

WANTED: Flow Chemistry Reaction Data

Benjamin J. Deadman^{*a,b}

Abstract: Flow reaction data could have an outsized impact in the datasets which train the reaction prediction, chemical synthesis planning, and experiment design tools of tomorrow. This paper discusses why we should be increasing the availability of flow reaction data, and presents the Open Reaction Database as a schema and repository for such data. Best practices for defining flow reactions in the schema are discussed, highlighting those parts of the schema which are particularly relevant to flow reactions. Telescoped flow processes, and transient flow conditions are more complex to define in the schema, but options are presented for several typical scenarios. The paper concludes by opening a conversation with the flow chemistry community about how they would prefer to search for flow reaction data, and how to archive their own reaction data.

Keywords: Database · Data standards · Flow chemistry · Machine learning · Organic synthesis



Benjamin Deadman is an independent Consultant Scientist specialising in Digital Chemistry. He provides project management services to the Open Reaction Database (ORD) and supports the ORD community as a Reaction Data Evangelist. Ben received an MSc (2009) from the University of Waikato (New Zealand) before completing his PhD (2013), specialising in flow chemistry, with Prof. Steven Ley at the

University of Cambridge. After postdoctoral studies with Prof. Anita Maguire at University College Cork (Ireland) Ben did further postdoctoral research at Imperial College London with Prof. Mimi Hii and Prof. Klaus Hellgardt. In 2018 they founded the Centre for Rapid Online Analysis of Reactions (ROAR) to provide the UK chemical research community with the tools and protocols needed to perform data-rich experimentation on chemical reactions.

1. Introduction

Over the past decade we have witnessed the normalisation of computer-assisted synthesis planning (CASP) as part of the synthesis chemistry toolbox.^[1–4] This change has partly been enabled by modern computational capabilities and the rise of data driven approaches, but it has also required the availability of very large datasets containing millions of reactions.^[2]

The largest of these datasets are the commercial literature databases of SciFinder^[5] and Reaxys.^[6] The largest open access datasets are derived from the US Patent and Trademark Office (USPTO) data,^[7] and there are several community efforts empowering the community to contribute their reaction data. Chemotion is an electronic laboratory notebook (ELN) and repository for reaction data, operating as part of the NFD14Chem consortium in Germany.^[8–10] AI4Green^[11] is also an ELN for reactions, with a focus on integrated green metrics calculations and tools, while RetroBioCat^[12–14] is a database and retrosynthesis tool for biocatalysis. While it lacks a front-end, the Unified Data Model (UDM) is a reaction data model which was opened to the wider community with the release of version 6 on GitHub in 2020.^[15,16]

The Open Reaction Database (ORD), of which I am currently the Program Manager, is a community initiative which originated on 31st October 2019 with a meeting of experts from pharma,

academia and the tech industry.^[17,18] The goal of the ORD is to support machine learning and related efforts in reaction prediction, chemical synthesis planning, and experiment design, through a structured data format and open access repository for organic reaction data. The ord-schema package can be used in Python to programmatically work with ORD datasets, but most users interact with the schema through the online graphical user interface at open-reaction-database.org. Both the online interface and the Python package can also be used to generate reaction datasets in bulk from a spreadsheet of reaction data. This feature is particularly relevant to high-throughput experiments which use automation to execute 100's or 1,000's of reactions.

Over the past 20 years Flow chemistry has also experienced a rapid growth in interest.^[19–22] Although flow chemistry is now a well-known tool in the synthesis toolbox, flow reactions still only constitute a small fraction of the reaction databases. Consequently, reaction databases are designed for batch chemistry first and foremost, with limited support given to flow chemistry. Recognising this as a problem, the ORD schema was extended to include support for flow, photo, and electrochemistry data in addition to standard batch reaction data. Table 1 lists some of the existing flow chemistry datasets in ORD.

2. Why is Flow Chemistry Data Needed?

While flow chemistry data are expected to remain a small proportion of reaction databases, including the ORD, the importance of this data should not be underestimated. The increased automation inherent in flow chemistry was an enabling factor in the development of the seminal nanoscale Suzuki-Miyaura coupling dataset by scientists at Pfizer.^[23,30] In recent years this automation has also enabled the rise of self-optimising reactors to explore reaction spaces by algorithms,^[31–37] transient flow systems to systematically explore continuous variables in extreme detail,^[27,38–43] and collect high-throughput differential kinetic data in flow.^[44]

Flow chemistry also extends parameter windows, facilitating access to high temperature and pressure conditions which are challenging to screen in batch. Furthermore, the residence time control of flow opens opportunities to spatially resolve the kinetics of fast reactions, in ways that are not possible in batch mode.^[45–49] Blackmond and coworkers remind us that the fundamental kinetic parameters of a reaction should be the same in

^{*}Correspondence: Dr. B. J. Deadman, E-mail: ben@bjdeadman.co.uk

^aOpen Reaction Database, open-reaction-database.org; ^bBJ Deadman Consultancy Ltd, 86-90 Paul Street, London EC2A 4NE, United Kingdom.

Table 1. Examples of flow chemistry datasets currently in the Open Reaction Database

entry	dataset ID	description	ref.	size
1	ord_dataset-68cb8b4b2b384e3d85b5b1efae58b203	Nanoscale high-throughput screen of Suzuki-Miyaura coupling conditions under plug flow conditions.	[23]	5760
2	ord_dataset-5eb7f2689f4a42eba63ad9e37e49a5cd	Synthesis of a sulfonamide library in a tubular flow reactor.	[24]	39
3	ord_dataset-2038a3c967db4a32a8fbce288437e929	4 case-studies which apply automation, online analytics and a feedback loop to optimize yield and turnover number in Suzuki-Miyaura cross-couplings in a multi-step flow reaction. Feedback loop reactor case study 1.	[25]	96
4	ord_dataset-2be30f5d8dcd471aa6ad410bdee05902	Feedback loop reactor case study 2.	[25]	97
5	ord_dataset-31989f1b2b9d4885b1dd2d9982da4517	Feedback loop reactor case study 3.	[25]	96
6	ord_dataset-bc349c19b4384756a2aee8aa525b6c2a	Feedback loop reactor case study 4.	[25]	96
7	ord_dataset-d9140e7c806047b78bcbbc85cfd5b7fc ^[a]	Design of experiments study of the dynamic kinetic resolution of an amine in packed bed flow reactors.	[26]	40
8	ord_dataset-3d64cf72f75d4b998411f352a1d3f909 ^[a]	Transient flow study of the dynamic kinetic resolution of an amine in packed bed flow reactors.	[27]	176
9	ord_dataset-970120dedeff402fa64c298f1ba86557 ^[a]	Optimization of a slug flow Buchwald-Hartwig coupling by Bayesian optimization and design of experiments, with additional kinetic experiments in flow.	[28]	127

^[a] These datasets are currently undergoing peer-review. The in-progress datasets can be accessed from the ord-data repo on GitHub.^[29]

flow as in batch.^[50] How might machine-learning generate new understandings of reactivity from disparate sources of batch and flow kinetic data? Surely this will be greatly enabled by community efforts to structure both batch and flow reaction data in a consistent representation.

Perhaps the most obvious reason for needing structured flow reaction data is that without this training data, the CASP tools of tomorrow are unlikely to recommend flow reaction methods. A team at SRI International recently reported that translating recommendations from their retrosynthetic planning tool (SynRoute), to procedures for their automated flow reaction platform (Auto-Syn) presented a number of challenges.^[51] While SynRoute was able to successfully recommend viable synthetic routes, these still required adaptation by experts to make them suitable for flow. Many of us will be familiar with the kinds of modifications that are often required to convert a batch process to flow: replacing reagents to improve solubility, accelerating reaction times, considering chemical and material compatibilities.

There is a clear need to increase the availability of flow reaction data, and ideally this data should be structured such that it is compatible with batch reaction data.

3. The ORD Schema

A key design philosophy of the ORD schema is that the most important fields are highly structured, with supplementary free text fields to flexibly accommodate additional details. This enables the commonalities between batch and flow to be consistently represented, while unambiguously defining how the reaction is performed in flow or batch.

At its top level, the ORD schema is made up of 9 sections, which each contain data fields, and sub-levels with further data fields. This structure has been described previously,^[17] but herein I will discuss some parts of the schema which are particularly relevant to flow chemistry reactions. Fig. 1 highlights some of these sections with reference to a typical flow reaction scheme.

3.1 Reaction Inputs

The way in which we introduce chemicals into a flow reaction is one of the key differentiators from batch mode chemistry. The inputs section of the ORD schema is designed to capture

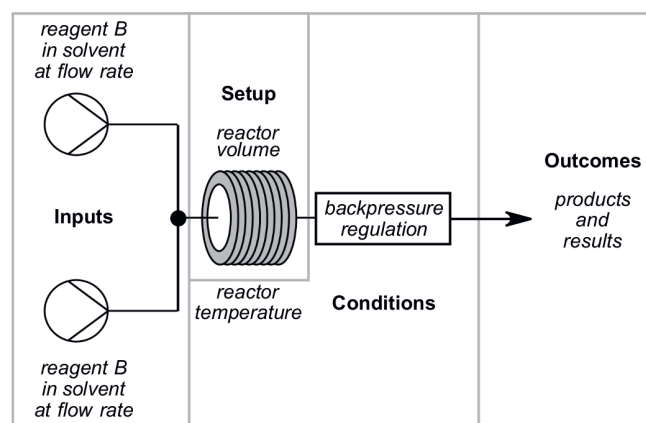


Fig. 1. Top-level overview of the ORD schema as it applies to flow reactions.

the details about which chemical components go into a reaction, and how they are introduced. A reaction record can contain any number of inputs, with each input being the addition of a chemical component or combination of chemical components (for example a solution). For both batch and flow, chemical components are described by a combination of identifiers (preferably line notation such as SMILES (Simplified Molecular-Input Line-Entry System) or InChI (International Chemical Identifier)^[52]) amounts, a defined role (for example reagent, reactant, solvent *etc.*) and optional details about preparations, sources and other features. In contrast to how flow reactions are typically represented in literature as concentrations, the ORD schema records the amount in mass, volume, or moles (or their prefixed equivalents). This ensures that batch and flow reactions are treated in an equivalent manner and allows these complementary techniques to be represented in a common format. Determining the amount typically requires the continuous flow reaction to be conceptualised as a defined volume of reaction, either as a 'slug' travelling through the reactor, or a sum of feed-stock volumes passing through the reactor over a longer period of time (Fig. 2). This concept should be recognisable to many flow chemists as this is how yields are often estimated for a continuous process.

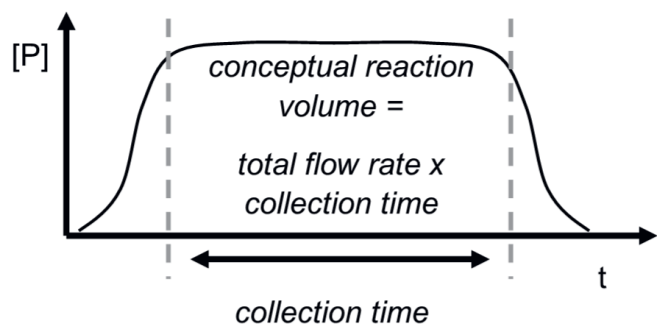


Fig. 2. A conceptual reaction volume is used to convert concentrations of reagents and products to amounts for the ORD.

Each input also has details about how it is introduced into the reaction, including addition order, speed or flow rate, time (relative to the first input), duration, temperature and of course the addition device. While many of these fields are also relevant to batch reactions, they have particular importance to flow reactions. In flow reactions the addition order is an index describing where input feeds join the main flow (Fig. 3). Where two inputs have the same addition order, this indicates that the input feeds enter concurrently, while a higher addition order indicates an input feed entering downstream. The speed or flow rate of addition is self-explanatory, while the addition temperature could be used to describe a pre-cooled or pre-heated input feed.

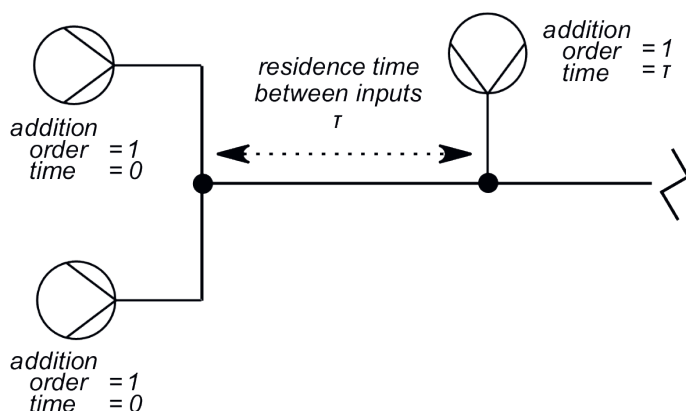


Fig. 3. Definition of addition order and time for the inputs of a flow reaction.

The duration of the addition should be defined as the time over which the input feed has merged into the conceptual reaction volume. Provided that all input feeds are operated concurrently, the duration will typically be the time over which the conceptual volume of reaction entered or exited the flow reactor. For flow reactions operating in ‘slug flow’ mode, typically with injection loop additions, the duration will be the short time interval over which the yield or other outcome measurements have been defined and collected. Whereas for flow reactions operating at steady-state conditions the duration is usually the full time period during which the reactor is at steady-state (*i.e.* excluding start-up and shut-down phases).

The addition device fields describe the technology used to introduce the input. The structured Enum field describes the type in broad terms such as piston, syringe, or peristaltic pump. There is also a custom option for use in cases where the pre-defined types do not provide a suitable representation. The supplementary details field allows for a free text description of the addition

technology and could include details such as the make and model of the pump or describe specific configurations and preparations of the device(s). The combination of the structured Enum field for pump type, and free text details permits broad freedom for the user to report the technical details, whilst ensuring that the database does not become fragmented down pump vendor lines.

The concept of a solution input will be immediately recognizable to flow chemists since this is often a fundamental step in how we plan and enact our reactions. But what about a catalyst introduced as a packed-bed reactor? While the presence of a packed bed reactor can be defined in the setup section (see below), the chemical composition of the packed bed is defined as another input containing one or more solid components. For a heterogeneous catalyst (*e.g.* 5 wt% Pd/Al₂O₃), or an immobilised reagent (*e.g.* Amberlyst™ 15) they can be defined as a single component with (where possible) a structural identifier for the active component, and additional identifiers (name, CAS number *etc.*) or source details to help unambiguously define it. Where the reagent or catalyst is mixed with additional support or other materials by the experimenter, as part of the packed bed reactor setup, then these should be specified as additional chemical components in the packed bed reactor input. This reflects the philosophy that an ORD record captures the experiment as it was conducted.

3.2 Setup and Conditions

The setup and conditions sections of the ORD schema define the physical reactor, and the conditions under which it is operated. For a flow reaction the setup is focused on that part of the flow reactor where the productive reaction occurs, ignoring upstream and downstream tubing and associated parts which are defined in the inputs and workups sections. The vessel is another Enum field with tube, packed-bed and continuously stirred tank reactors being the options most relevant to flow chemistry. The electrochemical cell would also be appropriate for flow electrochemistry, and the custom vessel is an option for alternative flow reactors. The vessel type also contains a range of options for batch reactions, reinforcing how the schema provides a consistent representation for both flow and batch reactions, while providing space for extended free text description of the reactor in the vessel details field. The setup details also define the reactor material with an Enum type and associated free text details to potentially enable future predictive models to understand the recommended reactor materials for reaction classes.

The vessel volume is the internal fluid volume of the active portion of the flow reactor, while the environment Enum and details specify if the flow reactor is on a bench, in a fumehood, glovebox or other location if this is relevant to its operation. Where there is automation of the reactor this is specified using a Boolean field, and there is the possibility of attaching automation code to the record.

The setup section also allows for various preparations and attachments to be defined. Particularly relevant to flow chemistry is the pressure regulator attachment which can be used to define a back pressure regulator at the end of the flow reactor.

For a flow reaction the conditions section defines things like temperature, pressure, and the atmosphere if relevant to the process. This section also includes subsections for flow chemistry, photochemistry, and electrochemistry specific conditions. In the flow chemistry conditions subsection there are options to define tubing and tubing diameters, and reactor types. Unfortunately, the evolution of the schema has resulted in some duplication of fields with the vessel type and input addition devices. Current best practice is to define pumps in their respective input addition devices since this permits finer detail about the configuration of the flow reactor.

It should be noted that the schema works best when the reaction conditions are static. For a flow reaction this will be when the process is at steady state, or pseudo-steady state, and the conditions can be defined as single values (or a small range where precision is defined). Where the conditions are not static this should be indicated using the dynamic conditions Boolean option.

3.3 Workups

A large range of workups can be defined for both batch and flow reactions. In the case of flow the options to define an addition feed, or flow through a scavenger column, are particularly relevant (Fig. 4). In these workup types there are extended options to define, in a structured way, these agents as downstream chemical inputs. Temperature changes can also be defined as a workup, which could be used to define a downstream thermal quench (Fig. 4c).

In situations where batch workup operations are conducted after the flow reaction, these should be included in the reaction record. An exception could be made if all the outcome measurements were made on the pre-workup material.

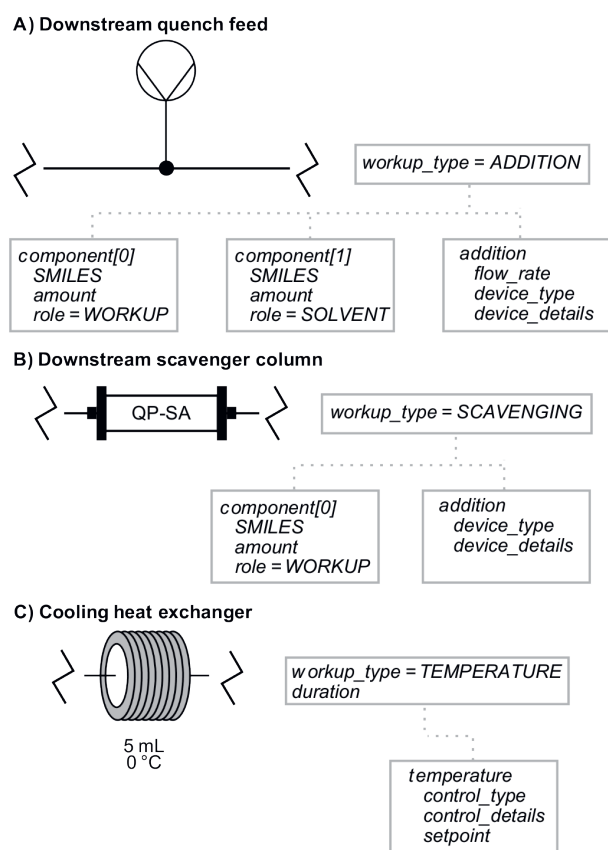


Fig. 4. Definition of (A) a downstream quench feed, (B) a downstream scavenger column, and (C) a heat exchanger to rapidly cool a superhot flow.

3.4 Outcomes

The products, yields and associated measurements are reported in the outcomes section. Flow and batch reactions are expected to be quite similar in how their outcomes are reported. However, a key difference is that the outcome time should be considered to be the residence time of the outcome measurement, typically taken to be relative to the start of the active reaction part of the flow reactor.

The schema permits multiple outcomes to be reported, and in the case of a flow reaction this would refer to measurement of the process at spatially separate points in the reactor. For each

outcome there can be multiple products defined, including residual reactants, by-products, side products, internal standards, and other reaction roles. There can also be multiple analysis types described, including different analysis types at different residence times (outcomes).

Online analysis techniques can be a powerful addition to flow reactions, enabling measurements to be made in the real time dimension in addition to the standard residence time dimension.^[53] The ORD schema has some limited capability to capture such process monitoring data. Details of the analysis technique can be defined using Enum types and text details as is the case in offline analysis. However, since the primary time dimension in a flow reaction record is the residence time, the time trends need to be summarised as single measurement data points in the ORD schema. This would typically be the average measurement at steady state, but alternative values could be defined using the available fields in the schema. The time trend data can also be stored in the reaction as an embedded file.

3.5 Other Sections

The treatment of the other top-level sections is generally similar for flow and batch reactions. The reaction identifiers allow RInChIs (International Chemical Identifier for Reactions), reaction type, notebook references, and other descriptors to be added, and can also be utilised to add subsets into datasets as demonstrated in Table 1, entry 7.

The notes section captures safety and procedure details, and the observations section is for time stamped records of observations made during the experiment. The final section covers the provenance of the reaction, including such details as who conducted the reaction, who created the ORD record, and links to any associated publication.

4. Telescoped Flow Processes

A particular strength of flow chemistry is the capability to telescope multiple reaction steps together. Defining such telescoped processes in a structured way can however be a challenge. The ORD schema was designed to record singular reactions, but there are scenarios where it can still make sense to define a telescoped flow process as a single reaction record. Consider a multi-component cascade reaction as an example where multiple reactants are introduced as inputs and the outcomes record the final observed product ratios. Such a process is inherently compatible with the ORD schema. The schema is not intended to record the intermediate steps in the cascade unless they are directly measured.

Consider also a reaction where the primary bond forming event takes place inside a tubular reactor, but the flow is then telescoped through a series of immobilised reagents to quench the reaction (Fig. 5A). The reaction record should focus on the primary bond forming reaction, but the downstream telescoped processes can be captured as workups, in a process that is analogous to batch reactions with a quench workup.

In the scenario where a reactive component is prepared *in situ* and then consumed by the downstream addition of the reactant, the primary bond forming might be considered the downstream reaction (Fig. 5B). Therefore, pre-cursor reactions could be defined in the input details section of the schema so that the focus is put on the reaction of interest.

In situations where it is desirable to record detailed information about multiple steps in a telescoped flow reaction, this can be achieved across multiple reaction records (Fig. 5C). Each reaction should focus on a single step in the process, with the outcomes of each reaction step being linked to the inputs of the downstream reaction as a crude component input. This structure is more complex than the examples described above, but it could be appropriate where online analysis is used to measure the levels of an intermediate component.

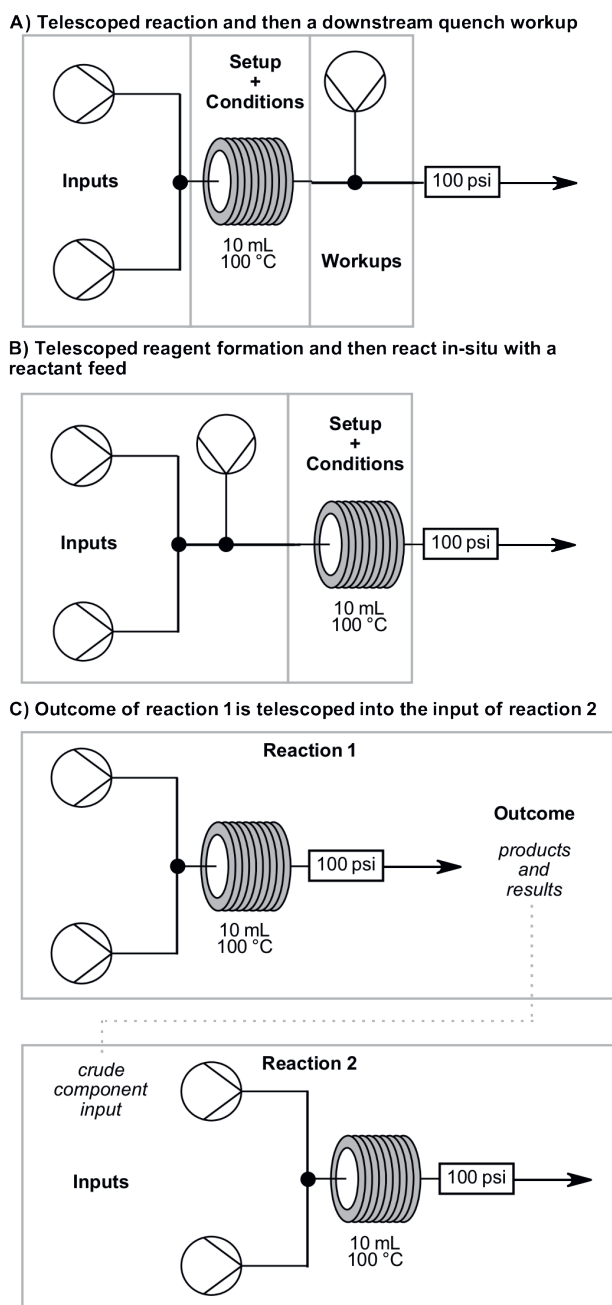


Fig. 5. Definition of some typical telescoped reactions in the ORD schema. (A) a primary reaction followed by a downstream quench feed, (B) reagent formation *in situ* followed by addition of the reactant to initiate the primary reaction, and (C) a complex telescoped process which requires definition as multiple reaction records, linked from outcomes to crude component inputs.

5. Transient Flow Conditions

Transient flow is a recent evolution of flow chemistry where parameters, such as temperatures, concentrations, and residence times, among others, are continuously modified throughout an experiment. These transient systems are able to systematically explore continuous variables in extreme detail.^[27,38–43]

While transient flow experiments are data rich, the dynamic conditions can be a challenge to define in any reaction schema, including the ORD. We have been experimenting with the definition of these processes, and our recommended best practice is to consider the transient flow experiment as a series of reaction records contained in a dataset.^[54]

Where the analysis is non-continuous, such as for HPLC where injections must be made at regular intervals, it can be simple to partition the transient into a series of reactions with pseudo-static conditions and coinciding with the HPLC injections. The mean reaction conditions for each partition should be extracted from the transients, and the variable nature of the parameter can be defined in its reported precision.

6. Community Conversation is Needed

The time is also right to have a conversation about how the community wants to find and report their flow chemistry reaction data. Should there be a database of flow reactions, or do we want to enhance the flow chemistry filtering and searching of existing databases? Whatever the community decides, the Open Reaction Database could provide a model platform for community or commercial activities in this space. It is an open database in every sense of the word, with data available to all users under the CC-BY-SA license, and the schema and other software tools available under the Apache license.^[55] Reuse of the data and code is encouraged, but efforts should be made to ensure the community uses the same schema where possible. This will require active dialogue to further evolve the schema to meet the diverse needs of batch, flow, and other sub-domains, whilst maintaining a consistent data structure. Failure to do this will inevitably lead to siloing of reaction data into batch, flow, and other domains, and hinder future development of predictive chemistry models.

Meanwhile the ORD continues to grow, and we encourage experimental groups to evaluate the schema for their own reactions, and to archive their new reactions alongside the publication of results in traditional journals. Where limitations are found, they should be reported on the ord-schema GitHub repo^[56] so that the community can work collaboratively on evolving the standard to meet the needs of the community, without losing sight of the goal to ‘support machine learning and related efforts in reaction prediction, chemical synthesis planning, and experiment design’ through a consistent and structured representation of organic chemical reaction data.

Received: March 8, 2025

- [1] B. A. Grzybowski, S. Szymkuć, E. P. Gajewska, K. Molga, P. Dittwald, A. Wołos, T. Klucznik, *Chem.* **2018**, *4*, 390, <https://doi.org/10.1016/j.chempr.2018.02.024>.
- [2] Z. Tu, S. J. Choure, M. H. Fong, J. Roh, I. Levin, K. Yu, J. F. Joung, N. Morgan, S.-C. Li, X. Sun, H. Lin, M. Murnin, J. P. Liles, T. J. Struble, M. E. Fortunato, M. Liu, W. H. Green, K. F. Jensen, C. W. Coley, *Acc. Chem. Res.* **2025**, <https://doi.org/10.1021/acs.accounts.5c00155>.
- [3] S. Genheden, A. Thakkar, V. Chadimová, J.-L. Reymond, O. Engkvist, E. Bjerrum, *J. Cheminf.* **2020**, *12*, 70, <https://doi.org/10.1186/s13321-020-00472-1>.
- [4] P. Schwaller, A. C. Vaucher, R. Laplaza, C. Bunne, A. Krause, C. Corminboeuf, T. Laino, *Wiley Interdiscip. Rev.: Comput. Mol. Sci.* **2022**, *12*, e1604, <https://doi.org/10.1002/wcms.1604>.
- [5] CAS SciFinder, <https://www.cas.org/solutions/cas-scifinder-discovery-platform/cas-scifinder/reactions>, accessed February 18, 2025.
- [6] Reaxys, <https://www.elsevier.com/products/reaxys>, accessed February 18, 2025.
- [7] ‘Chemical Reactions From US Patents’ 1976-2016, **2017**, <https://doi.org/10.6084/m9.figshare.5104873.v1>.
- [8] P. Tremouilhac, C.-L. Lin, P.-C. Huang, Y.-C. Huang, A. Nguyen, N. Jung, F. Bach, R. Ulrich, B. Neumair, A. Streit, S. Bräse, *Angew. Chem. Int. Ed.* **2020**, *59*, 22771, <https://doi.org/10.1002/anie.202007702>.
- [9] Chemotion, <https://chemotion.net/>, accessed February 18, 2025.
- [10] NFDI4Chem, <https://www.nfdi4chem.de/>, accessed March 7, 2025.
- [11] S. Boobier, J. C. Davies, I. N. Derbenev, C. M. Handley, J. D. Hirst, *J. Chem. Inf. Model.* **2023**, *63*, 2895, <https://doi.org/10.1021/acs.jcim.3c00306>.
- [12] W. Finnigan, M. Lubberink, L. J. Hepworth, J. Citoler, A. P. Matthey, G. J. Ford, J. Sangster, S. C. Cosgrove, B. Z. da Costa, R. S. Heath, T. W. Thorpe, Y. Yu, S. L. Flitsch, N. J. Turner, *ACS Catal.* **2023**, *13*, 11771, <https://doi.org/10.1021/acscatal.3c01418>.
- [13] RetroBioCat, <https://retrobiocat.com/>, accessed March 7, 2025.

- [14] Disyn Biotech, <https://disynbiotec.com/retrobiocat>, accessed March 7, 2025.
- [15] J. Tomczak, E. Herzog, M. Fischer, J. Swienty-Busch, F. van den Broek, G. Whittick, M. Kappler, B. Jones, G. Blanke, *Pure Appl. Chem.* **2022**, *94*, 687, <https://doi.org/10.1515/pac-2021-3013>.
- [16] PistoiaAlliance/UDM, <https://github.com/PistoiaAlliance/UDM>, accessed March 7, 2025.
- [17] S. M. Kearnes, M. R. Maser, M. Wlekinski, A. Kast, A. G. Doyle, S. D. Dreher, J. M. Hawkins, K. F. Jensen, C. W. Coley, *J. Am. Chem. Soc.* **2021**, *143*, 18820, <https://doi.org/10.1021/jacs.1c09820>.
- [18] Open Reaction Database, <https://open-reaction-database.org/>, accessed February 18, 2025.
- [19] M. B. Plutschack, B. Pieber, K. Gilmore, P. H. Seeberger, *Chem. Rev.* **2017**, *117*, 11796, <https://doi.org/10.1021/acs.chemrev.7b00183>.
- [20] F. Darvas, G. Dormán, V. Hessel, S. V. Ley, 'Flow Chemistry – Fundamentals', De Gruyter, Berlin, **2021**, <https://doi.org/10.1515/9783110693676>.
- [21] F. Darvas, G. Dormán, V. Hessel, S. V. Ley, 'Flow Chemistry – Applications', De Gruyter, Berlin, **2021**, <https://doi.org/10.1515/9783110693690>.
- [22] L. Capaldo, Z. Wen, T. Noël, *Chem. Sci.* **2023**, *14*, 4230, <https://doi.org/10.1039/D3SC00092K>.
- [23] D. Perera, J. W. Tucker, S. Brahmabhatt, C. J. Helal, A. Chong, W. Farrell, P. Richardson, N. W. Sach, *Science* **2018**, *359*, 429, <https://doi.org/10.1126/science.aap9112>.
- [24] A. Gioiello, E. Rosatelli, M. Teofrasti, P. Filipponi, R. Pellicciari, *ACS Comb. Sci.* **2013**, *15*, 235, <https://doi.org/10.1021/co400012m>.
- [25] B. J. Reizman, Y.-M. Wang, S. L. Buchwald, K. F. Jensen, *React. Chem. Eng.* **2016**, *1*, 658, <https://doi.org/10.1039/C6RE00153J>.
- [26] M. J. Takle, B. J. Deadman, K. Hellgardt, J. Dickhaut, A. Wieja, K. K. M. Hii, *ACS Catal.* **2023**, *13*, 10541, <https://doi.org/10.1021/acscatal.3c02859>.
- [27] M. J. Takle, L. Schrecker, B. J. Deadman, J. Dickhaut, A. Wieja, K. Hellgardt, K. K. Mimi Hii, *Org. Process Res. Dev.* **2025**, *29*, 545, <https://doi.org/10.1021/acs.oprd.4c00508>.
- [28] F. Wagner, P. Sagmeister, C. E. Jusner, T. G. Tampone, V. Manee, F. G. Buono, C. O. Kappe, *Adv. Sci.* **2024**, *11*, 2308034, <https://doi.org/10.1002/advs.202308034>.
- [29] ord-data, <https://github.com/open-reaction-database/ord-data>.
- [30] Rapid material-sparing screening of 5760 Suzuki-Miyaura coupling reactions, https://open-reaction-database.org/dataset/ord_dataset-68cb8b4b2b384e3d85b5b1efae58b203.
- [31] K. C. Felton, J. G. Rittig, A. A. Lapkin, *Chem.: Methods* **2021**, *1*, 116, <https://doi.org/10.1002/cmtd.202000051>.
- [32] A. D. Clayton, J. A. Manson, C. J. Taylor, T. W. Chamberlain, B. A. Taylor, G. Clemens, R. A. Bourne, *React. Chem. Eng.* **2019**, *4*, 1545, <https://doi.org/10.1039/C9RE00209J>.
- [33] F. L. Wagner, P. Sagmeister, T. G. Tampone, V. Manee, D. Yerkozhanov, F. G. Buono, J. D. Williams, C. O. Kappe, *ACS Sustainable Chem. Eng.* **2024**, *12*, 10002, <https://doi.org/10.1021/acssuschemeng.4c03253>.
- [34] S. L. Boyall, H. Clarke, T. Dixon, R. W. M. Davidson, K. Leslie, G. Clemens, F. L. Muller, A. D. Clayton, R. A. Bourne, T. W. Chamberlain, *ACS Sustainable Chem. Eng.* **2024**, *12*, 15125, <https://doi.org/10.1021/acssuschemeng.4c05015>.
- [35] C. J. Taylor, A. Pomberger, K. C. Felton, R. Grainger, M. Barecka, T. W. Chamberlain, R. A. Bourne, C. N. Johnson, A. A. Lapkin, *Chem. Rev.* **2023**, *123*, 3089, <https://doi.org/10.1021/acs.chemrev.2c00798>.
- [36] N. S. Eyke, T. N. Schneider, B. Jin, T. Hart, S. Monfette, J. M. Hawkins, P. D. Morse, R. M. Howard, D. M. Pfisterer, K. Y. Nandiwale, K. F. Jensen, *Chem. Sci.* **2023**, *14*, 8798, <https://doi.org/10.1039/D3SC02082G>.
- [37] C. P. Breen, A. M. K. Nambiar, T. F. Jamison, K. F. Jensen, *Trends Chem.* **2021**, *3*, 373, <https://doi.org/10.1016/j.trechm.2021.02.005>.
- [38] J. Van Herck, T. Junkers, *Chem.:Methods* **2022**, *2*, e202100090, <https://doi.org/10.1002/cmtd.202100090>.
- [39] T. Durand, C. Henry, D. Boliën, D. C. Harrowven, S. Bloodworth, X. Franck, R. J. Whitby, *React. Chem. Eng.* **2016**, *1*, 82, <https://doi.org/10.1039/C5RE00007F>.
- [40] C. A. Hone, N. Holmes, G. R. Akiën, R. A. Bourne, F. L. Muller, *React. Chem. Eng.* **2017**, *2*, 103, <https://doi.org/10.1039/C6RE00109B>.
- [41] F. Florit, A. M. K. Nambiar, C. P. Breen, T. F. Jamison, K. F. Jensen, *React. Chem. Eng.* **2021**, *6*, 2306, <https://doi.org/10.1039/D1RE00350J>.
- [42] C. Waldron, A. Pankajakshan, M. Quaglio, E. Cao, F. Galvanin, A. Gavriilidis, *React. Chem. Eng.* **2020**, *5*, 112, <https://doi.org/10.1039/C9RE00342H>.
- [43] L. Schrecker, J. Dickhaut, C. Holtze, P. Staehle, M. Vranceanu, A. Wieja, K. Hellgardt, K. Kuok Hii, *React. Chem. Eng.* **2024**, *9*, 1077, <https://doi.org/10.1039/D3RE00696D>.
- [44] G. Lennon, P. Dingwall, *Angew. Chem. Int. Ed.* **2024**, *63*, e202318146, <https://doi.org/10.1002/anie.202318146>.
- [45] Z. Gulsoy, I. Dorokhov, D. Ohlig, M. Gödde, K. Kuok Hii, K. Hellgardt, *Chem. Eng. J.* **2024**, *494*, 153184, <https://doi.org/10.1016/j.cej.2024.153184>.
- [46] J. S. Zhang, C. Y. Zhang, G. T. Liu, G. S. Luo, *Chem. Eng. J.* **2016**, *295*, 384, <https://doi.org/10.1016/j.cej.2016.01.100>.
- [47] M.-A. Schneider, F. Stoessel, *Chem. Eng. J.* **2005**, *115*, 73, <https://doi.org/10.1016/j.cej.2005.09.019>.
- [48] A. Ładosz, C. Kuhnle, K. F. Jensen, *React. Chem. Eng.* **2020**, *5*, 2115, <https://doi.org/10.1039/D0RE00304B>.
- [49] T. A. Frede, N. vom Hofe, R. J. Reuß, N. Kemmerling, T. Kock, F. Herbstritt, N. Kockmann, *React. Chem. Eng.* **2023**, *8*, 1051, <https://doi.org/10.1039/D2RE00565D>.
- [50] F. E. Valera, M. Quaranta, A. Moran, J. Blacker, A. Armstrong, J. T. Cabral, D. G. Blackmond, *Angew. Chem. Int. Ed.* **2010**, *49*, 2478, <https://doi.org/10.1002/anie.200906095>.
- [51] M. Latendresse, J. P. Malerich, J. Herson, M. Krummenacker, J. Szeto, V.-A. Vu, N. Collins, P. B. Madrid, *J. Chem. Inf. Model.* **2023**, *63*, 5484, <https://doi.org/10.1021/acs.jcim.3c00491>.
- [52] InChI, <https://www.inchi-trust.org/>, accessed March 6, 2025.
- [53] A. M. Kearney, S. G. Collins, A. R. Maguire, *React. Chem. Eng.* **2024**, *9*, 990, <https://doi.org/10.1039/D3RE00678F>.
- [54] TF study of flash thermal racemisation of an amine #221, <https://github.com/open-reaction-database/ord-data/pull/221>.
- [55] Open Reaction Database documentation, <https://docs.open-reaction-database.org/en/latest/overview.html#commitment-to-open-access>, accessed March 7, 2025.
- [56] ord-schema, <https://github.com/open-reaction-database/ord-schema>, accessed March 7, 2025.

License and Terms



This is an Open Access article under the terms of the Creative Commons Attribution License CC BY 4.0. The material may not be used for commercial purposes.

The license is subject to the CHIMIA terms and conditions: (<https://chimia.ch/chimia/about>).

The definitive version of this article is the electronic one that can be found at <https://doi.org/10.2533/chimia.2025.390>