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A Ten Year Review of the National Science Foundation Nanotechnology in Undergraduate Education (NUE) Program

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REVIEW

The National Science Foundation's Nanotechnology in Undergraduate Education (NUE) program recently completed its ten year anniversary. The program is a major source of funding for nanotechnology educators, supporting over one hundred eighty projects via grants totaling $27M between 2003 and 2013 inclusive. It has undergone several important changes as the fields of nanotechnology and nanotechnology education have evolved. This article presents the accomplishments of the NUE program, describes how the NUE program has changed since its inception and presents ideas for potential improvements. It is hoped that this article is of interest to those studying nanotechnology education policy and to nanotechnology education researchers, especially those who have received support or are seeking funding from the NUE program.

Keywords: Nanotechnology in Undergraduate Education, Review, National Science Foundation, National Nanotechnology Initiative.

CONTENTS

1. INTRODUCTION

The Nanotechnology in Undergraduate Education (NUE) program funds the majority of individual nanotechnology education research projects at the National Science Foundation (NSF). From its inception to the 2013 solicitation, the NUE program has funded 176 projects (Poats, personal communications, July 9, 2013 & March 13, 2014). By comparison, other NSF undergraduate education programs have supported only a handful of individual nanotechnology education projects: six by the Advanced Technology Education (ATE) program and twelve by the Course, Curriculum and Laboratory Improvement (CCLI) and the Transforming Undergraduate Education in STEM (TUES, formerly CCLI) programs (National Science Foundation, 2013). It is worth noting that the NSF also has funded nanotechnology education centers, such as the Nanotechnology Center for Learning and Teaching (NCLT), Nanotechnology Applications and Career Knowledge (NACK) Network, and Network for Informal Science Education (NISE) with multimillion dollar grants per year (National Science Foundation, 2012a; Murday et al., 2011). Many perspectives of the state of nanotechnology education have been published, but it is surprising that no article has focused on the NUE program and its ability to address challenges facing the nanotechnology education community. NSF has conducted a program evaluation which is discussed below (Manhattan Strategy Group, 2012). The NUE program has changed during its first ten years as the state of nanotechnology and nanotechnology education evolved. The article describes the brief history of the NUE program, the changes that have taken place to its annual solicitation, its annual funding and project results. Three successful NUE projects are highlighted to illustrate how NUE funding has benefited students. The final section recommends ways to improve assessment of individual projects and the NUE program as a whole and broaden participation in the NUE program among nanotechnology education community members.

Prior to the NUE program, the National Science Foundation supported individual nanotechnology education and outreach projects for K-12 students, undergraduates and the general public, such as the University of Wisconsin—Madison MRSEC Education Group. (MRSEC Education Group, 2013) The NSF also established Nanoscale Science and Engineering Centers (NSEC) in 2001 which included both research and educational components. Each of the six centers developed education programs for students in primary or secondary schools. Other education activities included workforce training, teacher training, undergraduate courses, and public outreach to local science museums (Roco, 2002).

2. ESTABLISHING THE NUE PROGRAM

The National Nanotechnology Initiative (NNI) program coordinates the U.S. federal government's investment in nanotechnology following a long-view strategy (Roco, 2011). Goals of the NNI include: a better understanding of nanotechnology through research and development, economic benefits created by new and improved nanotechnology-enabled products and processes, growth of a skilled workforce through nanotechnology education and training, and the responsible use of nanotechnology with respect to the environment and society. The NNI promotes several signature initiatives—applications of nanotechnology in fields such as solar energy, sustainable manufacturing and electronics (Roco, 2011). Sensors for protecting the environment and public health and building a "knowledge infrastructure" in the form of collaborations with the nanotechnology community and computer-based tools and resources are two new signature initiatives. (National Science and Technology Council, 2014). Twenty cabinet level departments and independent agencies contribute to NNI. Its budget increased steadily from its start in 2000 to 2010, reaching a cumulative total of about $20 billion including FY 2014. (National Nanotechnology Initiative, 2013) During that span, only the U.S. space program funded more non-military science and technology R&D. The NNI was the first large-scale government-funded nanotechnology program in the world; dozens of other countries created similar programs soon afterwards (Roco, 2011).

There are clear similarities between the goals of the NNI and the National Science Foundation (NSF). Each emphasizes research and development, education and societal impacts. The NSF played a leading role in establishing NNI and contributes about 25% of the NNI operating budget. (Gallo, 2009) The mission of the NSF is to advance basic scientific research in the United States. To that end, the NSF funds approximately 20% of all federally supported fundamental research in science (excluding medicine), engineering, and social science disciplines, as well as funding for K-12, college and post-graduate education in these fields. (National Science Foundation, n.d.) It has supported individual research projects (c.f. National Science Foundation, 1993), infrastructure and research programs in nanotechnology since the early 1990s. (Gallo, 2009).

The NNI provides the scientific and engineering community with a long-term, sustained and organized vision of nanotechnology. With direction from the NNI, researchers can build a coherent understanding of nanotechnology by exploring areas where knowledge is lacking. Scientists and engineers can develop the applications of nanotechnology that will provide societal and economic benefits. In order to achieve the goals of the NNI, students and the general public must learn about nanotechnology at all levels of schooling and in informal settings, respectively. Bringing applications of nanotechnology to market requires workers with knowledge and training in nanotechnology. Growth in the number of nanotechnology workers was 25% annually from 2000 to 2008. While the recession in 2009 lowered the rate of growth for several years, the number of participants in the nanotechnology workforce is expected to increase substantially as more products and applications are introduced (Roco, 2011).

As part of the National Nanotechnology Initiative, the NSF established the Nanoscale Science and Engineering (NSE) program, which included several research solicitations covering many areas of nanotechnology research. The Nanotechnology in Undergraduate Education program was first included in the NSE solicitation for FY 2003. (National Science Foundation, 2002).

3. CHANGES TO THE NUE PROGRAM SOLICITATION

The annual NUE solicitation has changed significantly over the past ten years, including project duration, funding amounts, eligibility requirements and topic emphasis. These changes are in addition to new NSF-wide

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requirements, such as greater emphasis on merit review criteria and the inclusion of additional supplementary documents (e.g., a data management plan).

After FY 2003, the next two NSF solicitations for nanotechnology education proposals were offered by the Nanoscience and Engineering Education (NSEE) program, which included funding for undergraduate education (NUE), informal education (NISE) and centers for learning and teaching (NCLT). (National Science Foundation, 2003, 2004). Fiscal Year 2006 marked the first time that NSF solicited proposals for NUE funding as a separate program. (National Science Foundation, 2006). This solicitation listed fewer supporting NSF directorates than in previous years—Directorates of Geosciences (GEO), Biological Sciences (BIO), and Math and Physical Sciences (MPS) did not participate. The Directorates for Engineering (ENG), Social, Behavioral, and Economic Sciences (SBE), and Education and Human Resources (EHR) have continued to support the NUE program solicitation.

This change in of support from some science directorates coincided with a significant shift in the emphasis of the NUE program. Until FY 2007, principal investigators from any discipline supported by NSF could submit a proposal. In that year's solicitation, the NUE program was renamed "Nanotechnology in Undergraduate Education (NUE) in Engineering," and only faculty affiliated with an engineering or engineering technology department could serve as a proposal PI. From that point to the present, faculty from science or social science departments were limited to serving as co-PI on an NUE proposal with an engineering faculty in the lead role (National Science Foundation, 2007).

Overall, NSF's nanotechnology education goals before 2002 emphasized graduate level programs (Murday, 2011). While some multidisciplinary courses on matter at the nanoscale existed for upper level undergraduate programs, there remained a lack of introductory class and laboratory curricula. Students did not learn about the emerging field of nanotechnology until they had mastered the broad, foundational knowledge of their discipline. In an attempt to "reverse the pyramid" (Roco, 2003), the NUE program requested grants designed for freshman and sophomore education projects for the first two solicitations. The NUE program lifted this condition so that investigators could target all undergraduate students in 2006. (National Science Foundation, 2006) Due to the growth of knowledge generated by nanotechnology research, the FY 2006 solicitation specified that proposals should address (1) nanoscale devices and systems, (2) societal, ethical, environmental or economic issues, or (3) both topics. These are among the eight program component areas of NNI that were established in 2006, and they have appeared in all NUE solicitations since then. At the time that the NNI was established, nanotechnology research was expected to evolve from the study and creation of passive systems during the decade of 2001–2010 to the design of active, complex structures beginning in 2011 (Roco, 2011). Thus, the NUE solicitation's interest in nanoscale devices is appropriate. During the second phase, products based on nanotechnology (e.g., consumer goods and medical treatments) were expected to be introduced. In order to inform the public about these new types of products, nanotechnology education needs to address the societal, ethical and related issues. The NUE guidelines will likely continue to change in response to new NNI goals, which in turn reflect the perceived nanotechnology research needs of the United States.

Funding guidelines for the NUE program also changed after its first two years. Initially, NSF awarded $100,000 for one-year proposals with funding rates of 41% and 49% in 2003 and 2004, respectively. Funding for the NUE program was $3.3 million per year. The third solicitation expanded funding to $200,000 for projects lasting two years. Unfortunately, funding for the NUE program decreased, so relatively fewer of the larger proposals received funding. Excluding the first two years, the funding rate for NUE averaged 14%. The average annual amount of funds available to support all projects was $2.4 million during the same period of time. The NSF received between 67 and 114 NUE proposals each year, but in only four years did the number of proposals exceed 80 submissions. (Poats, personal communications, July 9, 2013 & March 13, 2014). A summary of proposals received and awarded, their success rate, and the total available funding for 2003 through 2013 is shown in Table I.

In addition to the funding described in Table I, the NUE program received a portion of funds provided by the FY 2009 American Recovery and Reinvestment Act (ARRA, commonly referred to as the Stimulus). The NSF received a $3 billion dollar appropriation through this legislation, which it used to support highly rated proposals that NSF had not approved due to the lack of available funds. (National Science Foundation, 2012b) The NUE program received $450,000 to fund three projects. (Poats, personal communication, July 9, 2013).

Table I. Total annual NUE award funding, numbers of NUE proposals submitted and awarded, and proposal success rate (2003–2013).

Fiscal year	Total annual budget for awards (millions US $)	Number of proposals submitted	Number of proposals awarded	Success rate (%)
2003	3.3	80	33	41
2004	3.2	70	34	49
2005	2.7	87	14	16
2006	2.1	114	11	10
2007	2.3	75	12	16
2008	2.3	67	12	18
2009	3.0	96	15	16
2010	2.8	73	14	19
2011	2.2	74	11	15
2012	1.9	69	10	15
2013	2.0	81	10	12

4. OUTCOMES OF NUE PROJECTS

Projects funded prior to the 2013 NUE solicitation were included in the external evaluation. Between 2003 and 2012, The NUE program has funded 169 projects involving hundreds of faculty. These projects affected the education of more than 35,000 students, with over 1000 students benefiting from research experiences. In 2012, the Manhattan Strategy Group (MSG) conducted an analysis of the projects funded by the NUE program. (Manhattan Strategy Group, 2012) To date, it is the only published report on this topic. The MSG evaluation was conducted at the request of the Directorate for Engineering and the Division of Engineering Education and Centers of the NSF for the purpose of guiding the NSF as it ponders future changes to the program. The MSG collected data in order to identify the departments and colleges which participated in the projects, measure the outcomes of the projects (including K-12 outreach) and discover how these results were disseminated. Annual and final project reports provided some data, but most of the numerical data for the MSG report was collected through a project survey sent to all NUE project PIs. The results of these data sources were coded and organized for analysis. The MSG study presented results only from those projects which were completed so no projects funded after 2009 were included. Thus, the dataset includes 132 separate, completed NUE projects. Unless otherwise noted, all information presented in this section was provided by the MSG report.

Deliverables from NUE projects took many forms. Table II lists the categories of project outcomes and their quantities. The most common results of NUE projects were the development of lab and demonstration experiments and teaching lessons, with 106 projects developing 341 experiments and 85 projects creating 314 lessons. A total of 109 NUE projects supported the research of more than 1000 students. Investigators established 170 new courses, and twenty-five grants helped to implement new degree or certificate programs. Computer-based deliverables, such as software, online materials, and hardware were among the least commonly cited outcomes. Although some projects generated an impressive number of curriculum materials, they were the exception. Most investigators reported the development zero or one item. Program officers were consistent in the types of projects they approved for funding, despite the changes in program details described above. Therefore, it is reasonable to assume that the number of deliverables for each category in Table II is also fairly consistent throughout the period of analysis (2003–2009).

While Table II is informative with regards to the distribution of different outcomes, the data is incomplete in a number of ways. No details were provided about more than fifty items which were categorized as "Other." These numbers are based on results self-reported by the project investigators. In the absence of detailed instructions, investigators might fail to accurately specify the number of items developed, leading to an inaccurate count of total NUE project outcomes. In addition, a category labeled "curricular enhancements" was included in the report, but not in Table II. Its omission here is to minimize the appearance of an inaccurate count of deliverables since, according to the report, many investigators described their new experiments, classroom lessons, and other types of curricular materials as curriculum enhancements also.

Almost half of all NUE projects involved outreach to either teachers or students in elementary or secondary schools. This outcome is surprising since the NUE solicitations do not require or even suggest that PIs involve non-college students and teachers. Over eight thousand K-12 students and almost one thousand teachers participated in outreach programs developed with NUE funding, most often through workshops or other activities that promoted awareness and interest in nanotechnology.

Collaborations are common in nanotechnology due to the interdisciplinary nature of the subject. This is reflected by 82% of NUE projects building collaborations among faculty in different engineering departments and 61% of projects involving departments from other colleges. Approximately one third of projects included faculty from multiple schools within a campus system (28%) or from separate universities (8%). It is not clear whether or not those faculty members at different schools belonged to the same discipline. Collaborations among faculty from

Table II. Categories and quantities of NUE project outcomes (2003–2012).

Category	Number of projects with outcomes in a category	Total count of items developed for a category	Maximum number of deliverables by a project for a category
Individual teaching lessons	85	314	18
Individual lab experiments or demonstrations	106	341	14
In-class learning materials	77	141	21
Online learning materials	28	28	1
Workshops or seminars	34	62	9
Students performing research	109	> 1000*	*
Software	13	13	1
Hardware and other devices	14	21	5
Courses	96	170	8
Degree or certificate programs	25	26	2

Note: *Information about the number of research students supported by NUE funding was not provided in the MSG report.

different colleges and schools are especially desirable since the project leaders can potentially introduce any new curriculum materials to a more diverse student population. No data was provided to describe the extent of collaborations among faculty within a single department.

Although PIs reported that their projects involved a combined total of 35,000 students, the number of students involved in a particular project varied greatly, from less than ten to five thousand. Judging the impact of very large versus very small projects is complicated by the lack of useful assessment data collected and reported by PIs. One in five projects did not even report the number of students involved, much less any qualitative measure of the project success. Only 62% of projects involved any type of assessment, such as pre- and post-tests or student evaluations. Unfortunately, the quantity of students and the presence of any type of assessment were the most well documented measures of the NUE program's impact on students described in the MSG report.

Of the 82 projects that did perform any type of assessment, 57 project reports (70%) reported evidence of student learning. Projects reporting any positive student learning data were included in this count, regardless of the quality of the data. For instance, anecdotes from students were among the reported data of the 57 projects showing learning gains. Fifty-seven projects also cited efforts to improve students' nanotechnology career skills. A slightly greater number of projects (63 or 77% of those providing assessment data) reported improvement in students' interest in nanotechnology. Half of all projects made efforts to involve students belonging to groups underrepresented in STEM fields. Again, the lack of specific data provided by the PIs allowed for only a limited analysis of the extent of workforce development, attitudinal changes and outreach. The problem of a less than desired level of assessment in nanotechnology education has been noted elsewhere. (Jones, Blonder, Gardner, Albe, Falvo & Chevrier, 2013).

In their project reports, some PIs reflected on the major issues or challenges to nanotechnology education. In all, twenty-six reports cited thirty-one topics that relate to improving student learning of nanotechnology. The need and benefits of hands-on activities, such as using microscopy instrumentation, was mentioned eleven times, the most of any topic. PIs were also disappointed with the availability and quality of textbooks for the nanotechnology classes they taught (despite the fact that curriculum materials are among the most common deliverables from previous NUE grants). The needs and advantages of small class sizes, active learning environments, scaffolding assignments, student participation in research, improvement of student interest in the subject matter and student preparedness—topics that are commonly discussed by educators of other disciplines—were among the PIs' other reflections.

Project investigators shared results of NUE projects in conventional ways, including journal publications, websites and conference presentations. Excluding one investigator who reported the publication of 159 articles for one project, PIs of 78 projects published 249 articles, or three publications per project. In addition to these traditional dissemination methods, most projects shared results in other ways also.

It is worthwhile to consider the outcomes of the NUE program in a qualitative manner also. Below are three summaries of NUE-funded projects that have impacted many students. Obviously, many more examples could be cited. Articles found in volume 5, issues 1 and 2 of *The Journal of Nano Education*, a special double issue devoted to the NUE program, provide additional descriptions of successful NUE projects. (Winkelmann, 2013a, 2013b).

Undergraduate research provides the most effective way to improve students' attitudes and knowledge in STEM subjects. (National Science Foundation, 1990) Although not all students can take advantage of these opportunities to work within a research group, students can perform research as part of their coursework. In this way, students gain many of the same benefits in the teaching laboratory as they do in a research laboratory. Teri Odom and Vinayak Dravid of Northwestern University developed two research-based courses devoted to nanopatterning. The first course teaches top–down nanoscale fabrication and bottom-up synthesis techniques. Students learn to use instruments such as an atomic force microscope (AFM), learn experimental techniques such as soft lithography and complete a group project. (Meenakshi, Babayan & Odom, 2007; Odom, 2008; Babayan, Visawanathan, Odom, 2008). In the second course, students perform individual research projects under the supervision of an advisor. Examples of project topics include printing surface adsorbed monolayers using alkanethiols and preparing nanocrystals within microwells. All projects use easily available and inexpensive equipment. This enables schools with limited laboratory budgets to offer a similar course.

Following the model of "reversing the pyramid" discussed above, students learn about nanotechnology in the introductory chemistry class at Iowa State University. In the non-majors class, students learn about light, color and spectroscopy and how they are used to analyze nanomaterials. In the laboratory, students prepare and analyze CdSe nanoparticle of various sizes and colors. They also learn about applications of nanoparticles as fluorescent tags in medicine, light emitting diodes and photovoltaic cells. Students enrolled in the analogous course for science and engineering majors perform the same experiment but learn about the topics in greater depth. Students in a freshman seminar course studied the properties of pre-prepared CdSe nanoparticle samples. Similarly, students in a physical chemistry laboratory course used CdSe samples when studying fluorimetry. In this way, aspects of the same nanotechnology topic are taught at different levels within the curriculum to students with a wide variety of academic interests. (Larsen, Pienta & Larsen, 2007).

The author and his colleagues have developed a team-taught, interdisciplinary laboratory course in which students synthesize and characterize a variety of nanoscale materials. The course was originally taught in 2003 by faculty in physics, chemistry and chemical engineering with guest lectures by scientists and engineers from local industry and faculty in the biology department. The curriculum changes periodically so that instructors can include new topics, such as chemical etching of scanning tunneling microscope (STM) tips and societal impacts of nanotechnology. (Zaccardi, Winkelmann & Olson, 2010; Winkelmann, 2012). Besides chemical synthesis, students image materials using education-grade AFM and STM instruments. The success of this course led to the development of a nanotechnology minor at Florida Tech and summer camp activities for local high school students.

5. RECOMMENDATIONS

As noted above, the NUE program has changed in response to the growth of nanotechnology and the needs of the nanotechnology education community. Many educators have to suggested ways that the NUE program can have more impact on the STEM education community. These include improvements in the assessment of individual projects and the NUE program as a whole, a more organized effort for dissemination that takes advantage of online technology and expanding the eligibility of faculty to serve as project PIs.

The Manhattan Strategy Group cited the lack of clearly defined NUE program goals as a hindrance to their ability to evaluate its success. (Manhattan Strategy Group, 2012). Despite the many worthy accomplishments of NUE investigators, there is no clear answer to the question, "Has the NUE program met its goals?" because those goals are open ended concepts that can be difficult to measure. Their report suggests the NSF create of a theory of action that states the goals of the NUE program, the methods for achieving those goals and the means for evaluating their achievement. A theory of action helps to explain and predict actions taken by members of an organization and helps the organization plan ways for achieving the desired results. A more detailed explanation of the theory of action can be found elsewhere. (Friedman, 2001). Establishment of clearly defined project goals can help the NUE program officers request the most useful information from principal investigators. Understanding the goals of the NUE program can help proposal writers design their potential projects to be more consistent with the desired outcomes of the NUE program.

The NUE program would benefit from collecting data in a more standardized way. (Manhattan Strategy Group, 2012). For instance, the seemingly simple request for the number of students involved in an NUE project could lead to an enormous variety of responses. Some faculty would respond with the number of students who helped them design or implement the new curriculum materials. Other investigators would include students who were enrolled in classes that used the curriculum materials. Without detailed instructions, project investigators may unintentionally misstate the outcomes of their work, making it more difficult to measure the achievements of individual projects and those of the overall NUE program. The author suggests a project report format similar to that used by the NSF TUES program, another STEM education program at the NSF. Using an existing template for data collection would enable the NSF to compare the results of projects funded through NUE and other programs.

The first step in generating reliable and useful project data occurs when the principal investigator decides which data to collect during the project's assessment and evaluation. The NSF TUES program can provide some guidance here as well. That solicitation requires proposals to contain a detailed project assessment plan conducted by an outside evaluator (i.e., not a PI or co-PI) with a background in education research. A thorough assessment plan and can help guide the PI during the proposal writing stage and the project execution.

The 2013 solicitation for the NUE program already incorporated one suggestion made by the Manhattan Strategy Group and by others. That is, require online dissemination of project results at an existing nanotechnology education website (Manhattan Strategy Group, 2012; Murday, 2011; Murday, 2009). All new NUE grant awardees must post their project results and maintain a webpage at the NanoHUB site. (nanoHUB.org, 2009). This solves the problem of project results, including curriculum materials, being dispersed online with no easy way for educators to find them. NanoHUB tracks user statistics, allows users to add comments to each item and provides a searchable database of all of its content. The NanoHUB website already contains results of many other nanotechnology education projects and it seems to be a good choice for disseminating future NUE project results as well. A review of the NanoHUB site is available for those interested in learning more about it. (Winkelmann, Bernas & Saleh, 2013).

A final recommendation is to rescind the restriction of only engineering faculty serving as PIs for NUE projects. This requirement prevents the NSF from receiving more high quality proposals simply because the writer is not an engineer. If the solicitation explains that a goal of the NUE program is for projects to benefit engineering students, then the PI's discipline is irrelevant. Here is an example of the consequences of this restrictive policy. A chemistry professor proposes to design and implement a nanotechnology-focused curriculum for her General Chemistry for Engineers class. She should be PI since this was her idea and she teaches the class. Several engineering faculty could serve as co-PIs to provide guidance in selecting topics and class activities. Such a curriculum may be needed and beneficial to engineering students, but the NUE program would not review it.

In order to seek funding for her proposal, the faculty member could respond to another education research solicitation such as from the TUES or ATE program, competing against many more proposals from a wider array of disciplines. Another solution would be to ask an engineering faculty member to serve as PI, either as the true project leader or in name only. While the NSF does allow faculty to submit proposals to multiple programs (with some restrictions), neither of these alternatives seems reasonable in order for a faculty member to submit a proposal to improve nanotechnology education.

The principal investigator rule appears especially odd when considering that the term "interdisciplinary" is frequently applied to describe nanotechnology. Nanotechnology will impact not just engineering but all fields of science and social science fields (Gorman, 2003). George Whitesides (2003) speculates that nanobiology will be an important, emerging field this century. A review of current nanotechnology education policies points out that the weakest aspect of undergraduate nanotechnology education involves non-STEM students and cross-disciplinary courses (Murday, 2011). There is no lack of enthusiasm and interest in nanotechnology education outside of engineering colleges. As the MSG report indicates, the majority of NUE projects already include collaborations with science and social science departments (Manhattan Strategy Group, 2012).

6. CONCLUSION

The Nanotechnology in Undergraduate Education program has supported many worthy projects during the past ten years. Changes to the program solicitation during that time reflect the shifts in U.S. nanotechnology policy in general. As the program begins its second decade, the NUE program should improve the methods for collecting project data and continue to evaluate the program guidelines so that it can ascertain whether it is achieving its stated goals.

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