

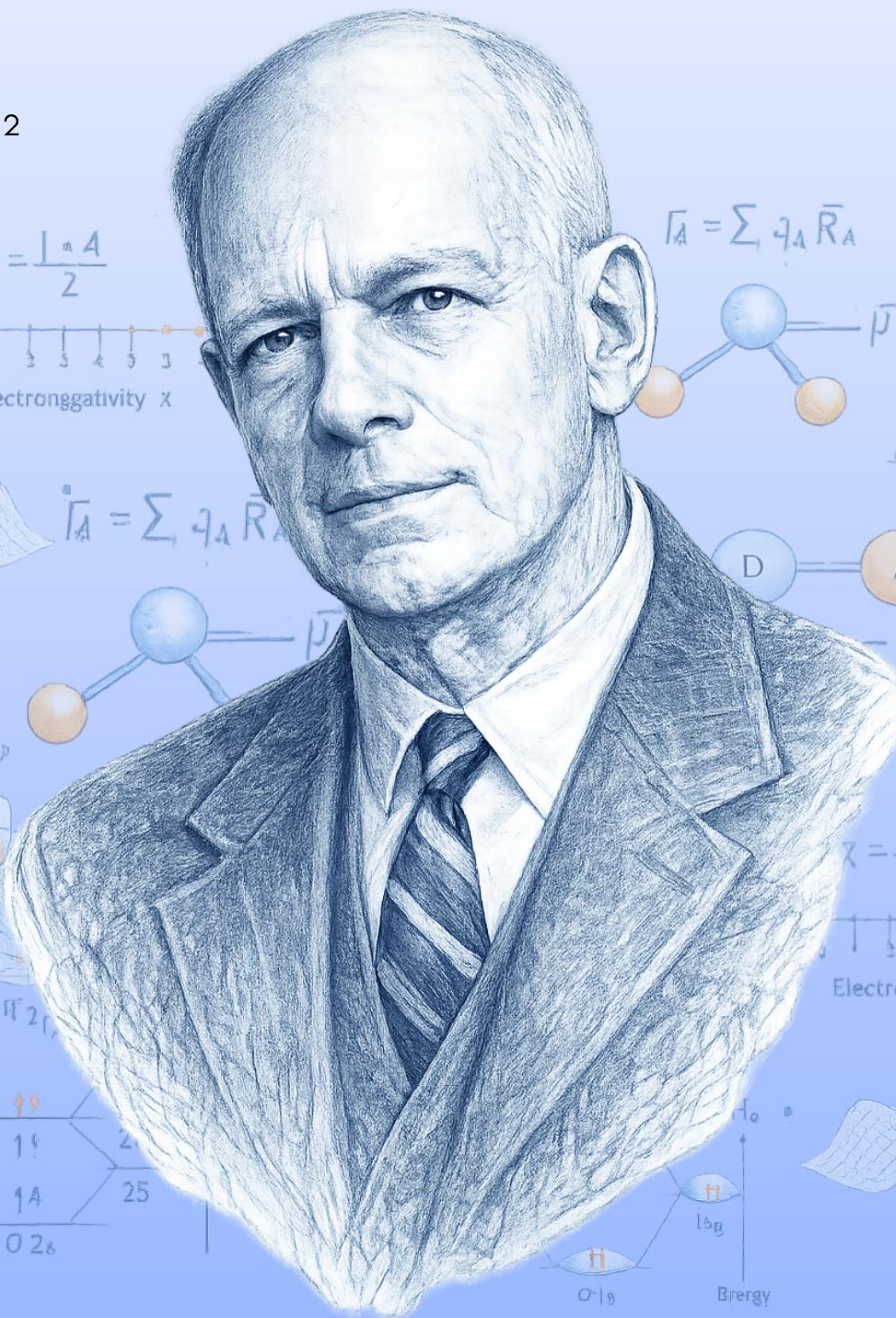


Kreative Chemistry Learning

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Robert S. Mulliken

Jun. 1896 - Oct. 1986

"The more accurate the calculations became, the more the concepts tended to vanish into thin air."

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2. Teaching chemistry for other disciplines and vice-versa
3. Novel experimental methods, simple alternate experiments
4. Interesting problems that bring out non-obvious features
5. Developments in chemistry research and teaching
6. Applications of chemistry
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8. Ideas for revamping chemistry curriculum, teaching, etc.
9. Summary of experiences in teaching revamped curricula

There are no article publication charges and access to the journal is free. Author instructions and manuscript preparation details will be shared on the journal website.

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Editorial

In recent times, with the large-scale invasion of digital information, books and printed material have been relegated to the background. This phenomenon can be corroborated with the significant reduction in footfall in the libraries compared with what we used to have, a few decades ago. This statement, of course, is made only from casual observations and discussions with professional librarians and is not based on any rigorous scientific study. The idea of the conversation here is only to make certain observations and not to conclude the correctness or otherwise of digital over print media.

Back in the 70s and around that time, literature search in chemistry used to be done by going through volumes of "Chem Abstracts". This used to be a very tedious and time-consuming process, usually taking up many weeks for a complete search of the literature. However, in the process of searching for material that one would want, one would often trip upon some extremely interesting material on a topic completely unrelated to the original search. This process of "accidental learning" was not at all uncommon and often resulted in the generation of new ideas and research paths. In present times, digital search with a set of carefully chosen keywords, results in the unearthing of all relevant material in quick time. Compared with the older method, digital search is usually exhaustive (depending on how carefully the keywords were chosen), quick and accurate. But we have completely lost the process of accidental learning, which was an essential and exciting component of our academic growth.

A similar trend is also becoming apparent in the use of textbooks in courses. In earlier days, certain textbooks were prescribed and the students were expected to follow these textbooks for their learning. Very often one resorted to consulting more than one textbook to grasp a concept; the reason being that different textbooks treated each concept using different approaches. Such exposure to varied presentations led to a deeper understanding of the concepts. Books were so much in demand that it was not unusual for someone to not locate popular textbooks in the library. They would always be away in circulation. One would then have to place a reservation to acquire the book when it was brought back for return, precluding the possibility of the earlier borrower renewing it for a further period. Such was the competition to obtain good textbooks. In the present days of digital material, the use of books seems to have diminished, which is not a very attractive option. It is now possible for someone to simply search the digital space, again using appropriate keywords, to download material that can serve as inputs for the answers one is seeking. In more recent times, one does not even download material to construct an answer; one simply downloads the answers themselves. The academic journey in arriving at an answer, and the joy that there is in such an exercise, seems to be lost.

None of the above reflections are meant to place one method as being superior to the other. Modern digital material and automated searches have come to stay. They cannot be done away with, nor should they be. The reflections are only meant to compare the pros and cons of the different approaches. With modern digital search techniques, it now becomes important for the teacher to adapt their teaching methods, to encourage students

to not just download answers but get to the depth of the problem in understanding the concepts. Conventional types of questions will not do any more since the answers to such questions will appear quickly in a digital search with modern tools. Questions have to be imaginative, which should force students to apply their minds, notwithstanding the assistance they may seek from modern search tools. It is a huge responsibility to thrust on the teachers, a responsibility that they better accept and deliver, if they are to stay relevant.

On behalf of the entire editorial team, I would like to thank the contributors to this issue. We have two articles, one of them being a discussion on the chemistry at nanoscale, which addresses the situation where the number of participating molecules is so small that classical chemical kinetics approaches would not be applicable. The second article is on Molecular Organic Frameworks (MOF) which has elicited extensive interest in recent times due to its varied applications.

We also would like to place on record with gratitude the contributions of Ms. Bipasha Nayak and Mr. Prakash John Mathew, who served as the student members of the Editorial Board. We gratefully acknowledge their contributions in laying the basic structure of the Journal and wish them the very best in their future endeavors. We also welcome the new student members to the Board, Ms. Tanishka Agarwal and Ms. Zoeya Ahmed, and we eagerly look forward to working with them.

K S Viswanathan
Editor

Chemistry at the Nanoscale – When Every Reaction is a Discrete Event¹

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Traditionally the kinetics of a chemical reaction has been studied as a set of coupled ordinary differential equations. The law of mass action, a tried and tested principle for reactions involving macroscopic quantities of reactants, gives rise to deterministic equations in which the variables are species concentrations. In recent years, though, as smaller and smaller systems – such as an individual biological cell, say – can be studied quantitatively, the importance of molecular discreteness in chemical reactions has increasingly been realized. This is particularly true when the system is far from the ‘thermodynamic limit’ when the numbers of all reacting molecular species involved are several orders of magnitude smaller than Avogadro’s number. In such situations, each reaction has to be treated as a probabilistic ‘event’ that occurs by chance when the appropriate reactants collide. Explicitly accounting for such processes has led to the development of sophisticated statistical methods for simulation of chemical reactions, particularly those occurring at the cellular and sub-cellular level. In this article, we describe this approach, the so-called stochastic simulation algorithm, and discuss applications to study the dynamics of model regulatory networks.

Keywords: Chemical kinetics, stochastic chemical kinetics, Gillespie’s stochastic simulation algorithm, synthetic gene oscillators.

1. Introduction

The subject of *chemical kinetics* essentially relates to the study of the progression of chemical reactions and the rates of transformation of chemical species from reactants to products [1, 2]. The discipline traces its origins to 1850 when the rate of

inversion of sucrose into glucose and fructose was modelled by the German chemist Ludwig Wilhelmy who used an ordinary differential equation (ODE) to describe the process mathematically. Shortly thereafter, Guldberg and Waage proposed the law of mass action, after which the subject developed rapidly, with

¹ This article is a reprint of “Chemistry at the Nanoscale (When Every Reaction is a Discrete Event)” by Ashwin B R Kumar and Ram Ramaswamy, originally published in *Resonance Journal of Science Education*, Vol 23, No.1, pp. 23-40 (2018). It is being reprinted with the permission from Resonance.

important contributions coming from Vant Hoff, Arrhenius and Ostwald, among others. The importance of understanding how chemical reactions occurred, and what factors affected their rates or efficiency has always been a matter of great practical importance. The major advances of the late 1800s were quickly recognised with Nobel Prizes, the very first in 1901 going to Vant Hoff for his work on the development of chemical kinetics, chemical dynamics, and on the concept of osmotic pressure. Arrhenius' derivation of the eponymous rate equation led to his Prize in 1903, and in 1909 to Ostwald, for several contributions to physical chemistry that included the principle of independence of chemical reactions, and the study of catalysis and chemical kinetics. *The classical approach to study the kinetics of a chemical reaction is to use one or more ODEs to analyse the time evolution of concentrations of the various chemical species involved. This approach, although recognising that chemical reactions are binary events on the molecular scale, encapsulates the details of all interactions into effective rates that apply when the chemical species are abundant.* The concept of the *order* of a reaction and the dependence of the rate on the stoichiometry of the reaction implies that the method for modelling chemical reactions is in terms of continuous variables that obey deterministic equations of motion.

However, this approach is inadequate when the populations of the chemical species are very low. For instance, in a typical biological cell, the total number of molecules ranges from 10⁹ (for bacteria) to 10¹³ (for a eukaryotic cell) or so. The number of molecules of biological interest is much smaller than this, ranging from one (for DNA) to a few hundred RNA to a few thousand proteins. Although the effective concentrations are in the nano or sub-nanomolar range, advances in experimental

techniques to study single molecules have made it possible to investigate the dynamics (and hence also the kinetics) at this scale. In such systems, a classical kinetics approach cannot accurately predict the behaviour; most of the assumptions underlying the law of mass action and kinetic theory are not valid.

At the microscopic level, chemical reactions occur when two molecules come close enough, in the proper relative orientations, and with the appropriate relative energies and angular momentum to interact, namely, either to make new chemical bonds or to break existing ones and sometimes both. The reaction mechanism for any given reaction is a way of interpreting this statement on a microscopic basis, while the macroscopic rate laws are a means of rationalising experimental results. Clearly, both these descriptions mask a wealth of detail since at the microscopic level, molecules scatter off each other with specific energy and angular momentum, and the probability of reaction is related to the scattering cross section. Such quantities cannot be computed with quantitative accuracy for any but the most elementary reactions: the calculations are straightforward but tedious, and essential inputs such as interaction potentials are not known to sufficient accuracy.

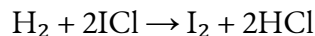
An intermediate – mesoscopic – approach recognises the fact that when the number of molecules is not very large, a probabilistic approach can be used. Thus, the collision of two reactant species can be thought of as a random event that depends on the number of each of them and the volume of the container. Each such collision leads to a reaction with some probability, and each reaction changes the number of each species in a discrete fashion. When there are several possible reactions, depending on the number and types of species, these are taken to be concurrent

random processes; the randomness and discreteness become very significant when the numbers are small and far from the so-called thermodynamic limit. The stochastic nature of chemical reactions in such situations becomes significant since noise plays a major role in the evolution and response of such systems.

Stochastic approaches to the study of chemical reactions can be traced back to the early work of Kramers [3] and Delbrück [4], who modelled the stochastic dynamics of an autocatalytic reaction, followed by numerous other studies that have been summarized in the very influential review article by McQuarrie in 1967 [5]. The practical implementation of this methodology was enunciated in a very lucid article by Gillespie [6] a decade later. *Today, his formulation of the stochastic simulation algorithm (SSA) is widely used to simulate the dynamics of chemical and biochemical reactions in nanoscale environments.* In addition to the already noted applications to cellular and subcellular processes, similar considerations will also apply to chemical reactions occurring on (say) dust grains in interstellar space where temperatures and densities are very low, and the probability of molecular encounters are consequently very small.

2. Stochastic Simulation Algorithm

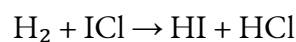
The law of mass action that is taught early in all chemical kinetics courses states that the rate of a chemical reaction is proportional to the product of the concentrations of the reacting substances, with each concentration raised a power that is the stoichiometric coefficient in the corresponding chemical equation. The fact that this is only true in limited cases becomes clear in even simple examples such as the reaction between hydrogen and iodine chloride, with the formation of iodine and hydrogen chloride [2],



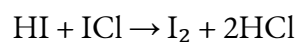
for which one would write (incorrectly, as it turns out) the rate as proportional to:

$$[\text{H}_2][\text{ICl}]^2$$

(where [X] represents the concentration of X), which is a third-order reaction. Experimentally, though, the reaction is seen to be of second-order, consistent with the microscopic description comprising two consecutive reactions,

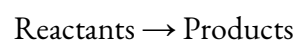


and



The first reaction is slow while the second is much more rapid. Thus, the rate is actually proportional to $[\text{H}_2][\text{ICl}]$, making it effectively a reaction of second-order.

The Gillespie approach is to treat such consecutive or concurrent reactions within a general framework. Say there are N chemical species, $\text{X}_1, \text{X}_2, \text{X}_3, \dots, \text{X}_N$, that can participate in M distinct reactions, each of which has the form:



The ‘Products’ on the right-hand side can be one or more of the molecules being considered here, namely from within the set of the X_i ’s, in which case these can subsequently participate in one or the other of the M reactions that are possible. The products can also be other molecules that do not participate in the reactions being considered, in which case these are denoted by θ . Similarly, the reactants can be from the set of the X_i ’s or can include other molecules, as will be made clear in the examples discussed below.

The configuration at any instant of time, namely the numbers of the different molecules

that are present, is denoted by the integers $n_1, n_2, \dots, n_N$. Each of the reactions is treated as a Poisson random process that occurs at a specific rate that depends on the propensity of the reaction. The propensity for each of the reactions depends on the configuration (see Box 1 for details of how these are computed). *The essential component of the Gillespie algorithm is a recipe for determining which of the M different reactions will actually occur, and more importantly, when it will occur.* At each step, therefore, one determines the time of the next reaction by generating an exponentially distributed random number which is based on the overall rate of any reaction occurring, given the specific configuration and the resulting propensities.

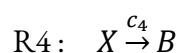
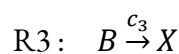
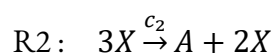
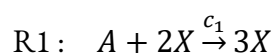
Therefore, given a configuration at a point in time, one can find out when the next reaction will occur as well as which reaction it will be. One simultaneously advances the internal time and changes the configuration, depending on the stoichiometry of the reaction that occurs. It is important to note that the direct version of the SSA is statistically exact. Being simple to understand, it is also easy to implement, although it can become computationally slow and expensive when the complexity of the system under consideration increases. At present, there are a number of improvements to the basic algorithm and alternative approaches that have made stochastic simulation methods considerably faster [7].

3. Modelling Stochastic Dynamics

Current experimental techniques allow for the measurement of the rates of many elementary reactions. *For a proper 'systems-level' understanding of biological processes, however, a computational approach is useful owing to the inherent complexity of the various interacting processes that are involved in even the simplest cases.* In conjunction with experiments,

computational modelling can, therefore, provide some insight into the system dynamics.

Implementation of SSA is best discussed in the context of simple model systems for which the dynamics can be analysed in detail. One such set of coupled autocatalytic reactions that was proposed by Schlögl [8] consists of four reactions R1–4 involving three species denoted as A, B, and X:



where the rates of the equations are indicated by the c_i 's. The populations of A and B are taken to remain constant and much larger than that of the species of interest, namely X. For these dynamics, it is straightforward to obtain the kinetic equation:

$$\frac{dx}{dt} = c_1ax^2 - c_2x^3 + c_3b - c_4x,$$

where a , b , and x are the concentrations of A, B, and X, respectively. Although nonlinear, the above equation can be easily solved for specific values of the rate constants c_i 's and a and b ; typical results are shown in *Figure 1*.

The key contrast between stochastic and deterministic modelling of a reaction system can be seen in this example. As we can see from the simulation of the Schlögl reactions shown in *Figure 1(b)*, each stochastic run gives a different trajectory for the time evolution of the reaction (each thin line represents a specific run), whereas in the deterministic modelling approach, every simulation will give the same trajectory for the specified initial conditions. One, therefore, takes an average of several stochastic simulations (the bold lines in *Figure*

$I(b))$ in order to make a proper comparison with the kinetic simulations in *Figure 1(a)*.

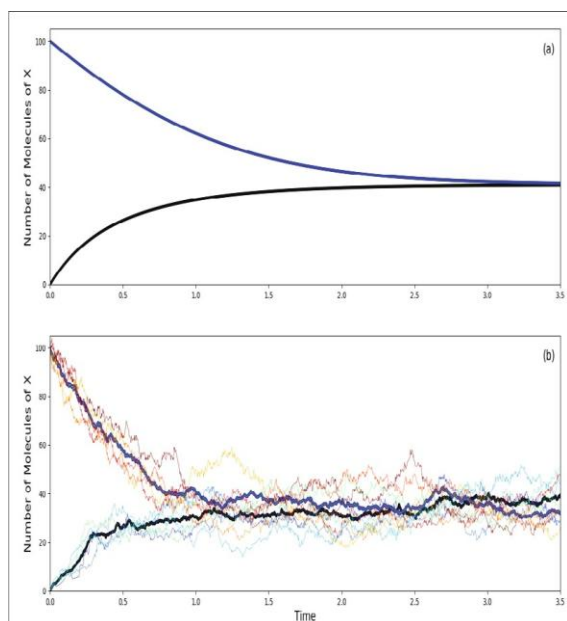


Figure 1. Panel (a) shows the temporal behaviour of X obtained by solving the kinetic equation for parameter values: $a = b = 10^5$, and $c_1 = 3 \cdot 10^{-7}$, $c_2 = 10^{-4}$, $c_3 = 10^{-3}$, and $c_4 = 3.5$ for two different values of the initial concentration of X , which in steady-state reaches a value of 40. Panel (b) shows the results from a stochastic simulation. The bold lines in (b) are averages of several independent runs carried out with similar initial conditions as in (a). As can be seen, there is clearly a similarity in the average stochastic behaviour and the results of the deterministic simulation, the agreement getting better as the system size is increased.

3.1. Dynamics of Biological Systems

This approach to chemical kinetics is particularly suited to the study of biological systems since, as pointed out earlier, many of the reactant species occur in small numbers within cells. Indeed, one of the earliest applications was to the kinetics of the genetic switch in the λ -phage system [9]. By now, there are numerous experiments that have directly shown the influence of stochasticity in

biochemical reactions in both prokaryotic and eukaryotic cells.

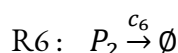
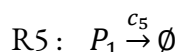
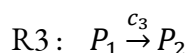
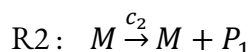
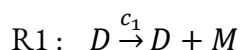
Here we focus on oscillatory behaviour. The maintenance of rhythms is extremely important in biology – many biological ‘clocks’ play a crucial role in the functioning of organisms. Oscillations in biology are known to range from timescales of milliseconds, as in neuronal processes, to seconds as in calcium oscillations or cardiac rhythms, to circadian clocks that have a periodicity of about one day or 24 hours. Longer periodicities are also known, such as ovarian cycles that last a month, and ecological cycles that have timescales of years. All such rhythms are dominated by fluctuations. In fact, to recognise and celebrate the importance of the research on biological clocks, the Nobel Prize in Physiology or Medicine for the year 2017 was awarded to Hall, Rosbash and Young for their research on molecular mechanisms of the circadian rhythm².

The area of systems biology, which aims to study the dynamics and behaviour of a network of biological reactions, is currently of great interest. In most biological systems, there are several reacting biochemical species, and an interesting aspect of the dynamics in such networks is sustained oscillation in the concentration of key molecules. *Such periodic variations play an extremely important role in regulation, a feature that has been studied extensively in naturally occurring systems as well as in synthetic oscillators.*

An early example of a synthetic gene oscillator model with oscillations was proposed by Goodwin [10] in which a gene produces a protein that represses its own expression, as

² For interesting information on ‘circadian rhythms’, see Series Article by K M Vaze, V K Sharma and K L Nikhil, *Resonance*, Vol.18, No.7, 9 and 11, 2013; Vol.19, No.2, 2014.

shown in *Figure 2*. This model consists of the following six reactions:



that involve four molecular species. D and M correspond respectively to the promoter region on the DNA and the messenger RNA. P_1 is the protein product from M , and P_2 is its transcriptional repressor form. The model has been used extensively for studying the dynamics of enzyme catalysis, transcriptional gene regulation, and multi-site protein phosphorylation processes.

The kinetic equations derived by Goodwin [10, 11] are:

$$\begin{aligned} \frac{dM}{dt} &= \frac{1}{1 + P_2^n} - \alpha M, \\ \frac{dP_1}{dt} &= M - \beta P_1, \\ \frac{dP_2}{dt} &= P_1 - \gamma P_2, \end{aligned}$$

where M , P_1 , and P_2 are the concentrations of M , P_1 , and P_2 , respectively. The negative feedback due to the inhibition caused by P_2 on the production of M is described by a Hill function, with the coefficient n being treated as a parameter. It is known [11] that below $n = 8$ the dynamics is damped, while for larger n there can be limit cycle oscillations for suitable values of other parameters.

Setting up the SSA for this system can be done in a straightforward manner, treating the

negative inhibition as a modification of the basic rate c_1 . When the system size s is included in the formalism, it can be shown that this changes the effective values of the propensity as $c_1 = 3sK^n / 4(K^n + P_2^n)$ molecules min^{-1} , where $K \equiv s$ molecules.

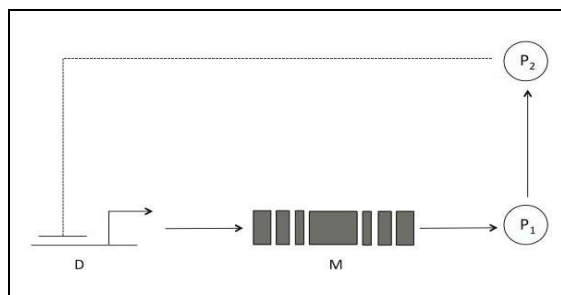


Figure 2. Biochemical network for the Goodwin model. D denotes the promoter region on the DNA, M denotes the mRNA, P_1 is the protein product, while P_2 is the transcriptional repressor form of P_1 .

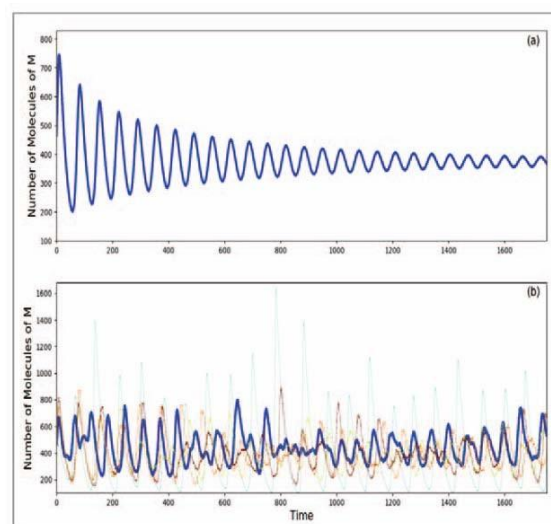


Figure 3. Dynamics of M in the Goodwin model for $n=10$. The other parameters have the values $c_2 = c_3 = 0.075 \text{ min}^{-1}$, $c_4 = c_5 = c_6 = 0.0375 \text{ min}^{-1}$ and $s = 300$. The deterministic dynamics are shown in (a) above, and the corresponding stochastic dynamics is shown in (b) below. While the deterministic dynamics at these values of the parameters clearly lead to damped oscillations in the stochastic version, the motion is not as clearly damped. Such a difference between deterministic and stochastic simulations highlights the need for stochastic simulations when the systems are small.

As can be seen in *Figures 3* and *4*, there are

significant similarities as well as differences between the deterministic dynamics and the stochastic dynamics even when describing the same system, emphasising the need to use the appropriate formalism depending on the situation being modelled.

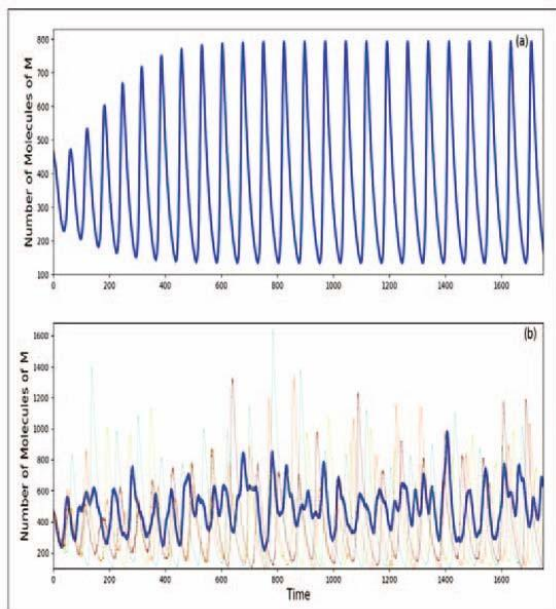


Figure 4. Dynamics of M in the Goodwin model for $n=15$; other parameters as in Figure 3. The deterministic dynamics are shown in (a)

above and the corresponding stochastic dynamics are shown in (b) below. The deterministic dynamics at these values of the parameters clearly leads to a limit cycle with sustained oscillations. In the stochastic version, however, the dynamics, while oscillatory, are not strictly periodic. This difference reduces as the volume increases.

Another simple model of biological oscillations was proposed by Vilar, Kueh, Barkai, and Leibler [12] (VKBL). The genetic network of this model, shown diagrammatically in Figure 5, is somewhat more complex than the simple feedback loop proposed by Goodwin and consists of two genes, an activator A , and a repressor R in a negative feedback loop. The activator A promotes its own transcription as well as that of R by binding to the corresponding promoters. The repressor R acts negatively by sequestering A through the formation of an activator-repressor complex. This combination of positive and negative feedback yields sustained oscillations.

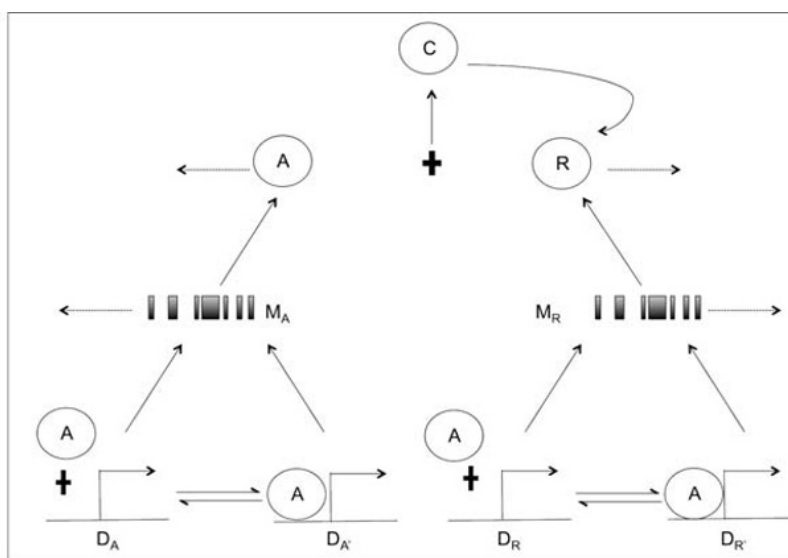


Figure 5. Biochemical network of the VKBL model [12]. D_A and D_R denotes the promoter regions on the DNA without the activator A bound for gene A or R ; D_A' and D_R' denotes the promoter regions on the DNA with the activator A bound for gene A or R ; M_A and M_R denotes the mRNA for A and R , while C represents the complex formed by A and R .

There are sixteen different processes that need to be considered in the VKBL network, and these give the following ‘chemical’ reactions:

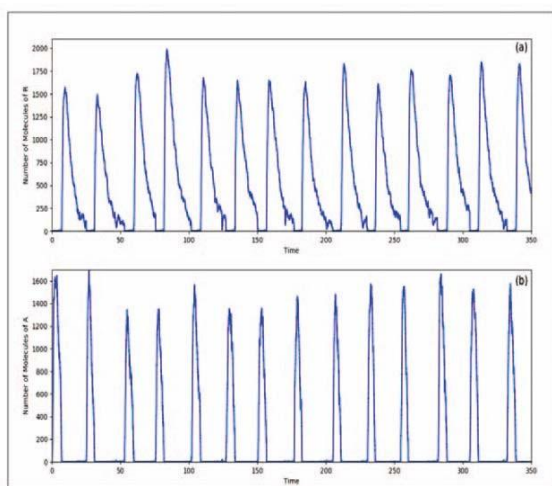
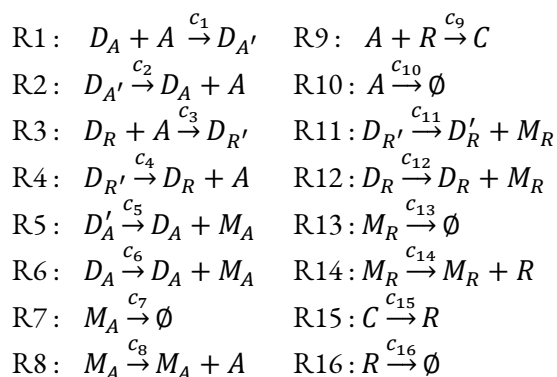


Figure 6. Results from the stochastic simulations of the VKBL model showing the variation of repressor in (a) and protein A in (b) as a function of time (in hours). The circadian nature of the oscillations is evident. In these simulations we have used the parameter values $c_1 = 1 \text{ mol}^{-1} \text{ h}^{-1}$; $c_2 = 50 \text{ h}^{-1}$; $c_3 = 1 \text{ mol}^{-1} \text{ h}^{-1}$; $c_4 = 100 \text{ h}^{-1}$; $c_5 = 500 \text{ h}^{-1}$; $c_6 = 50 \text{ h}^{-1}$; $c_7 = 10 \text{ h}^{-1}$; $c_8 = 50 \text{ h}^{-1}$; $c_9 = 2 \text{ mol}^{-1} \text{ h}^{-1}$; $c_{10} = 1 \text{ h}^{-1}$; $c_{11} = 50 \text{ h}^{-1}$; $c_{12} = 0.01 \text{ h}^{-1}$; $c_{13} = 0.5 \text{ h}^{-1}$; $c_{14} = 5 \text{ h}^{-1}$; $c_{15} = 1 \text{ h}^{-1}$; $c_{16} = 0.2 \text{ h}^{-1}$. Some of these reaction constants have been adjusted so as to give the near 24-hour periodicity. The initial conditions are $D_A = D_R = 1 \text{ mol}$, $D_{A'} = D_{R'} = M_A = M_R = A = R = C = 0$

Application of the stochastic simulation algorithm is fairly straight-forward, given the above equations. The temporal variations in R and A obtained through stochastic

simulations are shown in Figure 6. The reaction rates (see the caption of Figure 6 for their values) have been measured or estimated and putting all these together, one can clearly see that the concentrations of R and A vary in an oscillatory manner, with a period of about 24 hours.

4. Summary

Realistic simulations of biological systems have become possible since many of the basic rates – the c_i 's for many elementary processes – can now be measured, making the overall system amenable to modelling. This methodology has greatly enhanced our understanding of the existing genetic networks in biological cells and also helped in the design of new ‘synthetic’ regulatory modules that can be used to engineer novel biological and dynamical behaviour. Such modelling is an essential component of the *systems approach* that can be used to address complex biological issues. Some problems that have been explored through this technique include a study of the effect of miRNA on existing gene oscillators, the coupling of ensembles of genetic oscillators, the dynamics of regulatory modules, quorum sensing, natural and designed biological switches, and so on [13].

When dealing with nanoscale systems, a mesoscopic approach is often essential, in addition to being practical. The number of molecules of interest is much smaller than Avogadro's number but still too large to be treated accurately through atomistic simulations. Modelling processes at this scale requires stochastic methods. This has also helped to clarify the effects of noise and fluctuations on the dynamics, both at the level of isolated systems as well as at that of populations. In addition, as can be appreciated, other effects that are crucial in

realistic modelling can be incorporated fairly easily [14]. Diffusion can, for instance, be accounted for by the introduction of spatial degrees of freedom and increasing the number of ‘reactions’ to allow for species to move and to diffuse, while spatial heterogeneity can be included by having differential site-dependent diffusion rates. In order to account for time delay, the algorithms are somewhat more complex but a variety of procedures, both exact and approximate, have been worked out [14].

Although we have mainly discussed biological examples, it should be noted that stochastic simulations have also been used to study the dynamics of other systems wherein the number of participating entities is not very large and/or when the natural spatial dimensions are nano-scalar. Both these limits are realised in a variety of situations that range from, say, the case of modelling epidemics and similar processes in population dynamics to the simulation and study of reactions in confined media or on surfaces.

Box 1. Outline of the Stochastic Simulation Algorithm

Gillespie [6] developed the SSA as follows. For each reaction R_μ it is necessary to determine the probability that it can occur in the time interval $(t, t + dt)$, given the configuration at time t . This probability, denoted $a_\mu dt$, is computed from the stoichiometry of the reaction as well as the reaction constant c_μ :

$$a_\mu dt = h_\mu c_\mu dt,$$

where h_μ depends on the stoichiometry and the configuration. Thus, if the reaction is of the type $X_i \rightarrow \text{products}$, then $h_\mu = n_i$, namely the number of molecules of X_i available. If the reaction is of the form $X_i + X_j \rightarrow \text{products}$, then clearly $h_\mu = n_i n_j$, and if it is of the type $2X_i \rightarrow \text{products}$, then $h_\mu = n_i(n_i - 1)/2$, and so on. All kinetic and thermodynamic factors are subsumed in c_μ .

Given the instantaneous configuration and the reaction constants (which must be determined either via experiments or from other calculations), the relative probability of each of the reactions can be computed as $a_1, a_2, \dots, a_M$. Denote by $P_0(\tau)$ the probability that no reaction occurs at time τ . Clearly, the probability that there is no reaction up to time $\tau + d\tau$ is given by:

$$P_0(\tau + d\tau) = P_0(\tau) \left\{ 1 - \sum_{\mu=1}^M a_\mu d\tau \right\},$$

That is the probability that there was no reaction at time τ and further that no event occurs in the time interval $d\tau$. This is easily solved to give:

$$P_0(\tau) = \exp[-a_0 \tau],$$

where a_0 is the total propensity for the reactions to occur,

$$a_0 = \sum_{\mu=1}^M a_\mu.$$

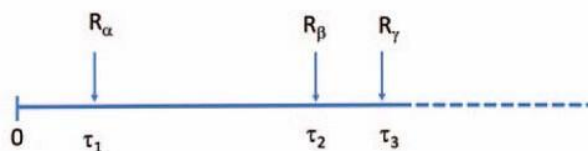


Figure A. Given the configuration at time $t=0$, one computes a_0 and generates an exponentially distributed random number to get the time τ_1 , namely the time for the first reaction. The first reaction is determined to be R_α (see Figure B). Carrying this out will change the configuration, and with this changed configuration, one recomputes a_0 to give the next time, τ_2 when reaction R_β occurs, and so on.

Box 1. Continued

The probability that reaction ν occurs after time τ is therefore:

$$P(\tau, \nu) = a_\nu P_0(\tau).$$

In other words, no reaction occurs for time τ , and then reaction ν occurs. It is clear, therefore, that the random variable τ , namely the time between reactions, follows an exponential distribution with rate a_0 , and this leads to the following straightforward algorithm.

- Step 1: Given a configuration, compute the propensity for each chemical reaction, namely the factors a_μ , $\mu = 1, \dots, M$ and therefore also a_0 .
- Step 2: Generate the uniform random number r_1 in the interval $[0,1]$.
- Step 3: The next reaction will take place at $\tau = (-\ln r_1)/a_0$ (τ thus has the required exponential distribution). A cartoon of this procedure is shown in *Figure A* (see caption).
- Step 4: Generate another uniform random number r_2 , also in the interval $[0,1]$.
- Step 5: Use r_2 to determine which reaction will take place as follows. Find ν such that,

$$\sum_{\mu=1}^{\nu-1} a_\mu < r_2 a_0 \leq \sum_{\mu=1}^{\nu} a_\mu.$$

(See *Figure B* for an illustration of how this is done.) Then reaction R_ν will take place after time τ , and this means that the configuration should be changed accordingly. Using the stoichiometry of the reaction R_ν , it is required that the number of the reactant species should be decreased, and correspondingly, the number of the product species should be increased.

- Step 6: Return to Step 1 with the changed configuration, having advanced the time by τ .



Figure B. Since one of the M reactions must occur, and the total propensity is a_0 , one simply lines up the different reactions $R_1, R_2, \dots, R_M$ and randomly selects one of these with probability proportional to its relative propensity.

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Metal Organic Frameworks – Porous Powerhouses for All That Room at the Bottom

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Since the advent of nanotechnology, the pursuit to put all that room at the bottom to good use has aided remarkable scientific progress. In this regard, the 2025 Nobel Prize in Chemistry was awarded to Richard Robson, Susumu Kitagawa, and Omar M. Yaghi for their immense contributions to establishing the field of metal organic frameworks (MOFs). MOFs are a class of porous materials generated via bonding interactions between organic “linker” molecules and inorganic metal oxide “nodes.” These bonding interactions, essentially three-dimensional coordination bonding, result in the formation of extended network structures enclosing pores/cavities of a specific size with tuneable chemical environments. As opposed to historically well-known zeolites, MOFs allow for greater flexibility via a variety of organic ligands to tune pore sizes and environments for a desired application. Since their discovery they have substantially expanded the scope for the applications of porous materials across industrial sectors such as gas capture, catalysis, separations via membrane fabrication, hazardous waste treatment, and electrochemical sensing to name a few applications. In this article we will be charting the questions that each of these pioneering scientists asked that resulted in the discovery of MOFs and their rapidly growing relevance in the modern research and industrial landscape.

Keywords: Metal Organic Frameworks, MOFs, Reticular Synthesis, Organic linkers, Nodes

1. Introduction

The modern materials science era can trace its advent back to a period of remarkable discoveries between the 1930s – 1950s, specifically the discovery of polymeric materials, semiconductors, and the practical implementation of electron microscopy. The development and rapid advances in Quantum theory also helped illuminate a more nuanced picture of materials at the nanoscopic and even atomic scale. These developments indicated the existence of avenues to “design” molecular

materials for purposes that could be directly correlated to their structure. Chief among these molecular materials have been porous materials for their potential to access enhanced surface areas for myriad applications. The earliest known and explored three-dimensional porous materials were zeolites, both naturally occurring and synthetically made inorganic composites that predominantly consist of alumina (Al_2O_3) and silica (SiO_2). However, zeolites offer little leeway in their general preparation or in the tuning of the chemical

environments within the cavities of their pores. While discoveries in polymerization had fundamentally transformed the quality of life globally, this was predominantly synthetic control in the one-dimensional regime. Challenges persisted in the preparation of well-designed 2D and 3D materials that offered flexibility in their chemical and mechanical properties well into the late 1980s.

The existence of extended 3D networks had previously been observed in Coordination compounds such as Prussian Blue, which consists of $\text{Fe}^{2+}/\text{Fe}^{3+}$ and CN^- ions as the individual building blocks in what has since been determined as a cubic crystallographic system.¹ Coupled with the existing knowledge of clathrate compounds (host-guest compounds wherein a “guest” molecule is held within a “host” framework), material scientists have always entertained the notion of the discovery and existence of tuneable 3D materials and their potential applications.² Advances in crystal structure determination and analytical tools that could probe molecular structure more accurately, also aided material scientists in discovering these materials more efficiently. Richard Robson set out to generate such extended structures as he recognised their potential to function as more versatile host frameworks than zeolites. The key to one of his earliest discoveries was understanding that such extended networks required complex ligands that offered multiple coordination sites.³

While his initial reports and their structural determination generated interest for their sheer

novelty, these early Metal Organic Frameworks (MOFs or Coordination polymers as Prof. Robson preferred to call them) were not very robust, even if they served as an important proof-of-concept.

Susumu Kitagawa and Omar Yaghi set out to address the stability issues of these early MOFs. Their findings have since become the template for robust MOF synthesis. Kitagawa’s persistence and contributions to improving their structural stability led to greater interest in these materials. Yaghi’s innovative use of charged organic linkers and metal oxide clusters as the building blocks, as opposed to Robson’s approach with neutral ligands and single metal ions, also paid off handsomely in ironing out the kinks in the design of these materials and establishing MOFs as materials with great promise for myriad applications.

2. Coordination Polymers with large cavities – Where it all began

Richard Robson was inspired by the tetrahedral structure of diamond, in which every carbon atom is linked to four others in a pyramid-like shape. He used copper ions and a molecule with four arms, 4,4',4'',4'''-tetracyanotetraphenylmethane (tctpm), with each -CN group coordinated to a Cu^{2+} ion forming a metal-nitrile linkage. Each arm of the tctpm ligand in conjunction with the Cu ion it is coordinated to functions as a “rod” (depicted as a black rod in Figure 1b) and has a length of 8.856 Å. Thus, a cavity is created between unit cells having a volume of 700 Å³.³

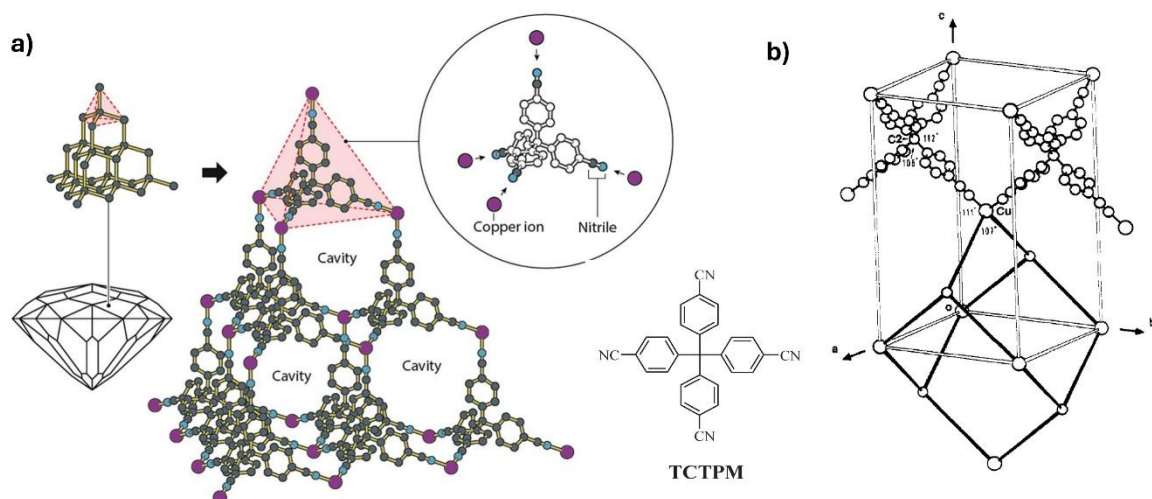


Figure 1. (a) The diamondoid-type structure of $\text{Cu}^{\text{I}}[4,4',4'',4''']\text{-Tetracyanotetraphenylethane}] \text{BF}_4 \cdot x\text{C}_6\text{H}_5\text{NO}_2$. (b) Each “rod” has a length of $8.856 \text{ \AA}$ and the cavity created has a volume of $700 \text{ \AA}^3$. Reprinted (Adapted or Reprinted in part) with permission from the American Chemical Society. Copyright [1989] [American Chemical Society].³

A flaw in these materials was that the bonding interactions between the neutral ligand and the metal ion (Cu^{2+} in this case) were not strong enough, and the structure came apart when the solvent or the guest molecule was removed.⁴ This was due to the exertion of capillary forces when the solvent was removed in order to access the pore structures, collapsing the general porous framework structure. The stability of these materials was also compromised by the presence of counter-anions that were present (and not part of the primary structure) to balance the charge on the metal ion (since the coordinating ligands were neutral).

Kitagawa addressed this stability quandary by generating interpenetrating structures for the organic linker for the creation of flexible channels and the involvement of the counter-anions with these linker sites as coordination sites to the metal ions.⁵ This approach thus offered greater stability and reversibility to these MOFs, thus overcoming the drawbacks of Robson’s iterations. Kitagawa also improved the stability of these MOFs by tuning their response to the gases they were

adsorbing. Yaghi provided the final basis for what is today known as “reticular synthesis”, where he used multidentate anionic organic ligands directly as the linker units to achieve remarkable stability as demonstrated by his group’s landmark report on MOF-5.⁶ Furthermore he chose to use Zinc oxide clusters as the secondary building units in (SBUs) in MOF-5 instead of zinc ions, overcoming the stability issues inherent in Robson’s MOFs. The metal oxide clusters formed the “nodes” at which the anionic organic ligands coordinated to the metal ions in the oxide cluster. With this, permanent porosity and stability of MOFs were achieved.

Future work on MOFs built on the above principles to enhance surface area and thermal stability. For instance, changing the length of the organic linker afforded versions of MOF-5 with larger cavity sizes, paving the way for size-selective adsorption by MOFs.⁷ Given these developments, MOFs have since been demonstrated with surface areas as high as $7000 \text{ m}^2/\text{g}$. To put this into perspective, that is the equivalent of the space available in a 1.7-acre plot of land, now held within 1 g of the

given MOF in a vial!⁸ Computationally predicted ceilings for the surface area have since been predicted to be as high as 14,600 m²/g. While zeolites continued to exist side-by-side, MOFs with improved stability have since been reported that offer room for diversity lacking in

porous aluminosilicates. MOFs, in direct contrast to zeolites, have also demonstrated an ability to be flexible and to retain their structure while adapting to mixtures of guest molecules within their confines.

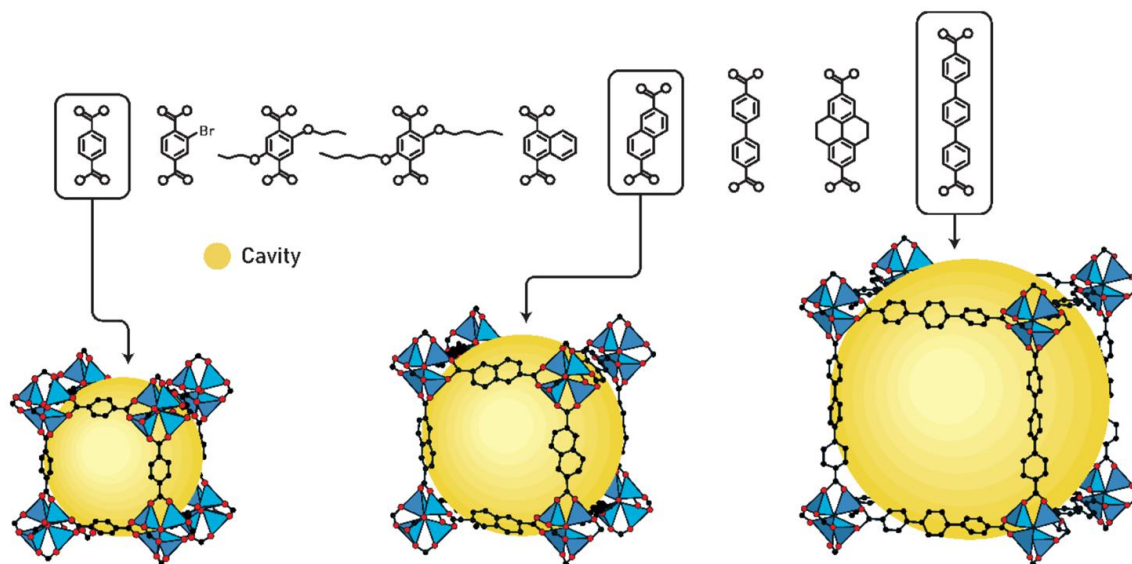


Figure 2. Isorecticular MOF variants of MOF-5, using the same Zinc oxide cluster secondary-building unit (SBU) but with different organic linkers to enhance cavity size.⁷

Such “breathing” MOFs, an example of which is the aluminium based MIL-53, have found diverse applications in the co-adsorption of gases, as efficient photocatalysts and as valuable additives for extrusion of industrial composites.⁹⁻¹¹

3. The standardized MOF synthesis template – Reticular Synthesis

Synthetically prepared zeolites use classical methodologies which often require harsh hydrothermal conditions, variations in pressure and the potential use of corrosive chemicals. As mentioned earlier, there was very little control in the tunability of the pore structure of these materials, and they also allowed limited room for post-synthetic modification, being predominantly inorganic in nature. Metal Organic Frameworks,

however relied on the principles of coordination chemistry wherein metal-ligand coordination had been known since Alfred Werner first demonstrated these compounds, with the toolset now introducing organic ligands into the mix for extended structures. While Robson demonstrated the possibility that coordination chemistry could be translated to generate network compounds with tuneable porous cavities, Kitagawa, and Yaghi’s contributions to the principles of “reticular synthesis” have since become the template to obtain stable MOFs with permanent porosity.

Given the nature of the coordinate bond, MOF synthesis thus relied on substantially gentler synthesis conditions. Furthermore, it also offered greater synthetic control over the final structure via ligand choice. Rigid ligands

and their coordination to the secondary building block (now uniformly accepted as metal oxide clusters) conferred the final morphology to the MOF template. An added benefit is that MOFs could also be post-synthetically modified at both the linker sectors using standard organic synthetic methodologies and via metal ion exchange at the secondary building units.¹² This ability to modify MOFs post-synthetically, absent in the

preparation of zeolites and other porous inorganic materials, conferred greater diversity to MOFs and their analogues. A general schematic for MOF synthesis is depicted in Figure 3a, while the reported conditions for the synthesis of the landmark MOF-5 are depicted in Figure 3b.

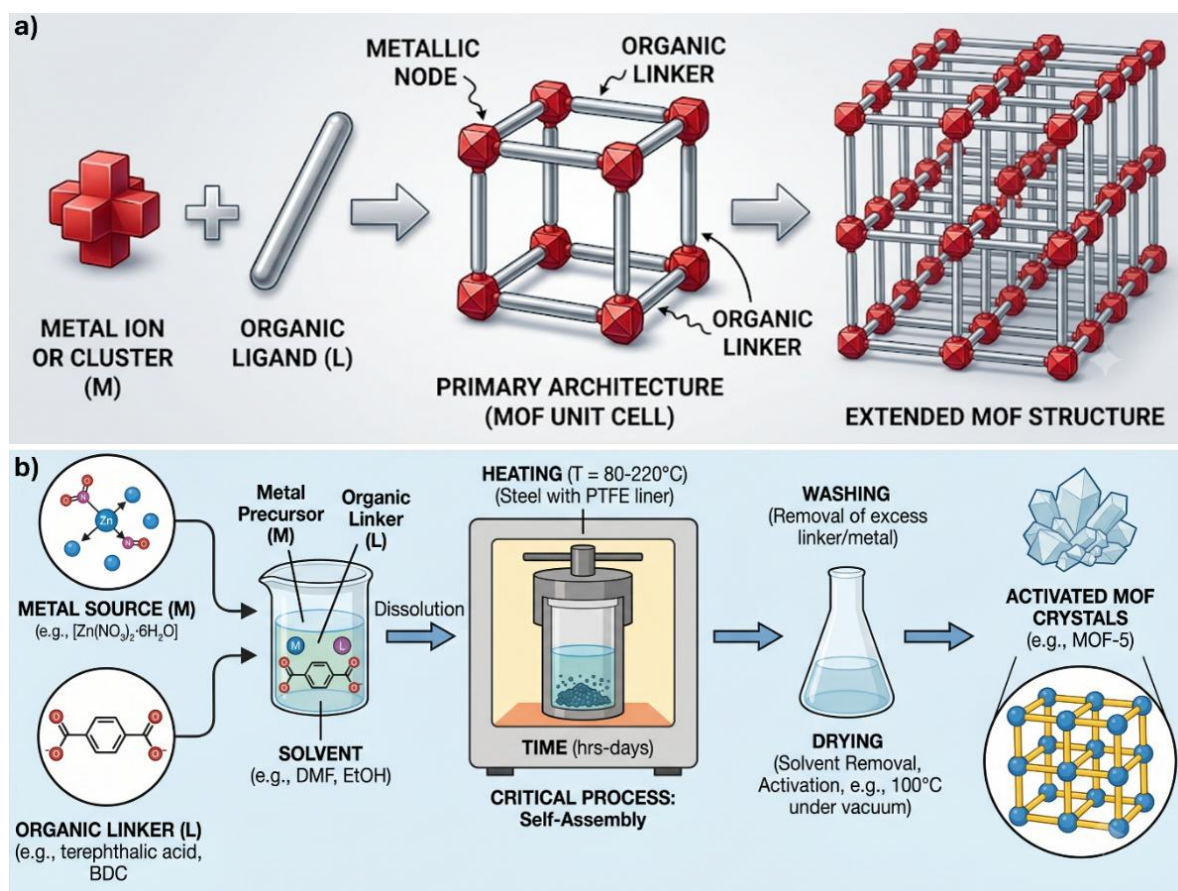


Figure 3. (a) The simplest depiction of the synthesis of metal-organic frameworks. (b) A more detailed schematic for the synthesis of MOF-5 reported by the Yaghi group⁶ (both images were generated using simple prompts provided to Google Gemini 3.5 Flash)

Greener synthetic routes for MOF synthesis have also been developed in the more recent past such as pushing for predominantly water-based synthetic protocols without compromising on the structural stability of the MOFs.¹³

4. MOFs are here to stay, so now what? - The applications of MOFs

Coordination Chemistry has essentially traversed a full circle from its inception when Alfred Werner first made the scientific community aware of its possibilities to the over

100,000 unique MOF structures deposited in the Cambridge Crystallographic Structure Data Centre (CCDC). Given that these structures have been discovered in the short span of just the last 35 years or so, and with roughly almost 6000 new structures being added to crystallographic databases every year, MOFs are here to stay and play vital roles across industrial sectors. Some key sectors where

MOFs have been demonstrated extensively will now be discussed.

4.1. Gas Capture and Separations

The vast majority of the MOFs discovered so far have predominantly been demonstrated for gas capture and separations.¹⁴ Some of these MOFs and the gas they adsorb/store are depicted below.

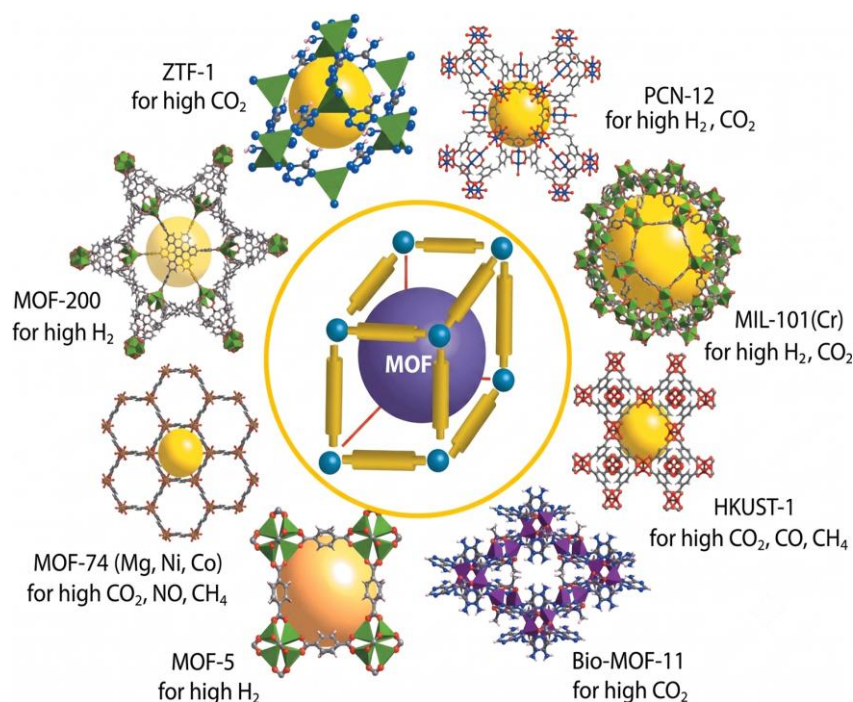


Figure 4. Some MOFs and the gases they selectively capture/store.¹⁴ Reprinted (Adapted or Reprinted in part) with permission from IUCr Journals.

In comparison to zeolites and popular modified porous silica materials such as the industry standard MCM-41 or SBA-15, MOFs have enhanced adsorption properties. While Zeolites and porous silicas tap out at surface areas of 1500 m²/g even with chemical modification, MOFs have been shown to approach surface areas of 7000 m²/g.⁸ Furthermore, the chemical environments within MOF channels/pores can be conveniently modified to selectively adsorb specific gases. The industrial implementation

of CALF-20, a cost-effective aluminium-based MOF, is an example of this.¹⁵ CALF-20 has been shown to selectively adsorb CO₂ in humid industrial flue gas release and has been commercialised on a large-scale by BASF and Svante in Europe. MOFs also render themselves readily for the separations of gases from gas mixtures as their microporous environments can be suitably designed to selectively capture one or more components in a gas mixture.¹⁶

4.2. Water harvesting in humid water-deprived geographical regions

As potable water resources diminish around the world, considerable research has been directed towards sorbent materials for harvesting water directly from air.¹⁷ Silica gel

has long been used as a water harvesting sorbent, but has relatively low water-uptake, working best in high humidity environments.¹⁸ MOFs such as MOF-801 and MOF-303 have been practically demonstrated as viable water-harvesting sorbents even in relatively low humidity desert environments.¹⁹

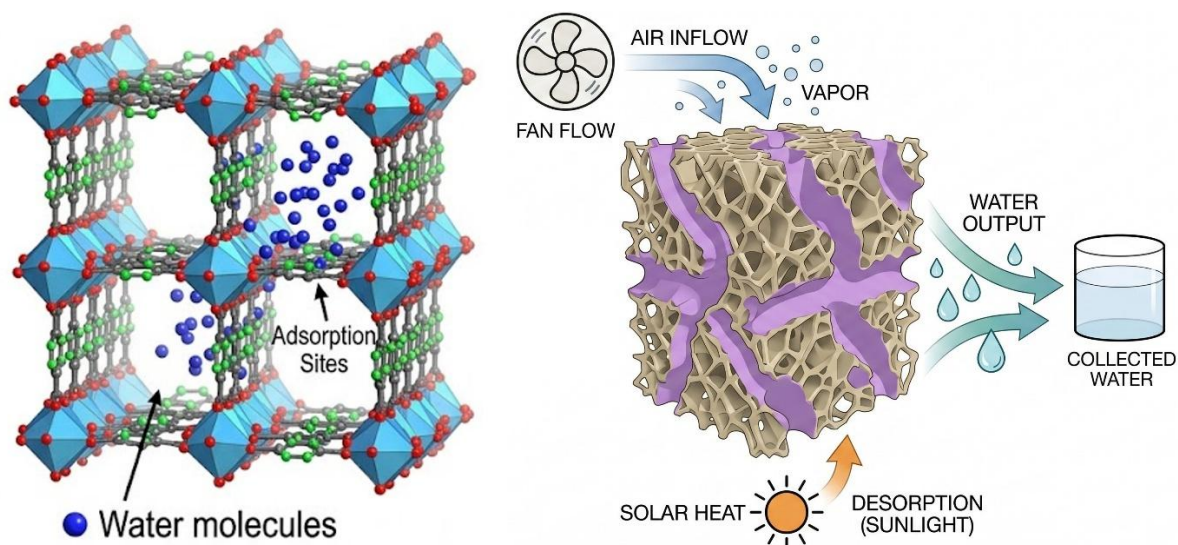


Figure 5. MOF-303 and a simple schematic demonstrating its ability to absorb and desorb harvested water.¹⁹ (both images were generated using simple prompts provided to Google Gemini 3.5 Flash)

MOF-303, containing Al oxide clusters as the nodes, is also scalable and cost-effective, having been demonstrated practically using just ambient cooling in the night for absorption and sunlight in the day for desorption of the harvested water.

4.3. The catalytic applications of MOFs

MOFs have also been demonstrated as robust platforms for heterogeneous catalysis. They have also played a critical role in narrowing the gap between homogeneous and heterogeneous catalysis, rendering them as more efficient platforms for selective transformations in comparison to zeolites.²⁰ Their molecular structures can be designed or modified making them closer as structural motifs to well-defined homogeneous catalysts. Linker modification

can also be utilized to create specific chemical environments within the MOF pores for monodisperse metal nanocluster size generation. In work carried out by Guo et al. the popular Zirconium MOF, UiO-66-NH₂, was utilized to get uniform 1.7 nm Pt nanoclusters embedded within its pores.²¹ This size confinement within the MOF pores afforded unconventional chemoselectivity to Platinum catalytic sites (Figure 6). In the selective hydrogenation of cinnamaldehyde to cinnamyl alcohol, the MOF encapsulated Pt nanoclusters demonstrate high selectivity (almost 91.7%) to the desired cinnamyl alcohol. In comparison standard platinum nanoparticles or small clusters supported on a conventional silica support generated the undesired fully hydrogenated product.

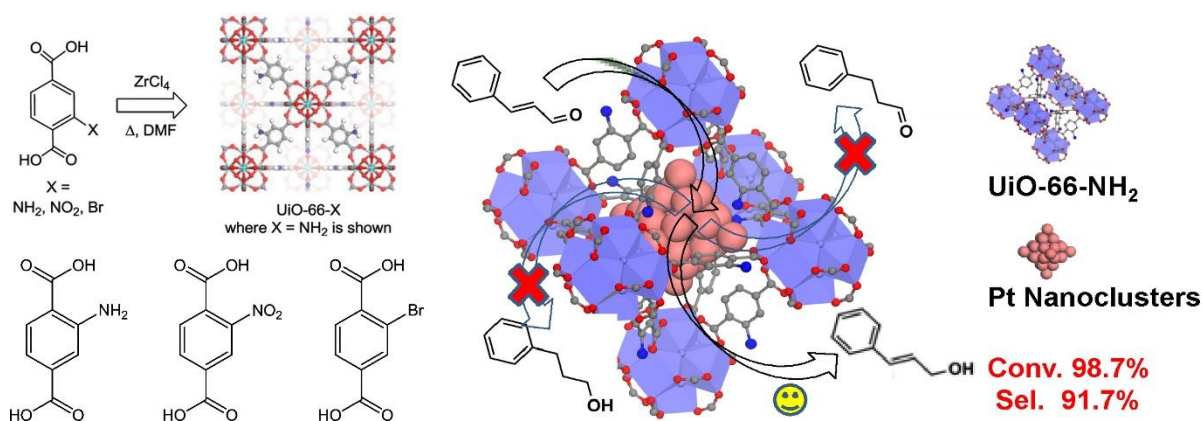


Figure 6. The Zirconium based MOF, UiO-66-NH₂, which uses 2-amino-1,4-benzenedicarboxylate (H₂N-BDC) as the organic linker. Reprinted (Adapted or Reprinted in part) with permission from the American Chemical Society. Copyright [2014] [American Chemical Society].^{21, 22}

4.4. Environmental remediation, radioactive waste treatment, and chemical sensing

Owing to the ability to exert substantial control over their design, vis-à-vis the incorporation of a variety of organic linkers to generate unique chemical environments, MOFs have also been successfully demonstrated for environmental remediation.²³ Besides MOFs, COFs (Covalent Organic Frameworks, which, like MOFs are highly crystalline but do not possess metal nodes) and POPs (Porous Organic Polymers, amorphous porous materials comprised of irreversible three-dimensional

organic linkages) have also been employed for this task, and all three classes of materials have demonstrated promise for potential large-scale implementation. MOFs, COFs and POPs have also been demonstrated as excellent sorbents for radionuclide waste contamination in water from nuclear plants.²⁴ Post-synthetic modification of a UiO-66-Br MOF to its amidoxime equivalent, UiO-66-AO in work by Chen et al. enabled the removal of 94.8% of uranyl ions from seawater samples.²⁵ Besides the selective capture of radioactive ions, MOFs have also been demonstrated as highly effective sensors for gases and volatile organic compounds, owing to their large surface areas and sensitivity to analytes based on their functionalization.²⁶

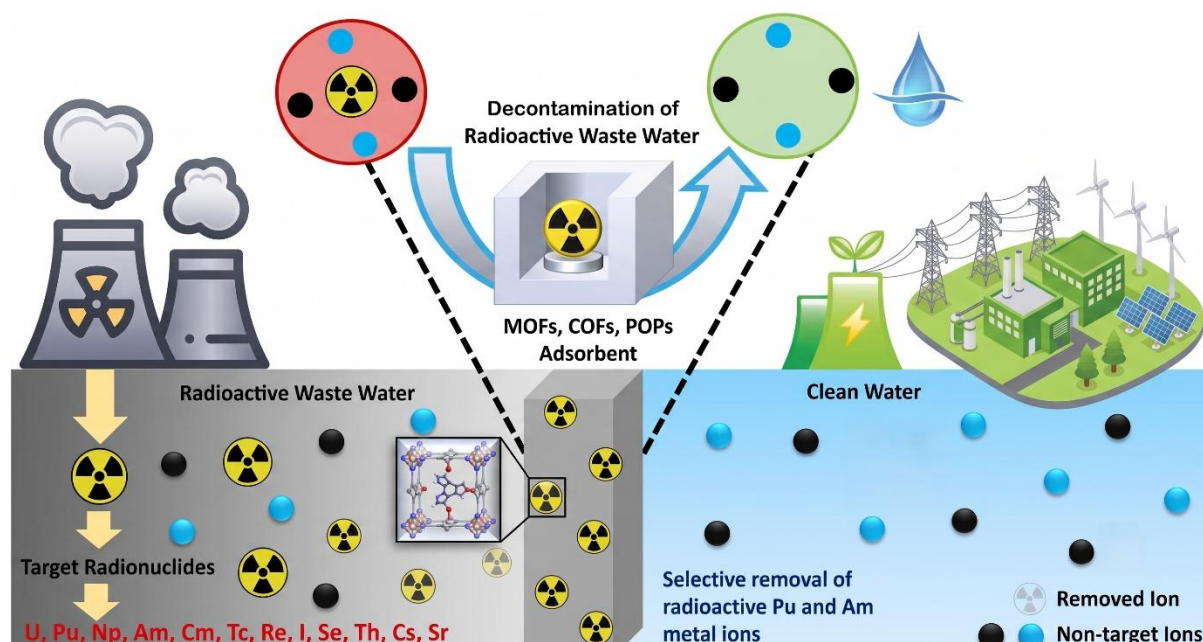


Figure 7. MOFs, COFs (Covalent Organic Frameworks), and POPs (Porous organic polymers) have demonstrated selectivity to the removal of radionuclide waste from contaminated water. Reprinted (Adapted or Reprinted in part) with permission from the American Chemical Society. Copyright [2025] [American Chemical Society].²⁴

4.5. Further applications of MOFs: Drug Delivery and Biomedical applications

MOFs and metal-free COFs and POPs, have also witnessed a surge in research interest in therapeutics, especially as drug delivery agents.²⁷ Biocompatible MOFs have since found greater acceptance owing to their ability to hold variable doses of small molecule pharmaceuticals more effectively as opposed to conventional mesoporous silica-based drug-delivery agents.²⁸ They have also been used to deliver macromolecular cargos such as proteins and nucleic acids, made possible by the flexible

organic environments that constitute this class of materials.²⁹ Biological imaging techniques such as MRI (magnetic resonance imaging) and X-Ray computed tomography (typically labelled as a CT scan) typically require large quantities of contrast agents to provide distinctions between normal and afflicted tissue in the patient. Nanoscale MOFs have since been developed as more effective contrast agents, owing to the ability to incorporate paramagnetic metal centres for better interaction with MRI machines, requiring lower quantities of the contrast agents in comparison to conventional Gadolinium-based small-molecule chelate contrast agents.³⁰

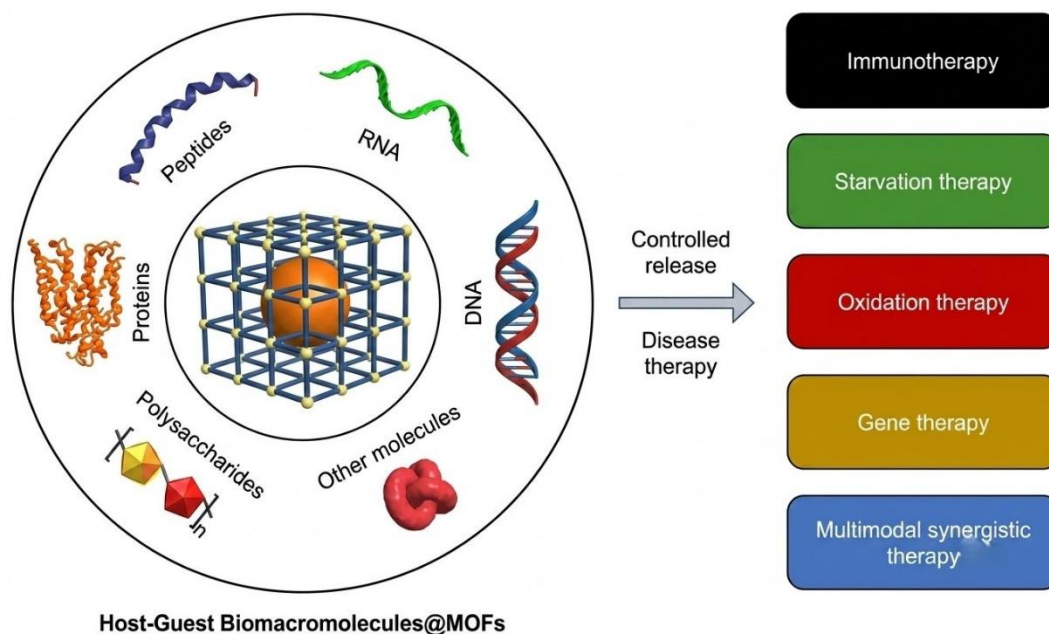


Figure 8. MOFs have also been demonstrated as efficient platforms for biological and medical applications. Reprinted (Adapted or Reprinted in part) from RSC publishing.²⁹ (the image was generated by providing the low-resolution TOC image from the original paper using Google Gemini 3.5 Flash)

5. Conclusion and Future Directions

This article has tried to give a brief overview of the significance of the discovery of metal organic frameworks, and why the Nobel Prize for Chemistry in 2025 was awarded to Robson, Kitagawa and Yaghi was timely. Going from Robson's first demonstration of the possibilities that MOFs could herald, and through the next three decades, MOFs have since overcome numerous challenges to become a viable technology on multiple fronts. A key obstacle any new class of material faces is its synthesis and implementation at industrial scales. In the case of MOFs, this has since been successfully transcended with some of the world's biggest chemical industries currently developing efficient, large-scale synthetic protocols for popular MOFs such as the ZIF (Zinc Imidazolate Framework), UiO (University of Oslo),

MIL (Materials of Institute Lavoisier), and HKUST (Hong Kong University of Science

and Technology) series of MOFs for their extensive use in gas capture, water harvesting and catalytic applications.^{31,32} While newer MOFs face some of the same teething problems that these classical MOFs have since surmounted to be viable at an industrial scale, advances in computational methodologies and synthetic approaches today are more likely to ensure that they overcome their shortcomings faster.

Today, these materials are no longer laboratory curiosities and have the potential to address many of humanity's pressing concerns from the environment to health. While key areas that they have already found widespread use in have been covered in this article, discoveries of their possible use in more nuanced sectors like healthcare and as chemical sensors are in their early stages. Yet they clearly demonstrate great promise even in these sectors. The pursuit to put all that room at the bottom to good use using these materials will have more takers in the coming years and one can be optimistic

enough to say their possibilities will continue to be limitless.

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ABOUT THE AUTHOR



Raghu Vamsy Maligal Ganesh is a materials chemist who works on the development of thermally robust inorganic composites and their application towards sustainable energy. He completed his PhD from Iowa State University, where he synthesized and evaluated encapsulated nanomaterials for applications in heterogeneous catalysis. Following his time at Iowa State, he held research positions at Breathe Applied Sciences Pvt Ltd, and at King Abdullah University of Science and Technology (KAUST). At both institutions, he focused on the direct and indirect utilisation of carbon dioxide as a feedstock for the synthesis of value-added fuels such as alcohols and dimethyl ether. Additionally, he has also worked with industrial entities such as Saudi Aramco, a primary partner at KAUST via the KAUST Catalysis Centre.

At Iowa State, he also taught various chemistry courses as both a teaching assistant and a course instructor, catering to a diverse range of students. In his role as a senior teaching assistant, he assisted course instructors in designing coursework and laboratory sessions, provided one-on-one tutoring to students, and trained junior colleagues in effective teaching methods. In addition to his teaching responsibilities, he mentored undergraduate research students and hosted DOE-sponsored research internship students from other institutions in the US.

Word Unscrambler

Instructions: Unscramble the following words to reveal chemistry-related words. Use the boxed letters and unscramble them to solve the final word.

MOYACARGTRHPOH □ _ _ _ _ _ _ _ _ _ _
 OEINFNCIRGTTUA _ _ _ _ _ _ _ _ □ _
 RCSEHYIMOTEHMR _ _ □ _ □ _ _ _ _ _
 SECEOLRTHOEIRPS _ _ _ _ □ _ _ _ _ _
 OESIRTEOERSMISM □ _ _ _ _ □ _ _ _ _ _
 EEITNCIOLGETRVYAT _ _ _ _ _ _ _ _ _ _ □
 TOIPAMRICPH _ _ _ □ _ _ _ _ _
 ECNOLCUILPHI _ _ _ _ _ _ _ □ _
 TPCSMRETOYOEHTOPR _ _ _ _ _ □ _ _ _ _ _
 IATNDEUTRAON _ _ _ □ _ _ _ _ _
 EEANMNROTI _ _ _ _ _ □ _ _ _

Final Word: _ _ _ _ _ _ _ _ _ _

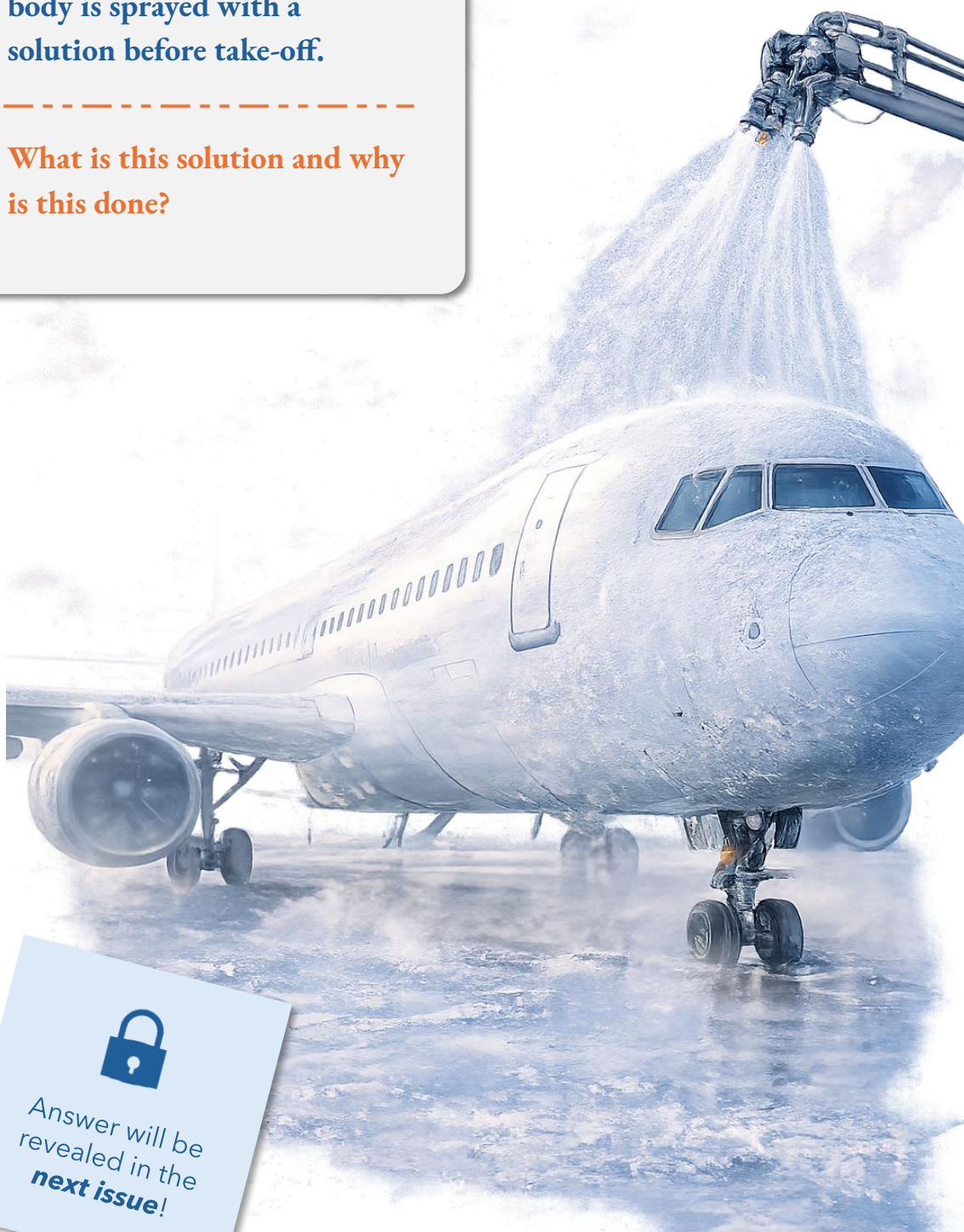
Solution to Crossword in Volume 1, Issue 1

		¹ T	E	² F	L	O	³ N									⁴ B
		E		U			Y		⁵ C	O	L	D			⁶ H	E
⁷ R		L		Z			L		O					⁸ V	E	N
E		L		Z		⁹ P	O	P	P	E	R				A	E
T		U		Y			N		E				¹⁰ F		V	D
R		R						¹¹ B	R	E	A	R	L	E	Y	I
O		¹² I	N	D	I	G	O		N				E			C
G		U							I		¹³ S		M			T
¹⁴ R	A	M	¹⁵ S	A	Y				C		H		I			U
A			A					¹⁶ F	U	S	I	O	N			S
D		¹⁷ D	C	P		¹⁸ P			S		R		G			
E			C			E		¹⁹ C			A					
	²⁰ W	O	H	L	E	R		A			K			²¹ B	²² R	
			A			²³ C	R	U	S	T	A	L		²⁴ L	E	A
			R			Y		S			W			I		M
			I				²⁵ W	A	R	F	A	R	I	N		A
		²⁶ S	N	O	W			L						²⁷ D	A	N

Question Everything

On extremely cold days, the outer surface of the aircraft's body is sprayed with a solution before take-off.

What is this solution and why is this done?



Answer will be
revealed in the
next issue!

Solutions from Volume 1, Issue 1

- 1) If you were to plot pressure versus time in your household LPG cylinder, what would the graph look like and why?

If a gas effuses out of a cylinder, say a cylinder of oxygen, a plot of pressure of the gas in the cylinder versus time will follow an exponential decrease. This can be explained on the basis that the rate of effusion of the gas will be proportional to the pressure of the gas in the cylinder. Higher the pressure of the gas in the cylinder, higher will be the rate of effusion of the gas from the cylinder; i.e., if one expresses the rate of effusion as $\frac{dP}{dt}$,

then one can write the differential equation as $\frac{dP}{dt} \propto P$. This is exactly the condition for first order kinetics, which has as its solution:

$$P = P_0 e^{-\alpha t}$$

From a cylinder of oxygen, or any permanent gas, the pressure versus time can be observed to be an exponential drop, as shown in Fig. 1.

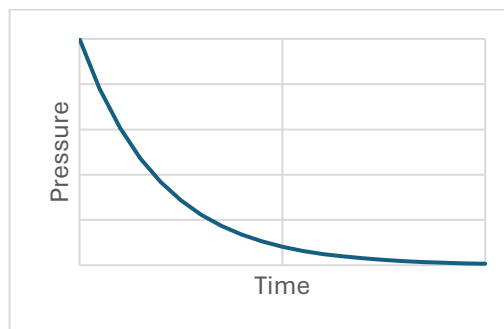


Figure 1.

If we assume the same exponential drop will also be followed by the gas in the LPG cylinder, then what would our observation be with regard to the intensity of the flame in the stove? If the pressure of the gas drops exponentially, the rate of the gas flow through the burner of the stove should also show an exponential drop. If this is so, the flame should become progressively smaller with time. With each passing day, cooking should take longer.

We know this is not the case. The flame actually stays constant over time dropping to zero abruptly, when the fuel finally runs out. The pressure versus time profile should therefore be flat, which sharply drops to zero when the fuel is exhausted as shown in Fig. 2. How do we explain this observation, which is different from that observed from an oxygen cylinder?



Figure 2.

LPG (which liquified petroleum gas) is not a permanent gas. LPG is actually a mixture of hydrocarbons, propane, and butane. These hydrocarbons are gases at atmospheric pressure but convert to liquids under pressure. They are in fact stored under pressure and exist as liquids in the cylinder. The vapour pressure of the liquid depends *only* on temperature and hence there is a constant pressure of the hydrocarbons above the liquid at all times. As the gas effuses out to the burner in the stove, more of the liquid evaporates to keep the pressure of the gas above the

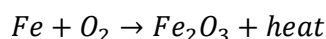
liquid, i.e., its vapour pressure, a constant. This process continues as long as there are liquid hydrocarbons present. Once the hydrocarbons are exhausted, the effusion stops and we then need to change the cylinder. The pressure versus time profile would be as shown in Fig. 2. To be accurate, the falling part of the curve in Fig 2, would be a steeply decaying exponential.

Pure propane/butane mixture is actually odourless. However, should there be a leak, one can notice a strong odour. Then what is this odour due to? Enjoy finding the answer.

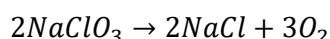
- 2) *In emergency situations in aircrafts, oxygen masks get deployed. Obviously, the aircraft cannot carry large oxygen cylinders to provide this oxygen as this will be an extra load for the plane to carry. What then is the source of this oxygen?*

"In the event of a loss in cabin pressure, oxygen masks will drop from the overhead panel," is familiar statement we have all heard before each flight. Should there be a drop in cabin pressure at high altitudes, passengers and crew could be subjected to decreased oxygen availability, which can result in hypoxia. This is because commercial flights fly at a height of about 30,000 feet where the air is too thin. Hence an auxiliary oxygen support system is required in such emergencies. Oxygen cylinders would be too heavy to be carried on flights.

The source of oxygen for emergency situations in planes is a chemical cocktail containing sodium chlorate (NaClO_3) and iron powder). During an emergency, when the air pressure in the cabin drops, the oxygen masks placed above the passenger seats are deployed. The passenger is required to pull at the mask, which sets off a trigger mechanism. This creates a miniature spark that initiates the reaction,



The heat produced in this reaction then triggers the decomposition of the sodium chlorate, which releases oxygen into the mask.



There is just enough of these chemicals provided in the cocktail, to supply oxygen for about 10-15 minutes, during which time, the pilot will bring the plane to a lower altitude, where there is sufficient oxygen to breathe.

This Month in Chemical History

Robert Sanderson Mulliken is a celebrated physical chemist who was responsible for the initial developments in molecular orbital calculations, which is used in determining molecular structures. For his important contributions, he received the Nobel Prize in Chemistry in 1966. He developed the theory in close collaboration with Hund, and the theory is sometimes referred to as Hund-Mulliken theory. Interestingly, while the two worked together very closely on the theory, they never coauthored a single paper. While at Chicago, he took a course with another Nobel laureate and another famous scientist with a similar-sounding name, Robert Millikan, of the oil-drop fame; a course which introduced him to quantum theory.

Mulliken made significant contributions in the study of atomic and molecular phenomenon and his name can be seen associated with various concepts such as the Mulliken electronegativity scale, Mulliken population analysis in MO calculations, which is a method used to assign charges on various atoms in a molecule, Mulliken symbols for irreducible representations in character tables, Mulliken's difference potentials and Walsh- Mulliken diagrams, to name a few. He also introduced the concept of the δ -bond in chemical bonding, a type of interaction which involves the overlap of d-orbitals. He also proposed the concept of halogen bonding, where a halogen interacts with an electron-rich centre. During the war, he was part of the plutonium project. Even as early as 1970s, he was a strong advocate for using computers in chemical research and it is believed that he spent some time at IBM learning how to write computer programs, at the age of 74.

In this issue, we celebrate the contributions of Prof R S Mulliken, who was born on June 7, 1896.



UNLOCKING THE SCIENCE THAT SHAPES OUR WORLD

Robert S. Mulliken revolutionized chemistry and our understanding of chemical bonding by introducing the molecular orbital theory. Grounded in quantum mechanics, MO explains how electrons are shared across an entire molecule, earning him the 1966 Nobel Prize in Chemistry and advancing work in materials science, spectroscopy, and computational chemistry.

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