Exploring the Broader Impacts of Science and Society in an Active Learning Environment

Sarah Alexander1* and Jessica TeSlaa2

1Department of Civil and Environmental Engineering, University of Wisconsin-Madison
2Wisconsin Institute for Science Education and Community Engagement, University of Wisconsin-Madison

Abstract

Science and society have always been intertwined. Today, scientists are increasingly encouraged to interact with the public by conducting transparent and participatory engaged scholarship, as opposed to the prevailing one-way transfer of information model. A renewed focus on the “broader impacts of science” from funding agencies has increased the urgency to train scientists equipped with an understanding of how their work intersects with the public interest. While aspiring scientists in STEM fields routinely develop disciplinary expertise and research skills, universities must also prepare undergraduate students for careers in STEM disciplines, where skills and knowledge to effectively engage with the public are increasingly necessary. This lesson guides students through an exploration of the broader impacts of scientific research, allowing students to situate their conceptual learning within a societal context. Through a jigsaw exercise, students examine specific examples of public engagement strategies used to translate science into the public sphere. A discussion of the article ‘Science’s new social contract with society’ defines key concepts surrounding the shifting relationship between science and society (1). Finally, students synthesize their understanding of complex science-society interactions in a concept mapping exercise. Student understanding of the concept ‘broader impacts of science’ is assessed using formative (e.g., discussion, concept map) and summative (e.g., pre-post minute paper) assessment. Self-reported data and pre-post analysis indicates that students found the lesson engaging, emerging with a deeper and more nuanced understanding of the interactions between science and society.

INTRODUCTION

Over the last century, the prevailing model of scholarship has been that new knowledge is developed in academic environments and subsequently shared with society at large for use by government, industry, and the general public (1-2). In the sciences, this one-way flow of knowledge assumes that the public need only be informed of the latest research findings, with minimal interaction between the producers and consumers of knowledge (2-5). Social science literature increasingly indicates that this model is ineffective (1,4,6). Rather, greater interaction between knowledge producers and users results in greater uptake of scientific knowledge and more effective solutions to public issues (7-13).

Scientists are increasingly encouraged to adopt a transparent and participatory model of public engagement (2,14). The National Science Foundation (NSF) began including broader impacts review criteria for funding in 1997, arguing that NSF projects should ‘contribute more broadly to achieving societal goals’ (15). Progress has been made in areas like citizen science and social media engagement, but the culture of science is changing slowly (14,16-17). Improving the education of early career scientists to build the skills necessary for engaged...
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Exploring Service in Science

We created the broader impacts lesson plan for undergraduate STEM students at any level and disciplinary focus. The lesson has been implemented in a first-year undergraduate seminar Exploring Service in Science during the spring and fall 2018 semesters. The discussion-based course enrolls up to 20 students a semester and provides an introduction to public engagement for new STEM majors at a large research university. Open to all STEM majors, the majority of students who enroll are in the life sciences. The lesson plan is easily adapted to fit any specific STEM discipline of interest.

Required Learning Time
The total time allotted to the lesson should be approximately 75 minutes. If students are unfamiliar with the jigsaw and concept map formats, or the class size is large, the lesson may take up to 90 minutes to complete. An additional 15 minutes should be allotted for assessment, either directly following the lesson or during the next class session. Note: discussions and activities could be expanded upon if time permits.

Prerequisite student knowledge
No specific prior knowledge is required.

Prerequisite teacher knowledge
The instructor should be able to describe why public engagement is important and what types of scientific information are shared with the public. They should be able to identify examples of broader impacts in science and present an overview of these topics using the accompanying PowerPoint presentation (Supporting File S3. Exploring broader impacts of science – Overview presentation slides). Finally, the instructor should be able to identify a variety of ways scientific information is communicated to both expert and public audiences (e.g., citizen science initiatives, personal interactions, mass media, and primary literature).

SCIENTIFIC TEACHING THEMES

Active Learning
Our lesson employs a variety of active learning approaches. Students begin the lesson by responding to a minute paper prompt that activates their prior knowledge. A jigsaw activity provides opportunities for students to engage in small and large group discussion. Students work together to brainstorm common themes from the assigned readings, and actively synthesize their understanding through completion of a concept map in class. Finally, students share how their understanding of the central concept of broader impacts has changed through an online discussion after the class period. This spread of activities allows students to communicate and synthesize their thoughts in multiple modes (classroom writing exercise, in-person discussion with peers, and in an online forum).

Assessment
A minute paper prompt administered before and after the lesson provides insight into prior understanding of broader impacts and how that understanding changes as a result of the lesson. The concept maps students create can be analyzed using a rubric that gauges elements of their complexity and accuracy. Formative assessment is provided throughout the lesson during small- and large-group discussion as well as instructor feedback during concept map development.

Inclusive Teaching
The lesson centers on the connections between scientific...
research and its public applications, an approach of particular benefit to groups of students who are underrepresented in the STEM disciplines (24-26). The lesson utilizes a variety of diverse teaching strategies to be inclusive of mixed learning styles and engage diverse students. Written approaches are demonstrated in the form of individual reflection during class and online minute papers after class. Concepts are also summarized visually (slides and concept maps) and orally (small and large group discussion). Small groups assigned by the instructor provide an opportunity to cluster students into groups containing a variety of disciplinary interests, career goals, and student backgrounds to foster peer-to-peer learning. Intentional group arrangements can also foster discussion and reflection on diverse ideas.

**LESSON PLAN**

**Pre-class Preparation**

Prior to the lesson, instructors should assign students a pre-reading which highlights how the relationship between science and society has shifted through time (1; or similar, see 28-29). Instructors should also print handouts for the lesson (Supporting File S1. Exploring broader impacts of science – Jigsaw activity student handout and Supporting File S2. Exploring broader impacts of science – Concept map student handout) and select four case study articles that highlight different methods and contexts for translating research into practice (references 30-33 are used for this course - one case study article per student, divided evenly). To find relevant case studies, instructors should search by topic and communication pathway (e.g., “environmental chemistry + citizen science”). Adding one of the United Nations Sustainable Development Goals may enhance the search results (34). Articles should be two to three pages, moderate in difficulty with an approximately upper high school reading level. The set of four articles should each highlight a different topic and public engagement strategy (e.g., citizen science, mass media, primary literature, public policy) to allow for comparison. Instructors may choose to assign students case study articles to read in advance of class, rather than using in-class time for reading. Assigning case studies as pre-reading is a more inclusive teaching approach that would allow students more time to think about the content and any implications.

**In-class Activities**

**Warm up**

Instruct students to take one or two minutes to reflect on the following question individually: *In one or two sentences, describe your understanding of the phrase ‘broader impacts in science.’* Minute paper responses help gauge pre-lesson knowledge of students on the topic for comparison with post-assessment. They also allow students time to activate prior knowledge and think individually before participating in group discussion.

**Instructor overview on broader impacts in science**

The lesson should continue with an introduction to the topic of broader impacts in science by the instructor through a short presentation. Use the PowerPoint slides (Supporting File S3. Exploring broader impacts of science – Overview presentation slides) to give a brief history of broader impacts, provide motivations for public engagement in science, and explore challenges such as communication or social/cultural considerations. Introduce the pathways for translating scientific understandings using real examples. These pathways include scientific literature, press/mass media, personal interaction, jointly written grant proposals, and citizen science initiatives. Case studies provide examples from a variety of disciplines, including (but not limited to) biology, technology, engineering, and mathematics. This overview reinforces the value of broader impacts, including examples of STEM content with direct application to society, overview of how STEM knowledge is communicated to different audiences, and introduction to the interplay between scientists and the larger community. As time allows, the interactive lecture could be expanded to further student engagement, for example: can students think of problematic examples involving lack of information, misinformation or authorities misrepresenting science?

**Jigsaw activity on public engagement strategies**

Following an overview of broader impacts, including possible engagement strategies, communication pathways, challenges, and considerations, a jigsaw activity allows students to connect these ideas with real-world examples and explore ways that scientific understandings from a variety of disciplines are translated to the public in attempt to impact society. Prior to the activity, the instructor should introduce the process of a jigsaw activity to students (if this is the students’ first experience with a jigsaw activity, the introduction may take longer). Emphasize that once students wrap up their first small group discussion, they will be responsible for sharing their article and results of the first discussion with a new group.

Divide students into small groups. Hand each group a different article (each representing different public engagement strategies and disciplinary content) to read and discuss (30-33; see pre-class preparation for suggestions finding alternative articles). Instruct students to spend five minutes reading their one article and making notes on the jigsaw activity handout (Supporting File S1. Exploring broader impacts of science – Jigsaw activity student handout). Each group then transitions to discussing the guiding questions on the handout for 10 minutes, including key scientific understandings, stakeholders involved, engagement strategy, and challenges. For example, Weltzin aims to collect phenology data to understand changes in seasonality by using citizen science strategies to engage the public in learning about plant and animal species. Students might discuss how citizen science projects allow more direct transfer of information between scientists and the public (stakeholders), but identify data quality as a notable challenge (30). Alternatively, Morris takes a more traditional approach, where scientists share their findings linking exercise to improved cognition in an academic paper (32). Challenges to this approach include accessibility of the article and understanding of technical language.

Students can also compare the level of interaction between researchers and the public in various public engagement strategies (i.e., direct when researchers are testifying in government [31]; or indirect through an online citizen science interface [30] or mass media article [33]). The discussion and handout help students highlight the main ideas in each article, identifying and evaluating the public engagement strategy and method of communication (Supporting File S1. Exploring broader impacts of science – Jigsaw activity student handout;
e.g., citizen science [30], public policy [31], primary literature [32], press/mass media [33]).

Once groups have talked through the guiding questions, mix students into new groups so each is comprised of students that read a different article. Instruct students to provide a brief summary of their article and the group’s discussion. Next, instruct each group to discuss the next set of questions in reference to all case studies (approximately 10 minutes):

- Compare the methods used in the different case studies to translate research into the public sphere. How effective is each method at creating an impact on society?
- What social or cultural factors are at play in each case study? How do they impact the public engagement strategy? To what extent are these factors similar or different across cases?
- For each public engagement strategy, identify the challenges that might come up during their use. How are these challenges similar or different across the case studies?

The second small group discussion allows for peer-to-peer learning and teaching, as students pool their knowledge and explore different methods of communicating scientific information for broader impact.

Allow five minutes for students to share highlights of their discussion to the class. Instructor may briefly summarize key points on the jigsaw activity handout (Supporting File S1. Exploring broader impacts of science – Jigsaw activity student handout) to ensure that students grasp the similarities and differences between case studies. This is also an opportunity for the instructor to provide feedback on student understanding of the material so far and identify any gaps or misconceptions. At a minimum, the jigsaw discussion should highlight a variety of methods and contexts where scientific knowledge is translated to (or applied by) society for broader impacts, providing concrete examples for students to understand the definition of “broader impacts of science” (learning objectives 1, 3, 5).

**Large group discussion on the relationship between science and society**

The jigsaw discussion of specific examples sets the stage for a large group discussion of the pre-reading assignment concerning how scientific knowledge is increasingly required to be transparent and participatory (1). In this discussion, students contextualize the relationship between science and society broadly, including how this relationship has shifted throughout time (learning objective 2). This discussion allows the students to think more deeply about the value of science to society and understand key concepts discussed in the reading (italicized below). The large group discussion should take around 10 minutes. Instructors can pose the following questions, as time and student interest allow:

- What is meant by the phrase “science must leave the ivory tower and enter the agora?” How has the relationship between science and society evolved over time?
- Based on the articles we read and discussed today, what is the current relationship between scientists and society? What benefits and challenges does this relationship bring to science? To members of the public?
- Based on the jigsaw exercise and reading, what strategies for public engagement are most effective today? How can we evaluate the effectiveness of different public engagement strategies?
- How do cultural and social factors shape dissemination and understanding of science? What challenges exist?

Through this discussion, students understand that new scientific knowledge is increasingly expected to be socially robust, with emphasis on the validity of scientific findings both in and outside of the laboratory, and involvement from a variety of disciplinary experts and non-experts during development (co-production). Public engagement with science and scientists can help communicate key social, cultural, and place-based considerations that result in contextualized knowledge (1).

Discussion also allows the instructor an opportunity to weave feedback on students’ understanding of key concepts from the article into the conversation and highlight connections to course content.

**Synthesizing science and society interactions through a concept map**

Students now have an understanding of the phrase “broader impacts of science,” have investigated a variety of public engagement strategies, and have explored the shifting relationship between science and society. We next use a concept map exercise to help students individually synthesize their learning, draw connections between lesson concepts, and as a method of formative assessment through which instructors can gauge students’ learning and provide feedback.

In a large group format, introduce the idea of a concept map (if this is the students’ first experience with a concept map, the introduction may take longer). Tell students that a concept map consists of circled key words (‘nodes’) linked by directional arrows labeled with a ‘linking term.’ Explain that linking terms may be used multiple times, however each node word should only appear once. Provide each student a copy of the concept map handout, including prescribed node words and suggested linking terms (Supporting File S2. Exploring broader impacts of science – Concept map student handout), and a blank sheet of paper. Challenge students to think about the value of exchanges between science and society and develop a concept map to illustrate the complex interactions between them (learning objectives 2 and 4). For consistency, each student should use ‘science’ as their central node.

Give students 10 minutes to individually work on the concept map activity. If pressed for time, the instructor should set a minimum number of node words for students to use to encourage quality and understanding over quantity. Then, bring the class together for a final 10-minute discussion that allows students to share their experience distilling the science/society relationship in a concept map.

The following questions may be posed to the class:

- Which relationship(s) is/are most important?
- Which concepts or relationships are the most ambiguous?
- What was difficult? Are certain terms particularly easy or hard to place on the map?
Instructors may wish to clarify any inaccuracies in student concept maps during the discussion. After the large group discussion, students briefly compare their maps in pairs and discuss what similarities or differences reflect about interactions between science and society. The final pair discussion allows students to distill ideas learned throughout the lesson. Following the comparison, instruct students to use remaining time to revise their concept map before turning in at the end of the period.

**Post-class Assignment**

Following the lesson, pose another question to provide students a chance to reflect and self-assess their learning (approximately 5 minutes), as well as capture changes in student understanding of broader impacts from the beginning of the lesson. The post-lesson question we asked in an online discussion forum was, “Following our class on broader impacts in STEM, please revisit this question: In one-two sentences, describe your understanding of the phrase ‘broader impacts in science.’ Then share how you think your understanding has changed since you were first asked to consider it at the beginning of our last class period.” Instructors may wish to provide students with their pre-class minute paper to compare against and type into the discussion forum. We used the pre/post responses as qualitative evidence of students’ learning (post-lesson prompt and possible student answers are included in Supporting File SS. Exploring broader impacts of science – Post lesson prompt and rubric).

**TEACHING DISCUSSION**

This lesson engages students with the broader impacts of science. Students explore the meaning of the phrase “broader impacts of science,” learn methods and contexts for communicating and applying science in the public sphere and investigate the complex intersections between science and society. The lesson is grounded in active learning strategies through which students interact with peers, review examples from popular media, and develop experience understanding and synthesizing academic prose. Lesson topics illuminate what types of understandings are shared (and not shared) between scientists and the public, and methods for making the application of science transparent and participatory. Outcomes of the lesson on student learning and possible modifications are described below.

**Pre-post minute paper responses show achievement of learning objectives**

We evaluated the effectiveness of these teaching materials in achieving the stated learning objectives using minute paper responses (pre-assessment) and online discussion forum responses (post-assessment). Concept maps were also used for post-assessment (discussed below). Minute paper responses assessed students’ understanding of broader impacts prior to participating in the lesson. Most responses were vague but generally accurate, and frequently referred to science benefiting society. For example, “using one’s knowledge of science to help the overall community” or “broader impacts in science have to do with how science plays a part in society and what impact research has outside the lab.” Some students described “broader impacts of science” as the application of science to real problems but did not provide examples, for instance, “broader impacts are application” or “science learned in the classroom utilized to generate tangible/real-world benefits to a community or solutions to problems.” We felt these responses revealed a fairly simplistic understanding of the complex relationship between science and society.

Following the lesson, all students shifted towards a more nuanced and complex understanding of the phrase “broader impacts of science.” Many described specific methods and contexts in which scientific research is translated into practice. For example, one student stated, “it is clear that ‘broader impacts in science’ covers a huge array of topics within society, from government to mass media.” Students acknowledged the importance of citizen and government engagement with science to enhance impact in reflections such as, “at the beginning of the class period I expected ‘broader impacts in science’ to mean the way in which scientists’ work benefits our quality of life and influences our community. I did not expect society, citizens, government and policy to have an equally as important and strong influence on science itself.” Rather than a one-way transfer of value from science to society, they discussed the importance of the public in creating socially-robust knowledge, multi-directional transfers of information, and the importance of two-way communication. For example, “throughout class, my mentality changed from solely the impacts of science on the community, I now think about ‘broader impacts in science’ as the ability for not only science to impact the community but also the ability for the community to impact science through pushing for change and communicating concerns. The community holds science accountable.” Students also included other aspects of broader impacts such as trust, policy, and activism, for example, “for science to have a broad impact, there must be communication between society and scientist in order for society to accept and trust the information provided by scientists.” Multiple students referenced a change in understanding as a direct result of the activities in the lesson. They highlighted that the jigsaw activity and concept map helped to expand their views of broader impacts in science and link concepts discussed throughout the course.

**Concept map enhances student understanding of learning objectives**

Concept maps are a recognized strategy for active learning that require students to move beyond declarative knowledge and understand how concepts relate to one another (35-37). The process of creating individual concept maps allows students to interweave lesson topics and organize a ‘mental model’ that links concepts and fosters retention of knowledge (35-37). We designed the concept map to provide an opportunity for students to self-assess their learning, receive instructor feedback and measure students’ learning as a result of the lesson. The concept map both created a platform for peer discussion and provided post-assessment. Nearly all students were able to utilize prescribed node words with appropriate linking words to directionally connect terms together, demonstrating basic understanding of key concepts. The diversity present in concept map structure was a valuable teaching and learning tool. Comparison with classmates’ maps uncovered the complexity inherent to science-society interactions and led to meaningful discussion where students were able to articulate and solidify their learning (see examples in Figure 1).
Lesson application across disciplines

The lesson offers students the opportunity to explore how scientific information is translated to the public for societal impact. While it was designed to be one class session during a first-year seminar on civic engagement in the sciences, the lesson may also fit well towards the end of an introductory STEM course, after students have explored a topic with societal ramifications (e.g., evolution, public health, genetic testing, sustainability, climate change). Depending on the discipline, objectives, and geographic content of the course, the lesson can be customized to align with course specific objectives. The core lesson plan and active teaching strategies are easily tailored through selection of readings, jigsaw articles, and concept map terms that align with the desired discipline or topic. For example, we drew examples from a wide range of disciplines for the jigsaw activity because our students are drawn from a variety of STEM disciplines. However, other articles may be substituted to provide locally relevant or more recent examples. If different jigsaw articles are substituted, ensure that a variety of methods of translating science into the public realm are represented, for best comparison in the second half of the jigsaw exercise. Depending on the disciplinary lens used with this lesson framework, the node and linking words for the concept map may also need to be amended. We suggest instructors require students to use a common word at the center of their concept map for consistency. While we used ‘science’ as our central node, this may differ based on the disciplinary focus of the course.

Lesson application across course formats

We developed and taught this lesson in a small seminar format, but the active learning strategies and lesson framework are transferable across course formats with minor modifications (e.g., large lectures, discussion sections, seminars, or labs). Depending on the number of students and classroom format, the jigsaw activity may require more instructor preparation. In a larger lecture format, the instructor may wish to assign groups in advance, convey the groupings to students ahead of the lesson, and ask students to sit in their groups upon arrival. However, the jigsaw format is flexible. Instructors may wish to add additional articles with a large number of students or split the class into sub-groups, with each sub-group performing the jigsaw activity as described through duplication of each article. For very large classes (> 200 students), students could randomly be assigned an article to read prior to class and be instructed to talk with others sitting nearby to limit movement during the exercise.

Similarly, modifications to the concept map activity can be adapted to fit many classroom environments and time constraints. If desired, the concept map activity could be moved to the following class session, split across multiple class sessions, performed in small groups, or assigned as an out-of-class assignment. Although the activity provides opportunity for student engagement in class, completion of the activity at a later time still allows students to map complex understandings between science and society (and may be more feasible in very large classes). Completing the map in small groups may increase interaction and learning. However, this may make it more difficult to track individual progress as a result of this lesson. Although it is possible to use a shorter post-assessment exercise, the concept map activity was favorably received by students and identified as an activity that facilitated learning and synthesis of lesson topics.
Conclusion
Broader impacts and public engagement are an increasingly
important facet of working in the STEM disciplines. This lesson
introduces the topic of broader impacts to students in an
engaging, active environment that promotes development of
key science process skills. Peer-to-peer learning is facilitated
through small and large group discussion and student-
centered activities, including jigsaw and concept mapping.
Several assessment strategies illustrate the effectiveness of
the lesson, and students highlight the key role of the concept
map exercise in expanding their learning. Overall, this is a
promising approach that can help students understand how
their disciplinary knowledge intersects with the public interest
and prepare them to champion engaged scholarship in future
careers.

SUPPORTING MATERIALS
• S1. Exploring broader impacts of science – Jigsaw activity
  student handout
• S2. Exploring broader impacts of science – Concept map
  student handout
• S3. Exploring broader impacts of science – Overview
  presentation slides
• S4. Exploring broader impacts of science – Concept map
  rubric
• S5. Exploring broader impacts of science – Post lesson
  prompt and rubric

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### Table 1. Broader Impacts Lesson Plan Teaching Timeline

<table>
<thead>
<tr>
<th>Activity</th>
<th>Description</th>
<th>Estimated Time</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Preparation for Class</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Prepare copies of case study and jigsaw materials for students.</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>1.</td>
<td>Make one copy of case study and concept map handouts for each student.</td>
<td>15 minutes</td>
<td>Jigsaw activity (case study) handout is provided in S1. Exploring broader impacts of science – Jigsaw activity student handout.</td>
</tr>
<tr>
<td>2.</td>
<td>Make copies of case study articles (1 study per student).</td>
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<td>Concept map handout is provided in S2. Exploring broader impacts of science – Concept map student handout.</td>
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<td></td>
<td></td>
<td></td>
<td>Suggested case study articles are included.</td>
</tr>
<tr>
<td><strong>Class Session 1</strong></td>
<td></td>
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<tr>
<td>Warm Up</td>
<td>Individual minute-paper.</td>
<td>5 minutes</td>
<td>Prompt included in S3. Exploring broader impacts of science – Overview presentation slides.</td>
</tr>
<tr>
<td>Review</td>
<td>Interactive lecture.</td>
<td>5-10 minutes</td>
<td>Lecture slides with notes are in S3. Exploring broader impacts of science – Overview presentation slides.</td>
</tr>
<tr>
<td>Jigsaw Activity</td>
<td>Small-group discussion of case studies.</td>
<td>30-35 minutes</td>
<td>Materials needed are included in S1. Exploring broader impacts of science – Jigsaw activity student handout and S3. Exploring broader impacts of science – Overview presentation slides.</td>
</tr>
<tr>
<td>Large Group Discussion and Concept Map Activity</td>
<td>Instructor-led class discussion to summarize reading, students develop concept maps individually, and a short discussion of concept map exercise concludes.</td>
<td>35-40 minutes</td>
<td>Reading is included (1). Concept map handout included in S2. Exploring broader impacts of science – Concept map student handout.</td>
</tr>
<tr>
<td><strong>Following the Class</strong></td>
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<td></td>
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</tr>
<tr>
<td>Post-class Assignment</td>
<td>Online discussion forum response.</td>
<td>5 minutes</td>
<td>Prompt included in the “post-class assignment” section of the lesson article.</td>
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