WORKSHOP REPORT

Modularity of Biological Systems
April 13-17, 2026

Organizers:
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Overview: [from the Workshop website]
The hypothesis that biological systems exhibit a modular structure is widely accepted. Beyond being a "fundamental law of biology," it has the potential for important applications, for instance in biomedicine and synthetic biology. It could also serve as an organizational principle for the analysis of high-dimensional complex -omics datasets. However, there is currently no widely accepted definition of what comprises a biological "module". There is also a lack of foundational research on modularity at both the theoretical and applied level. To address this problem, the proposed workshop will bring together an interdisciplinary group of researchers from biology, modeling, mathematics, and fields outside of biology that currently use the modularity concept, such as engineering and computer science. Participants will work collaboratively to outline a research program consisting of a set of specific research projects that will deliver a rigorous basis for theoretical, technical, and applied research in this field.

This workshop arose from the activities of a working group on this topic that had very humble beginnings in 2020 and has since grown to approximately 30 registered members.
https://laboratoryforsystemsmedicine.github.io/Modularity-Group/

Scientific scope:
As the title of the working group/workshop indicates, the topic reaches across all of biology, which represents a challenge when organizing a group of scientists around it: how to avoid fragmentation into a collection of subgroups that do not communicate much with each other, fitting the common definition of modularity? While most of the formal talks during the workshop were focused on molecular systems biology, there were speakers from other fields, such as synthetic biology, evolutionary biology, or neuroscience, in addition to speakers with a more theoretical mathematical bent. It appeared that almost all participants attended all the formal lectures, which we see as an indication that participants were willing to engage with topics not in their research area. The comments in the excellent NITMB survey of the 70 participants confirm this. The survey also makes clear that they matched the diversity of the science discussed, as well as the different career stages.

Talks and working groups:
An important goal for us was to encourage as much interaction between participants as possible and create a true workshop atmosphere rather than a conference with many formal technical talks. We scheduled a total of 15 formal talks for the week, including four introductory talks on the first day by the organizers. Thus, there were 3-4 formal talks per day, leaving ample time for other activities. The talks were of high quality and illuminated the subject from several different angles. The contrasting approaches to modularity in the different subfields of biology were very illuminating. Several mathematicians emphasized how this changed their view of the type of formalism that will be most useful.

The time outside of formal talks was mostly filled with activities of 8 working groups, most following initial suggestions the organizers made, but others initiated by participants. Time allotted each day for working group meetings averaged 3-4 hours. Topics included:

- Multiscale modules between cells and organs
- Bio-enabled AI models for systems biology: a funding program for modularity research
- Modularity in human macroscopic neurophysiology: A test case with EEG data
- Mathematical foundations of modularity
- Compare and contrast existing modularity concepts: commonalities and differences
- Developing a combinatorial/topological approach framework for testing modularity
- Identifying modules from high-throughput data, including GRN modules
- Introduction to biochemical control theory and development of a measure of modularity

The great majority of participants signed up for a working group and contributed to the sessions over the course of the week. Most working groups provided a final report of their activities, and several working groups are continuing to meet, including the working group on mathematical foundations of modularity and the group on comparing and contrasting definitions. Their plan is to publish a critical review and develop a database of annotated articles on the subject. As expected, not all working groups were equally successful, for a host of reasons, such as lack of focus, lack of effective leadership, or unreachable goals. Based on the reports submitted, all working groups made progress, however.

Some scientific insights:
The most important scientific takeaway from the workshop is that across all of biology, there does not seem to be a rigorous theory underlying the modularity concept that could be "operationalized" and applied to system analysis, control, and design. In many cases, the module concept is used to identify what should be considered a module, either structurally or functionally. But, with a very few exceptions, there is no vision of a theory that views a system as an assembly of modules. Exceptions include an approach to signaling pathways, engineering-inspired system design in synthetic biology, neuroscience, and biochemical control theory. The concept of module varies widely and is generally not defined rigorously or at all. This holds important lessons for the development of a mathematical theory of modularity. It provides a guide to the generality such a theory must provide to accommodate different approaches in different fields. In the other direction, such a theory can provide guidelines to practitioners about what level of rigor is needed for definitions of key concepts. This can be of great benefit for the examination of the biological basis for what different fields consider a module.

A great benefit of the workshop for the mathematical/theoretical participants was to see more clearly the biological reality and constraints any theory faces and what it might take to be useful in some practical sense. Conversely, participants working in or close to the life sciences were exposed to what a mathematical theory might look like and how it could be useful for them in their daily work.

Finally, many participants appreciated the opportunity to interact with researchers in other fields around a common problem. This opportunity is relatively rare since most events like conferences or workshops are much more focused on specialized fields. It shows that workshops like this can be successful with the right scientific focus and an opportunity for individual interaction rather than only an opportunity to hear technical lectures from experts in different fields that may, or may not, be close to a participant's technical interests or expertise.

Conclusion:
We believe that the workshop was a considerable success scientifically and "socially," in the sense that it brought a diverse group of scientists together around an important topic of general interest who engaged in a beneficial dialogue. The environment at NITMB played an essential role in this success. The ample availability of space for informal discussion, the integration of meals in this environment, and the superior staff support made all the difference. We are very grateful for the generous support provided.

As an early outcome of the workshop, the following manuscript was recently submitted for publication and is under review. While it was begun sometime before the workshop, it benefitted greatly from that week. Many of the authors attended the workshop. The support from NITMB is acknowledged:

R. Laubenbacher[1], J.L. Hellerstein, S. Wiley, H.M. Sauro, S.S. Andrews, [Listed alphabetically: V.S.N. Bavisetty, D.A. Cruz, E. Dimitrova, S. Feng, L.L. Fonseca, C. Kadelka, D. Murrugarra, D.R. Plaugher, T.J. Sego, S.A. Tsiorintsoa, A. Veliz-Cuba, M. Wheeler][2], Modularity in Biological Systems: Toward a Formal Conceptual Foundation, 2026, under review.

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