

Analyzing General Chemistry Texts' Treatment of Rates of Change Concepts in Reaction Kinetics Reveals Missing Conceptual Links

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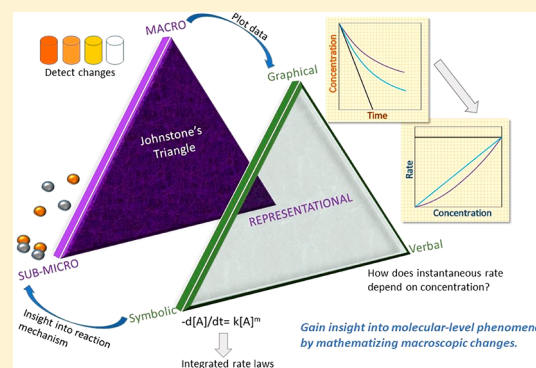
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S Supporting Information

ABSTRACT: Change over time is a crosscutting theme in the sciences that is pivotal to reaction kinetics, an anchoring concept in undergraduate chemistry, and students' struggles with rates of change are well-documented. Informed by the education scholarship in chemistry, physics, and mathematics, a research team with members from complementary disciplinary backgrounds developed a rubric to examine how 10 general chemistry textbooks used by top producers of American-Chemical-Society-approved chemistry baccalaureates treat rates of change concepts in reaction kinetics. The rubric is focused on four categories of students' challenges that emerged from the literature review: (i) fluency with graphical representations, (ii) meaning of sign of rate of change, (iii) distinction between average and instantaneous rates of change, and (iv) connections between differential and integrated forms of the rate laws. The analysis reveals interesting patterns but also variability among the texts that, intriguingly, is not explained by the degree to which a text is calculus-based. An especially powerful aspect of the discipline-based education research lens is its ability to reveal missing conceptual links in the texts. For example, the analysis makes apparent specific gaps in the supports needed to help students move between representational forms (words, symbols, graphs) in the development of the differential form of the rate laws. The paper discusses the implications of the findings for chemistry instructors and chemical education research.

KEYWORDS: First-Year Undergraduate/General, Chemical Education Research, Curriculum, Textbooks/Reference Books, Kinetics, Mathematics/Symbolic Mathematics

FEATURE: Chemical Education Research



BACKGROUND

Discipline-based education research (DBER) provides considerable insight into the conceptual challenges of learning specific topics. Better supporting the translation of DBER findings into practice and conducting DBER at the intersection between disciplines are among the recommended goals for future research made by the National Research Council.¹ These two goals have motivated the study described here, which uses DBER as a lens to pose the following research question: How do general chemistry textbooks treat rates of change concepts in reaction kinetics? By "DBER as a lens" we are referring to a goal-oriented, two-stage process of first examining and synthesizing the literature on teaching and learning rates of change, and then crafting an analytical instrument with its constituent criteria directly emergent from the documented challenges faced by learners. Johnstone's triangle, which connects three conceptual levels of chemistry (macro, submicro, representational), serves as a broad framework for

this study.^{2,3} The DBER lens developed here places particular scrutiny on Johnstone's representational level.

The topic of this study was selected because scholarship in chemistry education, physics education, and mathematics education reveals widespread difficulties faced by students when learning about and applying rates of change concepts. The notion of change over time is fundamental to kinetics, which the American Chemical Society (ACS) Examinations Institute considers one of 10 anchoring concepts or "big ideas" in undergraduate chemistry.⁴ Textbooks were chosen as the object of study because they are required or recommended in most first-year chemistry courses, and because they provide a conceptual narrative that buttresses what students learn in class. In a recent study of over 1000 students in a dozen introductory

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63 science courses, more than three-quarters of students reported
64 reading the textbook either often or sometimes.⁵

65 Reviews of the literature on teaching and learning chemical
66 kinetics have compiled a plethora of student difficulties and
67 misconceptions that commonly persist after instruction.^{6,7} The
68 most recent of these reviews also highlights how mathematics
69 education research on students' understanding of related rates
70 can inform this area of chemistry education.⁷ Here we drew
71 from the relevant literature in three disciplines (chemistry
72 education, physics education, mathematics education) to create
73 a list of students' rates of change challenges, which we then
74 considered in the context of introductory reaction kinetics. At
75 this intersection emerged four broad areas of student
76 difficulties: (i) drawing and interpreting graphs to understand
77 change over time, (ii) interpreting the sign in a rate of change,
78 (iii) distinguishing average and instantaneous rates of change,
79 and (iv) basic conceptual meaning behind derivatives and
80 integrals.

81 Graphical Representations

82 Undergraduate chemistry students have difficulty constructing
83 and interpreting graphs, and may experience anxiety with
84 chemistry problems that involve graphs.^{8,9} Graphing problems
85 that are purely mathematical prove less difficult than problems
86 involving the same mathematical content in a physical context
87 that introduces the need for translation of the context into
88 mathematical language.^{10–12} Students also face challenges when
89 integrating process skills such as graphing and comprehending
90 chemical events in a microworld.¹³ Because it appears
91 challenging for students to generalize the rate concept as
92 change over time, their interpretation of graphs is dependent
93 on the domain context as well as problem format.^{14–16}

94 When asked to sketch graphs of reaction rate versus time, a
95 significant number of chemistry teachers produced graphs with
96 unrealistic slopes, such as slope increasing exponentially
97 without decreasing.¹⁷ High school students and undergraduate
98 students also had difficulty sketching accurate reaction rate
99 versus time graphs, even when they were able to provide
100 accurate verbal descriptions of how the rate of a chemical
101 reaction changes over time.¹⁸ Because curved graphs involve
102 changes in both height and slope, students find them more
103 difficult to interpret.¹⁹ Giving students the opportunity to
104 predict the shapes of graphs and then compare the actual
105 graphs with their predictions may be especially suited to
106 promoting conceptual change.^{20,21}

107 Translating back and forth between different types of graphs
108 also presents challenges.¹⁹ Students commonly expect graphs to
109 remain the same after the variables on the axes are changed.^{15,20}
110 They fail to distinguish between rate versus time, rate versus
111 concentration, and concentration versus time graphs.¹⁸
112 Following traditional instruction in reaction kinetics, the vast
113 majority of first-year undergraduate students incorrectly
114 predicted that the reaction rate versus time graph would be
115 the same as the concentration versus time graph.¹⁶ The
116 opportunity to explore the relationships between graphs can
117 help students develop a more intuitive feel for doing so.²²

118 Sign of Rate of Change

119 Studies have documented undergraduate students' difficulties
120 with negative rates of change in various contexts, including
121 kinematics (the meaning of negative velocity and negative
122 acceleration), light intensity over distance from a point source,
123 and discharge of a capacitor in a simple circuit.^{19,23} For
124 example, when determining whether something is slowing

125 down or speeding up, students may base their responses on the
126 sign associated with the slope of the position versus time graph,
127 rather than the change in magnitude of the slope.¹⁹ They
128 struggle to attend to the magnitude or absolute value and the
129 sign of the rate of change simultaneously, and find it especially
130 confusing when rates are negative but increasing in
131 magnitude.²³ When solving equations or interpreting graphs,
132 students commonly confuse the sign of the slope with the sign
133 of the y -coordinate, or carelessly drop the negative sign.^{15,24}
134 These findings have implications for curricular treatment of the
135 negative sign associated with consumption of reactants.

136 Distinction between Average and Instantaneous Rates of 137 Change

138 Over the course of a chemical reaction, rate may remain
139 constant (zeroth-order), change linearly (first-order), or change
140 nonlinearly (second and other orders); the distinction between
141 average and instantaneous rates of change is thus central to
142 understanding relationships in reaction kinetics. Unfortunately,
143 students fail to distinguish initial rate, instantaneous rate, and
144 average rate over a time interval.¹⁸ They have difficulty saying
145 how the rate of reaction changes over time, and confound
146 constant and variable rates of change.^{7,25} A student who is able
147 to apply a procedure to calculate average rate of change may
148 not be able to explain the meaning of the average rate of
149 change.²⁶

150 Representationally, average and instantaneous rates of
151 change can be distinguished in words, graphically (slope of
152 the secant versus slope of the tangent), and in symbols (Δ
153 versus d), and moving between these representations presents a
154 suite of difficulties for students. Many undergraduate students
155 struggle with matching a text description with a graphical
156 representation.¹⁹ They have a poor understanding of the
157 symbol Δ .¹⁵ They may not understand that the average rate
158 equals the instantaneous rate on a linear graph.²⁷ They often
159 compute the slope at a point by simply dividing the y -value by
160 the x -value.^{19,20} They may not view the tangent as the limit of
161 the set of secants.²⁸ This research demonstrates that curricular
162 support is needed to help undergraduate students develop
163 fluency with moving between these rates of change
164 representations, which are all relevant to understanding average
165 and instantaneous rates of concentration change in introduc-
166 tory reaction kinetics.

167 Meaning of and Connections between Derivative and 168 Integral

169 Students who have completed an introductory calculus
170 sequence still commonly treat variables as symbols to be
171 manipulated, rather than quantities to be related.²⁹ The
172 differences between high school and undergraduate are not
173 significant for the first course in differential and integral
174 calculus, although undergraduates may have further lost touch
175 with earlier mathematical knowledge and skills, such as
176 graphing, and ceased to think in terms of rate of change.^{24,30}
177 Even when students do have an understanding of rate when
178 working with one kind of representation or context, this
179 understanding does not necessarily transfer to other
180 situations.³¹

181 A core principle in calculus (the fundamental theorem of
182 calculus) is that the accumulation of a quantity (determined by
183 integration) and the rate of change in the accumulation of the
184 quantity (determined by differentiation) are interrelated.³² This
185 principle, of course, underlies the connection between the rate
186 laws in their differential form and in their integral form. Ideally, 186

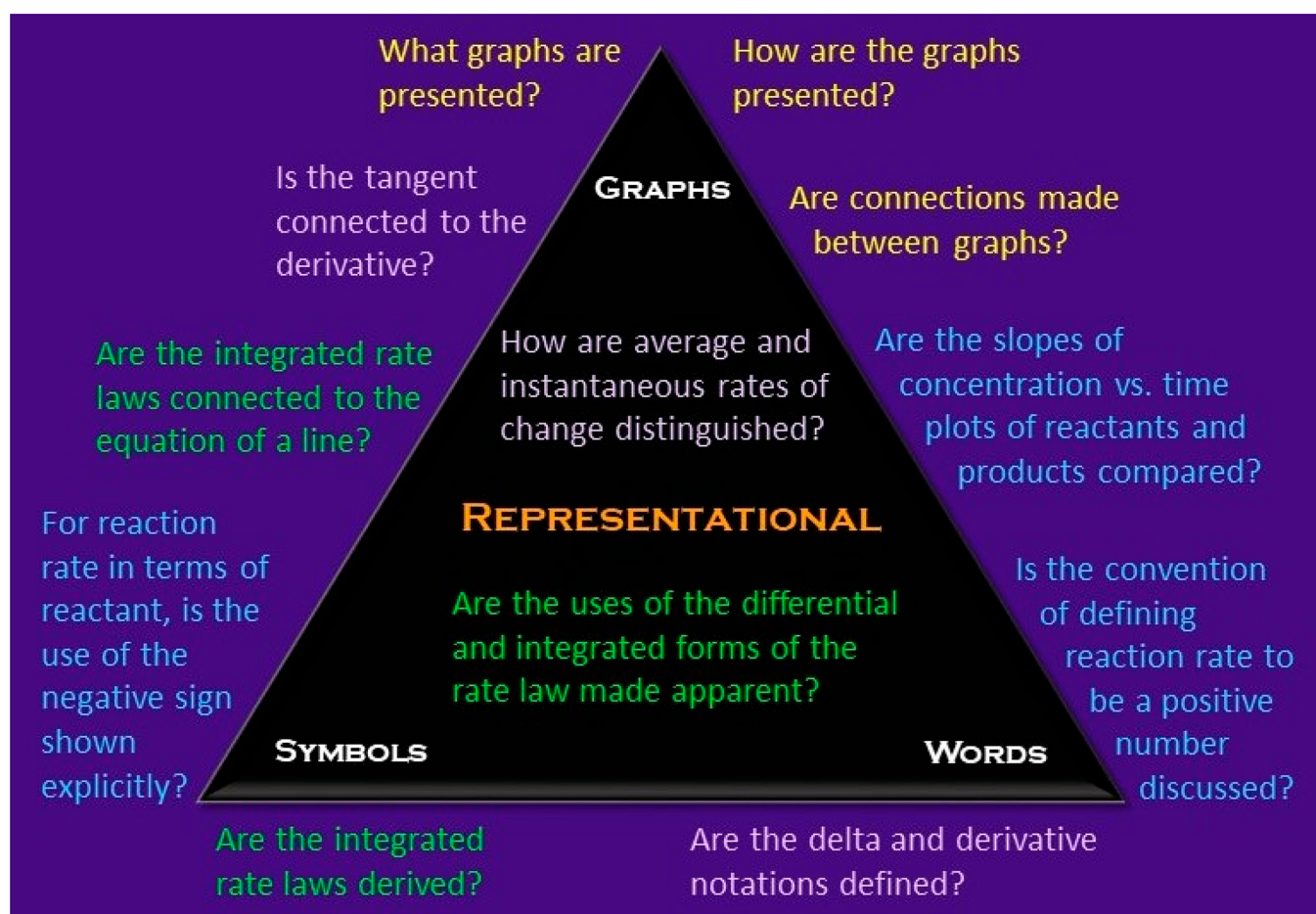


Figure 1. Supporting students to navigate the representational level of Johnstone's triangle. Color indicates the category of student difficulty: graphical representations (yellow), sign of rate of change (blue), distinction between average and instantaneous rates of change (lavender), and meaning of and connections between derivative and integral (green). To roughly indicate which representational level(s) are relevant for a particular question, the questions are positioned near a vertex, on a side between vertices, or between all three vertices (within the triangle).

187 students who have studied calculus would have internalized this
 188 basic idea and its implications, but this does not appear to be
 189 the case. Students frequently confound “amount” and “rate of
 190 change of amount” in general, and in particular, confound the
 191 rate of consumption of reactants with the amount of reactants
 192 during a reaction.^{14,25} They cannot correctly explain the
 193 meaning of terms in a differential equation, and mix up the
 194 function and its derivative.²⁵ Relevant to integration, students
 195 do not know what the area under the graph means.¹⁵ Finally,
 196 students who understand the terms in $y = mx + b$ and recognize
 197 it as the equation of a straight line cannot necessarily see the
 198 same (y -intercept, slope) relationships when other variables are
 199 involved.¹⁴ Although not strictly a calculus issue, fluency with
 200 the equation of a line is relevant to working with the integrated
 201 rate laws. These gaps in students' understanding of the
 202 connections between, and conceptual meaning of, the
 203 derivative and integral may not interfere with students' ability
 204 to plug and chug their way through simple kinetics problems,
 205 but such a piecemeal understanding will make it difficult for
 206 students to understand why they are doing what they are doing
 207 and apply their knowledge in new contexts. Highlighting this
 208 issue, a study that examined students' ability to use calculus
 209 concepts in a physical chemistry context presented a case of a
 210 student who had taken six semesters of undergraduate
 211 mathematics and could interpret the derivative in a

212 mathematics context, but could not use it to express change
 213 in a thermodynamics context.³³

214 The preceding discussion of the categories of students'
 215 difficulties with rates of change concepts underlying reaction
 216 kinetics underscores the particular challenges posed by the
 217 representational level of Johnstone's triangle.^{2,3} In reaction
 218 kinetics, various representations of macroscopic changes (i.e., of
 219 concentration) are created and manipulated to gain insight into
 220 molecular level phenomena (i.e., reaction mechanism). The
 221 representational level can be thought of as a “triangle within a
 222 triangle”, involving navigation between graphical, verbal, and
 223 symbolic representations. For each category of student
 224 difficulty discussed above, Figure 1 shows where questions
 225 about how texts address that area of difficulty fit within the
 226 representational level.

227 Given the extensive literature on students' challenges with
 228 these conceptual underpinnings of reaction kinetics, it is
 229 valuable to examine to what extent textbooks make the relevant
 230 connections explicit. Various studies have examined the content
 231 of chemistry textbooks: documenting the analogies used to
 232 explain abstract chemical concepts, creating a taxonomy of end-
 233 of-chapter problems, and examining linguistic characteristics
 234 and depth of cohesion of the narrative.^{34–36} One paper has
 235 previously pointed out the failure of chemistry texts to clarify
 236 that the rate and rate constant are ambiguous in the absence of
 237 an explicit statement of the balanced reaction equation to which

238 they apply.³⁷ The analysis presented here contributes to the
239 research on textbooks by providing insight into the collective
240 strengths and weaknesses of textbooks in handling rates of
241 change concepts in reaction kinetics.

242 ■ METHODS

243 Texts

244 The texts analyzed were the general chemistry textbooks
245 assigned by the top producers of ACS-approved chemistry
246 baccalaureates.³⁸ The textbooks used by the top 10 ACS-degree
247 producers were all included, except one (Zumdahl), which did
248 not have a chapter on reaction kinetics.³⁹ Books by unique
249 authors used by the next five producers were also included. To
250 avoid real or perceived bias, one book by Tro (*Chemistry:
251 Structure and Properties*) was not scored because another text by
252 Tro was already included in the top 10. Because three
253 textbooks (OpenStax, Oxtoby, and Tro's *Chemistry: A
254 Molecular Approach*) were each represented twice on the list
255 of top 15 ACS-degree producers, the score summary includes a
256 total of 10 textbooks (referred to hereafter as Atkins, Brown,
257 Chang, McMurry, McQuarrie, Oxtoby, Silberberg, Tro, Open-
258 Stax, UT Austin).^{40–49} The latter is an online text designed for
259 a specific course, and because its videos were core (not
260 supplemental) materials, their content was included in the
261 analysis.

262 Raters

263 Three raters provided insights from different disciplinary
264 perspectives. One rater was trained in chemistry (under-
265 graduate and doctorate) and has taught introductory chemistry
266 extensively at the undergraduate and community college level.
267 One rater was trained in chemistry (undergraduate) and
268 science education (doctorate). One rater was trained in
269 mathematics (undergraduate and master's) and mathematics
270 education (current Ph.D. student).

271 Scoring

272 The team developed the rubric based on the literature, and
273 then iteratively refined it. The three raters independently
274 scored all the texts. Initial interrater reliability was 85% (i.e.,
275 initial three-way agreement on 205 of 240 codes across the
276 texts). Discussion of the relevant narrative passages or figures
277 resolved the initial disagreements. Final interrater agreement
278 was 100%.

279 Rubric and Research Questions

280 The rubric (see Table 1) was developed to investigate texts'
281 treatment of rates of change concepts from the beginning of the
282 kinetics chapter(s), through rate expressions and the differential
283 form of the rate law, up to and including the presentation of the
284 integrated rate laws. Depending on the organization of the text,
285 this was an entire chapter, or the portion of the chapter before
286 the sections on reaction mechanism and catalysis. The rubric
287 comprised the four categories of students' challenges with rates
288 of change concepts relevant to reaction kinetics.

289 **What Graphical Representations Are Used and in
290 What Ways?** The finding that students have difficulty
291 predicting the shapes of rates of change graphs raises the
292 question of whether texts give students the opportunity to do
293 so. It is feasible for a textbook to include reflection prompts in
294 the flow of the narrative or in the margins, prior to the
295 introduction of fundamental graphs. The rubric asks about the
296 presence of such prompts.

Table 1. Code Summary for All Textbooks Analyzed^a

Rubric Categories and Questions Investigating the Treatment of Rates of Change Concepts in Selected Textbooks ^a	Present?	
	Yes	No
Use of Graphical Representations to Introduce the Topic		
1 Are students encouraged to predict the shapes of any reaction kinetics graphs?	1	9
2a Does the text juxtapose graphs/other visuals side by side to explain concepts or draw attention to distinguishing features? ^b	10	0
2b Does the text use the technique of plotting multiple lines or curves on the same graph for explanatory purposes? ^c	8	2
3a Does the text present the relevant reaction kinetics graphs:		
(i) Concentration (or pressure) versus time?	10	0
(ii) Rate versus time?	2	8
(iii) Rate versus concentration?	5	5
(iv) Natural logarithm of concentration versus time?	10	0
(v) Inverse of concentration versus time?	10	0
3b Are other graph types presented?	4	6
Sign within the Rate of Reaction Definition		
1a Is it made clear that		
(i) Rate of concentration change of a reactant is negative?	10	0
(ii) A negative sign is added to make a positive quantity?	9	1
(iii) This sign change is a convention to express the rate equivalently for all substances involved?	6	4
1b Is it implied (incorrectly) that a negative rate of change does not make sense?	0	10
Distinction between Average, Instantaneous, and Initial Rates of Change		
1a Are at least two of these distinguished in		
(i) Words?	9	1
(ii) Symbols?	6	4
(iii) Graphs?	7	3
1b Are the Δ and derivative notations defined?	3	7
2a For the concentration versus time graph, is the limitation of the rise/run slope calculation (secant) explained with reference to the tangent?	7	3
2b Is the connection between the derivative and tangent made explicit?	3	7
Introduction of the Integrated Rate Laws		
1 Does the text explain what one can learn from the differential form of the rate law compared to what one can learn from the integrated form and why (i.e., emphasizing the variable of time)?	9	1
2 Does the text show or explain how the integrated rate laws are derived?	5	5
3 Is the connection to $y = mx + b$ made explicit for each integrated rate law?	10	0

^aThe codes for each individual textbook of the 10 examined are available in the Supporting Information. ^bMedian number of juxtapositions per text = 3; mean = 3.2; range = 1–6. ^cMedian number of composite plots per text = 2; mean = 2.2; range = 0–5.

For students to move between reaction kinetics graphs (e.g., 297 concentration versus time, rate versus concentration, rate versus 298 time) and infer the shape of one from another, students must, 299 at minimum, be exposed to these different graphs. Thus, the 300 coding scheme documents what types of graphs are present at 301 least once in the text. Thoughtful juxtaposition of different 302 types of reaction kinetics graphs, as well as graphs alongside 303 other representations, is needed to support students' fluency of 304 movement between them. The coding scheme asks what 305 graphical representations texts juxtapose, either as separate 306 figures or via the inclusion of multiple data plots on the same 307 graph. 308

Table 2. Compilation of Juxtaposed Graphs and Visuals from Selected Textbooks and Their Purpose

Examples of Juxtaposed Graphs and Visual Elements	Pedagogical Purpose of the Visual Elements
Graphs of reactant concentration, natural logarithm of concentration, and inverse of concentration versus time (all).	Demonstrate how to determine reaction order from characteristic integrated rate law plots.
Graph of reactant concentration (or $[A]/[A]_0$) versus time with grid/molecular depictions showing concentrations at successive half-lives (Atkins, Chang, McMurry, Silberberg, Tro).	Connect to the molecular level to show how the concentration of a reactant decreases from one-half-life to the next in a first-order reaction.
Graph of reactant and product concentration versus time with molecular depictions showing their concentrations at different times (Chang).	Similar to the half-life graphs (see above) but both reactants and products are shown and time points do not correspond to half-lives.
Graphs of reactant concentration versus time and rate versus concentration (Silberberg and Tro).	Compare how the reactant concentration varies over time and how rate varies with concentration for zeroth-, first-, and second-order reactions.
Graphs of concentration versus time and rate versus time for zeroth-order reaction (Atkins).	Show that, for a zeroth-order reaction, reactant concentration falls at a constant rate and reaction rate is constant (until reactant is completely consumed).
Graphs of rate versus reactant concentration and rate versus reactant concentration squared (Atkins)	Illustrate that a rate can be directly proportional to the square of a reactant's concentration rather than concentration to the first power.
Plot of absorption of bromine versus wavelength for four concentrations with photo of corresponding bromine solutions (Chang).	Connect the visible color change to shape of the absorption spectrum.
Concentration versus time graphs for reactants and products, comparing two different reactions side by side (Silberberg).	Introduce the rate expression by showing that the relative rates of reactants and products depend on their stoichiometric coefficients.

309 **How Is the Sign of Rate of Change Treated?** The
 310 positive or negative sign associated with a rate of change carries
 311 meaning. In kinematics, the sign provides information about
 312 direction of motion; in kinetics, the sign provides information
 313 about whether a chemical species is consumed or produced.
 314 Because it is clear from the literature that interpreting the sign
 315 of a rate of change is troublesome for students, it is useful to
 316 examine how textbooks deal with the sign in reaction rate. The
 317 rubric asks if the texts explain the meaning of the sign, and if
 318 they make clear that the definition of reaction rate as a positive
 319 quantity is a convention.

320 **How Are Average and Instantaneous Rate Distinguished?** Because students have difficulty with the distinction
 321 between rate of change over time and rate of change at one
 322 point in time, and because this distinction is fundamental in
 323 reaction kinetics, it is important that texts elucidate the
 324 distinction between average and instantaneous rate of change,
 325 ideally in words, symbols, and graphs. Recognizing initial rate of
 326 change as a subcategory of instantaneous rate of change is
 327 pertinent to the method of initial rates. Therefore, the coding
 328 examined texts' distinction of these three rates of change
 329 (average, instantaneous, initial) in the three modes of
 330 presentation (words, symbols, graphs).

332 **What Scaffolds Are Provided To Help Students Understand and Connect the Differential and Integrated Forms of the Rate Laws?** Even if students have taken
 333 an introductory calculus sequence before they study reaction
 334 kinetics, mathematics education scholarship demonstrates that
 335 they are unlikely to have more than a rudimentary understanding of the meaning of a differential equation or integral.
 336 Therefore, in introducing reaction kinetics, texts must elucidate
 337 critical connections, such as the connection between the slope
 338 of the tangent and the instantaneous rate, and the way
 339 integrating the differential form of the rate law brings in the
 340 variable of time. The rubric examines texts for these
 341 connections, which can be made conceptually whether or not
 342 the text is calculus-based.

346 ■ RESULTS AND DISCUSSION

347 Graphical Representations

348 In general, the texts do not provide prompts to encourage
 349 students to predict the shapes of reaction kinetics graphs,
 350 although one text (Brown) partly did this in "Go Figure" and

"Give It Some Thought" prompts, for example, showing
 351 molecular depictions of reactants and products at three time
 352 points and asking students to estimate the concentration at an
 353 intermediary time.
 354

The study revealed considerable variation in terms of what
 355 graphs texts use to build up to and introduce the rate laws. On
 356 one hand, all 10 texts present graphs of the following:
 357 concentration (or pressure) versus time, natural logarithm of
 358 concentration versus time, and inverse of concentration versus
 359 time. On the other hand, only two texts (Atkins and
 360 McQuarrie) present graphs of rate versus time, and only half
 361 the texts present graphs of rate versus concentration. The texts
 362 include a few other graph types: rate versus square of
 363 concentration (Atkins), a femtosecond spectrum illustrating
 364 decomposition of a halide (Atkins), plots of absorbance versus
 365 wavelength for solutions at different concentrations (Brown,
 366 Chang), and a bar graph showing the influence of the rate law
 367 exponent on rate (McMurry).
 368

In terms of encouraging students to move between
 369 representations, the extent to which texts juxtapose two graphs,
 370 or a graph and another visual, also varies. The median number
 371 of juxtapositions per text is 3 (range 1–6). The most common
 372 use of juxtaposition is of the characteristic integrated rate law
 373 plots, with all the texts juxtaposing at least two of the three. The
 374 second most common juxtaposition, present in five texts, is a
 375 plot of concentration versus time with depictions of containers
 376 filled with spheres, dots, or squares that represent reactant
 377 concentration initially and at successive half-lives. In one text, a
 378 similar graph/dot juxtaposition shows the number of reactant
 379 and product molecules every 10 s.
 380

Notably, in introducing the differential form of the rate laws,
 381 only three texts juxtapose graphs to compare relationships
 382 between concentration and time, and rate and time or
 383 concentration. One text juxtaposes a graph of concentration
 384 versus time with a graph of rate versus time. Two texts
 385 juxtapose a graph of concentration versus time with a graph of
 386 rate versus concentration. Table 2 is a compilation of
 387 juxtaposition types found in the 10 texts.
 388

As is the case with juxtapositions, the extent to which texts
 389 use the technique of comparing multiple data sets on the same
 390 graph is highly variable. Median number of multiplot graphs per
 391 text is 2 (range 0–5). Most common are graphs of
 392 concentration versus time showing both reactants and products
 393 (Chang, McMurry, McQuarrie, Silberberg, Tro, OpenStax);
 394

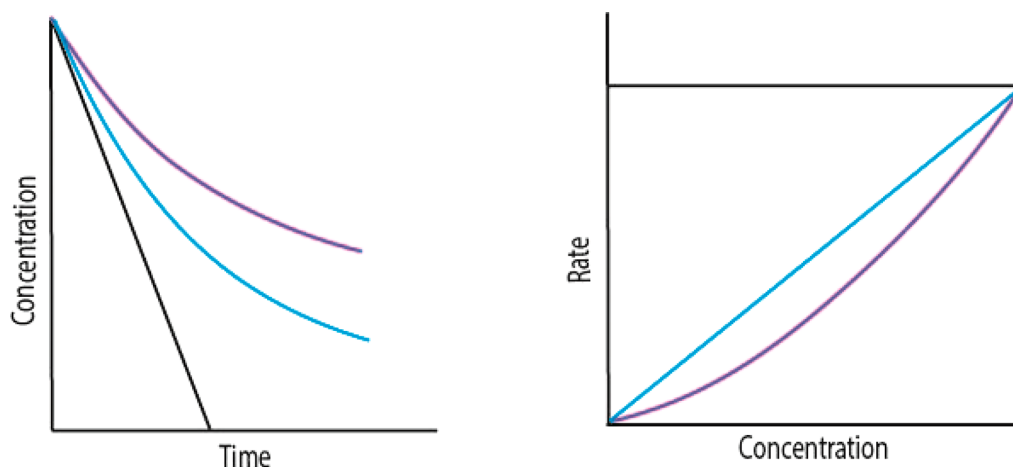


Figure 2. Juxtaposition of graphs of concentration versus time and rate versus concentration for a zeroth- (black), first- (blue), and second- (purple) order reaction.

395 another text shows reactants and products on a femtosecond
396 spectrum (Atkins). Four texts compare plots for different
397 reaction orders on the same axes: reactant concentration versus
398 time for a zeroth- and first-order reaction (Brown, OpenStax);
399 concentration versus time for a first- and second-order reaction
400 (Atkins); concentration versus time for a zeroth-, first-, and
401 second-order reaction (Silberberg and Tro); and rate versus
402 concentration for a zeroth-, first-, and second-order reaction
403 (Silberberg and Tro). **Figure 2** juxtaposes these two latter
404 multiplot graphs, as presented in Silberberg and Tro. Only one
405 other multiplot figure appears in more than one text:
406 absorbance versus wavelength for different concentrations
407 (Brown, Chang). One text (Atkins) presents three multiplot
408 graphs not used by other texts: concentration versus time for
409 various initial reactant concentrations, concentration versus
410 time for several rate constants, and ratio of current to initial
411 reactant concentration versus time to show dependence of half-
412 life of a first-order reaction on the rate constant.

413 Sign of Rate of Change

414 When introducing the rate expression, all the texts point out
415 that the rate of concentration change of a reactant is negative.
416 All but one (Oxtoby) indicate that a negative sign is added to
417 make the rate of reaction a positive quantity. Six of the texts
418 (Atkins, Brown, McMurry, Silberberg, Tro, OpenStax) point
419 out that this is a convention (or because rate of reaction is
420 defined as a positive quantity). None of the 10 texts scored here
421 stated or suggested that the negative sign does not make sense;
422 however, a statement to this effect was noted in another online
423 text:⁵⁰

424 *Since negative rates do not make much sense, rates expressed*
425 *in terms of a reactant concentration are **always** preceded by*
426 *a minus sign to make the rate come out positive.*

427 Average and Instantaneous Rate

428 **Words.** All the texts except one (UT Austin) distinguish
429 average, instantaneous, and initial rates of change using words.
430 The texts, except three (Tro, UT Austin, OpenStax), also
431 explain the difference between the tangent and the secant in
432 terms of the time interval being considered.

433 **Graphs.** Three texts (Atkins, McMurry, Silberberg) use
434 graphs to distinguish average, instantaneous, and initial rates.
435 Two texts (McQuarrie, Oxtoby) distinguish average and
436 instantaneous (but not initial) rates graphically, and two texts
437 (Brown, OpenStax) distinguish instantaneous and initial (but

not average) rates graphically. The remaining three texts do not
use graphs to distinguish the different kinds of rates.

Symbols. All the texts use the delta (Δ) notation. Four texts
(McMurry, McQuarrie, Silberberg, OpenStax) do not use the
derivative (d) notation; however, of the texts that use the Δ
and d notation, only three (Atkins, Brown, Oxtoby) defined
both notations. The remaining three texts (Chang, Tro, UT
Austin) use both notations without defining them.

Differential and Integrated Forms

In terms of the use of calculus in introducing the integrated rate
laws, the texts examined fell into three categories: narrative
presenting integrated rate laws without deriving them (Brown,
McMurry, McQuarrie, Silberberg, OpenStax), integration
shown as an aside in margin (Chang, Tro), and integration
central (Atkins, Oxtoby, UT Austin). Presence or absence of
calculus steps, however, does not predict a text's treatment of
the relationship between the tangent and the derivative. Only
three texts, two of which are calculus-based (Atkins and
Oxtoby) and one of which presents no calculus (Brown),
explicitly state the connection between the tangent and the
derivative. Another text (OpenStax) mentions that calculus is
used to evaluate the slope of tangent lines. The connection
between the tangent and the derivative, and the difficulty of
finding the tangent by hand, can help establish the need for the
integrated rate laws. As stated in Atkins (p 592)

*Because it is difficult to draw a tangent accurately by eye, it is
better to use a computer to analyze graphs of concentration
against time. A superior method—which is described in
Topic 7B [Integrated Rate Laws]—is to report rates using a
procedure that, although based on these definitions, avoids
the use of tangents altogether.*

For the most part, the texts fail to provide this chain of logic,
and two texts (Brown, Chang) calculate the slope of the
tangent using the rise over run calculation (the same as they use
for calculating the slope of the secant), without mentioning that
doing so by eye is error prone. Overall, the texts did a better job
of explaining what one can learn from the integrated rate laws,
with reference to the variable of time, and reminding students
about the equation/graph of a straight line in connection to the
integrated rate laws.

Two additional aspects of the texts' mathematics coverage
deserve mention. The first concerns the meaning of symbols.
The coder with the mathematics/mathematics education

481 background noted that students may not have encountered the
482 proportionality (\propto) symbol or the double inequality (\gg)
483 symbol in lower division mathematics classes, and furthermore,
484 these symbols may have different meanings in other contexts.
485 Along with the observation that some texts use the derivative
486 notation without defining it, this underscores the importance of
487 defining symbols.

488 The second aspect of the texts' mathematics coverage
489 concerns mathematical integrity. Most of the texts that
490 presented the integrated rate laws use single variables in
491 multiple ways within an individual definite integral. This stood
492 out to the coder from the mathematics/mathematics education
493 background (but not to the coders from chemistry back-
494 grounds, until it was brought to their attention). To illustrate,

495 consider $\int_0^c \frac{1}{c^2} dc = -2k \int_0^t dt$. Note that c is used as an
496 upper limit of integration \int_0^c , a variable in the integrand $\frac{1}{c^2}$, and

497 the variable of integration dc (similarly for the t on the right
498 side of the equation). Mathematicians distinguish between the
499 limits of integration and the variables of integration. For
500 example, they may write the above equation as

$\int_0^{c_1} \frac{1}{c^2} dc = -2k \int_0^{t_1} dt$, or simply use different variables for

501 the limits of integration. To do otherwise muddies the
502 distinction between values and variables, another area the
503 mathematics education literature points to as a source of
504 difficulty for students.^{51,52}

505 ■ IMPLICATIONS

506 The decisions made by curriculum designers may be conscious
507 or unconscious. Writing a textbook involves conscious trade-
508 offs between pedagogy and practicality due to publishers'
509 limitations on length, layout, number of figures, and available
510 color palette; moreover, in omitting or including calculus
511 derivations, textbook authors are making conscious choices to
512 appeal to specific audiences. Similarly, the author of every
513 textbook in this study recognized the need to explicitly connect
514 $y = mx + b$ with the integrated rate laws. Texts also had
515 explanations about logarithms and exponents; one even
516 included a figure to help students visualize how changing the
517 exponent in the differential form of the rate law affects the
518 reaction rate.

519 Yet, the most powerful aspect of the DBER lens is not in
520 assessing these conscious choices to help students negotiate the
521 representational level, but in revealing unconscious decisions.
522 By definition, the DBER lens places the learner's understanding
523 of a topic at the center of the analysis. Viewed from the
524 learner's perspective, "adding in" a negative sign to make the
525 rate of disappearance of reactant a positive quantity is puzzling
526 and at odds with students' prior mathematics experience. It is
527 unlikely to be a conscious pedagogical choice that some texts
528 lacked a clear statement that this practice is a convention to
529 express reaction rate equivalently for reactants and products.

530 Likewise, conceptual connections necessary to help students
531 move from the differential form of the rate law to the integrated
532 rate laws are often unconsciously glossed over, including the
533 following: the graphical distinction between average and
534 instantaneous rates of change, visual depictions of how the
535 reaction rate changes over time or concentration, the limitation
536 of the rise over run slope calculation, and the relationship
537 between the derivative and the tangent. These choices are not
538 attributable to the calculus level of the text. For example, the

non-calculus-based OpenStax textbook explains that calculus is
539 needed to determine the slope of the tangent; in contrast are
540 the texts that unproblematically calculate the slope of the
541 tangent using rise over run. The DBER lens thus highlights
542 where reaction kinetics instructional materials neglect the
543 learner-centered perspective, which may inadvertently encour-
544 age rote learning and seed the prevalent postinstruction
545 misconceptions documented in the literature. 546

These findings also provide actionable insights for chemistry
547 instructors and chemistry education researchers. 548

549 Chemistry Instructors

Many factors, including cost, influence textbook choice, and
550 individual instructors may not be free to choose the course
551 textbook when the decision is made at the departmental level.
552 This study provides criteria to help instructors "troubleshoot"
553 their textbooks, and design lessons and select supplemental
554 course materials to complement the text. DBER recommends
555 that students be given the opportunity to predict the shapes of
556 graphs and compare their predicted graphs with actual data, but
557 textbooks do not provide this opportunity. Instructors could
558 address this through small group work or clicker questions with
559 whole class discussion, by having students sketch graphs or
560 select from multiple-choice options and explain their choice.
561 For example: 562

- 563 • Which of these graphs do you think best depicts how the
564 concentration of the reactant will decrease over time:
565 linear decrease, sharply decreasing slope that levels off, or
566 level slope that subsequently drops off more rapidly?
- 567 • What do each of these graph shapes mean about the
568 progress of the reaction? (See also ref 21.)

Similarly, instruction can delve into how a rate versus time or
569 rate versus concentration graph can be constructed from
570 concentration versus time data. Furthermore, if the course text
571 is one with conceptual gaps in the introduction of the
572 integrated rate laws, armed with the rubric presented here,
573 instructors can readily identify and address such gaps. Students
574 in most introductory chemistry courses will have varied calculus
575 backgrounds: some students who are taking college calculus
576 concurrently, some students who last had calculus in high
577 school, and some students who are studying reaction kinetics
578 before taking calculus. Given this diversity of experiences, it is
579 especially important for instructors to take a learner-centered
580 perspective to design their reaction kinetics curriculum. 581

582 Chemistry Education Researchers

In addition to contributing to the important work of bridging
583 educational theory and classroom practice, these findings
584 provide chemistry education researchers with guidance to
585 develop testable hypotheses. For example, the coders in this
586 study considered the juxtaposition of the concentration versus
587 time and rate versus concentration multiplot graphs (see Figure
588 2) particularly informative, and a judicious use of textbook real
589 estate. The juxtaposition facilitates the comparison of the
590 shapes of the two graphs for three different reaction orders.
591 Nevertheless, this process involves a considerable cognitive load
592 for a novice: Do students attend to the axes? Do they follow the
593 colors (reaction orders) from one graph to the next? Do they
594 recognize that the slope of the first graph provides the y -
595 coordinate for the second graph? Therefore, although Mayer's
596 (2002) principles of multimedia learning provide general
597 guidance for the design of pedagogically effective figures,⁵³
598 this study, by documenting how visualizations are commonly
599

used in reaction kinetics chapters, raises more specific questions about how particular visual representations, or progressions of representations, can help or hinder the development of students' understanding of rates of change concepts in reaction kinetics.

STUDY LIMITATIONS

This study has two main limitations. The first has to do with the scope of the work. By design, it is specific to reaction kinetics, and the analysis is not intended to draw inferences about the entire content of general chemistry textbooks. As such it is not a ranking or rating of textbooks. The second limitation has to do with the fact that the DBER lens is constrained by the current state of knowledge regarding students' understanding of reaction kinetics. Given the large number of student challenges with rates of change concepts and the dearth of research on how students learn from specific representations in reaction kinetics, this study (despite its systematic approach) may have missed pedagogical choices in texts that could be problematic for some learners. Thus, any relevant new findings about this area would need to be incorporated into the DBER lens.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: [10.1021/acs.jchemed.7b00238](https://doi.org/10.1021/acs.jchemed.7b00238).

Supplemental document showing the codes for each textbook in the study (PDF)

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Notes

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