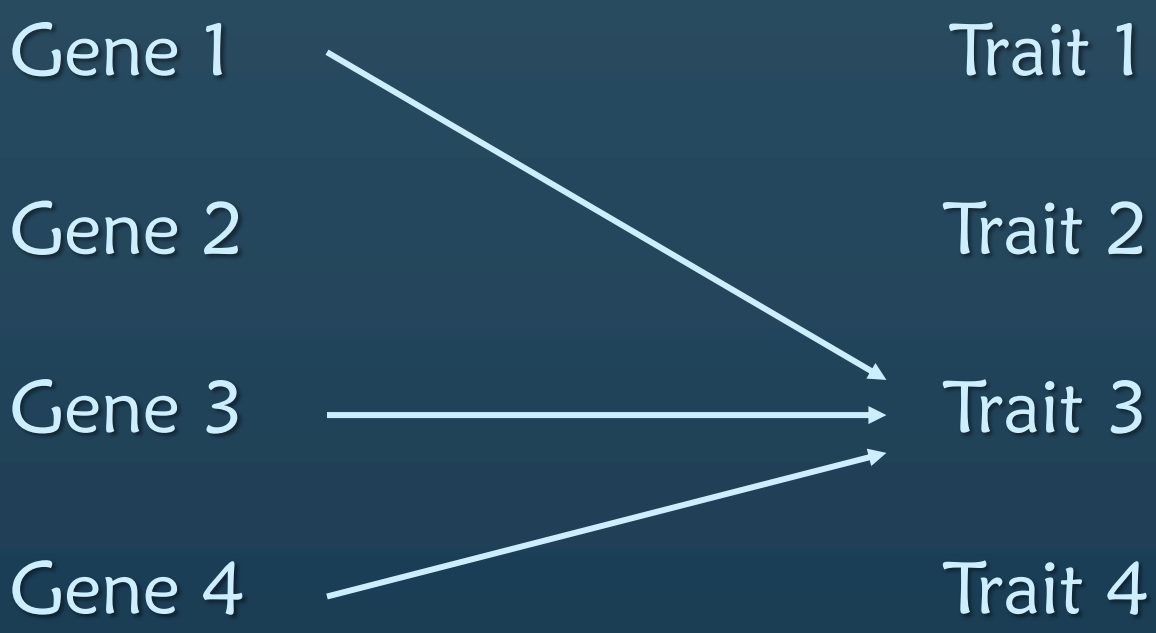


pleiotropic genes

The "Molecular" revolution



polygenic traits

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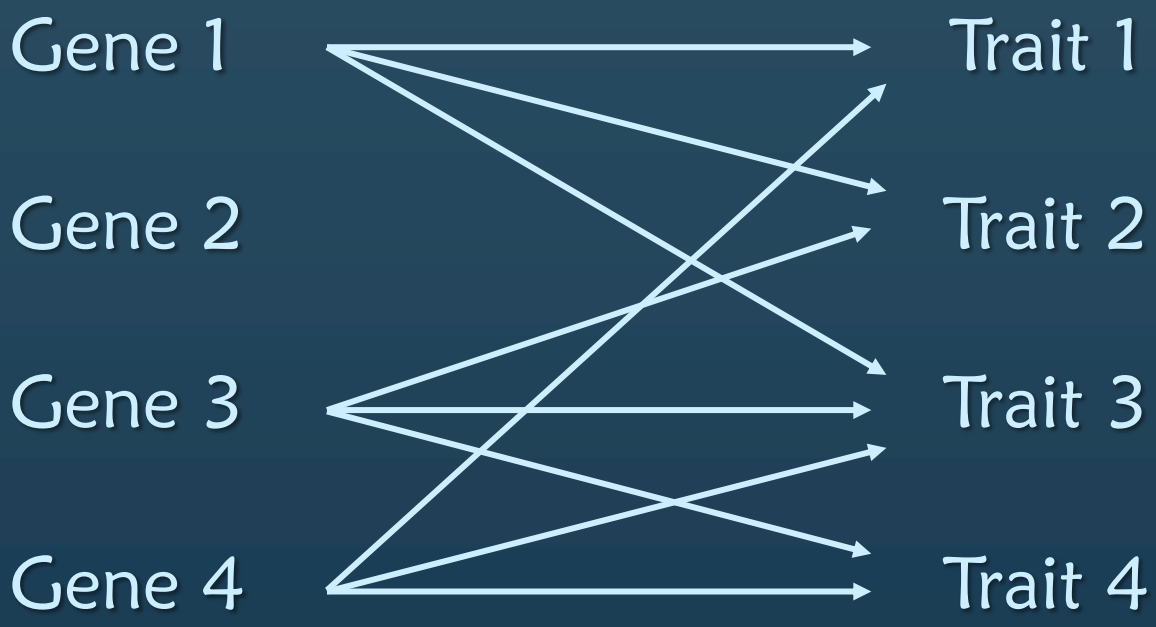

Overview

- Scientific revolutions and conceptual change
- The "Darwinian" revolution
- The "Molecular" revolution
- Revolution or … evolution?

Scientific revolutions and conceptual change

The Darwinian revolution

Species are specially created.
Evolution as a heretical idea.

↓

Speciation via evolution as mainstream idea

The Molecular revolution

Gene sequences determine traits

↓

DNA contains various sequences that are implicated in the development of traits

Revolution or … evolution?

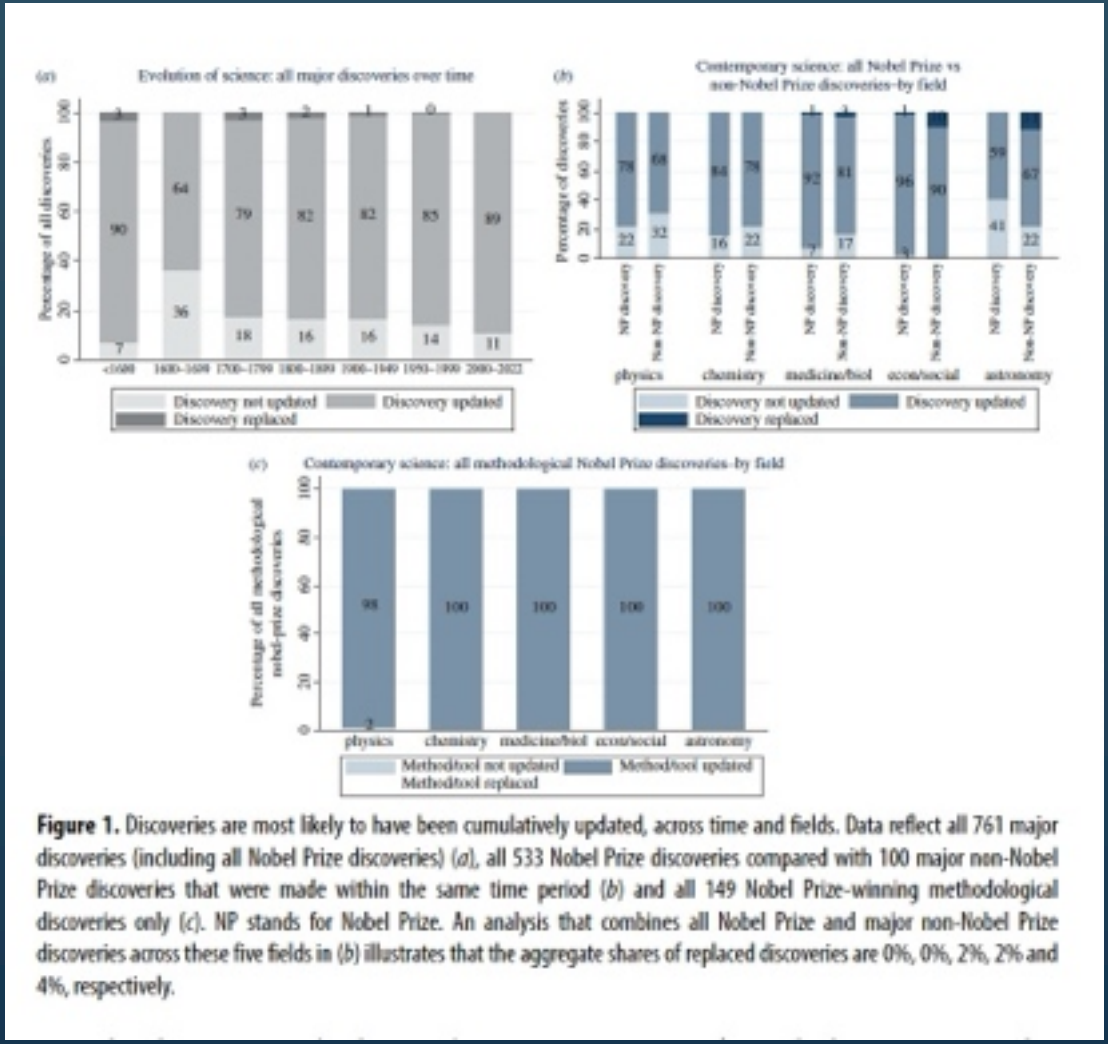

Figure 1. Discoveries are most likely to have been cumulatively updated, across time and fields. Data reflect all 761 major discoveries (including all Nobel Prize discoveries) (*a*), all 533 Nobel Prize discoveries compared with 100 major non-Nobel Prize discoveries that were made within the same time period (*b*) and all 149 Nobel Prize-winning methodological discoveries only (*c*). NP stands for Nobel Prize. An analysis that combines all Nobel Prize and major non-Nobel Prize discoveries across these five fields in (*b*) illustrates that the aggregate shares of replaced discoveries are 0%, 0%, 2%, 2% and 4%, respectively.

Krauss, A. (2024). Debunking revolutionary paradigm shifts: Evidence of cumulative scientific progress across science. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *480*(2302), Article 20240141.

Revolution or … evolution?

Table 2. Cumulative nature of science and scientific fields: central discoveries and the methods used to develop them build on each other over time. Data based on all 761 major discoveries. Years reflect when the central methods and discoveries were published. A number of other discoveries have also played an important role in these fields.

	discoveries in the field of genetics	heredity (Mendel 1865)	composition of nucleic acids (Kossel 1885)	role of genetics in evolution (Dobzhansky 1937)	genes regulate definite chemical events (Beadle and Tatum 1941)	bacteria display genetic mutations (Delbrück and Luria 1943)	mobile genetic elements (McClintock 1951)	DNA as bearer of genetic information (Hershey 1952)	structure of DNA molecule (Franklin, Crick and Watson 1953)	interpretation of genetic code (Holley, Khorana and Nirenberg 1961)	DNA sequencing (Gilbert and Sanger 1977)	genes causing genetic diseases (Collins 1989)	RNA interference (Fire and Mello 1998)	human genome (Watson and Venter 2004)	method for genome editing—CRISPR (Charpentier and Doudna 2012)
	central method/ instrument used to make the discovery	statistics, probability (1874)	hydrolysis (1888)	statistics, improved (1918)	X-ray analysis, improved (1912)	electron microscope (1933)	microscope, improved (1940)	isotopic labelling (1923)	X-ray diffraction (1953)	paper electrophoresis (1948)	electrophoresis, PAGE (1964)	chromosome jumping technique (1987)	ribosomes, improved (1955)	genome mapping, improved (2001)	DNA sequencing, improved (2004)

	discoveries in the field of electricity	nature of electricity (Franklin 1752)	animal electricity theory (Galvani 1791)	electric battery (Volta 1800)	electromagnetism (Ørsted 1820)	law of electromagnetism (Ampère 1827)	Ohm's Law (Ohm 1827)	electromagnetic induction (generator) (Faraday 1831)	self-inductance—principle of electricity (Henry 1832)	theory of electromagnetic radiation (Maxwell 1865)	Alternating current induction motor (Tesla 1882)	evidence of electromagnetic radiation (Hertz 1887)	Electron (Thomson 1897)
	central method/ instrument used to make the discovery	Leyden jar (1745)	Leyden jar (1745)	alternating (Volta Cruikshank 1800)	electric battery (1836)	magnetic conductor (Ampère 1822)	galvanometer (Ørsted 1820)	galvanometer (Ørsted 1820)	electromagnet, improved (1831)	mathematics, electromagnetic theory of light (1865)	electric generator/ dynamo (Faraday 1831)	induction coil (1836)	cathode ray tube, improved (1897)

Krauss, A. (2024). Debunking revolutionary paradigm shifts: Evidence of cumulative scientific progress across science. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 480(2302), Article 20240141.

The "Darwinian" and the "Molecular" revolutions in biology

13P035: Introduction à l'histoire et la philosophie des sciences

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