4da Computational Studies of Activated Processes in Complex Systems

Baron Peters

Kinetics has long been a cornerstone of chemical engineering, and kinetics concepts will likely retain their central importance as chemical engineers seek solutions to future problems. In the past two decades, electronic structure theory, molecular mechanics, and Monte Carlo techniques were extensively used in conjunction with transition state theory and molecular dynamics. The combinations of theoretical and computational techniques allowed the calculations of observables such as rate constants and diffusion constants from molecular level information. The impact of computation in chemical engineering has largely been its role in testing molecular level mechanisms. This paradigm will likely remain true, but increasingly, applications are requiring more sophisticated methods. Transition path sampling, committor analysis, and Bayesian inference molecular dynamics, and many other new methods have been developed to treat the dynamics of complex systems. These methods have been demonstrated on a number of challenging example problems. Recent applications have begun to use these methods for truly complex processes where the important dynamic variables are a priori unknown.

A number of challenging applications remain for these new methods. Likewise, a number of challenges remain in applying these methods. For example, generalized methods for choosing order parameters are needed. For nucleation of condensed phases, order parameters should capture local order much like the Steinhardt and tetrahedral order parameters that are used for water-ice systems. However, a general method is needed to systematically design order parameters from the structure of stable phases. It would also be useful to have a systematic way of removing redundancy from a large collection of order parameters.

Additionally, methods to obtain reaction coordinates from an ensemble of transition pathways are needed. A major problem in applications of transition path sampling studies is to identify the reaction coordinate. Typically, a reaction coordinate is assumed as one order parameter, or a combination of the order parameters. A committor analysis is then performed to determine whether the assumed reaction coordinate is correct. This trial and error approach has worked adequately for example problems, and, given some insight, it also works for very complex problems. However, truly challenging applications will likely require a more systematic approach.

These systematic approaches will allow an exciting new collection of applications. Chemical engineering already has significant overlap with the biotech industry. Here, a wide range of applications require an understanding of reactions that involve conformational changes of proteins and other biological macromolecules. Additional applications involve crystal nucleation and growth from solution, and complex catalytic mechanisms for which traditional methods are insufficient.

These are all processes for which a potential energy surface exists. However, transition path sampling does not actually require a potential energy surface. Some "activated" processes are initiated more generally by the occurrence of rare fluctuations. A general method to identify "reaction coordinates" from a set of order parameters would have far reaching applications to many stochastic processes. A powerful formalism of this sort could be generally useful to identify the nature of fluctuations that affect binary outcomes such as apoptosis or cell survival, extinction or species survival, bankruptcy or financial stability, etc.