World Premier International Research Center Initiative (WPI)
Executive Summary (For Extension Application Screening)

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Instruction:
Based on the Center's Progress Report and Progress Plan, prepare this summary within 6 pages.

A. Progress Report of the WPI Center

I. Summary

The production of life from non-living matter has been solved at least once, not by humans but rather by naturally occurring processes on the early Earth, more than 3.8 billion years ago. ELSI is inspired by the idea of following this successful historical example as both a scientific and organizational strategy to solve the challenging puzzle of the origins of life. This novel idea motivates a new kind of adaptive organization that evolves with the science, and creates opportunities that would not otherwise exist. We diversify our intellectual lineages (internationalization), we catalyze novel evolutionary innovations by concentrating and cross-fertilizing ideas from multiple fields (fusion), and we establish a unique culture that is adapted to our needs (reform).

ELSI creates value, and multiplies both the scientific and financial investments made by its researchers and benefactors. This is evidenced by the scientific and organizational breakthroughs, the new opportunities, connections, visions, solutions, and discoveries that ELSI makes possible as an institute. The assembly of a leading team of scientists to ELSI guaranteed that we would produce great science, but we have gone much further by achieving results (scientifically and organizationally) that would not have been possible without ELSI serving as a primary catalyst. We strongly leveraged WPI support, raising additional funding well in excess of the WPI grant, including development of large private donations from both Japan and abroad that are unprecedented in the history of Tokyo Tech.

Prior to ELSI, the origins of life field was slowly progressing, as specialists from different fields talked past (instead of to) one another, as artificial walls were constructed between phenomena whose natural collaboration is crucial to the origin of life, and where origins researchers did not have a place to call their home. Today, ELSI is home.

II. Items

1. Overall Image of Your Center

ELSI is the only brick-and-mortar research institution in the world dedicated to integrated studies of the origins of planets and life, and attracts top researchers from around the globe in our fields of study. We have capitalized on strong public and scientific interest in origins of life studies, and the possibility of life elsewhere in the universe. Our outreach activities, TV appearances, press releases, and internet presence has allowed ELSI to build a respected public image in Japan and abroad. ELSI has been a transformational presence at Tokyo Tech, both as an international oasis as well as a leading presence for our collective ambition to transform Japan's top science and engineering school into a globally top-ranked international university. We proudly carry the WPI banner, whose 4 pillars inspire us and have helped us to recruit many visionary leaders (both junior and senior) from around the world to come work at our home in Japan.

2. Advancing Research of the Highest Global Level

ELSI set out to address an ambitious science goal: the origins of life within the context of the origin of the Earth and other planets, and has been extraordinarily successful (~900 publications) in making significant progress and yielding a wide-reaching impact in all of these areas.

A. Origin of the Earth – ELSI scientists reconstructed key stages in the formation of the Earth, where and how our planet formed, what determined its composition and the changes in its internal state over time, how crucial elements responsible for the atmosphere and oceans were delivered and why they were retained, and how surface conditions responsible for life depended on these earlier stages. We developed the first integrated models of accretion and transport in stellar disks across scales from gas and dust, through crucial intermediates known as "pebbles," to the migrating orbits of early planets, and effects of

giant impacts. By combining computer models with cosmochemical evidence, we have explained the diversity seen in the solar system (as well as exoplanetary systems), while constraining the possible sources for light elements (C, O, Si, H, S, N) on early Earth.

Our researchers have also performed flagship work addressing questions about how to power planetary magnetic fields, connecting the deep interior of planets to the surface environment. We discovered that Earth's core incorporated much more hydrogen than previously thought. A key discovery at our world-leading high pressure experimental labs showed that early precipitation of silicon oxides from the core could have powered an early magnetic field protecting Earth's atmosphere from loss by solar wind, providing a new solution to a major paradox in geophysics.

Finally, we have learned that the cooling rate of early planetary surfaces is highly sensitive to solar irradiance and why, even with similar starting compositions, Venus dried and fell into a greenhouse from the beginning, while Earth retained an ocean and sequestered most of its CO_2 in the subsurface.

B. Birth of the Earth-Life System –We examined the origin of life as the emergence of a new geological system, accounting for the interactions between oceans, atmosphere, and solid Earth that are key ingredients for early chemical evolution. ELSI's researchers broke new ground to provide evidence for the formation and sustenance of a reducing environment on the early Earth, with important consequences for prebiotic organic chemistry. We discovered that a single late giant impact produces a secondary hydrogen atmosphere that lasts for 200 million years at the beginning of the Hadean eon. Consistent with these findings, the geochemistry team showed that complex stable isotope signatures of Sulfur in ancient rocks require a high ratio of CO to CO_2 well into the Archean, a breakthrough that has eluded geochemists for decades and a crucial condition for synthesis of complex organics.

Our work builds the case that diverse planetary surface conditions are essential to the emergence of life. We studied the roles of ocean bottoms and land as sources of nutrients, the roles of the sun, rock/water interface, and radioactive subsurface as sources of energy, the timing and extent of water delivery, and the composition of the earliest oceans and crust to predict the earliest conditions supporting prebiotic chemistry and the emergence of life. ELSI researchers developed a new field of study, geoelectrochemistry, where bulk-phase electrical potential interacts with geological redox chemistry to produce reactive C and N compounds, which drive downstream pathways that mimic the central metabolism of all extant life on Earth. In a seminal work of ELSI scientists, the requirements for life are identified and elaborated to further extend the example of early Earth geology into a framework for the search for other habitable planets.

The most important contribution that ELSI is presently making would not have been possible if theorists and experimentalists were not brought together under the same roof. Life did not emerge in a controlled laboratory setting, such as a beaker. ELSI scientists have established a new robust approach to move these studies into the realm of combinatorial complexity that characterizes real planetary geochemical environments, creating novel computational and analytic methodologies, and applying these to formation, structure, and properties of functional polymer families.

C. Coevolution of Life with the Earth – We worked to identify major transitions that shaped the evolving biosphere, its architecture, modes of evolution, and dependence on planetary conditions through time, and how bio-evolution has fed back to shape Earth's geological history.

ELSI researchers reconstructed genomes and bioenergetic systems of ancient bacteria, and shown how those changed in response to evolving planetary chemistry. We reconstructed isotopic and mineral signatures linking biological major transitions to the rock record, both for sulfur metabolism and for oxygenic photosynthesis, the biological innovation that has most impacted every surface environment on Earth. Genomes on Earth are carried by two kinds of lifecycles: one in free-living cells and the other in viruses. We have expanded worldwide knowledge of the diversity of viruses of thermophilic Archaea by nearly 100%, and are exploring the limiting conditions for single-stranded DNA and RNA viruses to understand constraints on an RNA world. ELSI now hosts one of the largest collections of Archaeal viruses of any institution in the world.

We integrated synthetic and evolutionary biology to understand elements of structure and function in early organisms. We demonstrated functional proteins translated using simpler genetic codes, and enzymes to synthesize key amino acids that do not require those acids in their sequences. We achieved increasingly complex functions in synthetic cell membranes, and coordination of molecular systems within and across them. To understand what processes drive biological innovation, we demonstrated new evolutionary paradigms for the

use of external constraints as scaffolds to create novel complexity. We have also shown how catalytic imprecision can be the gateway to new functions – likely an essential mechanism in early eras of short genomes and unreliable replication.

D. Life in the Universe – Our studies of the history of Earth and its Life reveal a unifying paradigm, of alternating stages of diversification and selection, which serves as a springboard to understand the habitability of planets around other stars and the principles that make life on them different or similar to our own.

Principles of life are essential features that can be formalized independently of the way they are expressed in Earth's biology. One such feature is heredity, without which selection cannot lead to adaptation. ELSI derived measures of capacity for heritable variation that do not depend on genes or genomes, and apply across a range of widely studied compositional models and even more general dynamical systems. Computational combinatorial methods allow us to ask which aspects of Earth-Life reflect inherent limits of chemistry, and thus may be universal. We have shown that the biological amino acids as a set cover a much wider range of properties essential to protein function than random sets of possible amino acids of similar size. Selection has made the biological set more unique because they are closer to the limits of chemical possibility.

A universal biology must explain how simple patterns of dynamical complexity create more complex patterns in a self-maintaining hierarchy. We have studied this problem for the emergence of lineages at the forming of the genetic code, showing how an era of innovation-sharing in which all components are exchanged independently can produce the error-buffering properties of the biological code, which then permit reliable protein synthesis, faithful molecular replication, and the emergence of vertical descent in a Darwinian world.

3. Generating Fused Disciplines

Nature did not produce life >3.8 billion years ago by constructing artificial walls between astrophysical, geological, and biological phenomena...neither should we. The achievement of great advances in the evolution of life, such as photosynthesis or multi-cellularity, required bringing unique combinations of life together (proximity), facilitating cross-fertilization (communication), and enabling the development of concerted and robust systems level behaviors (culture) in response to the same kinds of external influences. At ELSI we enable fusion between disciplines in much the same way as life achieved its major revolutions.

ELSI's fusion science has blossomed under these conditions. Our highlighted science results (above) are all catalyzed by hosting experimentalists and theorists under the same roof, and bringing together researchers from many fields. Interdisciplinary teams at ELSI have tackled numerous additional challenges together, including models for the origin and circulation of water in the Earth and use of amoebas as virtual computers to solve problems that are otherwise impossible to solve using conventional computers. We brought together astrophysicists and cosmochemists to explain Mars' composition and orbital radius, modeled prebiotic chemistry in icy moons, formulated new approaches to studying origin of life, and proposed biology-inspired models for the Earth's formation, composition, long-term evolution. We brought new ideas to the discussion of biomarkers on exoplanets, modeled nitrogen cycles in planets without life to see what they would look like, unified important ideas around the geochemical and geoelectrical output of deep sea vents and how they power life in a deep marine environment, and explored how the geochemical availability of various metals in the early Earth environment facilitated a variety of chemical pathways for biological metabolism. All of this work requires an unprecedented degree of breadth, which is critical for tackling the greatest challenges and opening new opportunities.

ELSI actively engages in creating conditions for fusion. Traditional funding is targeted to specialized subjects rather than broadly integrative fusion, so ELSI took advantage of interdisciplinary research funding opportunities and achieved great success, including the ELSI Origins Network (EON, PI: Hut) supported by the US-based Templeton Foundation, and interdisciplinary JSPS grants like Hadean Bioscience (FY2014-2019, PI: Kurokawa), Co-evolution of the Core and Mantle (FY2015-2020, PI: Tsuchiya), and Aquaplanetology (FY2017-2022, PI: Sekine). ELSI also established internal funding mechanisms to support fusion science within the institute that could not be covered by other grants. ELSI maintains interdisciplinary study groups, bringing together researchers from multiple fields to learn the best strategies to communicate and collaborate across discipline boundaries. We also established hands-on tutorials (ELSI "youchien"), strategy meetings, interdisciplinary courses led by ELSI PIs in campus departments, and beyond.

4. Realizing an International Research Environment

Nothing distinguishes ELSI's achievements more than its strong international research environment and staff, which are catalysts for breakthrough science (above) and

administrative reform (below). ELSI has grown a vast international network and recruited top scientists from around the world at both junior and senior levels. ELSI is now globally considered the place for the very highest level of research in our fields. Applications from graduate students are on the rise, and our staff positions are highly coveted.

ELSI's management has ardently worked to meet the requirements to be a WPI research center, including (1) establishing a research environment capable of attracting the world's best minds, (2) mandating English in all communications involving ELSI researchers and required for all events, workshops and institutional email lists, and (3) recruiting the majority of our junior and senior researchers from outside Tokyo Tech (including abroad). Today, 7 out of 17 PIs are world-class foreign researchers recruited from overseas, of which 4 are based in Tokyo full-time. Recruitment of talented bilingual secretarial staff and life support advisors was crucial to assist our international research staff, who provide relocation and daily life support, Japanese language classes, support for acquisition of competitive funds, safety management training, cultural diversity training, and a confidential method of reporting issues to the management.

ELSI pursues a targeted strategy for the recruitment of internationally competitive young researchers that is unique in Japanese universities. ELSI PIs employ their personal international networks to source top quality graduate students and postdocs as potential candidates. ELSI's activities to invite students of our symposium speakers, hosting winter and summer schools, and active sponsorship of young researcher conferences have paid great dividends. In our past junior recruitment, ELSI received 363 applications from more than 30 countries around the world, most of which (75%) were from abroad. ELSI also attracts competitive Japanese candidates applying from overseas.

ELSI maintains satellites at Ehime University, the Institute for Advanced Study, Harvard University, University of Tokyo, and Columbia University in New York. ELSI has formalized collaborations with 23 research institutes and universities around the world, a number that continues to expand. ELSI has hosted 7 international symposia, dozens of workshops, several short schools, has a vigorous visitor program to invite top scientists to spend time and collaborate at ELSI. The ELSI Origins Network (EON), launched by a large Templeton Foundation grant, provided a concrete measure of our global visibility. EON's funding for post-docs working half time in an institution abroad and the other half time at ELSI, and establishment a new global network in origins of life research allowed ELSI to significantly expand its profile, adding leverage to the funding provided by WPI.

5. Making Organizational Reforms

A key to ELSI's success is the implementation of new organizational strategies that are customized to our unique brand of science and position in the university. As a "special zone" within Tokyo Tech, where new administrative systems can be developed, tested, and exported to the broader university, ELSI is a key collaborator with our President in carrying out his vision to become a leading global university. Tokyo Tech administrative staff who regularly circulate into ELSI posts and then back to the broader university call it the "ELSI style," and we have seen many ELSI-inspired reforms advanced across the entire university via this conveyor system.

ELSI has worked with Tokyo Tech to achieve many important reforms, many of which have spread to the entire university:

●WPI style of top-down management under the leadership of a center Director, allowing flexibility we need to adapt to our special scientific, cultural, and logistical challenges.
●Performance-based salary system and competitive salaries in a global context.
●Cross-appointment system to acquire top researchers. After ELSI's first case, Tokyo Tech has utilized it to hire 22 researchers (as of January 2019).
●Amendment of regulations on private donations, enabling ELSI's first endowed professorship.
●Tokyo Tech adopted English-based support in university-wide email notifications, a consultation desk for personnel matters, safety training.
●Open and flat research organization that stimulates interdisciplinary research.
●Change in university regulations for travel insurance for work travel, and corporate credit card.
●Tokyo Tech USA non-profit organization enabling private donations from the US.

ELSI's signature achievement in administrative reform was to work with the Tokyo Tech President, our advisors, and MEXT to find a practical way to transition to a new Director following the initial WPI 10-year funding period. In 2018 we successfully recruited a prominent senior scientist and administrator from the US-National Aeronautics and Space Administration (NASA) to take on the new roles of Executive Director and Specially Appointed

Adviser to the President (of Tokyo Tech). Dr. Voytek is already active in improving ELSI's organizational and scientific strategy and efforts to develop new sources of funding (public and private).

6. Others

(1) ELSI has made a significant contribution towards nurturing the next generation of researchers by having our world-renowned scientists supervise graduate students. ELSI has also been contributing the development of postgraduate education programs by accepting excellent foreign students recruited through ELSI's overseas network.

(2) ELSI has received global funds in recognition of its unique research environment and its aspirational goals. In July 2015, ELSI was awarded funds totaling JPY670 million (USD1=JPY122) from the John Templeton Foundation in the United States. The purpose of the grant was to build an international network of origins of life research with ELSI as a hub. The fact that the John Templeton Foundation chose to award ELSI to be a key player in origins of life research is testament to ELSI's international reputation.

(3) ELSI is positioning itself as a leader in science communication. As an integral part of our internationalization efforts, ELSI is focused on transforming science communication in Japan that is conducted in English. We hosted the Japan Scicom Forum 2018 and 2019 as events to bring together communicators, writers, scientists, journalists and selected experts from abroad to share ideas and to inspire and boost the cohesion of science communication in Japan. In addition to building ELSI's communications, our new Communications Director (joined Nov. 2018), meets with Tokyo Tech PR to join efforts on increasing effective output.