Overview:

Imagine the new science of sound. A future in which humankind harnesses sound using properties analogous to the quantum world and vastly speeds up computational tasks. Imagine energy-efficient acoustic devices with functions that create a generational revolution in wireless technologies. A world with high-sensitivity acoustic sensors that continuously monitor and augment humankind's ability to sense changes in the natural and built environments. Imagine the possibilities of a new science of sound revolutionizing precision-medical diagnostics and therapeutic technologies. To reach these accomplishments in the next decades, the new Frontiers of Sound (*NewFoS*) STC will energetically pursue the essential convergent research, leap forward with the scientific foundations that translate to practical applications and fulfill contemporary societal challenges. These pathways will be made possible by the *NewFoS* community of US scientists and engineers who will embrace the attributes of acoustic waves that remained hidden, until very recently, to expand the frontiers of sound. To lead us to this future, *NewFoS* will exploit the complete range of acoustic wave properties under the vision to unite a diverse and inclusive community who reveal the full realm of possibilities for topological acoustics (TA) and create unprecedented acoustic wave technologies for US competitiveness and positive societal impacts.

Intellectual Merit:

Within use-inspired TA research and context-based education, *NewFoS* will advance knowledge by: (a) revealing and understanding the new scientific laws governing the untapped hidden attributes of TA waves; (b) enabling the convergence of multiple disciplines to exploit the full attributes of TA waves and advance their technological applications; and (c) creating context-based resources for education and a Mentoring Ecosystem to drive equity and empower applications of the new science of sound. *NewFoS* will discover yet-unknown aspects of TA with the potential to transform science and technology. *NewFoS* will use the untapped attributes (such as geometric phase, coherence, and robustness) as resources to address two types of high-impact integrative activities: (a) problem-driven projects that rely on TA approaches to achieve unique solutions to today's grand challenges in information science, telecommunication, sensing, and imaging; and (b) possibility-driven research approaches where TA is the engine of possibilities to envision the future. For example, *NewFoS* will ensure US leadership in a coherence-based complementary approach to quantum technology without suffering from the fragility of quantum systems. The STC will also develop the first operational, low-cost, miniaturized, low-power, and functional TA multiplexing devices that exploits robustness for advanced telecommunications. Further, *NewFoS* will overcome the current limits of remote sensing technologies to continuously monitor the natural environment using TA.

Broader impacts:

The *NewFoS* mission is to be a national resource for convergent research and education in the new science of sound and its applications. The STC will be greater than the sum of its parts across multiple research and education perspectives: mathematics; materials science; physics; mechanical, electrical, and civil engineering; and environmental, geo-, medical, information, and data sciences. Engaging industry will ensure the effective translation of legacy breakthroughs into new technologies and factor the contexts of pragmatic business and community imperatives. *NewFoS* will empower future generations by offering the scale to create the legacy workforce who champion transformative TA applications and build on the diversity, equity, and inclusion (DEI) values of *NewFoS*. The STC will develop the pedagogical and TA-based legacy resources for the next 50+ years of acoustic education and the first in-print and digital English-language textbook, a community college research workshop, and a curriculum-design seminar course. *NewFoS* will produce the foundations and evidence-based principles for a legacy multi-institution, transferable inclusive Mentoring Ecosystem to broaden participation based on research experience and mentoring and the DEI training of all researchers and staff.

4a. Problem Description and Rationale for Center Approach

Premise. Sound enables communication and perception. Sound already benefits society with numerous impactful technologies. Yet recently, scientists made incredible discoveries of sound-wave attributes never previously unveiled, which can robustly encode and convey information and augment humankind's sensing capabilities. We propose to launch an acoustic STC—the **New Frontiers of Sound** (***NewFoS***)—to educate, mentor, and train researchers, technologists, and leaders in this *new science of sound*. *NewFoS* will lead the fundamental transdisciplinary research and develop the transformative breakthroughs to apply these untapped attributes of sound waves for maximum societal impacts (e.g., see §4b.1.2 and §4b.1.3).

A revolution in the science of sound is underway. For 150 years, sound science created indispensable technologies for society: loudspeakers, microphones, radio frequency (RF) devices in smartphones, sonar, and medical ultrasound imaging, among many. Today, the emerging field of **topological acoustics** (TA) is revolutionizing sound science and advancing frontiers. For example, TA now reveals that sound waves can support quantum-like degrees of freedom (e.g., geometric phase [η] or spin) that were previously "hidden". TA also uncovers the possibility of coherence when parts of a wave or different waves correlate and "know" intimately about each other—analogous to a quantum mechanics phenomenon. Further, TA bestows the unprecedented attribute of robustness to disorder and imperfections, so that sound waves can propagate in environments with obstacles but without reflections or echoes. In addition, TA waves can encode greater information and data than conventional sound waves to augment perception in an environment. Also, with TA, sound-encoded data can multiplex for massively parallel information processing.

Vision. *NewFoS* unites a diverse and inclusive community who reveal the full realm of possibilities for TA and create unprecedented acoustic technologies for US competitiveness and positive societal impacts.

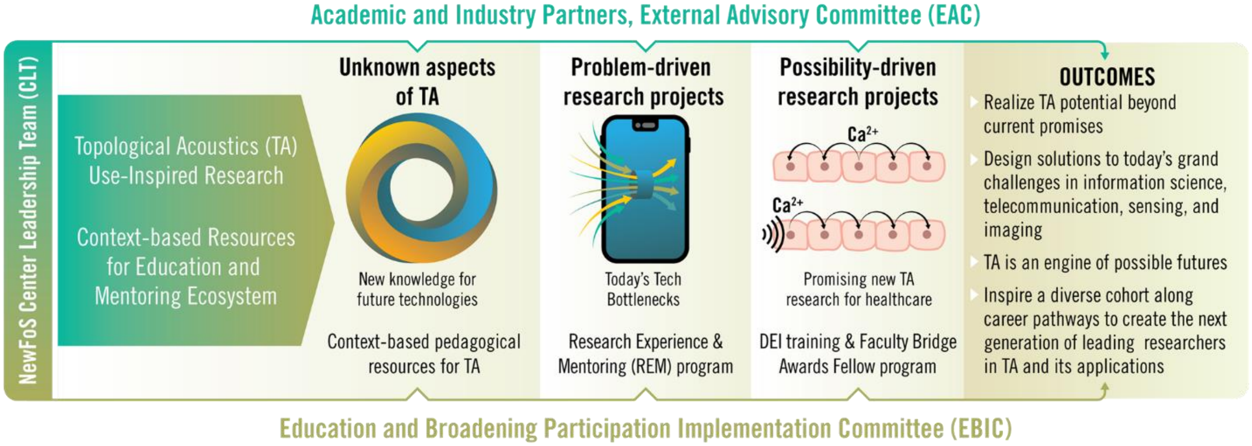


Figure 1. The integrative research and education plan for *NewFoS* (DEI = diversity, equity, and inclusion).

Mission. *NewFoS* will be a national resource for convergent research and education in the new science of sound for TA and its applications (**Fig. 1**). With use-inspired research and context-based education for TA, *NewFoS* will: (a) **reveal and understand the new scientific laws that govern the untapped hidden attributes of TA waves**; (b) **enable the convergence of multiple disciplines** to exploit the full attributes of TA waves and, collaboratively with industry, advance their applications in information processing, communication, sensing, and imaging [1]; and (c) **create context-based resources for an education and mentoring ecosystem** to drive diversity, equity, and inclusion and empower new acoustics applications.

The *NewFoS* value proposition. *NewFoS* will be greater than the sum of its parts. Only a *NewFoS* STC will integrate TA, mathematics, physical sciences, engineering disciplines, and materials, environmental, biomedical, information, and data sciences with stakeholder leaders and convergence workforce-ready education. *NewFoS* will provide the long-term research and education perspectives to realize the discoveries, technological innovations, and societal impacts from the new science of sound. An STC will be at the scale for an essential workforce to champion emerging and transformative applications, with a focus to advance TA research and its applications in information science, telecom, sensing, and imaging.

Timeliness. The *NewFoS* team are the US leaders in this emerging field; however, competitors in Asia and Europe are also pioneers or "catching up fast". *China Acoustic Valley* is a recent joint initiative of Nanjing

University, the Acoustical Society of China, and the National Changshu Economic and Technological Development zone to develop innovative acoustics technologies. Established in 2020 for this initiative, the International Institute of Acoustics Industry Technology is focusing on “sound”, “manufacturing”, and “life”. At Nanjing University, the Ministry of Education’s Key Laboratory of Modern Acoustics is developing the science of acoustics and TA for complex structures, new materials for sound propagation, ultrasound applications in life sciences, and acoustics in information processing. Other major Asian centers of research on TA include Wuhan University and the Hong Kong University of Science and Technology.

The EU-funded *All-Phononic Circuits Enabled by Opto-mechanics* (PHENOMEN) consortium tackled TA research and applications. With three research institutes (in Spain, Italy, and Finland), three universities (Universitat Politècnica de València [UPVLC], Università Politecnica delle Marche, and Université des Sciences et Technologie de Lille), and an industrial partner, PHENOMEN led a: “*Disruptive phononics-based approach to information technology*”. PHENOMEN, and its spin-off project *Lossless Information for Emerging Information Technologies*, lay the foundations to manipulate phonons and couple them to photons and RF electronics for information technology, and to run at lower power and exploit lossless topological channels for information transfer and quantum metrology. With the EU’s Erasmus+ Programme support, *Erasmus Mondus Master WAVES* (Waves, Acoustic, Vibrations, Engineering and Sound) is a recent two-year international Master program that federates the Universidad De Coimbra, UPVLC, Aix-Marseille Université, and Ecole Centrale Marseille to educate engineers in modern acoustics.

NewFoS will augment the US acoustic research and education landscape, e.g., the *National Center for Physical Acoustics* at the University of Mississippi, the *Center for Acoustics and Vibrations* at Penn State, and centers or research clusters at Clarkson University, Florida Atlantic University [FAU], Iowa State, Purdue University, Texas A&M, University of New Hampshire, and UT Austin. Indeed, existing US centers focus on *conventional* acoustics for hydro- and aero-acoustics, inspection, and biomedical acoustics, but neglect the significance of TA. The current curricula of US acoustic engineering programs (e.g., Belmont University, Brigham Young University, Georgia Tech, Johns Hopkins, Penn State, Purdue, University of Hartford, University of Rochester) or acoustics graduate programs (e.g., FAU, Naval Postgraduate School, Penn State, Portland State University, RPI) have not yet caught up with the emerging field of TA.

NewFoS aligns with NSF’s 10 big ideas: Future of Work at the Human-Technology Frontier, Growing Convergence Research, Harnessing the Data Revolution, Navigating the New Arctic, NSF INCLUDES, and Quantum Leap; and other national initiatives such as the Defense Department’s FutureG. Finally, the TA field has matured to the level that the *NewFoS* team can envision proposing pathways to impactful TA-based solutions for a broad range of contemporary societal problems. The scientific foundations of this field are sufficiently advanced for the *NewFoS* team to posit possible future discoveries and applications. An STC will ensure the essential US leadership in this critical field.

Aspirational model for *NewFoS* STC. The Optical Science Center (OSC) gave “birth” to the University of Arizona (UA) College of Optical Sciences (COS) and is a model for *NewFoS* STC. Founded in 1964, OSC responded to a “*de-emphasis of optics in academic teaching and research together and a tremendous increase in the application of optics and a consequent shortage of personnel with training in optics*” [2]. Since then, COS has grown to meet changing national needs and is a premier center for research and education in optical engineering, optical physics, photonics, and image science. OSC (COS) is at the origin of designating the Tucson area as *Optics Valley* with many companies spawned from research at UA.

During the past few years, there has been a contradiction in the field of acoustics similar to optics in the 1960s. Despite acoustics being one of the most diverse areas in engineering, with a tremendous increase in technologies and applications in humankind’s day-to-day lives [3], there is an ongoing decrease in people trained in acoustics and a de-emphasis in acoustics research funding. Indeed, as a snapshot of personnel trained in acoustics, the 2015 data for the Acoustical Society of America (ASA) membership reveals an aging community with 50% of members being 50 or older [4]. ASA identified the following critical challenges to the future of acoustics: “*1. Lack of sustainable funding for research in acoustics, 2. Lack of understanding among policymakers of the value of acoustics, and 3. New ideas/discoveries are happening at the intersection of disciplines, not directly in acoustics*” (e.g., TA). *NewFoS* is in a unique position to reverse this trend by promoting US-based research, education, and workforce training in a new science of sound.

Legacy—technological and societal impacts. *NewFoS* will have the breadth, depth, and integration for intellectual, infrastructure, technology, human, economic, and academic legacies. *NewFoS*’ intellectual legacy will be an established, executable common scientific and technical language critical for productive transdisciplinary advances in the TA field and societal applications. The Center's infrastructure legacy will be new theoretical, computational, and experimental tools fundamental to design, process, and test unprecedented TA modalities, materials, and devices. *NewFoS*' human legacy will be a diverse workforce, who build on the diversity, equity, and inclusion (DEI) values of *NewFoS*, continue to produce and transfer new knowledge, and champion the transformative applications of the new science of sound for a vibrant US economic legacy. Our academic legacy will be context-based education resources and a Mentoring Ecosystem framework for workforce readiness at human/technology interfaces, including research experience and mentoring (REM). Our technology legacy will harness the extraordinary properties of sound and propose impactful solutions for a broad range of contemporary societal problems in information science, telecommunication, sensing, and imaging, as well as emerging and yet-unknown applications.

4b. Description of the Research Objectives of the Center

The two major research objectives of the Center are: (1) to broaden our understanding of acoustics by revealing all the hidden aspects of TA; and (2) to exploit the attributes of TA to make new or better technologies in traditional and untraditional applications of acoustics.

Imagine a new science of sound. The broader and deeper understanding of TA will pave the way to realize acoustic-encoded data that can transport without attenuation—critically, but "simply", signals using much lower power. We envisage the acoustic data-encoding will achieve capabilities analogous to quantum computers but without quantum fragility, which will translate to robust, massively parallel quantum-analogue acoustic information storage and processing that complement non-acoustic technologies. We imagine modalities to exploit TA waves with the capacities to reveal currently inaccessible information that will augment perception and reach unparalleled levels in sensing and imaging, such as the remote continuous monitoring of infrastructures and natural environments for permafrost thawing or fire risk, without any constraints from line-of-sight imaging or costly interventions in field surveying. We predict new methods that will multiplex and parallel-process all the information stored in TA waves for a generational revolution in the form, fit, function, and features of "next G" telecommunication acoustic devices. We can conceive the new science of sound revolutionizing precision-diagnostics and therapeutic technologies by leveraging TA–biology interactions. We imagine a future in which humankind harnesses the exceptional *new science of sound* through our integrative research (see §4b.1.2, §4b.1.3, §4b.3.2, §4b.3.3, and §4b.3.4).

4b.1 Integrative research

NewFoS will discover **yet-unknown aspects of TA** with the potential to revolutionize science and technology. *NewFoS* will use currently untapped attributes of TA waves (η, coherence, and robustness) to tackle two types of integration: (a) **problem-driven research projects** (§4b.1.2) that rely on TA to achieve unique solutions to today's grand challenges in information science, telecommunication, sensing, and imaging [1,5]; and (b) **possibility-driven research "seed" approaches** (§4b.1.3) that envision the future with TA as a foundational "engine". *NewFoS* participants will be mutually accountable and integrate their efforts within use-inspired scientific and technological research activities and tasks. These research tasks will be transdisciplinary, complementary, synergistic, and driven by well-defined milestones and outputs (across theory, numerical, and analytical tools, proof-of-concept experiments, testbeds, and prototypes) and outcomes (e.g., societal impacts). Performance metrics and mitigation strategies will assess success and lower the risks with guidance from industry partners and the **External Advisory Committee** (**EAC**).

4b.1.1 Yet-unknown aspects of TA: *NewFoS* has a core of pioneers and experts in TA who will push the research beyond the already extraordinary properties of TA waves and η, coherence, and robustness. For instance, *NewFoS* will investigate higher-order topological phenomena and extend current knowledge to topological robustness in the presence of multiple degrees of freedom. We will also tackle the open areas of research in nonlinear TA. By using synthetic gauge fields and synthetic dimensions, *NewFoS* will extend TA beyond the current analogies of quantum physics to offer new advances for coherence. These yet-unknown advances will be foundational resources for longer-term technological development (see §4b.3.2).

4b.1.2 Problem-driven research projects: **Integrative project 1**: *NewFoS* will ensure US leadership in a complementary approach to quantum technology without suffering from the fragility of quantum systems. By exploiting the quantum analogies and coherence of spin in TA waves, *NewFoS* will set foundations to transition to promising and validated modes of storing, processing, and retrieving massive information.

Integrative project 2: *NewFoS* will enable a generational revolution in wireless technologies by developing the first operational, low-cost, miniaturized, low-power, and functional TA proof-of-concept devices that exploit acoustic spin and robustness for advanced telecommunications.

Integrative project 3: *NewFoS* will overcome the current limits of remote-sensing technologies to monitor the natural environment in response to climate change. We will develop a TA η-based sensing modality for remote high-sensitivity, direct, and continuous monitoring of forested areas threatened by climate change (e.g., permafrost thawing in the boreal forest or soil dryness to guide wildfire prevention in the US).

4b.1.3 Possibility-driven research "seed" approaches: *NewFoS* will also drive innovation through its seed research program for possibility-driven research. Our aim is to invest in promising new TA research directions, where seed-level support sprouts new ideas in underexplored TA application areas and ultimately defines new problem-driven research projects (§4b.1.2). We will explore opportunities in biomedical engineering and medical sciences to create possibilities for better diagnostics, precision and safer drug delivery, and the therapeutic effects of sound. The seed program will be a mechanism to dynamically evolve the *NewFoS* research portfolio for maximal societal impacts.

4b.2 Specific role of participants and partner organizations in each research topic/goal area

Academic partnerships. *NewFoS* is led by UA and integrates team members from Caltech, The City University of New York (CUNY), Georgia Tech (GT), Spelman College (SC), University of Alaska Fairbanks (Fairbanks), UCLA, University of Colorado Boulder (UCB), and Wayne State University (WSU). The *NewFoS* data science activities will leverage UA's CyVerse cyberinfrastructure.

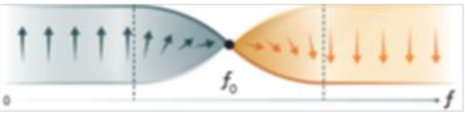
Industry partnerships. Through its EAC, *NewFoS* will engage industry in **information science** (General Atomics, Google LLC, Intel Corp.), **telecommunication and wireless technologies** (Qualcomm Inc.), **defense** (General Dynamics Mission Systems [GDMS], L3Harris Corp., BWD Associates LLC), and **microfabrication** (AdValue Photonics Inc., Intel Corp.) to effectively translate TA breakthroughs into new technologies. The EAC will include key stakeholder leaders who provide strategic oversight and enable our research and education activities to remain consistent with the Center's vision, while factoring in use-inspired guidance and the context of pragmatic business and community imperatives.

Education partnership. *NewFoS* will partner with experts in transdisciplinary and acoustic education, mentoring, DEI, evaluation (e.g., Online Learning Consortium), REM programs (e.g., at UW, Madison), and acoustic education (e.g., at Penn State). These experts will comprise our **Education and Broadening Participation Implementation Committee** (**EBIC**).

4b.3 Integration strategies and research plan

4b.3.1 A snapshot of the emerging TA field: Recent advances in fundamental TA are nucleating into a coherent body of knowledge. TA exploits the <u>complete range</u> of acoustic wave properties to embrace the domain of η—well beyond the traditional, canonical attributes of time (*t*) and frequency (*f*), the spatial degrees of freedom (***r*** or other coordinate systems), and the wave vector (***k***). Consequently, **TA is not an acoustics subdiscipline and redefines acoustics in terms of the full attributes of acoustic waves** [6].

The total phase of a wave is the sum of the dynamical phase and η. The former relates to the time it takes an acoustic wave to travel at its velocity along some path in the space it propagates. But η depends on the degrees of freedom of this wave that form its abstract parameter space (i.e., the "space of states" or Hilbert space and <u>not</u> the actual space in which sound propagates). The state of this wave is a vector in the Hilbert space, and η depends on the direction of the state vector. The η accumulated along a path in the parameter space represents the change in direction (or "angle") of the vector state in the Hilbert space given by the Berry connection [7,8]. To illustrate [7], the time evolution of the displacement of a driven harmonic oscillator follows the equation: $\frac{d^2u(t)}{dt^2} + f_0^2 u(t) = De^{ift}$ where f_0 and f are the oscillator's characteristic frequency and the driver's frequency, respectively, u is the oscillator's displacement, and D is the amplitude of the driver stimulus. The phase of the amplitude of u is zero if $f < f_0$ and otherwise π, and the amplitude is positive below f_0 and negative above. After normalizing the amplitude of u, we depict this behavior as a **geometric manifold** whose topology is a ribbon that spans the length of the frequency domain with a twist at f_0 (image *left*). The orientation angle of each arrow of the same length is η for the oscillator at that frequency.



For spatially dependent vibrational fields, and particularly a periodic-supporting medium, we can express the displacement field $u(\boldsymbol{r}, f)$ as a Fourier series over $\boldsymbol{k}$, which is also periodic. This series is a **coherent superposition** of $\boldsymbol{k}$-dependent states whereby the terms are phase locked. Then, we can represent the amplitude $u(\boldsymbol{k}, f)$ beyond the spectral and into the multidimensional $\boldsymbol{k}$ domain. Therefore, the geometric manifold in the periodic wave-vector domain may be a Möbius strip in the presence of a resonant or scattering process at a specific $\boldsymbol{k}_0$, which leads to a π change in η (image *right*). Importantly, the twist properties <u>preserve</u> for the Möbius strip manifold under continuous deformations, such as stretching (that changes f_0 or $\boldsymbol{k}_0$), crumpling, and bending—but not tearing or gluing. This invariance is the **signature of topological protection** against changes in the physical characteristics of the medium that supports the acoustic wave. **The TA "name" reflects the topological properties of the geometric manifold of acoustic waves**. Indeed, topology is the mathematical study of geometric objects/shapes that preserve or are "robust" under continuous deformation without cutting or gluing. For sound, examples of topologically induced properties are edge modes that exhibit **one-way propagation**, **backscattering immunity**, and **analogies to quantum mechanics**.

For topological properties, the medium or external stimuli must **break the symmetry** of the dynamics of acoustic waves. Conditions include breaking: (1) time-reversal symmetry, where $t \neq -t$; (2) parity symmetry, where $\boldsymbol{r} \neq -\boldsymbol{r}$; or (3) chiral symmetry for right- or left-handedness. Simple one-dimensional (1D) phononic structures, analogous to the condensed-matter Su-Schrieffer-Heeger (SSH) model, revealed many fundamental properties of TA waves, such as nontrivial topological invariants (e.g., Chern number), edge states at surfaces and interfaces between topologically different media, and bulk-boundary correspondence [9-12]. The latter is a powerful guide to design topologically protected edge modes [13], wherein the number of edge modes is the difference in Chern number between those topological phases sharing an interface. The SSH model breaks parity symmetry intrinsically via a system's structure. Spatiotemporal modulations of the elastic properties of 1D phononic structures can break time-reversal and parity symmetry [14,15]. Two- (2D) or three-dimensional (3D) TA systems exploited analogies with the quantum Hall effect (QHE) [16], quantum *spin* Hall effect (QSHE) [17], and quantum *valley* Hall effect (QVHE) [18]. 2D TA systems use triangular-lattice or graphene-like structures that exhibit Dirac degeneracies in their band structure, and symmetry breaking opens a gap associated with a nontrivial topology. Breaking symmetry intrinsically (e.g., parity symmetry) leads to acoustic analogues of the QSHE or QVHE. Extrinsically breaking time-reversal symmetry results in acoustic analogues of QHE. 3D acoustic and mechanical metamaterials demonstrated Weyl points and Fermi arc-like surface states [19]. The hallmark of spin-Hall insulators is the gapless edge states with different "spins" moving in opposite directions that lead to backscattering immunity.

NewFoS will build on TA knowledge to develop impactful applications for contemporary grand challenges and move into yet-unknown aspects of TA to create resources for future technologies.

4b.3.2 Yet-unknown aspects of TA that will revolutionize science and technology: The area of **higher-order topological phenomena** has been studied superficially. The notion of **topological immunity in the presence of multiple degrees of freedom** (i.e., when wave modes couple) remains a challenging aspect of topological protection. Open areas of research also include investigating the effects of **nonlinearity** on topological properties and nonlinearity onsets in TA. TA can exploit **synthetic gauge fields and synthetic dimensions** to advance beyond the current analogies of quantum physics. Next, we describe *NewFoS* research for each of these aspects.

Higher-order topological phenomena. **What is it?** We will tackle the possibility of realizing higher-order topological insulators (HOTIs) of n-th order in d dimensions [20,21]. HOTIs support the localization of $d-n$ or lower-dimensional gapless topological edge states, while bulk states and the entire hierarchy of $d-(n+1)$ to $d-1$ boundary states (surfaces states for $d=3$) have gapped spectra. Already, our team has realized proof-of-concept acoustic HOTIs based on Wannier-polarization and higher-order topology driven by generalized chiral symmetry, for 2D (d = 2) and 3D (d = 3). Yet, there is no implementation of higher-order Chern insulators (HOCI) in any physical system because of the complexity of their design. **Why does it matter?** Conventional polarization, wavelength division, space division, and normal modes approaches to multiplexing signals all inherently suffer from unwanted perturbations and defects in the channel, which lead to crosstalk and lower data rates. A topological multiplexing technology based on HOCI will be <u>immune to imperfections and unveil a new paradigm for robust signal processing</u>.

Topological immunity in the presence of multiple degrees of freedom. **What is it?** So far, TA immunity to defects on waveguides and substrates have been limited to a small number of degrees of freedom, and to a limited number of wave modes and polarizations [22]. *NewFoS* will drive fundamental knowledge on the robustness of immunity and challenge the notion of topological protection: (1) when multiple interacting wave polarizations exist; and (2) where coupling of wave modes may lead to diffraction and mode conversion phenomena. **Why does it matter?** Answering scientific questions about the sensitivity to defects of topological waveguides in the presence of mode hybridization will reveal novel design methodologies for higher data-rate acoustic filters and circuits for future "G" telecommunication.

***Nonlinearity*. What is it?** The effect of nonlinearities on topological properties and the onset of nonlinearities in TA are completely open areas. *NewFoS* will leverage pioneering preliminary findings in theory [23] and experiments [24] that suggest new TA phenomena, such as the delocalization of edge modes to the bulk, self-induced topological transitions [25,26], and topological nonlinear modes (e.g., topological solitons [27,28] or coherent superpositions of nonlinear modes [29]). **Why does it matter?** Nonlinearities in TA, such as amplitude-dependent edge states or the onset of topological solitons, open exciting opportunities to achieve low-loss, tunable, nondispersive wave-transport for telecommunication devices. The presence of sub/super harmonics may extend the scale of topological wave Hilbert spaces to the promise of massively parallel quantum-like computing platforms.

***Synthetic gauge fields and synthetic dimensions*. What is it?** To date, achieving robust edge modes in 1D requires the design of 2D topological spatial lattices. An alternative is to use nonspatial *synthetic* degrees of freedom to increase system dimensionality (e.g., a lattice with a specific sequence of modes in a mechanical system) [30,31]. It is possible to create topological states when the coupling of the *synthetic* sites and resulting gauge fields is from an additional external perturbation or geometrical parameters [32]. Transport for topological insulators in *synthetic* dimensions is at the edges of the *synthetic* space—not the system's spatial edges. **Why does it matter?** Modal synthetic dimensions can access arbitrary geometries and potentials that are unavailable in real-space lattices. High-dimensionality *synthetic* space with exotic features (e.g., long-range coupling, high dimensionality) will increase the data encoding capacity and lead to RF device designs with reduced form-factor and robust nonreciprocal transport.

4b.3.3 Problem-driven research projects (see §4b.1.2):

Integrative project 1 – TA quantum analogies for QIS

The quantum problem: At the core of quantum information science (QIS), quantum entanglement has the property of non-separability. While non-separability creates the possibility of operating in parallel on the coherent superpositions of states for multipartite quantum systems, the quantum coherent superpositions of wave functions (probability amplitude) collapse upon measurement or thermal fluctuations. Costly solutions are cryogenics and error corrections, which both use significant hardware and software resources.

State-of-the-art in quantum computing: Generating large, entangled states is a metric to characterize the performance of quantum information processing platforms. Experimentally, large multi-qubit entangled states (from a few to 65 qubits) have supported superconducting or photonic qubits, or trapped ions [33].

Advancing sound as a classical analogue of quantum-scalable, non-separable, multipartite states: Quantum computing is essentially phase computing; it exploits the possibility of achieving and rotating the coherent superpositions of states of correlated multipartite systems with complex amplitudes that are represented as vectors in large, exponentially complex Hilbert spaces. The notion of "classical entanglement" for sound waves has the non-separability and complexity essential to reach the promise of parallelism in quantum computing, yet without the fragility of decoherence even at room temperature. *NewFoS* members are pioneers of non-separable acoustic waves as classical analogues of quantum non-separable states [34] and introduced the "phi-bits" concept [35]. A phi-bit is a two-state degree of freedom of an acoustic wave (the acoustic spin), which can be in a coherent superposition of states with complex amplitude coefficients. Hence, a phi-bit is a qubit classical analogue—the critical component of QIS platforms. Theoretically, computationally, and experimentally (**Fig. 2**) we demonstrated the exponentially complex and scalable Hilbert space of states of multiple phi-bits (≤16 with 2^{16}D space) and the non-separability of coherent superpositions to reveal their QIS applicability [36].

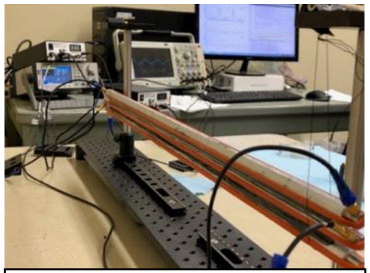


Figure 2. Coupled acoustic waveguide arrays supporting coherent superpositions of 16 nonlinear phi-bits.

NewFoS research tasks and products: In the tasks for integrative project 1 (**Table 1** and below), we will address the development of TA platforms supporting: (a) large exponentially-complex scalable spaces of states (Hilbert space) for multiple nonlinear phi-bits; (b) non-separability of coherent superpositions of nonlinear phi-bits; and (c) operations on coherent superpositions of large multiple phi-bit systems.

Table 1: TA quantum analogies for QIS – *NewFoS* research tasks and products.

Research Task (Problem-driven Project 1)	**Products**
Investigate nonlinear topological harmonic acoustics	Tunable coherent superpositions of large nonlinear phi-bit systems
Design/test coupled acoustic waveguide arrays to support superpositions of multiple nonlinear phi-bits (**Fig. 2**)	Establish experimental testbeds
Derive mathematics to quantum-like represent nonlinear multi phi-bits systems (Hilbert space change in coordinates)	Design high-dimensional Hilbert spaces
Develop the data analytics, ML search, and visualization of high-dimensional Hilbert spaces	Describe relation between experiments and representations
Complete discrete and continuous modeling and simulation	Systems evaluation and validation
Perform unitary operations in multi phi-bit Hilbert spaces	Large unitary operators/algorithms

(a) Exponentially complex scalable spaces of states (Hilbert space) of multiple nonlinear phi-bits. When driven externally at two frequencies, a metamaterial of an array of three elastically coupled acoustic waveguides produced a nonlinear displacement field, which we partitioned in the frequency domain [36]. Each waveguide is a finite-length aluminum rod with circular cross section that we arrange in a linear array with epoxy-filled lateral gaps (**Fig. 2**). Ultrasonic transducers drive and detect the acoustic field at the rod ends. Function generators and amplifiers excite two driving transducers at the ends of two waveguides with sinusoidal signals at frequency f_1 and f_2. Three detecting transducers at the opposite ends collect data on the displacement field. The nonlinearity of this driven system leads to many ways of mixing f_1 and f_2.

The displacement field measured at the waveguides' detection-ends are the Fourier sum of many linear and nonlinear modes, each with a characteristic frequency. The nonlinear modes (i.e., the phi-bits) correlate via the nonlinear interactions of the waveguide-transducer-amplifier-generator assembly. Subsequently, we define a logical phi-bit as a two-level, nonlinear mode of vibration whose state is a nonlinearly mixed frequency and spatial mode associated with two independent relative phases of the displacement between the waveguides. For an externally driven three-waveguide nonlinear system, we define the state of a phi-bit in a nonlinear acoustic mode, "*i*", by a 2 × 1 vector: $\vec{U}_{(i)} = \begin{pmatrix} \hat{c}_2 e^{i\varphi_{12}^{i}} \\ \hat{c}_3 e^{i\varphi_{13}^{i}} \end{pmatrix} e^{i\omega^{(i)}t}$ where the nonlinear angular frequency $\omega^{(i)}$ is a mixture of the driving frequencies. We normalize the magnitudes $\hat{C}_2$ and $\hat{C}_3$ to the first waveguide, and $\varphi_{12}^{i} = \varphi_2^{i} - \varphi_1^{i}$ and $\varphi_{13}^{i} = \varphi_3^{i} - \varphi_1^{i}$ are the two independent phases in waveguides 2 and 3 relative to waveguide 1. We unambiguously measure the amplitude and phases at the waveguide ends. This single phi-bit state lives in a 2D Hilbert space $h_{(i)}$ and spans the Bloch sphere.

The phi-bits colocate within the same physical space and are subject to distance-independent interactions. Tensor-product structures of systems that comprise many logical phi-bits (*P*=16) can support non-separable states in scalable, exponentially complex Hilbert spaces. Indeed, a noninteracting *P* phi-bit system's state is the tensor products of single phi-bit states, namely: $\vec{W} = \vec{U}_{(1)} \otimes \ldots \otimes \vec{U}_{(P)}$. The tensor product of the basis vectors of single phi-bit forms a complete basis for the states of the noninteracting multi phi-bit system. This basis defines a 2^P dimensional Hilbert space *H*, which is the tensor product of the *P* Hilbert spaces of the individual noninteracting phi-bits, $H = h_{(1)} \otimes \ldots \otimes h_{(P)}$. For nonlinear coupled-waveguide systems, the phi-bits interact and the Hilbert space is the same as for a noninteracting system; however, a state of the interacting system may be a separable or non-separable linear combination (with complex coefficients) of the basis vectors of *H*. We can then define different representations of the *P* logical phi-bit system by applying unitary transformations to the basis of *H*.

NewFoS will explore the space of representations leading to a multipartite tensor product structure conditioned by the measurability of the phases of each logical phi-bit. A representation can be chosen for its practicality in implementing large-scale non-separability or quantum-like operation. From a physical point of view for composite large numbers of *P* logical phi-bits (i.e., a set of $\{\omega^{(i)}\}$), we will investigate the relationships between driving parameters, including: 1) multiple frequencies (≥ 2); 2) relative magnitude of external driving forces, $\vec{F}_D$; 3) magnitude and range of tuning of driving frequencies; and 4) the relative phase between drivers, on the tiling of 2^P-dimensional Hilbert space *H.*

The description of high-dimensional Hilbert spaces needs both abstract and tangible metaphors. Our goals are to capture the coverage and investigate the variations of experimental parameters for discovery. We will directly plot responses and angle coverage, where tractable. We will use techniques for dimensionality reduction, such as PCA [37], ISOMap [38], and t-SNE [39], to convert our data to low-dimensional embeddings and view the intrinsic geometry of the data manifold. Finally, tools such as Mapper [39] will apply topological data analysis to the high-dimensional space, producing not only measures of sampling but also identifying the "structure" and "shape". This work will shed light on the scalability and controllability of large, exponentially complex non-separable superpositions of nonlinear acoustic waves at dimensions comparable to the current state-of-the-art in quantum systems.

(b) Non-separability of coherent superpositions of multiple nonlinear phi-bits. We will use density matrix, reduced density matrix ρ_r, and von Neumann's entropy to characterize the classical entanglement of coherent superposition of states of multiple logical phi-bits. Within a representation, a state "i" of a *N* phi-bit system is given by a $2^N \times 1$ vector with complex components, $|\psi_i\rangle$. By constructing the $2^N \times 2^N$ density matrix ($\rho = |\psi_i\rangle\langle\psi_i|$), we can calculate ρ_r for a chosen partition of the system into two subsystems. We calculate ρ_r by taking the partial trace over one subsystem. In turn, ρ_r can numerically determine the von Neumann's entropy ($S(\rho_r) = -\mathrm{tr}(\rho_r \log(\rho_r))$) as a measure of the classical entanglement of the partitioned subsystems [40,41]. A nonzero value of the von Neumann's entropy indicates non-separability. $S(\rho_r) = \ln\ 2$ is indicative of maximal entanglement. $S(\rho_r) = 0$ occurs when we can write $|\psi_i\rangle$ as a tensor product. In the case of multiple logical phi-bits, there will be many ways to partition the system, such as tracing out every phi-bit or pairs of phi-bits. Non-separability for different partitioning will quantify the overall entanglement of a multiple phi-bit system (**Fig. 3**).

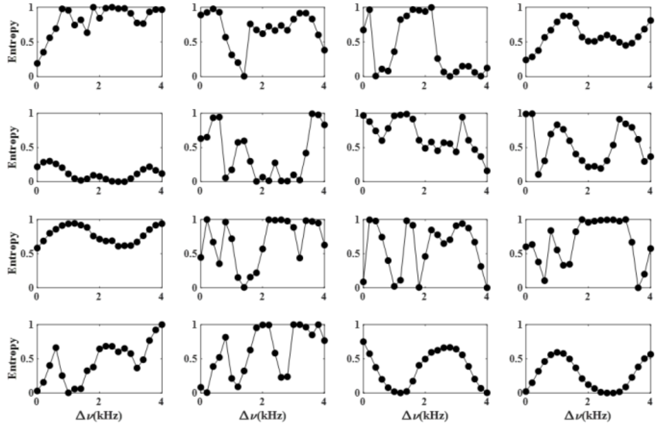


Figure 3. Variations in the entropy of entanglement (normalized to log2) of a 16 logical phi-bit system for all partitions of 1 phi-bit and 15 others. Δv is a tuning parameter of the driving frequencies. The data show extensive entanglement between all phi-bits.

ML will be fundamental for data analysis. We will apply recent techniques that train neural networks to classify separability [42] and quantum states [43]. Through gradient-based optimization [44], we will take a data-driven approach to identify optimal representations for desirable states. In addition, we will use ML processes to help enumerate possible samples that span and/or tile the large Hilbert spaces in *(a)* above. These will help steer our experiments to find ideal configurations for the desirable representations. Together, our visualization *(a)* and ML tools will: be vehicles for evaluation and validation; directly impact our risk mitigation components; and support our design phases for *(c)* below.

(c) Operations on coherent superpositions of multiple nonlinear phi-bits. Multi-bit logic gates are key to unlock quantum computing by implementing quantum algorithms. The multi phi-bit acoustic qubit analogue from *(a)* and *(b)* above will be the "hardware" for a quantum analogue computing platform, which is not susceptible to the drawbacks that plague current quantum computers. Importantly, developing multi phi-bit gates will demonstrate a possible strategy to implement "software" on a unique platform. Single-bit (Hadamard or phase gates) and two-bit gates (e.g., the fundamental Controlled-NOT [CNOT] gate) can form a universal set of logic gates for quantum-like algorithms; however, algorithms based on a universal set of gates suffer from significant computing overhead. To reduce overhead, we will seek single, large unitary transformations on multiple phi-bits that can operate as composites of conventional smaller operations. We will scaleup ML search to unitary transformations (gates) operating on large multi-logical phi-bit systems with high-dimensional Hilbert spaces and tunable experimental degrees of freedom [45]. We will use ML with gradient optimization to support the choice of representation to achieve the desired unitary operations. ML tools using enumeration algorithms will produce the different tilings of a Hilbert space within a given representation that leads to the desired operations.

Output: A tabletop operational 50 phi-bit quantum analogue information processing platform.

Outcomes: Decoherence-free, measurement-able, operable, non-separable TA-based phi-bits—analogous to qubits—will be core components for practical technologies that do not suffer from quantum fragility. *NewFoS* will open up promising and validated modes of storing, processing, and retrieving information that complement qubit technologies and drive US quantum leadership.

Integrative project 2 – TA wave RF devices

The RF acoustic wave device problem: Surface and bulk acoustic wave, S(B)AW, devices provide essential elastic energy transport in telecommunications to filter, guide, and delay RF signals [46]. Wireless technologies use S(B)AW devices due to the short wavelength of acoustic waves at cellular frequencies, small footprint, and high-quality factor. 4G smartphones use ~14 AW devices in a RF front-end module to filter signals of 4G RF bands. 5G demands even more filters with smaller bandwidth. Yet, since 2010 the device footprint has stagnated at ~1 mm^2 and temperature sensitivity degrades performance (50^{o}C increases the insertion loss by ~10–40 dB). Functionality is limited to guiding and filtering, which requires electronic/acoustic signal conversions with power loss. The generation of low-loss high-level functions is as a major opportunity in the development of AW devices to transform the technological landscape.

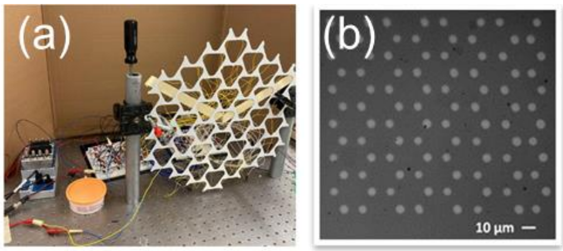


Figure 4. (***a***) Macroscale reconfigurable acoustic multiplexer–demultiplexer. (***b***) Microscale rewritable laser-patterned spin Hall insulator in a phase-change material film.

State-of-the-art: A SAW excites on a piezoelectric crystal substrate through interdigitated transducers, which determine the spectral characteristics. Elastic gratings reflect the wave and reduce insertion loss. Common single-crystal materials are lithium niobate and tantalate, which are anisotropic and serve only as mere wave generating and transport media. New functionalities will require more complex patterning, including deep (sub-)micrometer structures. Such patterning techniques are used for lithium niobate integrated optical devices (e.g., dry etching) but low-cost chemical (wet) etching is usually unusable for deep structures in lithium niobate [47].

Harnessing TA wave robustness and functionalities: Implementing guided-wave technologies in SAWs is a significant challenge due to the losses from defects, disorder, and sharp angles. Topologically protected edge/interface modes in large-scale structures will overcome this challenge by using efficient and robust signal transport with the support of backscattering-immune topological protection over broad frequency ranges. The tunability of the wave-supporting medium created switchable topologically protected interface states and enabled acoustic waves to travel efficiently from an input source to multiple output receivers, or vice versa, via dynamic topological interfaces [48]. Therefore, a TA multiplexer/demultiplexer [49] and also logic gates [50, 51] can add highly desirable functionalities to SAW devices (**Fig. 4a**). Microscale interface modes have been realized using complex microfabrication techniques [52]; however, the industry is high volume. Therefore, for the impactful integration and miniaturization of TA concepts into telecommunication products, we must break a materials/device microfabrication barrier. Indeed, it is highly desirable to use low-cost, industry-accepted constitutive materials with the elastic contrast, ease-of-patterning, and possible reconfigurability to produce the TA components with the desired transmission and functionality.

NewFoS research tasks and products: In the tasks for integrative project 2 (**Table 2** and below), we will: (a) design macroscale and microscale TA RF devices; (b) fabricate miniaturize TA RF devices on deep-structured piezoelectric substrates; (c) develop a nonvolatile TA RF material platform (**Fig. 4b**); and (d) test macroscale and miniaturized TA RF devices.

Table 2: TA wave RF devices – *NewFoS* research tasks and products.

Research Task (Problem-driven Project 2)	Products
Tune topological protection in acoustic spin-Hall insulators	Symmetry breaking principle for interface mode design
Design/test functional macroscale TA wave structures (**Fig. 4a**)	Macroscale testbeds
Fabricate lithium niobate-based guided-wave SAW devices	Microscale testbeds
Integrate the multiphysics simulation tools with ML	Fast TA computational design tool for devices
Demonstrate phase change material (PCM) 2D films on piezoelectric substrates and laser pattern TA structures (**Fig. 4b**)	Establish TA materials platform
Complete 3D micro-scanning testing of patterned substrates	Validate thin-film design

Test topological AW devices	TA RF devices performance

(a) Design macroscale and microscale TA RF devices. The boundary correspondence guides the design of topological phononic structures conditioned by the: (1) creation of counter-propagating edge modes with orthogonal degrees of freedom that may suppress backscattering; and (2) degrees of freedom that scatterers cannot mix. We will investigate the finite size effects that may lead to overlap between edge modes and eliminate immunity, and the effects of the structure or symmetry of scatterers on edge modes. A finite-element method will model and simulate macro- and microscale TA RF devices. Models in the COMSOL Multiphysics® Mechanical module will solve the 3D elastic wave equations numerically, including external driving. Devices will be plates for macroscale and thin films that we suspend or attach to a (piezo) substrate in miniaturized systems. For supported films, we will address confinement and wave leakage into the substrate. We will consider coupling in multimode band structures, and models will use experimental data for the elastic properties of constitutive materials. With the constraint of practical materials, we will design geometries that break symmetry, lead to edge modes with one-way propagation, and have tunability.

We will implement efficient methods to rapidly explore and optimize the band structures of periodic structures and classify their topological characteristics for complex unit-cell geometries. ML successfully augments the capability for traditional numeric simulation [54]. We will demonstrate ML benefits for TA multiphysics simulations and develop the computational infrastructure. Using ML, we will integrate experimental observations to feed data-driven input constraints to TA simulation. Further, as ML can infer sub-grid resolution properties, this approach will improve the fidelity of simulations and reduce the overall computational cost. We will employ such techniques in TA simulations to improve the quality and quantity of simulation data, and enable *NewFoS* to couple simulation outputs at multiple scales simultaneously.

(b) Fabricate miniaturized TA RF devices on deep-structured piezoelectric substrates. Lithium niobate is a robust piezoelectric material readily available in single-crystal substrate forms to fabricate miniaturized TA-RF devices. It is an ideal platform to create, detect, and control acoustic signals at the microscale through the lithography of interdigitated or other-patterned electrodes. Direct topological control of the resulting acoustic wave can then occur through hole patterning of the substrate itself. The large contrast in elastic constant between the air-holes and the solid substrate will enable the design and fabrication of low-loss, sharp-angle integrated acoustic circuits. A main obstacle to broadly develop this platform, however, is that lithium niobate is incompatible with standard CMOS process. Therefore, we will develop an alternative rapid fabrication approach for low-cost TA circuits with high spatial resolution and high tolerance, using laser micromachining. This method has been commercialized by one of our industrial partners (AdValue Photonics Inc.) to micromachine solid substrates at the microscale using high-power fiber-laser sources (**Fig. 5**). The spatial resolution limit is the diffraction limit. Hence, we will collaborate with AdValue Photonics to use its ultraviolet (UV) fiber-laser and develop a process that rapidly fabricates large-scale, complex micron-scale hole patterns on single crystals compatible with acoustic wavelength and miniaturize TA-RF devices.

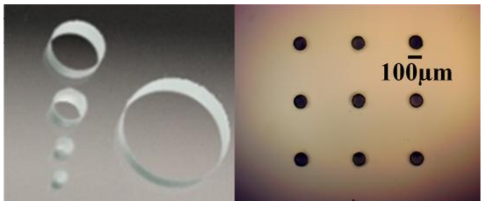


Figure 5. Submillimeter hole patterning in a solid substrate by near-infrared laser micromachining.

(c) Develop a nonvolatile TA RF material platform. We will develop a novel material platform to design endlessly reconfigurable and tunable TA-RF circuits. This platform will exploit the properties of PCMs such as GeSbTe, which can reversibly switch between crystalline and amorphous phases with electrical or optical actuation [53]. This is a well-established platform in microelectrionic and optical storage due to the high contrast in conductivity and reflectivity between the two phases, which can binary encode information. The two phases also have a high contrast in elasticity (>50%), which so far has not been exploited for acoustic-based applications. We will fabricate and demonstrate the potential of TA-RF circuits based on PCMs. The expected advantages include ultrafast switching for rapid modulation (nanosecond), extensive cyclability for long device life (10^{15} cycles), and CMOS processing compatibility. Highly complex patterns with topologically protected edge/interface modes can be produced on the microscale (see **Fig. 6**). The resulting circuits

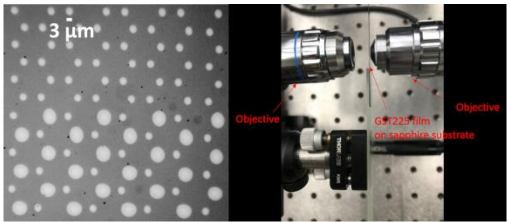


Figure 6. Microscale patterning of an antisymmetric structure photo-written on a PCM film of composition $Ge_2Sb_2Te_5$.

are nonvolatile, i.e., stable without power, yet they can be reconfigured/modulated at MGhz speed. We will address several materials challenge, such as matching the PCM bandgap and laser wavelength to optimize the switching in thick (several µm) PCM slabs compatible with acoustic wave transmissions.

(d) Test macroscale and miniaturized TA RF devices. Our high-throughput testing of TA patterns in lithium niobate or PCM will use a Polytec MSA-100-3DSV Micro System Analyzer with a sub-picometer amplitude resolution regardless of the vibration direction. That is, it acquires and analyzes the complete motion vector with high resolution both for out-of-plane and in-plane components. We will analyze the dynamical behavior of TA-RF structures over a wide bandwidth and in real time to provide a window on the band structure and mode symmetry. We will test the performance of promising TA-RF patterns integrated with interdigitated electrodes (using the *NewFoS* accessible micro-nano-fabrication facilities and with industry partners Intel Corp.) for loss, quality factor, transmissibility, temperature sensitivity, and functionality. We will integrate PCM-based platforms within piezoelectric device structures.

Outputs: Microscale TA wave device with low loss (i.e., frequency × Quality factors >10^{13}), tight temperature drift, 5G-exceeding data transfer rates of 20 Gbps, and multiplexing and tunability functionalities.

Outcomes: Demonstrating the first low-loss topological AW filter and functional devices will “game change” the telecommunications industry. CMOS compatibility and laser-induced phase-tuning will tremendously extend the operation and application ranges of TA-based AW technologies.

Integrative project 3 – TA sensing of the natural environment

Environmental and societal problems: Melting arctic permafrost and alpine-ground release greenhouse gases, affect local communities with subsidence, and threaten infrastructure [55]. A drier future sets the stage for devastating forest wildfires across the US. Adapting to this future will require effective and continuous monitoring of ground changes.

State-of-the-art sensing: Boreholes and drilling sites remain the main data sources to construct rough permafrost maps, but without continuous monitoring. Remote sensing relies on aerial and satellite imaging that indirectly measure ground characteristics. Optical methods have limited utility in forested environments with features outside the direct field of view, whereas acoustics bypass the constraints of optical obstructions in an alternate for remote sensing. Seismic methods monitor the state of permafrost by the velocity changes for compressional- and/or shear-waves following freezing/thawing of soil [56].

TA sensing approach to exploit η: Essentially, the conventional approach to acoustic sensing has relied on the spectral or intensity response of a system or environment’s sound field. The geometric phase of acoustic waves (η) has hitherto been excluded from sensing approaches. Therefore, incorporating η in sensing modalities will reinvigorate the field of acoustic or seismic sensing.

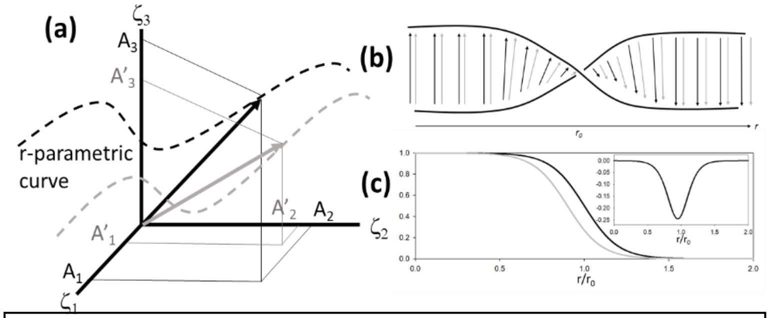


Figure 7. Navigating the Green’s function Hilbert space by varying the driving parameter *r*. (***a***) The state vectors in the absence and presence of a perturbation (*black and grey arrows*, respectively) are expressed in a basis ζ_1, ζ_2, and ζ_3 and span the paths shown as *dashed lines*. (***b***) Schematic of the corresponding topological manifold as a twisted-ribbon supporting the state vector of the unperturbed (*black arrows*) and perturbed (*grey arrows*) systems as *r* is varied. The additional rotation in Hilbert space for a given *r* due to the effect of the perturbation, leading to an effective translation to the right on the manifold (*grey arrows*) along the *r* axis. (***c***) Schematic of the rotation angle of the state vectors (η) (in units of π) for the unperturbed (*black line*) and perturbed (*grey line*) systems. *Inset*, $\Delta\eta(r) = \eta(\text{perturbed}) - \eta(\text{unperturbed})$ shows large sensitivity to the perturbation near the twist.

There is an intimate connection between an acoustic wave’s η and its Green’s function [57]. The acoustic Green’s function is the point displacement response of a system given an impulse at another point in the system, which depends on the response and stimulus positions. An external driver produces a stimulus that is controllable through parameters such as the magnitude and distribution of applied forces, frequency, and/or time. On an orthonormal basis, the Green’s function is a vector in a multidimensional complex Hilbert space and η depends on the state vector direction (**Fig. 7**). By varying the driver controllable parameters, the state vector parametrically spans a path in the Hilbert space. η accumulating along a parametric path is the change in direction (or "angle") of the vector state in the Hilbert space. We depict the variation of the state vector as a geometric manifold whose topology may not be conventional. Due to scattering, perturbations such as imperfections, structural defects, or local or global changes in properties of the system/environment lead to an additional rotation of the state vector, which will follow another parametric path and span a different part of the topological manifold. Manifold regions with sharp topological features, such as twists, offer high sensitivity to the presence of perturbations. There is no theoretical limit to the magnitude of detectable perturbations.

From an experimental viewpoint, the sensitivity will depend on the accuracy of the phase measurement. The choice of basis (i.e., the mathematical representation of the Green's function determines the sharpness of topological features in its Hilbert space) can also help maximize the TA sensing modality's sensitivity. Dissipation may affect sensitivity through the sharpness of topological features, e.g., for resonant scattering. We experimentally validated this method with our industry partner GDMS by: (1) using arrays of coupled acoustic waveguides (see **Fig. 2**); and (2) varying the driver's force distribution to detect a small mass defect by η change [58]. A 1% mass change led to a large, easily detectable change in phase of nearly π/4.

By exploiting η, TA can be a sensing modality for the remote, direct, and continuous monitoring of forested areas. Long-wavelength seismic waves are pertinent for the TA sensing of forested environments. Few-tens of Hz seismic waves interact strongly with trees [59] by resonant scattering that changes η. The ground stiffness influences this phase change, which relates to subsurface temperatures changes for permafrost and/or forest-floor moisture levels. For model forests, *NewFoS* members demonstrated the nonlinear behaviour and high sensitivity in the change of η with the ground state. Our preliminary theory predicts large detectable changes in phase due to changes in ground stiffness/temperature (up to 3π/1^{o}C) for frequencies near tree resonances [60], versus a wave velocity change of only 2–3%/1–3^{o}C for current seismic methods [61]. The power of TA sensing lies in η being a sensitive global metric for the wave-scattering environment.

Table 3: TA sensing of the natural environment – *NewFoS* research tasks and milestones.

Research Task (Problem-driven Project 3)	**Products**
Develop Green's function approach for TA sensing	η and resonant scattering theory
Implement laboratory-scale acoustic models for testing TA sensing modalities for forested landscape (**Fig. 8**)	Experimental laboratory-scale testbed
Develop cross-correlation retrieval of the Green's function's phase from detector arrays [62] and understand dissipation	ML modality to extract η in dissipative media
Demonstrate the inverse problem physics-based ML for uncertainty quantification and optimization	Method evaluation and validation
Execute km-scale seismic testbed deployment and testing	Scaled-up testbed
Deploy at the Murphy Dome testing site (Alaska)	Qualification

NewFoS research tasks and products: In the tasks for integrative project 3 (**Table 3** and below), we will develop TA sensing modalities through: (a) modelling; (b) laboratory-scale; and (c) field-scale experiments.

(a) Modeling. We will use Interface Response Theory [63,64] to calculate the diffusion matrix of the Green's function for model systems of ground-connected trees, which shows a scattered wave's phase with respect to frequency. Here, frequency is the controllable stimulus parameter. We will model the ground as a semi-infinite elastic medium with an elastic slab representing the permafrost top layer. Trees will be 1D-stubs elastically attached to the ground. The Green's function for the slab and semi-infinite ground are known in Fourier space and will require 2D Fourier transform to convert from k- to real space. We calculate the Berry connection (i.e., variation in η as a function of the eigenvalue E, or effectively the frequency ω) as $BC(E) = -i\,Tr\left(\hat{G}^*(E)\,\frac{d\hat{G}(E)}{dE}\right)$, where *Tr* is the trace over the entire spatial domain spanned by the Green's function. After we calculate the η versus ω for a particular spatial distribution of trees, we will ascertain the relationship between η and the ground stiffness and connect the calculations to ground temperature. Experimental field data relate permafrost stiffness to temperature—the elastic modulus of permafrost varies inversely with temperature from as high as 8 GPa to as low as 2 GPa over -12°C to -1°C [65]. We will numerically extend the model to incorporate dissipation and nonlinearities using the finite element method.

(b) Laboratory-scale experiments. We will use three laboratory-scale models to investigate the topology of the Green's function manifold. The *first model* (**Fig. 8**) will be a mock-up of a forested environment with metal substrate (ground) and elastically attached resonating stubs (trees). Here resonant scattering by the stubs will lead to π jumps in the phase. A corresponding twist in the Green's function manifold will enable sensitive detection of changes in the properties of the substrate and its relation to the topography and heterogeneity of the stubs. The *second model* will be an array of elastically coupled waveguides (see **Fig. 2**) to investigate the detection of added masses by varying the drivers' force magnitudes and relative phases. This system will have the extra advantage of exploring the choice of representation for the Green's function, i.e., the choice of basis for altering the topological manifold and understanding how to optimize the sensitivity of the phase to defects. The *third model* will be a granular system comprising a finite number of elastic spheres that couple via a controllable nonlinear Hertzian contact. In a nonlinear regime, we can express the driven displacement field (Green's function) as a product basis of nonlinear normal modes, which define the system's Hilbert space and topological manifold. The complex coefficients of that representation are Fourier sums of harmonics and time dependent. Time parametrizes the path in the system's Hilbert space, enabling detection of perturbations near sharp topological features. The nonlinearity of the second model will also allow us to investigate time parametrization. These three models will shed light on important factors that we may encounter in the following field-scale experiments, namely: topography and heterogeneity of the environment; spatial and magnitude characteristics of the stimulus; and dissipation and nonlinear effects.

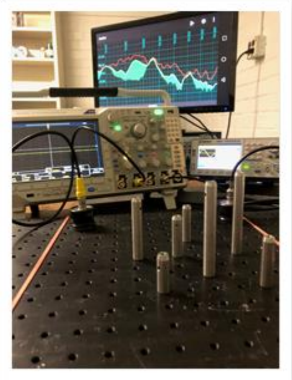


Figure 8. Laboratory-scale proof-of-concept acoustic model of a forested landscape built with steel stubs on an aluminum plate.

(c) Field-scale experiments. We will use seismic sensors to monitor ground-supported waves (e.g., Rayleigh waves and Q [Love] seismic waves scattered by the longitudinal and flexural vibrational modes of trees). Wave sources may include natural seismic and human-caused activities due to oil and gas prospection, construction, and ground transportation. We will sense waves with a frequency up to a few hundred Hz, and test several commercially available broadband portable seismometers (to be loaned from the NSF-supported Incorporated Research Institutions for Seismology consortium) for their ability to provide phase information through postprocessing. The on-loan seismograph stations will also include data recorders, telemetry, and reception systems (see §5).

We will measure the environment's acoustic response by two approaches. One way is to excite an acoustic wave at one location and measure the response with a seismic detector at a second location. Using the detector's response, we can then relate changes in the seismic wave's η to changes in permafrost properties. A passive approach is to use an ambient noise correlation for at least two seismic detectors to measure latent acoustic waves in the environment due to human and natural processes [66,67]. We will cross-correlate the spectra of the two sensors to extract the Green's function and its phase [68-70]. We will enhance this approach with ML techniques and data mining to extract signals from the noisy data. Following best practice in seismic sensing, our km-scale network will comprise a minimum of three seismograph stations to accurately triangulate a source of ground-supported sound—important in case we do not know the source's location. With location identified, we can then separate the dynamical phase from η. The spectral dependency of η will be the global signature of the land cover characteristics.

Our primary testing sites in interior Alaska will be at Murphy Dome at the edge of the tree line in the boreal forest (64°57'09.4"N 148°21'11.8"W). This site exemplifies many characteristics of the intersection of the built and natural environments. Being near a former gold mine and a public road, this area has a freshwater river system and is on an airline corridor for "the bush" planes and global commercial routes (Asia, great-circle, and Arctic flights). Approximately 25-km from Fairbanks, the Murphy Dome location is private, and we have use permits. The location is ideal as we have all the GIS and environmental data at hand.

Output: High-sensitivity, km-scale field tested TA-seismic ground sensing platform that respects the Interagency Arctic Research Policy Committee's code of conduct.

Outcomes: TA will forge practical, low-cost analytical strategies to extend acoustic sensing, characterize landscapes with continuous/regular monitoring, and alleviate expensive platforms, such as satellite imaging. Due to its topological nature, this method will aid in developing grid-based atlases of ground quality and be easily translated to continuous monitoring of other environmental and infrastructure changes.

4b.3.4 Possibility-driven research "seed" approaches program *(see §4b.1.3)*: Our seed program will support 1–2-year possibility-driven projects. The competition for funds will be open to faculty at *NewFoS*-participating institutions, and their students/postdoctoral researchers (postdocs) with endorsement from the faculty advisor(s). Proposal solicitations will be two months before the **all-Center annual meetings** (§4f.2). A committee of the Center Leadership Team (CLT) and EAC members will evaluate proposals against our mission and consider intellectual merit, transdisciplinarity, path to a proof-of-concept, and broader impacts. We will announce funded projects at the next all-Center meeting. Below, we describe biosignaling examples of possibility-driven projects. Other examples include water purification using acoustic cavitation [71], and enhanced sensitivity in the nondestructive evaluation of infrastructures using exceptional points [72].

Examples for TA and biosignaling

The effects of sound on health: Sound wave and living tissue interactions were reported in the early 20th Century. Today, ultrasound-based therapies treat many medical disorders [73]. But prolonged exposure to noise is a major environment-related cause of ill health, including cardiovascular diseases [74]. The therapeutic and ill-health effects of sound on biological processes are essentially unknown or speculative.

TA and calcium signaling in endothelial tissues: Ca^{2+} is a universal messenger and mediates dynamics in cell functions [75]. *NewFoS* researchers hypothesized a previously unrecognized effect of sound waves on gap-junction-based Ca^{2+} intercellular signaling, e.g., in biological tissues comprising endothelial cells [76]. We posited that sound irradiation may create topological Ca^{2+} signals with unidirectional propagation, via the spatiotemporal modulation of cell-to-cell conductance to break parity and time-reversal symmetry.

NewFoS research tasks and products: In the example tasks in **Table 4**, we will identify and experimentally study the phenomena of nonconventional topology and nonreciprocity of propagation for gap-junctions-based intercellular signaling induced by acoustic irradiation.

Table 4: TA and biosignaling – *NewFoS* research tasks and milestones.

Research Task (Possibility-driven Project)	Products
Culture/pattern endothelial cell networks	Experimental testbeds
Design a fluorescence microscope supporting acoustic waves and test sound-induced symmetry breaking of Ca^{2+} signals	Experimental demonstration setup
Ultrasound sensing and imaging of endothelial Ca^{2+} signal	imaging-signal interactions

Output: Experimental demonstration of sound-induced topological biological signal.

Outcome: This high-risk, possibility-driven research will significantly impact the interpretations of biological phenomena tied to the beneficial or harmful effects of sound on health.

4.b.3.5 Integration of projects: Our problem-driven integrative projects will use the three complementary untapped attributes of TA waves (η, coherence, and robustness). In integrative project 1, the control of classically entangled TA waves with measurable η will inform new strategies in integrative project 3 to exploit coherence for scattering-based η sensing with reduced noise-to-signal-ratio. In integrative project 2, the design of robust edge modes in microscale devices offers paths to: (1) generate new types of acoustic spin-based coherent non-separable superpositions of states; and (2) miniaturization of platforms to support these states relevant to integrative project 1. In the example possibility-driven project, we will propose strategies to exploit strong nonlinearity relevant to integrative projects 1–3.

4c. Description of the Education and Human Resource Development Objectives of the Center

4c.1 Education and Human Resource Development (E&HRD) objectives, focus, and recruitment

Center E&HRD objective. *NewFoS* will graduate students and postdocs as technologists, researchers, leaders, and policymakers who are well-versed in the broad science, technology, and societal aspects of the new science of sound. The expected outcome is a diverse workforce who contributes to society through team-based science-of-sound and engineering solutions, develops marketable products for US economic growth and positive societal impacts, and drives research to advance revolutionary sound applications.

Focus of E&HRD activities. We will develop and pilot the resources to prepare a diverse workforce with the key baseline knowledge to understand the complex and difficult notion of TA for effective applications in information, communication, imaging, and sensing. A Logic Model (**Table 5**, below) shows how we will tailor experiences by designing, applying, and evaluating integrated programming for: (1) **Convergence Education** in the new science of sound (this Section); and (2) a **Mentoring Ecosystem** (see §4d).

An all-institution **E&HRD and Broadening Participation Implementation Team** (**EBIT**, see §4f) with expertise in DEI and mentoring will guide the E&HRD activities.

Integrative education. The education program will be *outcome* and *output* driven to effectively integrate with *NewFoS'* research and build on the commitment to DEI that the Hispanic-Serving Institution (HSI) designation symbolizes at UA. **Outcome 1**: Develop the context-based and pedagogical TA resources necessary for the next 50 years of acoustic education [77, 78]. **Output 1**: Produce the first textbook for the broad field of TA—beyond *conventional* acoustics—to establish the executable common scientific and technical language critical for interdisciplinary advances and productive US societal applications. **Outcome 2**: Produce the foundations and evidence-based principles for a multi-institution, transferable Mentoring Ecosystem and workforce readiness at human/technology interfaces [79,80-82]. **Output 2**: Across *NewFoS*, deliver an effective trans-university and inclusive Mentoring Ecosystem based on REM principles.

Integrative education activities. Our E&HRD activities are to: (1) create a TA textbook that informs the field for the next 50 years and inspires the societally impactful solutions of the next 20 years; (2) develop undergraduate research opportunities in transdisciplinary TA fields; and (3) offer an undergraduate-level *New Science of Sound* curriculum-design seminar course.

Recruitment and retention of students. ***Recruitment.*** We will recruit on four fronts: (1) marketing at conferences, e.g., AISES (American Indian Science and Engineering Society), ASEE (American Society for Engineering Education), HACU (Hispanic Association of Colleges and Universities), and SACNAS (Society for Advancement of Chicanos/Hispanic and Native Americans in Science); (2) leveraging the established undergraduate research programs at all partners, e.g., NSF REU and Louis Stokes Alliance for Minority Participation (LSAMP) projects; (3) engaging the TRiO Student Support Services and McNair programs at UCB, CUNY, and UA, and UA's S-STEM projects, to access their national networks—students are first-generation, low-income, and/or from groups historically underrepresented in STEM; and (4) using NSF's Education and Training Application. Building on the established UA-UC San Diego (UCSD) REM program, prospective students will prepare two essays: their motivations for research in a societal context and their aspirations as a STEM researcher. The EBIT will review applications and select students to invite for our E&HRD programs. ***Retention.*** Multiple E&HRD activities at *NewFoS* will promote student retention, including inclusive practices, undergraduate research and mentoring, and cultural responsiveness and context programs. Our Mentoring Ecosystem (see §4d*)* will be a cornerstone in how *NewFoS* creates the environment to support students' successes, maintain students "on track", and increase retention.

Table 5: Logic Model for Convergence Education (E&HRD) and Mentoring Ecosystem (BP) Activities.

Inputs	Activities	Five-year Outputs	**Outcomes: S** = Short; **M** = Mid; and **L** = Long **Term**
STC Funds Researchers	**Convergence Education** ***Context-Based Textbook Modules.*** Develop curriculum per 5**E** framework [88]; Real-life examples; Solution driven.	10 TA textbook modules tied to societal impacts (inclusive, asset-based); DEI metrics	**S:** UGs with TA laboratory experiences

(Faculty and Postdocs) Staff Educators Students (Undergraduate [UG] and Graduate) Institutional partners Industry Partners Online Curriculum Design Experts UA Facilities Evaluators	***Community College (CC) Research Workshop.*** TA introductory workshop for CC transferees to 4-year institutions. ***Curriculum-Design Seminar Course.*** Semester course; 5E lesson design. **Mentoring Ecosystem** ***REM 12-month Program.*** Eight-week summer program + nine-month one-unit seminar courses (weekly meetings); Monthly EBIT-led all-REM student digital meetups; Student presentations/ posters to research teams/EAC. ***DEI Training for all Researchers and Staff.*** Design all-Center DEI program; Training plus annual workshops; Monthly development meetings; Sessions at annual all-Center meetings. ***Faculty Bridge Awards program.*** CLT nominate.	Print and digital textbook versions for distribution 20+ student-designed module addendums (Years 2–5) One publication/PhD student every two years 80+ UGs enroll in the Curriculum Design Seminar course 20+ PhDs awarded 10+ postdocs trained in TA and mentoring 56 UG students apply to REM, including from minoritized backgrounds 56+ student presentations/ posters 100+ of all-Center personnel complete DEI Training DEI Training and support modules/program dissemination Two HSI Faculty Bridge Awards project proposals/year	**S:** Active and diverse student pathways into TA workforce and research **S:** Students cocreate textbook modules **M:** First TA textbook used in UG and graduate student courses **M:** Students create online module addendum **M:** HSI-trained faculty use DEI practices with their groups **L:** Active and diverse workforce knowledgeable of the science of sound **L:** Replicable inclusive-excellence Center model **L:** HSI-trained faculty seek leadership pathways and positions to introduce institutional practices within their unit, department, or institution
Evaluation: Formative and summative methods. Tools include pre/post surveys, interviews, reflections of all-Center participants, evaluation of Center products, reports of demographic data and the DEI program design.			

4c.2 E&HRD Activities

E&HRD Activity 1 – Acoustic and TA textbook

An acoustic education problem: For 100 years, students studied vibrations and sound propagation mostly through a limited number of textbooks [83,84] grounded in Rayleigh's "Theory of Sound" [85]. Since TA extends beyond conventional acoustics, students need contemporary educational resources.

Activity: Based on our experience [86,87], we will develop a textbook for the theory of acoustics and TA. Real-life examples and models will follow 5**E** Inquiry-Based Instructional best practice [88] and context-based learning. Experiential reasoning will **e**ngage students with real-world problems and challenge them to **e**xplore and uncover aspects that help them **e**xplain complex TA phenomena. We will challenge students to **e**laborate their understanding through knowledge transference activities that showcase their deepening understanding and use reflections and feedback to **e**valuate learning. This textbook will include hands-on contextualized considerations related to experimental techniques, TA materials/structures, data analysis and analytics, and societal impacts. To further engage students and scaffold their skills and knowledge acquisition, *NewFoS* students will co-design content to capture the learner perspective, with mentoring.

This textbook will rely on timely, relevant content with support from useful, attention-grabbing digital content, including virtual content, videos, and digital demonstrations that explain, contextualize, and explore the societal impacts of acoustics and TA. Exercises with corrections and interactive quizzes will engage students in the learning experience and enable them to elaborate on their understanding. Suggested accessible activities, simulation tools, and low-cost laboratory experiments will provide transferable resources for educators and exploration platforms for students. To support the curriculum-design process, we will offer a hybrid TA curriculum-design seminar each Fall that captures the relevant hands-on activities that students want as part of their learning experiences (see E&HRD Activity 3 below, for additional details).

Student support: Undergraduate and graduate students will participate in the design of the modules to ensure they are more inclusive of how students want to be taught.

Evaluation: Evaluators will collect publisher metrics as a measure of the textbook success (see §4f.5).

Potential impact: With wide distribution (probable publisher: Springer), the textbook will become essential for 50+ years of acoustic and TA education. The textbook will establish the executable common scientific and technical language critical to advance TA through interdisciplinary developments. The next-generation TA curricula will educate and train a culturally and technically diverse workforce to translate TA innovations and entrepreneurship within the contexts of societal impacts and values.

E&HRD Activity 2 – Community College research workshop

Activity: Opportunities to foster undergraduate pathways into the emergent field of TA will be critical in the learning experience. We will create a five-day undergraduate research workshop for Community College (CC) transfer-students, specifically to: (1) introduce students to TA from a societally relevance lens; and (2) connect to the science and mathematics that underpin the field. This will be a Phase 1 learning experience for CC students transferring to a four-year institution, to take place while they are still at a CC. We will also encourage the transfer students to apply for the REM program (Phase 2 learning experience) over the following summers when they are rising juniors or seniors at a four-year institution.

Evaluation: Evaluators will conduct pre/post surveys and interviews, and assess students' products for comprehension, communication effectiveness, and societal relevance (see §4f.5).

Potential impacts: Cohorts of CC undergraduate-transfer students will gain a strong sense of belonging in STEM, *NewFoS*, and higher education, and opportunities for rich careers in STEM-related fields.

E&HRD Activity 3 – Curriculum-design seminar course

Activity: We will offer a 1–3 unit design seminar for students to learn about TA curriculum design. The course will be in two sections: one at UA and one at UCB. Undergraduates in the REM program will automatically be part of the TA curriculum-design seminar. We will partner students with faculty to work on modules—going through the curriculum-design refinement process to create TA modules for learners. The seminar course will help college-level students to breakdown the elements of lesson design, identify scaffolding needs, and capture experiential-learning ideas that convey the complexity of a subject. Team members successfully used this approach for graduate students partnered with Tucson middle school teachers, which led to student-designed lessons and learning activities.

The course will also help guide students on how to apply effective digital-learning pedagogies tied to universal design and inclusive learning relevant for TA textbook activities (E&HRD Activity 1). Students will use approaches that are: (1) effective in serving diverse learners [89,90]; and (2) grounded in systems conceptualization and integrated thinking to adapt to the needs of both the learners and future employers [81, 91]. Thus, we will ensure to design inclusive experiential-based lessons and digital practices. In Year 1, EBIT will support the faculty and students to design the modules, train faculty on inclusive practices, and use metacognitive and work-based pedagogy [92,93] to educate students in the transdisciplinary TA field. To ensure cultural responsiveness and context, students will conduct a community needs assessment to determine what elements of sound are of interest or concern to local communities and industry [94,95].

The seminar course will: (1) expose students to an understanding of the elements of curriculum design based on real-life needs; (2) introduce students and faculty/researcher partners to the lesson-design process; and (3) develop skills in writing and communication of TA-based technology. Designed in Year 1, we will "soft launch" the course in Year 2 at UA and UCB with a maximum of **10 students at each location**. We expect an **average of 10 UA and 10 UCB students each year** to complete this course during Years 2–5 for a conservative total of **80+ students**. For Years 3–5, we will recruit from all the *NewFoS* partner institutions and ask prior participants to recommend the course. Additionally, advisors will solicit the course to students during their spring advising session in time for fall enrollments.

Evaluation: Evaluators will inform the development of the seminar design course via formative course surveys, curriculum reviews, and evaluations of the faculty, staff, researcher, and student experiences (see §4f.5). They will leverage evidence-based strategies for curriculum design [78,81,89,96,97], and guide faculty to apply *Universal Design for Learning* [98] and engage, represent, and express in learning spaces [99, 100].

Potential impacts: Students who co-create the modules will gain publication credit. Ultimately, students will gain skills to design societally relevant addendum modules or projects that become available online.

4d. Description of the Broadening Participation Objectives of the Center

4d.1 Broadening Participation (BP) objectives, focus, and recruitment

Mentoring Ecosystem objective. *NewFoS* will pursue the following BP objective: "By adopting the methods and principles of inclusive excellence, *NewFoS* will create a multi-institution transferable **Mentoring Ecosystem** to develop an inclusive culture and recruit, retain, and achieve a diverse workforce." The Mentoring Ecosystem will realize richer professional relationship building, successful educational experiences, and stronger team dynamics for students, postdocs, and early-career scientists—in a collective of innovation. This strategy will complement our **Convergence Education** (§4c) to: (1) positively impact mentees and ensure DEI; (2) reveal and prepare career paths; and (3) build professional skills.

Focus of BP activities. BP activities will be the responsibility of EBIT (see §4c). *NewFoS* will ground its DEI focus in an inclusive excellence model from the *Making Excellence Inclusive* initiative. This multiyear model seeks an entity: "*both different than its constituent elements and stronger and more durable*." Our key components will be to: (1) integrate DEI with our research and E&HRD activities; (2) situate DEI at the core of all functions to broaden participation; and (3) realize and sustain the benefits at all organizational levels and institutions [101-103]. To achieve DEI, we will train *NewFoS* faculty and staff, including asset-based inclusive teaching and mentoring practices for cultural responsiveness and empathy [101,103,104].

Yearlong *NewFoS* mentoring will engage all our: (1) female students, postdocs, and early-career scientists; and (2) first-generation and/or low-income undergraduates. We will use a network-based intentional approach for mentoring [81, 105,106]. A key element [81,106] for each mentee is a constellation of mentors ("mentor team") who include researchers, staff, educators, postdocs, graduate students, and more experienced peers involved in *NewFoS* projects. With this network-based approach, we will create a mentor/mentee community and ecosystem in which mentors bring their different skill sets, resources (content expertise, laboratory access, academic support, and career preparation assistance), and life experiences to support the mentees. After their mandatory *Center for Improvement of Mentoring Experiences in Research* (CIMER) training [107], *NewFoS* students, postdocs, and early-career scientists will commit to team mentor the preceding cohort to ensure strong, well-connected pathways to success.

Figure 9. Students from the multi-university (UA-UCSD) REM program at the ERN Conference in STEM in Washington, DC, with *NewFoS* faculty mentors.

4d.2 Mentoring ecosystem BP activities

Three distinct but complementary activities will implement a Center-wide robust and effective Mentoring Ecosystem: (1) the REM program, i.e., research experiences tied to mentoring (**Fig. 9**); (2) DEI training and a supportive 12-month program for all researchers and staff; and (3) a Faculty Bridge Awards program.

BP Activity 1 – REM program

Activity: *NewFoS* will build on a successful UA-UCSD 12-month REM program for undergraduates [80,81,106,108,109] with elements for: (1) mentor networks; (2) eight-weeks of summer research and weekly debriefs with a program coordinator; (3) research presentations at summer end, which catalyze their further research during the academic year; (4) participation in two, one-unit seminars (Fall and Spring semesters); and (5) select mentees presenting their work at a professional conference, e.g., the Emerging Researchers National (ERN) conference. *NewFoS'* initial Year 2 expansion will add GT and Spelman College—an undergraduate partner institution—and support **8 students**. In Years 3–5, we will expand to include all eight partner institutions and fund **16 students each year** for **56 students over Years 2–5**. We also plan to submit NSF REU Site proposals to further expand our REM impact beyond **56 students**.

Evaluation: REM evaluation will include a pre/post mentee science identity and resiliency survey, mentee reflections, and interviews, and assess final research projects (see §4f.5).

Potential impacts: *NewFoS* cohorts of active and inclusive thinkers from diverse backgrounds (gender, ethnic, socioeconomic, international) will seek impactful solutions to advance science and technology.

BP Activity 2 – DEI training of all researchers and staff

Activity: We will host faculty, staff, researcher, and graduate student DEI training and supportive professional development programs to prepare for a diverse student population. We will launch the training in Year 1 for **40 Center members** who represent all organizational levels of *NewFoS*. In Years 2–5, we will continue to train new members and conduct online refresher sessions. At a minimum, we will train **100 individuals**. Our inclusive teaching practices will apply asset-based education practices [98,103] and embrace the perspectives of historically underrepresented STEM populations [94-98]. We will use CIMER's *Engineering Research Training Seminar* module, which we will augment by adding the topic of prosocial cultural values in which minoritized students assign value to tasks and careers that afford opportunities to help others or their communities [98]. In addition, An expert will conduct training and development workshops for faculty, students, and staff to include *Inclusive Lesson Design, Addressing Bias*, *Microaggressions*, and the *Core Five Components to Social Justice.* To maintain a current competency around DEI, the faculty and staff will receive a series of dialogue opportunities for clarity and engagement [110], and guidance and advice on best practices in their roles as professionals. Students will receive mentorship opportunities to continue their longitudinal growth and development in the competency areas of DEI.

Evaluation: Evaluators will conduct training surveys to examine future products from *NewFoS* members, such as curriculum samples (for DEI practice), mentee surveys, and individual interviews (see §4f.5).

Potential impacts: Our Center faculty, researchers, and staff will utilize inclusive teaching and learning best practices in their courses (in-person and digital), labs, mentoring, and broader impact activities. Our Center will provide a model to train and develop a culture of inclusiveness that will be evident by our recruitment and retention of culturally and linguistically diverse students.

BP Activity 3 – Faculty Bridge leadership program

Activity: We will implement a *NewFoS* Faculty Bridge Awards program with a mini-grant competition to seed faculty/postdocs who facilitate and support the interinstitutional or undergraduate-to-graduate mentored transfer of diverse students. This will be a collaboration with the UA vice-provost for I Initiatives. From Year 2, annually the CLT will select two Center members HSI fellows to join that year's leadership cohort. One new fellow will be at UA and the other at a *NewFoS* partner institution who will connect remotely. This critical partnership will provide Center members with an understanding of effective and inclusive leadership practices. Key products the fellows creating project proposals to further inclusive practices in their department, unit, or institution. We will select a total of **8 fellows** during Years 2–5.

Evaluation: Evaluators will perform formative reflections and a summative survey of the final project proposals (see §4f.5).

Potential impacts: Our HSI fellows will promote DEI practices at their institutions. Their leadership training will create opportunities to advocate for, and be allies of, minoritized populations.

4e. Description of the Knowledge Transfer Objectives of the Center

Knowledge Transfer (KT) objective. The overriding KT objective is to sustain theoretical and experimental frameworks for the broad interfaces and application domains of TA. This integration will encourage breakthroughs with positive societal impacts by ingraining input from *NewFoS* stakeholders, including industry, small businesses, community leaders, policymakers, education-thought leaders, and society.

Focus of KT activities. Our KT plan requires we excel at essential multiparty interactions: (1) KT *between members* to robustly integrate our research and education among all team members; (2) KT *with industry* to rapidly translate our scientific breakthroughs into new technologies; and (3) KT *with policymakers, community leaders, and society* to effectively inform the widest possible audiences and societal needs.

Partnering academic institutions KT. The KT Director and one Research Scientist ("KT Team") will coordinate communication and activities across the three research foci of: (1) yet-unknown aspects of TA (§4b.3.2); (2) problem-driven research projects (§4b.1.2); and (3) possibility driven research "seed" approaches (§4b.1.3). The KT Team will also foster regional geographic networks in the Center with regular on-site or virtual visits and discussions: CUNY and WSU; Caltech and UCLA; GT and Spelman; Fairbanks, UA, and UCB. These geographic networks have natural affinities to readily integrate participants into *NewFoS* and beyond to grow the TA community. The commitment of each *NewFoS* partnering institution goes well beyond the efforts of an individual team member. All institutions fully support the integrative research, educational, and DEI activities that comprise the Center's core mission to include universities that host one or two faculty. In summary, *NewFoS*' network-of-networks approach will ensure a thorough, fluent, and comprehensive integration of efforts for **all** partnering institutions. Frequent interactions among the CLT, KT Team, and the leads for the research foci activities will ensure rapid interventions to mitigate risk.

During the COVID-19 pandemic, UA and the *NewFoS* partner institutions ensured student and employee safety, and the integrity of educational and research programs. With such institutional support and safety guidelines, *NewFoS* team members have: (1) established effective protocols to conduct research; (2) converted curricula to effective online delivery modalities; (3) maintained cohesion of research teams within digital environments; (4) used digital media for positive advisory and mentorship support; and (5) reprioritized and redirected financial and human resources. *NewFoS* will embrace these effective digital environments for KT, e.g., with assessment approaches that reflect the ability to remotely evaluate our trans-university activities. *NewFoS* will also have a data science platform to support the seamless exchange of data products between its members (see Data Management Plan §13).

Specific goal: Through frequent in-person and digital contacts, including in-person visits to partnering institutions, the KT Team will converge activities across the Center, identify problems, and drive solutions.

Expected impacts: The KT Team will enable **all** academic partner institutions to be up-to-date about vital progress, roadblocks, and new research opportunities. All organizational levels will be able to express interests and concerns for other parts of *NewFoS* and the CLT through frequent contact with the KT Team.

Partnering industries KT. *NewFoS* will grow "deep benches" for four levels of industry engagement. Level 1 will engage companies through a representative serving on the EAC and participating in the Annual all-Center meetings (see below). Level 2 will involve two-way personnel exchanges, e.g., student internships and temporary company-personnel embeds in the Center (see below, *Student internships in industry* and *Embedded academic and industry personnel*). Level 3 will open access to company equipment and/or facilities otherwise unavailable to academic institutions. Finally, Level 4 will fund satellite projects of interest to a company that build on the Center's expertise. Several industry partners are willing to explore providing *NewFoS* with Level 3 access, e.g., to: (1) micro-device fabrication facilities (Intel Corp.); (2) a specialized laser-drilling machine (AdValue Photonics Inc.); and (3) quantum physics/chemistry expertise (BWD Assoc. LLC). GDMS is already at Level 4 in supporting acoustic quantum-analogue illumination projects at UA.

Specific goal: Through engagement Levels 1–4, industry will provide strategic oversight and enable our research and education activities to factor use-inspired guidance and the context of business imperatives. Industry will provide access to expertise, facilities, and equipment not available in academic settings.

Expected impact: Industry partnerships will rapidly translate our breakthroughs to new technologies.

Intellectual Property (IP). All participating institutions will be parties to the *NewFoS* IP Management (IPM) agreement to enable open, productive discussions and collaborations. UA's Office of Research Contracts will negotiate the IPM agreement—based on executed agreements. The emphasis of the approach to IP management for *NewFoS*, particularly via nonexclusive royalty free (NERF) licenses, is the free and open sharing of *NewFoS* research and education among our organizations as an engine for integration and inclusion. As lead, UA will also foster the team in building a strong IP portfolio to support licensing. We will follow the Bayh-Dole Act (35 U.S.C. §200-212) with IP ownership based on applicable US patent and copyright law. An Inter-Institutional Agreement (IIA, to be finalized) among the *NewFoS* institutions will be the basis to negotiate specific IP management responsibilities for jointly owned IP, on a case-by-case basis. In the unlikely event an IIA cannot be finalized, the basis for any reasonable fees, costs, expenditures, and revenues for IP created will be each institution's total cumulative percentage of inventorship, as the sum attributed to each institution's inventors. Institutions with *NewFoS* inventions will: (1) notify the *NewFoS* KT Director, who will notify other partner organizations; and (2) provide a NERF license for noncommercial internal research and education purposes to all *NewFoS* organizations.

Specific goals: The IPM agreement will address: (1) jointly owned IP management; (2) the right of each institution to publish results from *NewFoS*-funded activities; (3) the availability of *NewFoS*-funded IP to all *NewFoS* institutions for teaching, research, and public service missions; and (4) visiting researchers.

Expected impacts: Close interactions of *NewFoS* team members with their institutional technology transfer offices will fully support the use and translation of IP. In addition, *NewFoS* collaborations with industry stakeholders and entrepreneurs will move such knowledge and inventions from the Center to market.

Annual all-Center meetings. As a catalyst for integration, we will host conference-style *NewFoS* annual meetings for all team members to share their advances and best practices in research, education, and BP. The *NewFoS* Student Council and CLT will select the agendas. Annual all-Center meetings will coincide with EAC meetings to drive intellectual exchanges among the team and stakeholders. The EBIT will share evaluation and DEI updates, and provide training and guidance in mentoring and diversity awareness.

Specific goals: The annual all-Center meetings will be forums for everyone in *NewFoS* to engage in intellectual exchanges as a team and with stakeholders on the EAC and EBIC. The concurrent scheduling of EAC will facilitate KT activities by: (1) informing stakeholders about our recent progress; (2) engaging thought-leaders on best practices for E&HRD and BP activities (also with EBIC); (3) providing stakeholder feedback on research "seed" approaches; and (4) aligning E&HRD and BP targets with stakeholder needs.

Expected impacts: These annual meetings will energize the research and education directions of our team members' by fostering collaborative and inclusive discussions at all levels. By concurrently hosting the EAC/EBIC meetings, we will facilitate feedback and feedforward KT to stakeholders, including how *NewFoS* and stakeholders envision future research, E&HRD, and BP activities for maximal positive societal impact.

Embedded academic and industry personnel. Recognizing a two-way exchange of personnel is effective for KT between academia and industry, we will establish a **Faculty Fellow program** for *NewFoS* personnel to conduct R&D at industry partners. We will also encourage industry researchers to embed in the STC environment to germinate ideas and enhance innovation, e.g., **visiting researcher summer internships** at *NewFoS* funded by the companies. EAC industry members will be conduits to facilitate these programs.

Specific goals: These extended academic–industry interactions will: (1) enroot significant intellectual exchanges among *NewFoS* team members and industry stakeholders; and (2) as immersive opportunities, broaden and deepen the relationships and positive impacts that *NewFoS* and our industry partners provide to society through sound-based technological advances.

Expected impacts: The exchange of personnel at the faculty and industrial engineer/scientist levels will create essential pathways between the development of new science of sound innovations and their applications in cutting-edge technologies. These exchanges will greatly accelerate the implementation of the Center's new science and "push" team members to consider real-world challenges.

Student internships in industry. We will request each industrial partner, via their EAC representative, to provide reciprocal internship opportunities for *NewFoS*-funded undergraduate students. Embedded industry personnel (see above) will each pair with an undergraduate student while on an internship.

Specific goal: Working within *NewFoS* Mentoring Ecosystem (see §4d), embedded industry personnel will share their unique experience to broaden the scope of the undergraduate student experience.

Expected impacts: Connecting undergraduates with practicing members of the industrial community is of particular importance for students from communities historically underrepresented in STEM and our Mentoring Ecosystem. As an essential component of our Convergence Education (see §4c), student internships in industry will be practical experiences in industrial settings and further workforce readiness.

Policymakers, community and community leaders, and society. Community leaders from nonprofit organizations and local/state communities and governments on the EAC will be important conduits for KT that benefits communities and society as a whole. *NewFoS* will also engage the International Phononics Society (IPS). With members from all continents, IPS and its biannual international conference are venues for *NewFoS* outreach. Indeed, as one of the three founding members of IPS, *NewFoS* Director **Deymier** will engage the IPS board members in TA-related outreach activities to raises awareness in DEI-conscious practices that relate sound to all areas of life. The latter will include *NewFoS*' contributions to the annual UNESCO Week of Sound, which UNESCO's 39th session proclaimed for January each year. Through the first English-language context-based textbook and digital resources in the broad field of TA, *NewFoS* will transfer up-to-date knowledge and societal relevance critical to help inform policymakers.

Specific goals: The annual all-Center meetings will provide opportunities to integrate the perspectives of stakeholders who represent the scientific community, industry, education thought-leaders, policymakers, and community leaders—and grow the societal impact awareness of all *NewFoS* team members. Local, regional, national, and international presentations, discussion panels, and publications will share our major research findings and their significance, with feedback sought, for maximum societal impact.

Expected impacts: These KT activities with policymakers, community leaders, and society will: (1) refine new technologies for TA applications; (2) raise global awareness of sound-based technologies; and (3) be a platform for significant intellectual exchange among the *NewFoS* team, the community, industry partners, and decision makers within the context of societal impacts and user-defined challenges.

4f. Description of the Management Plan for the Research, Education, Broadening Participation, and Knowledge Transfer Activities of the Center

The following *NewFoS* **core values** will underpin our management strategy: (a) collaboration and accountability with personalized and innovative approaches; (b) commitment to excellence and integrity with flexibility, agility, and entrepreneurial spirit; (c) partnership through honest, open, and frequent communication; and (d) education and mentoring, ensuring DEI. PI Deymier has the extensive strategic and organizational leadership to direct the Center. Co-PIs will lead/co-lead the “yet-unknown aspects of TA” research (§4b.3.2). We will hire a Center Manager with substantial technical and operational team-science management experience and a KT Director. These leaders will form the *NewFoS* CLT who meet biweekly. As a catalyst to integrate activities, our annual all-Center *NewFoS* meetings will: (1) share recent advances and best practices in research, education, mentoring, and DEI; (2) create a culture of collaboration, inclusiveness, and common purpose; (3) implement mechanisms to achieve excellence in impactful research, education, and KT; and (4) gather diverse inputs to prioritize and revise Center activities with feedback from constituencies (e.g., phase out unproductive projects or support new “seed” approaches).

4.f.2 Organizational Relationships and Reporting Structure

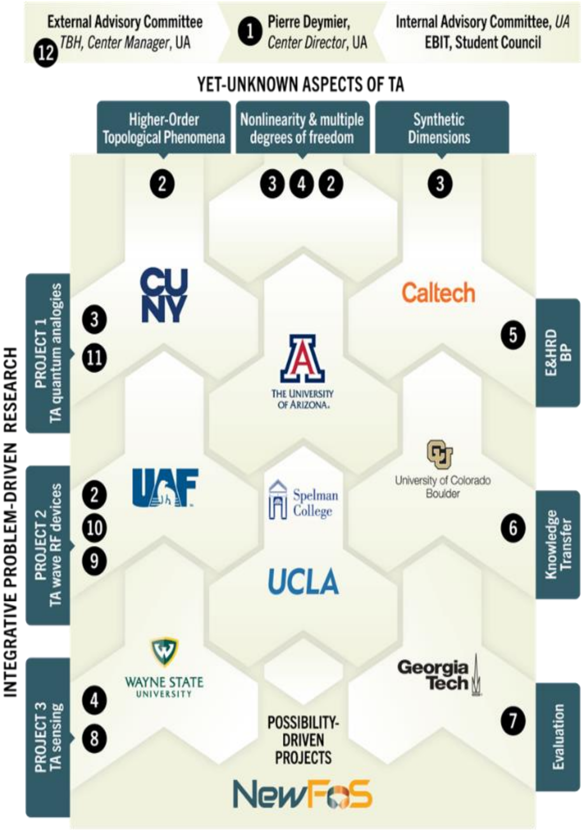


Figure 10. The *NewFoS* integrative management organization showing the responsibilities of the institutions.

Integrative Management Strategy. Establishing and sustaining an integrated and productive transdisciplinary Center (**Fig. 10**) is the central tenet of the CLT’s management strategy. *NewFoS* will take full advantage of three essential strategies for a successful and collaborative Center: (1) **frequent communication between all members** to fully integrate activities under the matrix of yet-unknown aspects of TA, problem-driven research projects, possibility-driven research “seed” approaches, Convergence Education, Mentoring Ecosystem, and KT; (2) **regular personnel exchanges** between all partners to access complementary expertise and facilities, support and ingrain our mentoring culture, and foster successful and integrated transitions along education-to-professional career paths; and (3) **visible, widespread KT to stakeholders** to maximize positive societal impacts. The Center Manager and E&HRD/BP Lead will manage the *NewFoS* member-only intranet site to ensure file sharing and resource coordination between all team members.

Role of Each Key Participant/Component. The Center Director will be accountable to: (1) integrate and manage the overall Center against the vision and mission; (2) ensure prioritization and effective collaboration amongst the participants; (3) overall decision-making; and (4) maintain communications with NSF and the EAC/EBIC and **Internal Advisory Committee (IAC**). The CLT will oversee strategic and tactical management activities and promote a DEI culture to ensure we achieve the *NewFoS* objectives and criteria to prioritize Center activities across all partnering institutions. The E&HRD and BP Coordinators will report to the E&HRD/BP Lead. The EBIT (see §4c) and a Student Council will meet monthly. With support from the E&HRD/BP Lead and Center Manager, the Student Council will comprise a representative from each partner institution in a cohort who provide feedback from the students’ perspectives and the voice of *NewFoS* students. Each research lead/co-lead(s) and the E&HRD/BP Lead will conduct monthly meetings accessible to the entire Center to facilitate interactions, assess progress, and integrate our current and planned activities. On a quarterly basis, the EBIT and Student Council will provide updates to the CLT.

Faculty will be responsible and accountable for implementing and enforcing *NewFoS* Ethics (see §11), the Mentoring Ecosystem, and institutional Environmental, Safety & Health (ES&H) practices at the highest possible level in conjunction with their group members, visitors, and volunteers.

EAC, EBIC, and IAC. The EAC will represent industry, federal laboratories, and local/state communities and governments. The 6–8 members will share their expertise in applications, societal impacts, education and workforce development, and DEI. With multiyear memberships, the EAC will offer strategic advice to the CLT consistent with our vision and mission, and ensure we maintain forward-looking plans also from the contexts of pragmatic business, municipality, and government imperatives. The EAC will also advise on workforce development for the future of work. The EBIC members will parallel the EAC but focus on the *NewFoS* E&HRD/BP plan exclusively. EBIC will comprise external members with leading experience and expertise in transdisciplinary education resource development, mentoring, and DEI. With multiyear membership, the EBIC will ensure that the CLT executes the E&HRD/BP plan with maximum impact on acoustic education and workforce development. The CLT and EAC/EBIC will engage at least semiannually.

To ensure UA's institutional and operational support for the Center Director, the IAC will include: the Colleges of Education, Science, and Engineering Deans; the Assistant Vice Provost for HSI Initiatives; the Chief of Staff for the Senior VP, Research & Innovation; and the Tech Launch Arizona Assistant VP. The Center Director and IAC will engage at least quarterly.

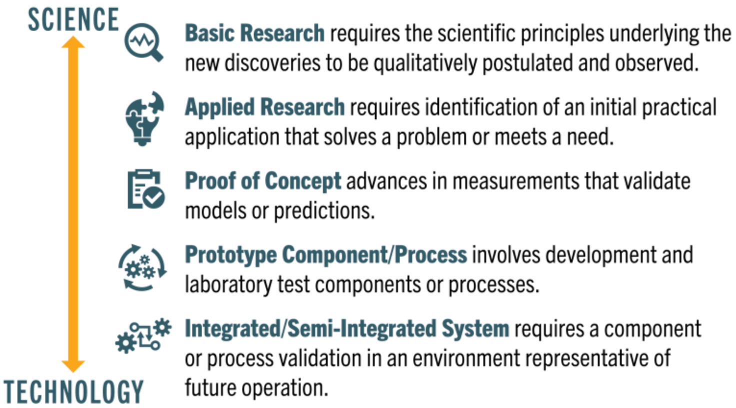
Responsibilities of the Lead and Partner Organizations. UA will be responsible to provide institutional administrative structure and resources to support the Center Director, KT Director, and Manager. As an HSI, UA's campus culture will be a role model for DEI underpinning the Center's BP objectives. Partner institutions will be responsible to foster an integrative and inclusive culture in research and E&HRD. Each institution will be responsible and accountable to enforce ES&H and BP processes and culture at the highest possible level. Industry partners will be *NewFoS* stakeholders, who will provide real-world guidance.

Annual All-Center Meetings. The annual all-Center meetings will create a culture of collaboration, DEI, and common purpose, and be a mechanism to achieve excellence in research, E&HRD, KT, and BP. We will gather diverse inputs to prioritize and revise Center activities with feedback from all constituencies. The example agenda below has activities based on our experience in best practice for similar meetings. While all-Center annual meetings will be in person, preferably, each *NewFoS* institution has invested in technologies to ensure accessible digital environments when in-person participation is impractical.

Day 0: Evening reception with recognition of graduating students and awards received.	
Day 1: **All-Center** (EAC/EBIC/IAC) 8:00–8:15am; Greetings from the Center Director. 8:15–8:45am; Yet-unknown aspects of TA Leads: progress/directions. 8:45–9:45am; Problem-driven projects Leads: progress/directions. 9:45–10:00am; possibility-driven projects Leads: progress/directions. 10:00–10:30am; Director: Current/proposed budget. 10:30–10:45; Break. 10:45–11:30am; E&HRD/BP Lead: progress/directions. 11:30am–noon; KT Lead: progress/directions. Noon–1:00pm; EAC/EBIC/IAC lunch with Student Council. 1:00–3:00pm; Lightening talks (research/E&HRD activities). 3:00–5:00pm; Posters (research/E&HRD/BP activities). 6:00–9:00pm; Professional development workshop.	**Day 2**: **Management, EAC, EBIC, and IAC** *Parallel Session 2.1*: **EAC/EBIC/IAC Meeting** 8:00–10:00am; EAC/IAC draft report. *Parallel Session 2.2*: **Center Director**, **Leads**, and **Center Manager Meeting** 8:00–10:00am; Center path forward, priorities, and budget revisions. 10:00–10:15am; Break. **CLT and EAC/EBIC/IAC Meeting** 10:15–10:45am; EAC/EBIT/IAC recommendations to CLT. 10:45–11:15am; Center path forward. 11:15–12:30pm; Prioritization/forward plan.

4f.3 Criteria for Prioritizing Center Activities and Allocation of Funds

Semiannually, the Center Director and CLT will formally: (1) assess the collaborative contributions and productivity of *NewFoS* faculty against the current research, education, and BP plans; (2) invite and evaluate exploratory activities and unanticipated research directions (possibility-driven research "seed" approaches) ahead of all-Center meetings; and (3) plan to sunset any unproductive activities and/or faculty prior to all-Center meetings. The Center Director will share this information with the EAC to establish the path forward for 12-month research plans and budget allocations. The Center Director will prioritize and allocate research funds based on progress versus the five criteria in **Figure 11**. Criteria 1 and 2 will evaluate the yet-unknown aspects of TA. Criteria 3, 4, and 5 will evaluate the problem-driven research projects.



Basic Research requires the scientific principles underlying the new discoveries to be qualitatively postulated and observed.

Applied Research requires identification of an initial practical application that solves a problem or meets a need.

Proof of Concept advances in measurements that validate models or predictions.

Prototype Component/Process involves development and laboratory test components or processes.

Integrated/Semi-Integrated System requires a component or process validation in an environment representative of future operation.

Figure 11. *NewFoS* progress assessment and prioritization criteria—from basic scientific discovery to technological systems.

NewFoS will support possibility-driven research "seed" approaches and emergent research opportunities. These "seed" projects will provide full or partial support for students and/or postdocs, and operation, materials, and supplies costs, as applicable. The competition for seed funds will be open to proposals from *NewFoS* faculty and their students/postdocs (after endorsement from the faculty advisor). We will solicit seed projects two-months ahead of all-Center annual meetings. Project selection will consider intellectual merit, transdisciplinarity and broader impacts by a subcommittee of the CLT and EAC. The CLT will announce the funded projects at the next all-Center annual meeting. We anticipate assessment of possibility-driven projects to fall at the intersection of criteria 2 and 3.

4f.4 Process to Select a Replacement for the Center Director

Should the Center Director be incapacitated, the IAC will appoint an *Interim* (preferentially from the CLT for continuity). If the need arises to replace the Center Director, the IAC will appoint an *Interim* and execute a nationwide search for a suitable replacement at UA. The IAC will allocate the resources for this search. The IAC, CLT, and EBIT will jointly appoint the search committee to reflect the DEI values of *NewFoS*.

4f.5 Evaluation

NewFoS includes a team of evaluation/educational research experts who will engage from the onset in the design of evaluation tools and data gathering. Evaluation efforts will answer: "*Has NewFoS prepared students to think in the critical and cross-functional systems-thinking desired by industry and higher education institutions?*"; and "*Have digital learning training activities for NewFoS faculty and staff created inclusive online environments for culturally and linguistically diverse students?*". The evaluator team will meet regularly with the Director, Co-PIs, and EBIT to review activity plans, and provide immediate feedback and recommendations on activity design. Thereafter, the evaluators will conduct mixed-methods formative evaluations to track progress, challenges, and successes. The evaluators will be integral to ensure we make a difference and create the inclusive Center we envision as a core value. The EBIT will meet bimonthly with the evaluators to adapt, edit, and re-design based on the assessment results they glean from the participants. The evaluators will formally present to the CLT and EBIC every six months.

Formative evaluation methods will be at the launch of new courses, programs, and practices to ensure we achieve our objectives and refine our practices. UA will oversee data collection and data management for *NewFoS*, and compile and analyze data for evaluation. The evaluators will use surveys, interviews, reflections, and feedback forms to: (1) inform and improve our activities; and (2) understand students' attitudes, interests, belongingness, science identity, retention, and resiliency patterns. They will use text-mining software and assessment rubrics to quantify data, and collect longitudinal data on all participants—from initial Center engagement. Formative methods will use qualitative interviews and surveys, and assess student-produced products (e.g., co-produced learning modules to accompany text, online experiential modules, research posters, presentations, reports).

Interviews of mentees and Center researchers, staff, and students will ascertain the effectiveness of inclusivity training and uncover any concerns tied to mentoring. Evaluators will initialize interviews after conducting a Qualtrics survey that documents member participation activities. With this survey, evaluators will identify participants to interview and uncover successes and concerns in more detail. Evaluators will use a culturally responsive focus group method she routinely implements for more robust, meaningful, and informative evaluations. The evaluators will also assess: (1) student product samples for level of comprehension, communication effectiveness, and strength of societal associations; (2) project team successes to determine what works, what challenges they face, and what efforts we might improve; (3) student demographics, paying attention to first-generation status, Black, Indigenous, People of Color identity, low socioeconomic background, persons with disabilities, LGBTQ+, and women. Evaluators will also track education-relevant student outputs, or success measures, such as: degrees earned, majors pursued, graduate school applications and programs, and academic and workforce positions attained.

4g. Institutional Commitment to Diversity and Inclusion

All *NewFoS* partner institutions have dedicated programs and funds to ensure priority for DEI excellence. Three institutions (UA, UCB, GT) were early recipients of the NSF ADVANCE Institutional Transformation awards. Three institutions (Caltech, WSU, and UA) are AAAS STEMM Equity Achievement (SEA) Charter Members but did not receive awards. UA also has US Department of Education Title 3 and Title 5 grants to improve STEM experiences for undergraduates, community-college transfer students, and mathematics education, all from culturally responsive lenses. Furthermore, reflecting the HSI designation, UA has invested in the growth of the following offices to better serve the needs of students, faculty, and staff in the context of DEI: (1) within the office of the Senior VP, Research & Innovation—the Office of Societal Impact, the Office of Undergraduate Research and Inquiry, and the STEM Learning Center; and (2) within the Provost's office—the Office of Diversity and Inclusion, and the Office of Faculty Development. UA's DEI values reflect its location on the land and territories of Indigenous peoples, and a land-grant mission. The CUNY Graduate Center is an HSI, Spelman College is an HBCU, and Fairbanks is an Alaska Native and Native Hawaiian Serving Institution (AANH). The above institutional DEI commitments and leadership will be integral to ensure *NewFoS* drives towards excellence as an inclusive and welcoming community.