Office of Technology, Policy and Strategy

A STRATEGIC LENS ON QUANTUM SENSING FOR SPACE APPLICATIONS

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EXECUTIVE SUMMARY

As classical technologies approach their theoretical power limits, quantum technologies, including computing, communications, and sensing, are often credited as the next science and engineering revolution.[1] Quantum sensors are the basis of quantum computing and communications technologies, but also have unique uses for security, medical, and space-related applications.[2] Regarding NASA's agency goals, quantum sensing can improve climate change monitoring, enable navigations systems for deep space, and enhance fundamental astrophysics research.[3] This report outlines the findings from an independent intern project on the ways NASA can strategically invest in quantum sensing technologies. This report also outlines policy barriers to developing the technology, largely related to communication difficulties, unfamiliarity with quantum, and lengthy approval processes. The information on tools and challenges relevant to quantum technology was gathered from literature reviews, online research, and discussions with NASA individuals. This report concludes with strategic recommendations to answer the question: what policies should NASA implement to effectively research and develop quantum sensing technologies?

[1]National Science Foundation. (n. d.) *Leading the Quantum Revolution* [Fact Sheet]. https://www.nsf.gov/news/factsheets/Quantum_Factsheet_v2_D.pdf

[2] Hoofnagle, C. J., & Garfinkel S. L. (2021, November) *Law & Policy in the Quantum Age*. Cambridge University Press. 31-32. https://doi.org/10.1017/9781108883719

[3]Kaltenbaek, R., Acin, A., Bacsardi, L., Bianco, P., Bouyer, P., Diamanti, E., Marquardt, C., Omar, Y., Pruneri, V., Rasel, E., Sang, B., Seidel, S., Ulbricht, H., Ursin, R., Villoresi, P., Bossche, M. van den, von Klitzing, W., Zbinden, H., Paternostro, M., & Bassi, A. (2021, July 3). *Quantum technologies in space. Exp Astron* 51, 1677–1694 (2021). https://doi.org/10.1007/s10686-021-09731-x

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INTRODUCTION

The phrase "quantum mechanics" was first used in a 1925 paper by German physicist Max Born in which he and another physicist extended the matrix formulation to electrodynamic interactions.[4] Almost a century later, the word "quantum" still makes any science or technology initiative sound ahead of its time. While quantum systems hold vast potential to revolutionize modern technology, a strategist's role is to filter through the perceived limitless nature of those technologies and understand what the real strengths and weaknesses of quantum systems are compared to their classical counterparts, as well as the barriers and tools on the path to realizing such advantages. To aid NASA's recently formed Office of Technology, Policy, and Strategy (OTPS), this report will take a strategic lens on a particular quantum technology, with a specific focus on policy implementation and working relationships. Since its creation in the fall of 2021, the purpose of OTPS has been to keep the agency organized and cutting-edge,

[4] Born, M., Jordan, P. On quantum mechanics. *Z. Physik* **34,** 858-888 (1925). https://doi.org/10.1007/BF01328531

coordinating between leadership and the research centers to determine how to implement NASA's strategic priorities. The potential of quantum technologies to revolutionize scientific research and space exploration makes the field highly relevant to NASA and highly relevant to OTPS as the center of the agency's strategic methodology.

Quantum technology refers to three primary categories: quantum computing (QC), quantum communication (QCOMM), and quantum sensing (QS). This paper will focus on quantum sensing, as sensors are an integral component of both computing and communication; however, a more long-term study could explore all three areas of quantum technology and the relationships between them. NASA has various quantum sensing projects at its research centers, for example Goddard Space Flight Center (GSFC) in Greenbelt, Maryland, and the Jet Propulsion Laboratory (JPL) in Pasadena, California. NASA Technical Fellow Dr. Upendra Singh is currently conducting a quantum sensing technical assessment to evaluate internal and external capabilities of the technology. To complement that assessment, this report will focus less on NASA's quantum sensing activities themselves, but instead on possible policy routes to take once the results of the technical assessment can provide a full picture of the agency's relationship to the technology.

The approach of this independent project involved a literature review, online research, and coordinated discussions with NASA individuals, including subject matter experts and technological leaders at headquarters and various research centers. The intended use of this report is to provide OTPS with an overview of the barriers and potential policies related to efficiently developing quantum sensing technology, information which can serve as a starting point for follow-on studies.

THE CASE FOR QUANTUM SENSING

Quantum sensing is the detection of changes in a system using the physical properties and interactions of particles. The sensitivity of quantum systems to these changes, or "perturbations" are commonly a weakness when trying to control such systems. Quantum sensing, however, turns this fragility into a strength, and surpasses the resolution limits of "classical" sensors, which cannot differentiate between quantum states.

NASA's fundamental research activities are designed to support specified applications or goals, a result of the agency's mission-oriented structure. As such, to make the case for bolstering quantum sensing research and development, it is important to outline the missions and agency goals which would be significantly strengthened by enhanced sensing capabilities. The primary applications of quantum sensing most relevant to NASA include Earth observation, space navigation, and fundamental physics experiments.

With the Biden administration's holistic approach to federal climate change policy, NASA, among other government agencies, has demonstrated a clear commitment to using its resources and manpower to mitigate climate change.[5] NASA has a unique role in monitoring changes in the Earth's climate, producing data on sea levels, greenhouses gases, and temperatures which are vital to assessing climate policy. These data points fall under the broader field of geodesy, the study of Earth's shape, orientation, and gravitational field, which can be significantly enhanced by incorporating quantum sensing techniques into geodetic measurement systems. For example, The Gravity Recovery and Climate Experiment Follow-on (GRACE-FO) mission is NASA climate-related project that currently uses microwaves, a classical sensing method, to take data on Earth's water composition.[6] A future version of GRACE could use atom interferometry, a quantum sensing technique, to obtain higher resolution data and understand the effects of greenhouse gases on our planet on an even deeper level.[7] In fact, researchers at GSFC have created a prototype quantum sensor for satellite gravimetry, a project of over ten years in the making that, could be incorporated into such a follow-on mission.[8]

Space navigation is another promising use of quantum sensing technology, especially as NASA allocates more of its resources to the Moon and Mars, areas where the Global Positioning System (GPS) may become unreliable or unavailable. Not only is it time consuming to rely on PNT techniques which require a signal to travel from Earth to a spacecraft, but quantum PNT systems are also orders of magnitude more precise than GPS satellites. Atomic clocks are a mature quantum sensing technology which are integral to the functions of modern electronic devices and GPS satellites, but other configurations such as atomic accelerators and atomic gyroscopes have the potential to further enhance space PNT systems.[9] NASA's Deep Space Atomic Clock (DSAC) was launched in 2019 to test out a specific atomic clock system that is "[u]p to 50 times more stable than the atomic clocks on GPS satellites."[10] It is important for the safe and secure navigation of Lunar and Martian missions that NASA continue to fund the DSAC program, with a

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[5]National Aeronautics and Space Administration. (2021, October 7). *NASA Releases Climate Action Plan* [Press release]. https://www.nasa.gov/press-release/nasa-releases-climate-action-plan

[6] National Aeronautics and Space Administration. (n.d.) *GRACE-FO: Gravity Recovery and Climate Experiment Follow-On* [Fact Sheet]. https://gracefo.jpl.nasa.gov/resources/38/grace-fo-fact-sheet/

[7] Belenchia, A., Carlesso, M., Bayraktar, Ö., Dequal, D., Derkach, I., Gasbarri, G., Herr, W., Li, Y. L., Rademacher, M., Sidhu, J., Oi, D. K. L., Seidel, S. T., Kaltenbaek, R., Marquardt, C., Ulbricht, H., Usenko, V. C., Wörner, L., Xuereb, A., & Bassi, A. (2022, March 11). *Quantum Physics in space*. *Physics Reports,* 951, 44. https://doi.org/10.1016/j.physrep.2021.11.004

[8] Keesey, Lori. (2018, December 20). NASA-Industry Team Creates and Demonstrates First Quantum Sensor for Satellite Gravimetry [Press Release]. NASA Goddard Space Flight Center. https://www.nasa.gov/feature/goddard/2018/nasa-industry-team-creates-and-demonstrates-first-quantum-sensor-for-satellite-gravimetry

[9] Feng, Donghui. (2019). Review of Quantum navigation. IOP Conference Series: Earth and Environmental Science. 237. 032027. https://doi.org/10.1088/1755-1315/237/3/032027 .

[10] Space Technology Mission Directorate. (n. d.). *Deep Space Atomic Clock (DSAC).* National Aeronautics and Space Administration. https://www.nasa.gov/mission_pages/tdm/clock/index.html

follow-on mission scheduled to fly on the VERITAS mission to Venus, as well as experiment with innovative quantum sensing navigation techniques.[11]

Additionally, fundamental physics experiments that use quantum sensing can strengthen our understanding of the universe. NASA's access to microgravity facilities, an ideal environment for fundamental physics tests, gives the agency the unique ability to support such research. The Cold Atom Lab is an example of a microgravity physics experiment, currently operating on the International Space Station, creates ultracold atomic clouds and performs atom interferometry experiments that can provide insight into fundamental quantum mechanical behavior. [12] Quantum sensor experiments in space can further our understanding of various topics in physics, such as dark matter and dark energy, gravitational waves, and the connections between quantum mechanics and general relativity.[13]

Quantum sensing is highly relevant to NASA's agency-wide goals related to climate change, deep space exploration, and astrophysical research. As the technology encompasses a variety of techniques, some more mature than others, NASA can both implement more advanced systems in the short term and explore early-stage approaches with long-term goals. Even if NASA leadership ultimately decide not to invest in quantum sensing research & development (R&D) firsthand, it will still be imperative to develop a workforce that can operate and understand the technology as it becomes more prominent across all scientific spheres. As a government agency, NASA has the unique strength of being able to commit resources to emerging technologies that may not yet be profitable for industry development. NASA can, and should, leverage this strength to innovate quantum sensing.

ADVANTAGE OF PARTNERSHIPS

NASA prioritizes forming partnerships in technological development processes to maximize efficiency and build relationships with industry, other government agencies (OGA), or academia. Quantum sensing is an especially good candidate for collaborative efforts because it has wide-ranging potential applications. With existing interest from other governmental agencies and industry, partnerships can bolster quantum sensing R&D. The report *Bringing Quantum Sensors to Fruition* released in March of 2022 by the National Science & Technology Council (NSTC) was compiled by an array of representatives from various government agencies, including NASA, the Department of Defense (DOD), the Department of Energy (DOE), the

[11] Cofield, Calla. (2021, June 30). *Deep Space Atomic Clock Moves Toward Increased Spacecraft Autonomy*. National Aeronautics and Space Administration. https://www.nasa.gov/feature/jpl/deep-space-atomic-clock-moves-toward-increased-spacecraft-autonomy

[12] National Aeronautics and Space Administration. (2018, July 27). Space Station Experiment Reaches Ultracold Milestone. https://www.nasa.gov/feature/jpl/space-station-experiment-reaches-ultracold-milestone

[13] Belenchia, A., et al. *Quantum Physics in space*. https://doi.org/10.1016/j.physrep.2021.11.004

National Reconnaissance Office (NRO), and the National Science Foundation (NSF), among others.[14] The diversity of participation in this report is a testament to the extensive interest in quantum sensing and the potential for collaboration on technological development in the field. In fact, the first recommendation in the NSTC report is to "seek appropriate partnerships with end users in U.S. Government, industry, and academia" to coordinate quantum sensing R&D most effectively.

Fortunately, NASA has many existing outlets to form partnerships that could be leveraged for the purpose of bolstering quantum sensing activities. One such resource is the Science & Technology (S&T) Partnership Forum, comprised of NASA, Space Force, and NRO, which provides an existing platform to have discussions about emerging technologies with multiple governmental stakeholder communities.[15] NASA also has a dedicated Partnership Office to navigate the technicalities of collaboration, such as legal and financial policies a NASA entity must abide by.[16] In general, partnerships are divided between the official and the unofficial. Any sharing of funds, equipment, or facilities requires an official partnership, so Congress has a record of where its appropriations for government agencies are being spent. This official written agreement goes through an online NASA platform called the Partnership Agreement Maker (PAM). PAM allows multiple parties to view and sign a partnership agreement; such parties often include multiple research centers, a legal team, and a finance team, to name a few, meaning the process of obtaining all the required signatures can be lengthy. On the other hand, an unofficial partnership, often referred to as a Memorandum of Understanding (MOU), is a shared understanding of goals without the sharing of resources. For example, in October of 2020, NASA and DOE released an MOU reaffirming their partnership on "energy-related civil space activities." The MOU describes the shared goals of the agencies but does not go into legal or financial details since it did not necessitate the overlap of funds.[17]

A resource which can streamline collaboration is the IBM Watson Explorer (WEX) tool, a language processing system that has been adapted for NASA use. When given data sets of an organization's relevant activities or interests, WEX analyzes the language and provides data visualizations on the commonly found themes in the information. WEX can supplement

[14] Subcommittee on Quantum Information Science, Committee on Science. (2022, March). *Bringing Quantum Sensors to Fruition*. National Science & Technology Council. https://www.quantum.gov/wp-content/uploads/2022/03/BringingQuantumSensorstoFruition.pdf
[15] Office of Technology, Policy, and Strategy. (n.d). *Science & Technology Partnership Forum*. National Aeronautics and Space Administration. https://www.nasa.gov/offices/oct/science-and-technology-partnership-forum.html
[16] National Aeronautics and Space Administration. (n.d.). *NASA Partnerships*. https://www.nasa.gov/partnerships.html
[17] Memorandum of Understanding Between National Aeronautics Space Administration and U.S. Department of Energy-Related Civil Space Activities. NASA-DOE. (2020, October 19). https://www.nasa.gov/sites/default/files/atoms/files/nasa_doe_mou_energy_related_space_activities.pdf

collaborative efforts between parties by identifying overlapping areas of interest from a data-based approach, combatting inefficiencies caused by bias or human error.

The diverse potential applications of quantum sensing make collaborative efforts among OGAs a particularly sensible approach to quantum R&D. However, holistic development of quantum sensing on the government side is not important only for government use – public investment will also facilitate industry activity. An article published by consulting firm McKinsey & Co asserted that "[r]egardless of industry, broad adoption of QS applications will not occur until stakeholders are convinced that the performance benefits justify their higher costs."[18] Investment in quantum sensing technology from the government could advance the technology readiness levels (TRLs) enough to allow profitable development in the commercial sphere.

BARRIERS TO QUANTUM SENSING TECHNOLOGY DEVELOPMENT

Despite the readily available resources, there are still many barriers to developing quantum sensing technology for space applications within NASA. Information about such barriers was collected from discussions with individuals in OTPS and at NASA research centers.

One barrier to the maturation of quantum sensing technology is the lengthy partnership approval process. If any licenses, patents, or shared equipment are involved in a potential collaborative process, and official agreement with signatures from NASA's legal team, and all other involved parties, is required. However, gaining approval on an agreement through PAM can take up to six months, even for a partnership that may only be 12 months long. This cumbersome process deters the short-term collaborations with external research groups that could have otherwise been valuable to innovation in quantum technology. Another problem related to partnerships is that the burden is largely on NASA individuals to identify candidates for collaboration, as there is no streamlined way for external researchers to assess the potential for partnerships with the agency.

There are also issues that arise when discussing quantum sensing because of a lack of comfort with what "quantum" encompasses. The association of a technology with the label "quantum" can evoke an emerging, cutting-edge, almost exotic branding, when in reality, the strengths, weaknesses, and maturities of quantum sensing are more specific to its exact system than they are to its general categorization. "Quantum sensing" includes everything from atomic clocks,

[18] Batra, G., Gschwendtner, M., Ostojic, I., Queirolo, A., Soller, H., Wester, L. (2021, December 21). *Shaping the long race in quantum communication and quantum sensing*. McKinsey & Company. https://www.mckinsey.com/industries/advanced-electronics/our-insights/shaping-the-long-race-in-quantum-communication-and-quantum-sensing

which have been in use since the 1950s, to atom interferometry, which has potential near-term applications, to emerging photonic methods.[19] [20]

When the workforce with experience in quantum science and technology is concentrated in laboratories and research facilities, as opposed to being dispersed across the agency in leadership and organizational positions as well, communication between scientists and supervisors is difficult for many reasons. Understanding the basic function of a telescope or a space shuttle is straightforward, but quantum sensing technology does not provide the same immediate, intuitive understanding. As such, supervisors may be resistant to giving their researchers additional resources or leeway to explore quantum sensing in unique ways. Additionally, quantum sensing has a broad range of possible applications, but gauging the feasibility requires research & development; we need to invest in the technology to understand where it's most useful, a timeline which conflicts with NASA's mission structure. Because NASA operates according to directed missions, reasoning for more strategic investment in quantum sensing must revolve around specific uses of technology, not general possibilities.

Given the vast array of scientific pursuits in NASA, these factors can dissuade agency policymakers from investing internal resources into quantum sensing development, especially when OGAs and industry are also interested in the subject. According to the National Quantum Initiative's (NQI) *Supplement to the President's FY 2022 Budget*, the request budget authority for government spending on quantum technologies in FY (fiscal year) 2022 is $877 million, a 10.6% increase from the enacted budget authority of 2021. These funds are spread across six government agencies, including NASA, and a variety of quantum initiatives, with the largest funding blocks going to quantum computing and fundamental science. As such, quantum sensing at NASA makes up only a small fraction of the total budget, and the question of how to spend the money depends on the priorities identified by agency policymakers. Given the information collected from discussions with individuals across the agency, from policy to center leadership to laboratories, the following section encompasses a potential quantum space strategy.

QUANTUM SENSING FOR SPACE APPLICATIONS STRATEGY

First and foremost, NASA's quantum sensing strategy should be informed by the detailed findings of the quantum sensing technical report currently being conducted by NESC Technical Fellow Upendra Singh and JPL Research Scientist Nan Yu. This assessment will provide in depth

[19] Belenchia, A., et al. *Quantum Physics in space*. https://doi.org/10.1016/j.physrep.2021.11.004
[20] Keesey, Lori. NASA-Industry Team Creates and Demonstrates First Quantum Sensor for Satellite Gravimetry [Press Release]. https://www.nasa.gov/feature/goddard/2018/nasa-industry-team-creates-and-demonstrates-first-quantum-sensor-for-satellite-gravimetry

information on quantum sensing technology and expert knowledge that can thoroughly inform future strategy; the recommendations in this report are intended to be a precursor to help OTPS understand *how* to use the study's results, instead of to replicate what those results may be.

The first strategic point, and perhaps most vital, is that NASA develop a skilled quantum workforce. Even if NASA decides to outsource all quantum sensing equipment from industry, instead of developing it in-house, the agency will still need individuals who know how to develop quantum algorithms for space applications and who understand how to implement quantum technologies to further the agency's goals. Forming partnerships with OGAs or industry also requires having quantum "fluent" individuals at NASA who can assess how much effort and funding is needed to modify an existing quantum sensor for NASA's specific needs. As previously stated, these quantum experts should not be concentrated in research settings; having leadership officials that understand the needs of quantum scientists will create optimal intra-agency communication. Leadership officials that understand the pull of quantum technology will also be more willing to approve innovate quantum sensing initiatives, keeping the agency's commitment to furthering early-stage technologies alive as we live in an ongoing "quantum revolution." As OTPS grows and solidifies its role in NASA, adding an individual with quantum expertise could aid in the development of NASA's quantum activities; perhaps the next Chief Technologist, Policy Analyst, or OTPS Fellow should be someone with a passion for the space applications of quantum technology. Dispersing quantum fluency throughout the agency will ensure that NASA is prepared to develop its own quantum sensing for space applications *and* adapt to external innovation.

Partnerships are another strategic imperative for all quantum technologies, including quantum sensing. Many government agencies, such as DOD, DOE, NSF, and NIH, are investing in quantum sensing R&D. While each agency has unique applications in mind, all of them will require the same basic technological development, making cross-agency collaboration a particularly effective strategy. For example, NASA and Space Force could collaborate to create a prototype atom interferometer for quantum navigation. Working with industry is also a mutually beneficial partnership because NASA can more efficiently an innovative quantum sensor for space applications while the commercial partner brings the technology closer to a maturity level that could result in a return on investment. Goddard Space Flight Center has held a partnership with sensing company AOSense for over ten years that resulted in the first atom interferometer for satellite gravity missions.[21] The success of this partnership can serve as a

[21] Keesey, Lori. (2018, December 20). *NASA-Industry Team Creates and Demonstrates First Quantum Sensor for Satellite Gravimetry* [Press Release]. NASA Goddard Space Flight Center. https://aosense.com/nasa-industry-team-creates-and-demonstrates-first-quantum-sensor-for-satellite-gravimetry/

model for future industry partnerships that focus on other techniques and applications, such as atomic clocks for deep space navigation or nitrogen-vacancy center sensors for extraterrestrial magnetic field measurements.

The final recommendation is that to create a cohesive quantum strategy at NASA requires either a centralized point of authority on quantum activity or easily identifiable center-specific quantum initiatives. A combination of these two models could potentially be implemented as well, but at least one is necessary for a more organized quantum infrastructure. The former would take shape as a single individual or office, which would be cross-cutting across mission directorates, with the goal of tracking quantum activity throughout the agency and advocating to meet the needs of quantum technological development. This would create a clear path of communication between agency policymakers and research scientists alike who are dedicated to keeping NASA cutting-edge on quantum. Similar to a Center Chief Technologist's (CCT's) relationship to a research center, in which the CCT advocates for investment in technological development at the center that will further NASA's goals, this "head of quantum" would strategically track and advocate for quantum investment that meets NASA's mission needs.

The latter method for quantum cohesiveness is similar to the DOE's current model of quantum R&D, which includes five "National Quantum Information Sciences Research Centers." At five different DOE National Labs there is a dedicated and easily identifiable quantum research program, each of which "represents a partnership of labs, universities, and private companies." For example, the Quantum Research Center (QRC) at Oak Ridge National Laboratory is a hub for developing quantum materials and algorithms.[22] Implementing a similar model in a NASA research center that has existing quantum activity would create a more organized research environment that would be more conducive to collaboration. The results of the QTSA can be particularly useful here, as a map of current quantum sensing capabilities will inform where to best centralize quantum research activity. Perhaps JPL, which houses the Deep Space Atomic Clock, Cold Atom Lab, and other quantum sensing activities, would be the best candidate for a "NASA Quantum Sensing Research Program," while Goddard, which has robust quantum computing and sensing activity, should house the "Quantum for Space Innovation Laboratory." Note that the creation of these hubs would not necessitate *more* quantum research, though that certainly could be a component; the main point of strategy involves making NASA's quantum research more organized and easily identifiable. The NASA Quantum Artificial Intelligence Laboratory (QuAIL) at Ames Research Center is an existing example of a quantum program with a clear purpose.[23] This model would make it easier for external scientists to

[22] Department of Energy Office of Science. (n. d.). *The National Quantum Information Science Research Centers: Leading the Quantum Revolution* [Brochure]. https://science.osti.gov/-/media/QIS/pdf/QuantumBrochure2021.pdf
[23] National Aeronautics and Space Administration. (n. d.). *NASA Quantum Artificial Intelligence Laboratory (QuAIL).* https://ti.arc.nasa.gov/tech/dash/groups/quail/

approach the agency with partnership ideas, solving the aforementioned issue of the burden being on NASA individuals to reach out for collaboration.

Quantum sensing technologies have a variety of maturity levels, system configurations, and potential applications, and strategizing about how quantum sensing fits into NASA's mission structure will be an intensive endeavor. In fact, the strategy may require a two-pronged approach, implementing the higher TRL devices like atomic clocks and atom interferometers into existing missions, while investing in innovative methods like medical quantum sensing for monitoring astronaut health or using nitrogen-vacancy center sensors to measure the magnetic fields of other planets. Regardless of which applications are deemed most appropriate to explore, based on the barriers evaluated through this independent project, the key strategic points are creating a skilled quantum workforce, enabling OGA and industry partnerships, and centralizing quantum activity at the center-level and/or at headquarters. Quantum sensing will inevitably be an important aspect of the future of space technology, and as a leading institution for science and technological development, NASA should carefully consider how to quantum sensing can enhance the agency's goals. Embracing the advantages that the technology has to offer could be the first step in ushering American science and space exploration into a new era of innovative thinkers and an infrastructure bolstered by quantum.

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An accompanying presentation, identically titled *A Strategic Lens on Quantum Sensing for Space Applications*, is available for public access. Check the NASA Technical Reports Server or contact:

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