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In-Depth Coursework in Undergraduate Inorganic Chemistry: Results from a National Survey of Inorganic Chemistry Faculty

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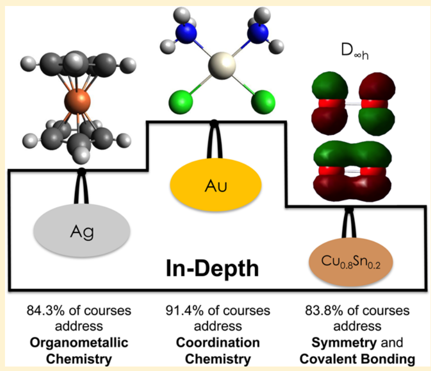
Supporting Information

ABSTRACT: A national survey of inorganic chemists explored the self-reported topics covered in in-depth inorganic chemistry courses at the postsecondary level; an in-depth course is defined by the American Chemical Society's Committee on Professional Training as a course that integrates and covers topics that were introduced in introductory and foundation courses in a more thorough manner. Anecdotal evidence suggested that more than one type of in-depth course was offered in the undergraduate chemistry curriculum. Cluster analysis confirmed this evidence and revealed three distinct types of in-depth inorganic chemistry courses with unique topical profiles. These results confirm diversity in the inorganic chemistry curriculum and the need for awareness that our students leave degree programs with varying understanding of inorganic chemistry based on the coursework offered at their respective institutions.



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■ INTRODUCTION

In contrast to the undergraduate general chemistry, organic chemistry, and physical chemistry curricula, the undergraduate inorganic chemistry curriculum is less uniform across institutions. There is great diversity among inorganic chemistry curricula. Courses such as general chemistry and organic chemistry have a more standardized course structure and a well-defined place in lower-division coursework, whereas courses in inorganic chemistry may have minimal overlap in content and can be found in multiple places in the undergraduate program. The content covered in general chemistry and organic chemistry usually prepares students for more advanced courses or preprofessional exams, whereas a course in inorganic chemistry primarily serves chemistry majors and is usually not required for courses other than other inorganic chemistry courses. Thus, inorganic chemistry does not suffer the same constraints as general chemistry and organic chemistry and has greater opportunity for flexibility and specialization. Such a variable curriculum makes it difficult to generalize what content and skills a student has acquired through inorganic chemistry courses. This, in turn, impacts how undergraduate and graduate degree programs and future employers evaluate a given student's or graduate's understanding of inorganic chemistry.

The great diversity in the topics taught, the number of courses offered in inorganic chemistry at a given institution, and where these courses are located in the overall undergraduate chemistry degree program are partially a result of the way that the inorganic chemistry curriculum evolved.[1−6] One way to describe the curriculum is by using the two levels of coursework defined by the American Chemical Society's (ACS) Committee on Professional Training (CPT): foundation and in-depth. "Foundation course work provides breadth and lays the groundwork for the in-depth coursework."[7] CPT guidelines specify that the textbook for the foundation course must be a discipline-based textbook and not a general chemistry text. "The goals of the in-depth course work are both to integrate topics introduced in the foundation courses and to investigate these topics more thoroughly."[7] According to the CPT guidelines, a student must complete four one-semester courses (or six one-quarter courses) at an in-depth level to earn an ACS-certified degree.[7]

Because of the variability in the inorganic chemistry curriculum, the operationalization of course descriptions in inorganic chemistry is not as clear as in disciplines such as physical and organic chemistry. It is possible to have a two-semester sequence in inorganic chemistry in which the foundation course is Inorganic Chemistry 1 and the in-depth course is Inorganic Chemistry 2, a continuation of the first semester. Another model is to have a one-semester course as the foundation course with an optional in-depth course; for example, a descriptive chemistry course could be taught as the foundation course with a transition metal focused course or a survey course as the in-depth course. These definitions may also be confusing because some foundation courses in inorganic chemistry may require physical or organic chemistry as prerequisites and others not.

In summary, the inorganic chemistry curriculum is diverse in the number of courses, levels of distinction (i.e., foundation and in-depth), and topical focus. Four archetypal courses were identified at the foundation level (see companion paper in this *Journal*); in this paper, we will examine the self-reported topics covered in in-depth inorganic chemistry courses with the same intent—to explore the existence of archetypal courses. The following research questions will be answered: Is more than one type of in-depth inorganic chemistry course offered in the undergraduate chemistry curriculum? If so, how are those courses characterized by topics covered?

■ METHODOLOGY

Members (n = 5,551) of the Division of Inorganic Chemistry (DIC) of the ACS were asked to participate in a survey on the content of their undergraduate inorganic chemistry courses; to increase the response rate, members (n = 679) of the Virtual Inorganic Pedagogical Electronic Resource (VIPEr) community, a subset of the DIC community, were sent a reminder email to participate. A total of 435 inorganic chemistry faculty responded; a response rate is unable to be accurately determined due to an inability to characterize the total population of inorganic chemistry faculty; at the time of the survey, approximately one-third of the membership of the DIC reported their primary job title as 'Professor/Instructor/Administrator.' This sampling strategy, likewise, does not ensure that all faculty who teach an undergraduate course in inorganic chemistry were sampled; it can be supposed that there are inorganic chemistry faculty who are not members of the ACS or specifically the Division of Inorganic Chemistry. Our analyses, however, suggest that a diverse set of in-depth courses was reported and thus confirm the overarching hypothesis. (Such an analysis does not necessitate a representative sample population.) A nonrepresentative population allows for the different types of courses to be explored; however, the sample does not allow us to make conclusions about how prevalent the courses are in the curriculum. Implications of the results will be constrained to the result that different in-depth courses in inorganic chemistry exist.

Of the respondents, 47.8% were from bachelors degree awarding institutions, 44.8% were from doctoral degree awarding institutions, and 7.4% were from masters degree awarding institutions.

Each respondent was asked whether they had taught an in-depth inorganic chemistry course during the last three years; an in-depth course was defined to the respondents as "the prerequisite course is the foundational course in inorganic chemistry. For the purposes of this survey, the in-depth course should refer to a second course in inorganic chemistry at your institution, not a specialized advanced topics course."

Only those who had taught an in-depth course were asked to characterize topics taught in the course. The survey respondents characterized 185 in-depth inorganic chemistry courses based on the content covered in the course. Information gathered about these courses included the overarching topics and subtopics covered in the course and how the coverage of those topics has changed over the last five years. Survey questions were modified from an earlier survey of inorganic chemistry course content coverage.[8] The list of overarching topics and subtopics was developed by four inorganic chemistry education practitioners with comprehensive understanding of the state of inorganic chemistry education and with assistance from the 2014 Inorganic Chemistry ACS Exam Committee; in addition, members of the Leadership Council of the Interactive Online Network of Inorganic Chemists provided recommendations and review. These data were analyzed using descriptive statistics and cluster analysis. (Overviews of cluster analysis are reported elsewhere.[9−11] Salient methodological components will be noted as appropriate.)

■ RESULTS AND DISCUSSION

Topical Coverage of In-Depth Inorganic Chemistry Courses

In a preceding paper, the authors discussed the content covered in foundation inorganic chemistry courses. While the topic of what should be taught in inorganic chemistry has provoked much discussion, the overall content covered in undergraduate foundation inorganic chemistry courses reflects the selection of topics suggested by the guidelines originally provided by the ACS Inorganic Chemistry Subcommittee of the Curriculum Committee in 1972,[12] an ad hoc subcommittee to advise on content in 1991, and the current ACS CPT Guidelines.[13] The content covered is also similar to what was reported in the 2001 survey on the content covered in undergraduate inorganic chemistry courses.[8] Despite these overarching similarities, four distinct foundation level courses were observed. This study used the same set of topics as the foundation courses to explore the content covered in the in-depth inorganic chemistry courses. Respondents were asked to report whether they teach an in-depth course in inorganic chemistry and then to select which of 14 broad topics are covered in that course; in all, 185 respondents reported teaching such a course. The percentages of respondents covering each topic are reported in Table 1.

There are four topics that are taught in most in-depth courses: Transition Metal Complexes & Coordination Chemistry, Organometallic Chemistry, Covalent Bonding & Molecular Orbital Theory, and Symmetry & Group Theory. Topics beyond these four are covered at varying levels. Cluster analysis is needed to interpret how these other topics are incorporated in the in-depth courses.

Identification of Three Distinct Courses

As with the foundation course in inorganic chemistry, there is interest in confirming anecdotal evidence collected by the authors that suggested that a unique in-depth inorganic

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Table 1. Percent of Respondents Covering Each Topic in an In-Depth Inorganic Chemistry Course

Topic	Percentage Covering (n = 185)
Transition Metal Complexes & Coordination Chemistry	91.4
Organometallic Chemistry	84.3
Covalent Bonding & Molecular Orbital Theory	83.8
Symmetry & Group Theory	83.8
Atoms & Electronic Structure	62.7
Bioinorganic Chemistry	54.1
Solids & Solid State Chemistry	49.7
Acids, Bases, & Solvents	48.1
Redox Chemistry	46.0
Main Group & Descriptive Chemistry	33.5
Materials Chemistry & Nanoscience	33.0
Analytical Techniques	29.2
Nuclear Chemistry	8.1
Green Chemistry	7.6

chemistry course does not exist. To test this hypothesis, a hierarchical cluster analysis was conducted using Ward's linkage[14] and a matching similarity matrix for binary data.[15] Visual inspection of the resultant dendrogram (see Supporting Information) and application of Duda and Hart stopping rules[16] led us to determine that a three-cluster solution best represented the data; $Je(2)/Je(1) = 0.9035$ and pseudo-T^2 = 10.68. Duda and Hart stopping rules consider "the sum of squared errors (of the similarity measure) to devise a quantitative measure for choosing appropriate clusters... A cluster solution should have a large ratio of the sum of squared errors in the two resulting groups, that is, Je(2), versus the sum of squared errors within the groups, that is, Je(1), and a small pseudo-T-squared value."[16−18] The percentages of respondents in each cluster group covering each topic are reported in Table 2; nonuniform coverage of these topics is apparent from visual inspection of Table 2. Fisher exact tests were additionally run to determine distinctness of the clusters; eight of 14 topic areas showed association between coverage and the cluster groupings.

Discussion among the authors led to a consensus assignment of an explanatory title for each of the cluster groups: In-Depth Survey: Core, In-Depth Survey: Comprehensive, and Advanced Inorganic: Selected Topics. Each cluster group represented a distinguishable set of content coverage that identifies with inorganic chemistry courses taught by or known to the authors.

A course from the In-Depth Survey: Core cluster covers the most commonly encountered topics in an upper-level inorganic chemistry course (i.e., Transition Metal Complexes & Coordination Chemistry, Organometallic Chemistry, Covalent Bonding & Molecular Orbital Theory, Symmetry & Group Theory, and Atoms & Electronic Structure). It is difficult to characterize this cluster without considering what comes before it. For example, if this course were to follow a more descriptive chemistry-oriented foundation course, it might be envisioned as the second course in a sequence in which the topics are covered in more depth or from a more theoretical perspective.

A course from the In-Depth Survey: Comprehensive cluster is marked by coverage of almost every topic. If this is the only advanced inorganic chemistry course, this might pair with an instructor's desire or need to cover everything in a relatively short period of time. If this is the second inorganic chemistry course, it might suggest a more spiral approach,[19,20] whereby all the topics are covered again but at a deeper and more sophisticated level.

Finally, a course from the Advanced Inorganic: Special Topics cluster is marked by coverage of more focused topics. Further inspection of the cluster solution revealed that this cluster is much more diverse than the other two; this conclusion was made by visual observation of the dendrogram for solutions with larger numbers of cluster groupings. While the three cluster solution is the best, when considering 10 or more cluster groupings, this cluster subdivides into six clusters for these solutions (see Supporting Information for the three and 10 cluster dendrograms). Five of the courses are relatively similar, with a focus on transition metals and organometallic chemistry. Covalent bonding, symmetry, and bioinorganic

Table 2. Percent of Courses Covering Each Topic in In-Depth Inorganic Chemistry Courses by Cluster Grouping

n_{total} = 185	In-Depth Survey: Core	In-Depth Survey: Comprehensive	Advanced Inorganic: Selected Topics	Fisher Exact Test[a]
n =	33	50	102	
Percentage of total respondents	18%	27%	55%	
Transition Metal Complexes & Coordination Chemistry	100.0	90.0	89.2	
Organometallic Chemistry	84.9	84.0	84.3	
Covalent Bonding & Molecular Orbital Theory	100.0	98.0	71.6	$p < 0.0001$
Symmetry & Group Theory	93.9	94.0	75.5	$p < 0.0036$
Atoms & Electronic Structure	97.0	84.0	41.2	$p < 0.0001$
Bioinorganic Chemistry	27.3	66.0	56.9	
Solids & Solid State Chemistry	66.7	86.0	26.5	$p < 0.0001$
Acids, Bases, & Solvents	100.0	82.0	14.7	$p < 0.0001$
Redox Chemistry	57.6	78.0	26.5	$p < 0.0001$
Main Group & Descriptive Chemistry	0.0	90.0	16.7	$p < 0.0001$
Materials Chemistry & Nanoscience	9.1	50.0	32.4	
Analytical Techniques	21.2	22.0	35.3	
Nuclear Chemistry	6.1	18.0	3.9	
Green Chemistry	0.0	16.0	5.9	

[a]Adjusted for 14 simultaneous tests ($p < 0.0036$, $p < 0.0007$, $p < 0.0001$).

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chemistry also have a strong presence in this subcluster. The sixth course has a high coverage of symmetry and physical methods and strongly resembles a course in group theory and physical methods.

Analogous to the foundation course, the cluster analysis and characterization of cluster solutions suggest confirmation of the proposed hypothesis that more than one in-depth course exists in inorganic chemistry. The method in which data were collected prohibit extrapolation to how prevalent each of these course types are in the national curriculum; however, each cluster grouping was described by a suitable number of respondents to warrant consideration of the course's existence in the undergraduate inorganic chemistry curriculum.

Changes in Content Coverage

In addition to asking respondents to note topics covered in their course, respondents were asked to rate changes in the content covered over the last five years: increased, stayed the same, decreased, or not applicable. Table 3 summarizes the content coverage change for all respondents. Apparent movements toward increased or decreased coverage can be noted through visual inspection of the results: Topics such as Organometallic Chemistry, Bioinorganic Chemistry, and Materials & Nanoscience appear to be increasing overall. Topics such as Acids & Bases and Main Group & Descriptive Chemistry appear to be decreasing overall. In 2001, Pesterfield et al. reported that there was a large increase in people reporting more coverage in Symmetry and Group Theory, Organometallic, Bioinorganic Chemistry, and Materials. These increases were all greater than 40%.[8] The coverage of these topics is still increasing as reported by our respondents, but a smaller increase is reported relative to the increases reported in 2001.

Table 3. Distribution of Responses to Changes in Content Coverage in In-Depth Inorganic Chemistry Courses over the Last 5 Years

n_{total} = 185	% Increased	% Stayed the Same	% Decreased	% Not Applicable
Transition Metal Complexes & Coordination Chemistry	20.3	69.8	2.8	7.1
Organometallic Chemistry	32.4	50.3	5.6	11.7
Covalent Bonding & Molecular Orbital Theory	15.8	71.2	2.8	10.2
Symmetry & Group Theory	19.3	65.3	5.1	10.2
Atoms & Electronic Structure	4.6	60.1	9.8	25.4
Bioinorganic Chemistry	23.7	35.8	8.7	31.8
Solids & Solid State Chemistry	15.7	36.6	12.8	34.9
Acids, Bases, & Solvents	6.7	41.8	19.4	32.1
Redox Chemistry	6.5	50.0	10.0	33.5
Main Group & Descriptive Chemistry	2.9	33.3	17.5	46.2
Materials Chemistry & Nanoscience	28.1	20.4	4.2	47.3
Analytical Techniques	10.4	30.1	3.1	56.4
Nuclear Chemistry	0.6	16.8	8.1	74.5

Our overarching hypothesis of multiple in-depth inorganic chemistry courses was confirmed by the three-cluster grouping. Thus, it is important to consider how respondents in each of the cluster groupings perceived change in content coverage over the past five years. Table 4 reports the average content coverage change for each topic area by cluster grouping; responses of increasing coverage were coded as 1, coverage stayed the same were coded as 0, and decreasing coverage were coded as −1; not applicable responses were removed from the analysis. An average change around 1 suggests that respondents in the cluster grouping all reported the coverage increasing, an average of 0 suggests coverage staying the same, and an average of −1 suggests coverage decreasing.

Two observations should be made about Table 4. First, there is consistency in the increasing coverage of Organometallic Chemistry and Materials Chemistry & Nanoscience. This suggests a movement toward incorporating more recent advances in the field and the increasing importance of organometallic chemistry as a central research area in inorganic chemistry research. Second, there is consistency in the decreasing coverage of Nuclear Chemistry and Main Group & Descriptive Chemistry. For Nuclear Chemistry, such movement is most likely the result of the diminishing focus of nuclear chemistry in the chemistry discipline and coverage across the broader undergraduate chemistry curriculum.[21] For Main Group & Descriptive Chemistry, such movement may be the result of the content being covered in other courses (e.g., general chemistry), the content being a major focus in a corresponding foundation course, or the content being incorporated into the presentation of the other topics and therefore not covered as an independent topic. (Given how the survey question was asked, a faculty member teaching Main Group & Descriptive Chemistry in the context of other topics may or may not have reported covering this topic.) In addition, it may be the case that this material is perceived as a canon of knowledge to be memorized rather than a set of contents organized in a coherent theoretical framework; thus, faculty may choose to abandon teaching this content and leave this material to independent learning for the students.

■ LIMITATIONS

There are two sets of questions that are of interest to inorganic chemistry educators when discussing the inorganic chemistry courses taught in the curriculum:

(1) How does inorganic chemistry fit into the curriculum at a particular institution? If the in-depth course is the only "advanced" course offered in inorganic chemistry, do the topics covered the most represent the core of what a student should learn in inorganic chemistry? Are there topics that may be expected to rank higher in percent covered but actually appear in lower percentages because the topics are taught in other noninorganic chemistry courses in the curriculum?

(2) How do courses in inorganic chemistry in a single institution relate to each other? If the in-depth course does follow a foundation course, do the topics covered reflect the more "advanced" topics in inorganic chemistry?

These are difficult questions to answer because of the diverse ways that inorganic chemistry is worked into the curriculum at each individual institution. The historical evolution of the curriculum has led to multiple groupings of courses, different

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Table 4. Mean Change in Content Coverage in In-Depth Inorganic Chemistry Courses over the Last 5 Years[a,b]

	In-Depth Survey: Core	In-Depth Survey: Comprehensive	Advanced Inorganic: Selected Topics	*n*
Transition Metal Complexes & Coordination Chemistry	0.24	0.07	0.23	*169*
Organometallic Chemistry	0.32	0.29	0.30	*158*
Covalent Bonding & Molecular Orbital Theory	0.12	0.07	0.20	*159*
Symmetry & Group Theory	0.16	0.11	0.18	*158*
Atoms & Electronic Structure	-0.03	-0.10	-0.07	*129*
Bioinorganic Chemistry	0.06	0.29	0.22	*118*
Solids & Solid State Chemistry	0.12	0.20	-0.13	*112*
Acids, Bases, and Solvents	0.00	-0.27	-0.25	*112*
Redox Chemistry	-0.14	-0.07	0.00	*113*
Main Group & Descriptive Chemistry	-0.70	-0.19	-0.26	*92*
Materials Chemistry & Nanoscience	0.36	0.57	0.41	*88*
Analytical Techniques	0.10	0.18	0.18	*71*
Nuclear Chemistry	-0.33	-0.19	-0.38	*41*

[a]Responses were coded 1 = increasing, 0 = stayed the same, −1 = decreasing. [b]Cells shaded green have mean values greater than 0.25; cells shaded red have mean values less than −0.25.

times offered within the curriculum, and different places in the curriculum where cross-disciplinary topics such as organometallics are taught (e.g., in an advanced synthetic organic chemistry course).[1]

The data collected in the survey do not afford us the opportunity to fully answer either set of questions; reasons for why topics were or were not covered were not collected. However, the percent covered does fit the authors' understanding of the topics generally thought to be more associated with an in-depth-level course. Readers are encouraged to draw their own conclusions based on the data in Table 2.

With the characterization of several in-depth inorganic chemistry courses, coupled with a preceding paper on characterizing the content of foundation inorganic chemistry courses, it is logical to want to consider the pairings of courses when an institution offers multiple courses. A key limitation of our survey is that participants were only asked to characterize a course as foundation or in-depth if they had taught the course in the three years prior to completing the survey. Of the 435 respondents, 382 reported that their institution taught a foundation course; only 317 actually taught that course in the prior three years. Of the 435 respondents, 241 reported that their institution taught an in-depth course; only 185 actually taught that course in the prior three years. Of the 241 reported in-depth courses offered, 194 (80%) were at institutions where a foundation course was offered. When considering the courses characterized in this paper, 113 (61%) of our 185 in-depth courses were taught by respondents who also taught a foundation course. When cross-tabulating these 113 respondents by foundation course and in-depth course characterizations, a Fisher exact test revealed no association ($p = 0.117$) between the two course characterizations. There is no evidence in the data to support a particular sequence of inorganic chemistry courses in the curriculum. None of the in-depth courses are preceded by a particular foundation course, and none of the foundation courses are followed by a particular in-depth course.

The role of the in-depth course is sometimes to drive home the fundamentals of inorganic chemistry. Other in-depth courses seek to accomplish something completely different, for example, to present a special topic in its entirety. This variation, too, is a reflection of the way in which the inorganic chemistry curriculum has evolved from a bottom-up rather than top-down approach. Different educators approach it at their own level and in the context of their own institution. We believe this diversity is positive for the field, but it makes it challenging to draw conclusions.

■ IMPLICATIONS

These results do not offer a prescription for an in-depth course in inorganic chemistry. There is no one single course in inorganic chemistry, and there is no single undergraduate inorganic chemistry curriculum. The authors believe that the variation in the number of courses and types of courses is a strength of the inorganic chemistry curriculum. How and why the curricular variants arose have been discussed in the chemical education literature,[1,2,4,12,13,22] but one also must consider the opportunities and limitations of institutional size (e.g., small schools may only employ one inorganic chemist). In comparison to a more prescribed curriculum for introductory chemistry courses, the inorganic chemistry curriculum is flexible and provides many opportunities to incorporate recent developments in the field and serve the needs of individual programs.

The diversity at the in-depth course level muddles the ability for undergraduate and graduate chemistry degree programs to comparatively evaluate student learning in inorganic chemistry beyond an individual institution. When standards are considered, one must take into account the variability of inorganic chemistry curricula, including how to evaluate student learning when students may have learned different content at different points in the curricula and with differing levels of difficulty.

We would like to echo the calls of the community in 1980 and again in 1991 to make sure that when the CPT guidelines are implemented,[13,22] inorganic chemistry merits the same emphasis given to other disciplines. In practice, this means that two or more inorganic chemistry courses or purposeful structuring of in-depth courses across the chemistry curriculum may be necessary to cover the abundance of chemistry under the purview of inorganic chemistry.

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CONCLUSION

A national survey of inorganic chemists was conducted in which data on topics covered in 185 in-depth inorganic chemistry courses were gathered. Three distinct courses were found via cluster analysis: In-Depth Survey: Core, In-Depth Survey: Comprehensive, and Advanced Inorganic: Selected Topics. Respondents in each course grouping reported variations as to how each topic area is increasing, decreasing, or staying the same in coverage with consistency of movement across several topics. Movement in coverage mirrors the changes in emphasis on topic areas in research endeavors in inorganic chemistry (e.g., Materials Chemistry & Nanoscience). The results of this work suggest that degree programs at the undergraduate and graduate level as well as future employers should be aware of the varying inorganic chemistry educational experiences of their students and employees.

ASSOCIATED CONTENT

Supporting Information

The dendrograms for the three and ten cluster solutions and relevant items from the survey instrument. This material is available via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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