Neutral Theory of Molecular Evolution

1. The Background: Why Was a New Theory Needed?

By the mid-20th century, the Synthetic Theory of Evolution had successfully merged Darwinian natural selection with Mendelian genetics. However, as molecular biology advanced in the 1960s, researchers began sequencing proteins and DNA. They observed a puzzling trend: the molecular differences between species appeared to accumulate at a remarkably constant rate, almost like a clock ticking steadily through time.

This was surprising because, under natural selection, evolutionary rates should vary depending on environmental pressures and adaptation needs. These unexpected results led scientists to reconsider the forces driving evolution at the molecular level. Thus emerged the Neutral Theory of Molecular Evolution.

2. The Proponent: Motoo Kimura

Motoo Kimura, a Japanese geneticist, proposed the Neutral Theory in 1968 through his paper "Evolutionary Rate at the Molecular Level". He later expanded his ideas in his book "The Neutral Theory of Molecular Evolution" published in 1983. Kimura suggested that most evolutionary changes at the molecular level are not driven by natural selection, but by random genetic drift of mutant alleles that are selectively neutral. His theory introduced a new perspective on how genetic variation and molecular evolution occur over time.

3. Core Concepts of Neutral Theory

The Neutral Theory makes several key claims about evolution at the molecular level:

First, it proposes that most mutations at the molecular level are neutral. Neutral mutations are changes in DNA that neither benefit nor harm the organism’s fitness. For example, a mutation that changes one DNA base but does not alter the resulting amino acid due to the redundancy of the genetic code is often neutral.

Second, the theory emphasizes that random genetic drift, rather than natural selection, is the primary force driving changes at the molecular level. While natural selection remains crucial for shaping visible traits like body structures and behaviors, at the level of DNA and proteins, random drift dominates.

Third, the Neutral Theory underpins the concept of the molecular clock. Since neutral mutations accumulate at a relatively constant rate over time, scientists can use them to estimate the time of divergence between two species. For instance, molecular evidence based on DNA differences has been used to estimate that humans and chimpanzees shared a common ancestor around six to seven million years ago.

4. Detailed Points of the Neutral Theory

To clearly understand the differences between the traditional Darwinian view and Kimura's Neutral Theory, it helps to compare them directly:

In Darwinism, evolution is driven mainly by adaptation through natural selection, with a focus on visible, phenotypic traits. In contrast, the Neutral Theory suggests that at the molecular level, most evolutionary change is the result of the random fixation of neutral mutations. Natural selection is not absent, but it plays a much smaller role compared to genetic drift when it comes to changes in DNA and protein structures.

The rate of evolutionary change is another point of contrast. Under Darwinian selection, the rate would vary depending on environmental pressures and the advantages of certain traits. However, under the Neutral Theory, the rate of molecular evolution tends to be constant because neutral mutations arise and become fixed at a steady pace, unaffected by selection pressures.

5. Types of Mutations in the Context of Neutral Theory

Mutations can be categorized based on their effect on the organism:

Neutral mutations have no effect on fitness. These are the core focus of the Neutral Theory. An example would be a synonymous codon change in the DNA that does not alter the resulting protein.

Deleterious mutations are harmful and tend to be quickly eliminated by natural selection. For instance, a mutation that produces a nonfunctional enzyme critical for metabolism would be deleterious.

Advantageous mutations are rare but important because they are favored by natural selection. An example would be a mutation that gives bacteria resistance to antibiotics.

The Neutral Theory acknowledges that while some mutations are deleterious or advantageous, the vast majority are neutral, especially at the molecular level.

6. Criticism and Refinement of Neutral Theory

The Neutral Theory was not universally accepted without challenges. Critics pointed out that many mutations have small but real effects on fitness, and that molecular evolution is not purely neutral. Certain genes, especially those involved in the immune system, seem to evolve under strong selective pressures.

In response to these criticisms, Tomoko Ohta, a student of Kimura, proposed the Nearly Neutral Theory. This refined version suggests that many mutations are only slightly deleterious or slightly advantageous and that the importance of genetic drift versus selection depends on the effective population size.

Today, most scientists agree that molecular evolution is driven by a combination of neutral drift and selection, with the balance varying depending on the gene, the species, and the ecological context.

7. Importance in Anthropology

The Neutral Theory has significant applications in anthropology. Anthropologists use neutral genetic markers, such as mitochondrial DNA and Y-chromosome sequences, to trace human migration patterns and ancestral relationships. For example, the "Out of Africa" theory of modern human origins is supported by molecular data that largely follow neutral expectations.

Moreover, the molecular clock concept, rooted in the Neutral Theory, allows anthropologists to estimate divergence times between different human populations and between humans and other primates. This helps in reconstructing the evolutionary history of Homo sapiens and our relatives like Neanderthals and Denisovans.