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Kinetics, Models, and Mechanism

Commentary on Wolfgang Marquardt

1 Chemical Engineering vs. Chemistry

Wolfgang Marquardt describes chemical engineering as ‘an engineering science that focuses on the foundations of any kind of transformation of matter in order to change its molecular or morphological constitution’ (2013, 187). This makes it sound close to the ‘pure science’ of chemistry, and it certainly is, but I would like to start by highlighting some differences between the two kinds of models: in their scope, in the direction of their representational fit, and in the practical and epistemic interests that constrain their construction.

Starting with scope, chemical engineering models often represent complete production processes, including the logistics of the supply of reactants, their preparation, their reaction, and the purification and distribution of the products (Marquardt 2013, 188; van Brakel 2000, Chapter 7; van Brakel 2011, 533). The processes typically studied by chemistry form only part of the overall production process. The basic modeling strategy for dealing with the complexity that comes with broad scope is to break a multi-stage and multi-scale process down into its components (‘unit operations’ such as mixing, flow, chemical transformation and separation), so that the process as a whole is considered as a series of interacting systems. So chemical processes are there at the heart of the production process as modelled by the chemical engineer, and are themselves broken down further, into the basic kinds of chemical change such as oxidation, reduction or polymerisation (van Brakel 2011, 535–7). And as we shall see later, it is crucial to the understanding of reaction kinetics that basic chemical changes themselves are understood to consist of a series of basic kinds of step at the molecular level.

Turning next to direction of fit, one might think of a ‘pure’ scientific model as an abstract mathematical object, which is developed as a representation of some part of the world. The model is amended to fit the world, not the other way round. In contrast, engineering disciplines seek to change the world, not just to understand it. Process development in chemical engineering involves not only the construction and refinement of a mathematical model, but the construction and refinement of a concrete model production process, which is then scaled up to a full production process. The concrete model is designed in the light of the abstract model, while the abstract model is refined in the light of the behaviour of the concrete model, and so on. Thus according to Jaap van Brakel, model and reality are mutually attuned in a two-way, rather than a one-way process (van Brakel 2000, Chapter 7; 2011, 545). The interaction between model and experimental system can be complex: van Brakel attributes the growth of *ab initio* design in chemical engineering to the tailoring of chemical processes so that they realise 'idealised circumstances, circumstances for which the initial and boundary conditions are manageable in such a way that the increasing power of computational methods can be exploited' (van Brakel 2011, 534). In other words, computational resources constrain the kinds of experimental system that get built. It is possible to overstate the contrast between pure and engineering science, however. Experimental investigation typically involves some kind of material construction: the development of devices that reliably behave in certain ways, displaying new kinds of behaviour (Hacking 1983, Chapter 13), and, given that theoretical understanding evolves in tandem with the device, the process looks similar to van Brakel's interactive account of engineering science. This, in fact, is just how Jed Buchwald describes the discovery of electric waves in his scientific biography of Heinrich Hertz (Buchwald 1994).

Lastly there are the interests that govern model construction: Marquardt describes the aim of modeling as the construction of 'useful models at minimum engineering effort' (Marquardt 2013, 189). This suggests a pragmatic trade-off between, on the one hand, quantitative accuracy (good enough for the practical purposes at hand), and qualitative understanding, versus computational and experimental effort on the other hand. In a commercial environment this pragmatic choice will also involve economic and even environmental considerations (van Brakel 2011, 534).

2 The MEXA Methodology

Marquardt presents his 'model-based experimental analysis' (or MEXA for short), which is a detailed method for constructing and refining kinetic models of chemical reactions. After a pilot experiment on the relevant reaction, '[e]xperimental evidence and the available a-priori knowledge are used to build a first structured mathematical model of the experiment' (Marquardt 2013, 190). The experimental system is simulated so as to provide some (fallible) insight into its behaviour in non-actual situations, and the experiment itself is then performed under 'a telling set of experimental conditions' (2013, 190). This process provides a mixture of qualitative and quantitative information, which acts as a constraint on the refinement of the model. The improved model is then used to refine the experimental set-up further. The process is repeated until consistency between model and experiment is achieved at the required level of accuracy. As Marquardt puts it, citing Karl Popper's book *The Logic of Scientific Discovery* (Popper 1959): 'The investigations should ideally only be terminated if the model can not be falsified by any conceivable experiment' (2013, 190–191). Marquardt characterises his approach to model identification as *incremental*, in the sense that different aspects of the model's structure are identified step by step, exploiting the 'natural hierarchy in kinetic models of process systems' (2013, 196). He carefully distinguishes this approach from what he calls 'simultaneous model identification' (2013, 196), in which decisions are made simultaneously on the various structural features and parameters that identify the model.

I would like to pick up on two specific features of MEXA mentioned by Marquardt. The first is the pursuit of the method within a framework of *a priori* constraints. This sounds curious: the efficacy of an iterative method like MEXA is highly dependent on the choice of its starting point. If the starting point is poorly chosen, then, even when the optimizing process is carried out properly, it may result in a poor model, because it finds only a local optimum, which in global terms may be very poor. This raises the question of how such an important role could be played by *a priori* knowledge. In the following I will identify the relevant *a priori* knowledge as molecular structure and dynamics, and explain why 'a priori' is not as odd a description as it may sound. The second feature is the reference to Popper's falsificationist methodology. Now Popper's falsificationism is also canvassed by Barry Carpenter as the underlying methodology by which reaction mechanisms are tested by kinetic data (Carpenter 1984, Chapter 1), but falsificationism is often criticised for being too negative: in particular, Popper's scepticism about induction precludes experiments providing positive support for any kind of generalisation, and therefore knowledge of the future behaviour of any experimental system. For that very reason, it is often regarded as failing to explain how experimental knowledge can be applied in practical contexts, including engineering (see for instance Putnam 1974, Section 2). Michael Weisberg instead identifies eliminative induction as the framework for understanding how reaction mechanisms are confirmed (see Weisberg, Needham and Hendry 2011, Section 5.2.). This is a choice with which I would agree, if one must pick one of the classical conceptions of scientific method. But the main difference between eliminative induction and Popper's falsificationism is that the former, but not the latter, requires that a small handful of possible alternative theories be identified at the start of the testing process, all but one of these theories are then eliminated by experiment. How is that small handful identified? That is a crucial question, because the efficacy of eliminative induction is very sensitive to the choice. In the next section I will argue that this role too is played by molecular structure and dynamics.

3 Kinetics and Reaction Mechanism

What is a kinetic model of a chemical reaction? It might be taken simply to be a mathematical expression of how the amounts (or concentrations) of the various reactants and products vary over time. Consider the following reaction, in which substances A and B react in the proportions w:x to form the products C and D in the proportions y:z (these proportions are the *stoichiometry* of the reaction):

$$wA + xB \rightarrow yC + zD$$

The rate of the reaction is just the rate at which A and B are used up, or the rate at which C and D are generated. Since the reaction cannot proceed if there is no A or B present, the reaction rate must depend in some way on the amounts of A and B present (or rather, on their concentrations [A] and [B]), but the actual dependence is expressed in the *rate law*:

$$\text{Rate of reaction} \propto [A]^n[B]^m$$

In a simple world, the dependence of rate on reactant concentrations would reflect just the stoichiometry of the reaction: n and m would just be w and x. But as kinetics textbooks always point out, this is only rarely the case, and the order of the reaction (i.e. n and m) must be identified experimentally (see for instance Sykes 1981, 39–40). So is a kinetic model just an empirically-based rate law? And is the rate law just an expression of the above form with the parameters n and m filled in by inspecting the *actual* time dependence of the concentrations of the relevant species? No: firstly, this would be of little use, as it provides no information about how the system would evolve under slightly different conditions. That requires some knowledge of the *dependence* of the rate of reaction on various determining factors, whether physical (e.g. temperature and pressure) or chemical (the amounts or concentrations of the reactants). Secondly, under certain conditions a reaction may display a *pseudo*-order dependence. That is, the rate of reaction may appear to depend on (or be independent of) the concentration of one of the reactants in a way that it would not under normal conditions. Thus, for instance, a reaction might ‘really’ be first order in A (i.e. the rate proportional to [A]), but if A is in vast excess over the other reactants its concentration will remain relatively constant and the dependence would be masked. I take it that the distinction between order and pseudo-order would not make sense if the kinetic model were just the actual variation of the concentrations of the reactants and products over time.

In fact the understanding of reaction kinetics, and the distinction between order and pseudo-order, is tied intimately to knowledge of reaction mechanism. So what is a reaction mechanism? William Goodwin identifies two conceptions at work in chemical explanation. On the *thick* conception, a reaction mechanism is 'roughly, a complete characterization of the dynamic process of transforming a set of reactant molecules into a set of product molecules' (2011, 310). This would involve something like a 'motion picture' that 'traces, as a continuous path, the motions of the atomic nuclei' (2011, 310). On the *thin* conception, mechanisms are 'discrete characterizations of a transformation as a sequence of steps' (2011, 310). The steps in question fall into a relatively small number of basic kinds: an atom or group of atoms leaving a molecule, or joining a molecule. It is the thin conception that underwrites kinetic explanation: a reaction can only proceed as fast as its slowest step – the rate-determining step – and the rate will tend to depend only on the concentrations of species involved in this step.

Consider a textbook example: the reaction of an alkyl halide RX (for instance bromoethane) with a nucleophilic ion Nuc^- (for instance the hydroxyl ion OH^-):

$$\mathrm{RX} + \mathrm{Nuc}^- \rightarrow \mathrm{RNuc} + \mathrm{X}^-$$

Depending on the nature of the alkyl group R, the 'leaving group' X^-, and the conditions under which the reaction takes place (e.g. the nature of the solvent), the reaction may proceed via two different mechanisms, resulting in two different rate laws. In the $\mathrm{S_N1}$ mechanism ('$\mathrm{S_N1}$' meaning 'unimolecular nucleophilic substitution'), RX first dissociates (slowly) into R^+ and X^- (this is the unimolecular rate-determining step), and then combines (quickly) with the nucleophile. The reaction can be expected to be first order in RX, and the rate independent of nucleophile concentration (i.e. zero order). The bimolecular $\mathrm{S_N2}$ mechanism, in contrast, proceeds via a mechanism in which, in a single concerted step, the nucleophile attacks the alkyl group and the leaving group departs. Since the reaction requires a molecular collision between the nucleophile and the alkyl halide, the rate can be expected to be proportional to both [RX] and $[\mathrm{Nuc}^-]$.

How does this relate to the earlier theme of molecular structure and dynamics providing a framework that delimits the possibilities at the molecular level? It is simply that, for a given reaction, there will be a limited number of structurally possible ways to get from the reactants to the products. Using detailed knowledge of the structure and dynamics of molecules it will be feasible to work out these possible mechanisms and conduct a series of experiments to determine which mechanism is realised under which conditions. As Sykes puts it, ‘[N]o reaction mechanism can ever be *proved* to be correct!’ but

> Sufficient data can nevertheless usually be gathered just to show that one or more theoretically possible mechanisms are just not compatible with the experimental results, and/or to demonstrate that of several alternatives one is a good deal more likely than the others. (1981, 43)

Roald Hoffmann gives a beautiful illustration of this process (1995, Chapter 29), describing three possible mechanisms for the photolysis of ethane to ethylene, and how H. Okabe and J. R. McNesby used isotopic labelling to eliminate two of them. By studying the kinetics of a reaction and the structure of its products (and any intermediates), and using further techniques like isotopic labelling, it is often possible to conduct a series of experiments which are collectively *crucial*, in the traditional philosophical sense that they pick out one of the various theoretical possibilities as the actual. This brings us back to eliminative induction, and the question of how *a priori* knowledge can delimit the structural possibilities in this way. The relevant body of structural theory has its origin in the 1860s, and has always been expressed through the medium of visual images rather than mathematical equations (Rocke 2010). It is perhaps one of the securest and longest-lived bodies of knowledge in science. According to G. N. Lewis, ‘No generalization of science, even if we include those capable of exact mathematical statement, has ever achieved a greater success in assembling in simple form a multitude of heterogeneous observations than this group of ideas which we call structural theory’ (Lewis 1923, 20–21). As a body of explanatory theory it is, of course, under empirical control, but one of its great explanatory advantages has always been that it is also under the control of *a priori* spatial intuition. It is spatial intuition that tells us that, in identifying a range of alternative mechanisms, we have exhausted the possibilities. It is only given this (fallible) judgement that we can have good reason to believe that, among the possible mechanisms *we* have thought of, the one best supported by the evidence (or least undermined by it) has any real chance of being correct. It is more than just the last one standing: the best of a bad bunch.

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