

The Quantifiable Life:

Harnessing Mathematical Models to Decode and Predict Biological Phenomena

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Modern biology has fundamentally transformed from a non-quantitative science to a quantitative one, driven by advances in technology and methodology. During my elementary years, I learned how Robert Hooke used a microscope to discover cells, and in high school, I acknowledged that Aristotle had determined whales are viviparous. These early studies prioritized objective observations. In contrast, modern biology relies heavily on quantitative data. Noteworthy examples include the discovery of the genome of extinct species and human evolution. This shift reflects the influence of foundational sciences, which have long embraced quantification. Erwin Schrödinger's seminal question in 'What is Life?'—'How can events within a living organism be accounted for by physics and chemistry?'—highlights this inevitable transition in biological research from qualitative observation to quantitative precision.

Quantitative models serve as bridges between experimental data and theories, moving away from black box approaches to data interpretation. These models allow us to understand the underlying principles of a system, offering an approach to summarize, predict, and verify changes methodically. It enables systematic control over phenomena and even fosters the creation of new systems based on these principles. While trial and error method has its place, it will eventually be replaced by research and production guided by theoretical models.

In this course, we have explored several elegant yet simple quantitative models that demonstrate their practical value in biological contexts. For instance, concepts like bi-stability, hysteresis, and bifurcations explain why equilibrium states differ when approached from two different directions. These models show how biological systems can maintain stability or generate various response to different initial conditions. Furthermore, we've seen how binding probability and fold-change are used to describe repression mechanisms, providing a quantitative framework for

understanding gene regulation. Additionally, graph theory has proved instrumental in managing models of simple activation, helping us visualize and analyze complex networks of interactions within biological systems.

Future advancements in biological technology will increasingly rely on quantitative data and models, with fields like synthetic biology poised for significant breakthroughs. Synthetic biology can now redesign genomics and metabolic pathways, transforming cells and even creating synthetic cells, offering boundless possibilities. Gradually, experimental biologists will require a theoretical basis to estimate how to engineer cells, a foundation that only quantitative biology can provide. While past modeling primarily focused on metabolic networks, modeling at the cellular and multicellular levels is still developing. The recent rise of AI for Science (AI4Sci) could also aid in extracting undiscovered scientific principles from data, optimizing and interpreting models, and gradually demystifying complex processes.

In conclusion, modern biology's transformation into a quantitative science underscores the necessity of using quantitative data and models. As discussed, these models are crucial for understanding complex biological systems and for pioneering advances in areas like synthetic biology. The mantra of this course, "quantitative data demands quantitative models," captures this shift effectively. This approach is essential, as it moves us beyond mere observation to a deeper, systematic understanding of life's complexities. As biology continues to evolve, quantitative models will remain indispensable in driving forward the next wave of scientific discoveries.