

Neural Engineering: Computation, Representation, and Dynamics in Neurobiological Systems

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We present and demonstrate a unified approach to understanding neurobiological systems that employs the quantitative tools of engineers while respecting neuroscientific results. We suggest that this is a fruitful approach to adopt because brains are physical systems and engineers have at their disposal a number of theoretical tools that focus on quantifying the functioning of real-world systems, including information theory, control theory and signal processing theory. In other words, engineers are practical scientists who have to build things that work in the real world — so too does mother nature. So it should not be surprising that the engineering disciplines have embraced and developed the kinds of mathematical tools that are ideally suited to describing dynamic information processing systems under real-world conditions, i.e., nervous systems.

In applying these tools to neurobiological systems, we develop specific accounts of representation, computation, and dynamics in such systems. We extend standard accounts of both single cell and population level representation to provide a novel means of characterizing neural representation over both time and over neural populations. This ‘population-temporal’ representation has a general form that can be used to capture the representation of scalars, vectors, functions, vector fields, and so on. This generality allows us to employ, and switch between higher-level and neural-level representations concurrently in a single model.

Our account of neural computation is a straightforward extension of the account of representation. Thus it is a simple matter to account for feed-forward transformations of the representations characterized as a population-temporal code. To include interesting and complex dynamics in our approach, we turn to the well-established field of control theory. We suggest that it is useful to understand the representations in neurobiological systems as state variables in a modern control theoretic description of the system’s dynamics. We show that it is possible to include the intrinsic dynamics of neural systems in an account as general as that provided by standard control theory. Given such generality, our framework uncovers interesting relations between contemporary work in motor control, central pattern generators, working memory, and dynamical attractor networks.

In addition to providing this framework, we present a means of applying it for generating neurally responsible models. In essence, this methodology provides something like a ‘recipe’ for building simulations that can be used to both test and generate hypotheses regarding the target system.

Summary of our methodology

1. System description

- Identify relevant neurobiological properties (i.e., tuning curves, connectivity, etc.).
- Provide a functional description including specification of subsystems and overall system architecture.
- Specify representations as variables (e.g. scalars, vectors, functions, etc.).
- Provide mathematical description of system function.

2. Design specification

- Specify range, precision, and signal-to-noise ratio for each variable.
- Specify temporal and dynamic characteristics for each variable.

3. Implementation

- Determine the decoding rules for implementing specified transformations.
- Determine which parts of the model are to be simulated to which degrees of detail.
- Perform numerical experiments using resulting simulation.

In our forthcoming book, whose title is the same as above and presently under technical review by MIT Press, we present the framework in greater detail and show numerous examples of the application of it using this methodology. In this presentation we will discuss only one, the neural integrator.