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Special Collection: Fundamentals and Applications of Metamaterials: Breaking the Limits

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I. INTRODUCTION

Metamaterials are rationally designed composites with engineered architectures that deliver exceptional effective material parameters translated into unprecedented functionalities.[1] After the first applications in optics,[2,3] metamaterials have rapidly entered various physical fields, including photonics,[4] acoustics,[5] materials science,[6,7] mechanics,[8] and plasmonics,[9] and enabled mind-blowing phenomena, like invisibility cloaking,[10,11] programmable and mechanism-based behavior,[12] topological invariant states,[13] and many others.[14,15] Nowadays, metamaterials have been attracting continuously growing attention because of their negative or extreme elastic, thermal, structural, mechanical, and dynamic properties that are highly demanded in numerous applications, e.g., energy harvesting, sensors, biomedical, automotive, aerospace, speech recognition, signal processing, to name a few. The development of metamaterials strongly benefits from rapid progress in manufacturing technologies, especially additive manufacturing, including optical 3D printing, advanced lithography, multi–photon 4D printing, and nano-printing.[16,17]

The goal of this Special Topic is to highlight the latest trends in the design of metamaterials and to discuss the expansion of metamaterials' functionalities. Considering the strong application potential of metamaterials and their increasing uptake in various branches of industry, we also aim to overview promising technological developments and application breakthroughs. We believe that this Special Topic collecting studies from leading research groups represents the state-of-the-art and will further stimulate research on metamaterials.

II. BREAKING THE DESIGN LIMITS

Metamaterial architecture is a key to achieving fascinating functionalities. The design strategies, initially driven by physical intuition, become more diverse and evolve constantly. Nowadays, metamaterial architectures are created based on nonlinear properties and unusual combinations of constituent materials, bio-inspired or biomimetic approaches, advanced computational and artificial intelligence tools, hierarchical principles, etc. Conversely, the expansion of the design limits on metamaterial architectures is supported by growing possibilities in additive manufacturing, which enable the production of almost arbitrary complex metamaterials.

Representative examples of the multitude of architected designs can be found in elastic metamaterials, also known as phononics, that exhibit frequency bandgaps for acoustic waves in solids. Many phononic architectures are based on lattices as these allow combining bandgap functionality with a small structural weight. Among them, octet truss-based metamaterials are known for their high strength-to-weight ratio due to a stretch-dominated architecture. Oudich *et al.*[18] experimentally characterized homogenous (equal thickness) and hybrid (two alternating thicknesses) octet metastructures and showed that the strongest vibration attenuation is achieved in the designs with thin trusses due to a combination of material damping and bandgap mechanism. Bandgap bounds and attenuation levels can be increased by introducing curved structural elements[19] or breaking the symmetry in the lattice designs.[20] For instance, the non-symmetric architecture with a non-symmorphic p4gm symmetry group delivers anisotropic behavior and enables strong suppression of shear waves, which can be advantageous for specific applications.[20]

Anisotropy can also be harnessed to enhance backscattering for microwaves. It has been experimentally demonstrated for a biomimetic radially anisotropic metamaterial that replicates the optical function of nanospheres found in the tapetum reflector of the eye of the *Litopenaeus vannamei* shrimp. The obtained metamaterial component, which can manipulate radar return signals, was 3D-printed and showed more than doubled monostatic radar cross section as compared to an equivalent isotropic structure, thanks to its design.[21] The advantages of the bio-inspired design include a simplified fabrication process, close to optimal structural format, and adaptable functionality that can potentially be tuned to other wavelength regimes, thus translated to a broad range of possible applications.[21]

Tunable architectures, which can deliver multiple, switchable, or adaptable functionalities, are another desired feature in the metamaterials design that can greatly extend the range of applications. A promising approach to achieve tunability is to use bi- and multi-stable elements. In cable-bar networks, a monostable-to-bistable transition can be achieved by changing geometry or self-stress level in multi-node elementary units, thus providing metamaterials with adjustable multi-stable behavior.[22] The analysis of a one-dimensional assembly of such units with a polygonal base has shown tailorable nonlinear features and solitary wave propagation.[23] Bistable resonators can also deliver switchable vibration attenuation capacity due to effective localization of energy and reduced amplitude of elastic waves in one of its stable topological states. This approach was experimentally demonstrated for additively manufactured resonators with kirigami-inspired bistable springs.[24] Metamaterials with multi-stable elements and tunable soft defects for patterning structural phases provide greater design flexibility as compared to other existing approaches and can be easily extended to two-dimensional architectures with complex morphologies.[25]

An alternative approach to tunability is the design of metamaterials with nonlinear components. In acoustics, abundant theoretical studies of nonlinear metamaterials for surface acoustic waves are now supplemented by an experimental demonstration of the tuning of the surface wave dispersion by using the nonlinear local resonance effect.[26] The amplitude-dependent dispersion emerges from the interaction of surface waves with nonlinear resonators and provides a means to realize amplitude-dependent self-tuning metamaterials that can passively adapt to loading conditions without the need for external stimuli. In nonlinear optics, a second-harmonic generation is used to effectively convert initial photons into photons of twice higher frequency. Li *et al.*[27] have proposed to link this phenomenon to the Fano resonances in plasmonic nanostructures (photonic metasurfaces), which can be used to manipulate the near-field distribution and plasmonic resonance frequencies. Specifically, magnetic Fano resonances have been tuned to enhance the efficiency of a second harmonic generation in chiral hybrid bismuth halides formed by two asymmetric silver square split rings and a chiral perovskite film. Tuning the geometry of square split rings has allowed the shifting of the magnetic Fano dip and reaching the maximum enhancement factor of four orders of magnitude, thus promoting the evolution of nonlinear optics applications.[27]

Other design efforts are aimed at developing topological metamaterials, which exhibit topology-controlled properties and topological bands. In acoustics, topological insulators open exciting possibilities for the robust manipulation of sound in topologically protected boundary states, which can direct sound propagation along desired paths without backscattering. To efficiently trap sound in a tightly confined space, Liu *et al.*[28] have proposed to use a topological acoustic rainbow trapping phenomenon that has been realized experimentally in gradient one-dimensional sonic crystals. Their design is represented by Helmholtz resonators coupled to an acoustic waveguide and can activate topological nontrivial interface states by varying the neck widths of the resonators. It represents the first acoustic analogy of the 1D Su–Schrieffer–Heeger model. The advantages of this design are simple structure and easy fabrication compared with the previous works, where the acoustic rainbow trapping effect was realized by using more complex and bulky metamaterial architectures.[28]

In nano-photonics and optics, many fascinating metamaterial functionalities rely on local resonances. Hence, it becomes fundamentally important to estimate the limits to which one can tune the bandwidth of a resonator, which is characterized by the quality (Q) factor. Deshmukh and Milton[29] derived tight bounds correlating the peak absorption with the Q-factor in two-phase quasi-static metamaterials and plasmonic resonators. They have shown that such composites can include well-separated clusters of plasmonic particles and described the designs of optimal metamaterial architectures attaining the bounds. It will be interesting to see experimental validation of these results.

High Q-factor values result in a narrowband response that is relevant, e.g., for narrowband filters or near-field enhancement. In other application scenarios, including sensors, optical switching, and slow light devices, one may require broadband behavior, e.g., broadband transparency. The recent study[30] shows that broadband transparency can be achieved in Babinet checkboard complementary metamaterials and demonstrates absolute transparency in a very broad frequency range in the microwave regime. This functionality originates from the modified multipole interaction of layers with shifted centers of radiation, suggesting a simple, reproducible, and scalable design of the Babinet metamaterial for broadband transparent devices at any frequency, including THz and optical ranges.[30]

III. BREAKING THE FUNCTIONALITY LIMITS

Metamaterials have enabled many intriguing properties and functionalities that forced to revise basic concepts in different branches of physics. These include negative refraction, topological behavior, unidirectional wave propagation, and many others that have enabled super-resolution, focusing breaking the diffraction limit, optical transparency, scattering-free wave propagation, etc. In the following, we present recent breakthroughs that expand the metamaterial functionalities further and describe their potential applications.

In plasmonics, one can achieve extraordinary optical transmission through subwavelength plasmonic nanoapertures because of the funneling of light via surface plasmons at resonant wavelengths through the apertures. This functionality has recently allowed advancing photolithography, near-field microscopy, light-emitting diodes, sensors, surface-enhanced IR absorption and fluorescence, and other applications. As an alternative approach, Verma and Srivastava[31] have experimentally demonstrated plasmon-mediated optical transmission of visible light through plasmonic metagrating, which does not have any aperture. It appeared to be possible because surface plasmons generated at the metal–air interface can penetrate through metagrating and couple with the surface plasmons supported by the metal–substrate interface. This phenomenon enriches the understanding of extraordinary optical transmission mechanisms and enables costeffective plasmonic metagrating-based photonic devices, e.g., sensors, spectral filters, and polarizers.[31]

The optical transparency of metamaterials is attributed to a negative index of refraction, which implies simultaneously negative permittivity and permeability. This transparency is prohibited in a single negative material with negative permittivity or permeability because of the presence of a stop band for light or electromagnetic waves below a plasma frequency. Therefore, it is unusual to expect optical transparency by combining two metallic wire lattices with negative permittivity. Yet, the recent experimental study[32] has revealed the anomalous transmission of light through two interlaced sets of metallic wire lattices at a low-frequency pure longitudinal mode and proved the realization of an ultra-broad passband below a modified plasma frequency. This unique spectral feature opens an exciting opportunity to investigate the pure longitudinal physics in the range that has exclusively been "reserved" for transverse modes and facilitates the observation of related plasmonic effects in bulk.[32]

Negative refraction has been explored not only for electromagnetic or acoustic waves but also for elastic Lamb waves in thin elastic structures to deliver subwavelength wave focusing and imaging. Different mechanisms for creating super-focusing flat lenses are based on anisotropy in phononic crystals, time-driven super-oscillations, or local resonance effects. Danawe and Tol[33] have experimentally verified the super-resolution focusing of flexural Lamb waves by coupling evanescent waves with the bound mode of a square-lattice phononic slab. Such functionality may be beneficial in structural health monitoring, nondestructive testing, and energy harvesting applications.

In addition to negative refraction, negative reflection is another unusual phenomenon relevant in applications aimed at elastic wave control, e.g., beam steering, elastic imaging, and structural health monitoring. The numerical study by Meirbekova *et al.*[34] shows that negative angles of reflection for out-of-plane waves in a homogenous elastic medium can be achieved at an interface with a phononic material formed by a grating of fixed inclusions embedded in a linear elastic matrix. Importantly, the negative reflection is not due to a subwavelength metastructure or materials with negative mechanical properties, yet it is clearly observed for out-of-plane shear waves under different angles of incidence and frequencies.[34]

Topological insulators and topological Weyl semimetals have changed classic definitions and interpretations of insulators and metals. One of the crucial discoveries here is a dispersion relation that exhibits a linear crossing of two energy bands and satisfies the relativistic Weyl equation near the crossing point—a Weyl point, which has excitation characteristics of chiral Weyl fermions.[35] In condensed systems, Weyl quasiparticles have a massless nature and reveal relativistic chiral phenomena, e.g., Klein tunneling or chiral anomaly. In photonic systems, Weyl points are, however, symmetry-protected with multiple chiral Weyl points at the same energy level that challenges the generation of chirality-related effects. This hindrance can be overcome by introducing a perturbation breaking the mirror symmetry in a metallic saddle structure and effectively separating the energies of distinct chiral Weyl points.[35] It enables experimentally measuring the spectral intensity of each Weyl band and assessing the chirality imbalance among the Weyl points. This approach is promising to study the phenomenon of imbalanced chirality in photonic Weyl semimetals in real space opening the way for a deeper understanding of the chiral physics of pseudo-fermionic fields in photonic materials.

After the principles of quantum-mechanics topological insulators entered the domains of acoustics and wave dynamics, the robust edge-mode localization functionality appeared to be appealing for the development of various wave control devices. However, this important feature is frequency specific that makes tunability an important design component for topological waveguides. A simple approach to tuning the frequency of a topological edge mode remotely and in real-time implies using 3D-printing of a device from a photo-responsive polymer that is sensitive to laser excitation. Chaplain *et al.*[36] have demonstrated this idea experimentally for the classical Su–Schrieffer–Heeger topological system.

Another approach to breaking conventional bulk-boundary correspondence relies on a non-Hermitian skin effect, which enables bulk modes localization at open boundaries in one- or higher-dimensional metastructures. In elastic systems, the non-Hermitian skin effect was mainly implemented through a feedback control mechanism in one-dimensional mechanical metamaterials or lattices. Zhong *et al.*[37] have extended this idea to a two-dimensional continuous elastic system with active piezoelectric components and demonstrated different localized modes based on the reconfigurable properties of the piezoelectric material. These results offer a feedback control strategy to introduce the non-Hermitian skin effect in vibration control, energy harvesting, and sensing applications.[37]

The plethora of wavefront engineering phenomena enabled by metamaterials includes unidirectional transmission that is defined as a one-way energy transport behavior. Numerous studies have proposed metasurface-based unidirectional devices. However, the design of their basic units remains complicated, while the working bands are limited by resonances. These and other limitations hinder the applications of such meta-devices. To overcome these issues, it has been proposed to achieve the desired acoustic energy transfer behavior by implementing fractional stimulated Raman adiabatic passage (f-STIRAP) in a functional acoustic waveguide coupler.[38] The output port of the coupler can be manipulated by the superposition of different incident waves, while the double f-STIRAP converts the zero-order wave into a one-order wave unidirectionally. An acoustic metamaterial formed by an array of such mode converters provides a desired unidirectional beam splitting on broadband frequencies. The simple configuration and validated performance of this metamaterial can stimulate further explorations of quantum technologies to promote advanced wavefront modulation by acoustic metamaterials.

Metamaterial concepts are also used to develop bio-inspired scale-covered substrates that utilize the geometry of scales and their sliding kinematics to uncover a spectrum of intriguing mechanical functionalities. The latter include armor-like behavior and nonlinear friction and fracture driven by the geometry of collective scales contacts. For instance, dry static friction was found to add stiffness to such a substrate and simultaneously limit the range of motion due to an additional locking phase. Ebrahimi *et al.*[39] have made the first step toward the analysis of dissipative behavior from scales sliding in the dynamic regime and emphasized the importance of including visco-elastic material dissipation as an essential ingredient of damping in a biomimetic scale architectured substrate, in addition to geometrical factors. The implementation of more realistic dissipation models[40] will provide a deeper understanding of this phenomenon and further stimulate the design of scale-like smart skins, appendages for soft robotics, and tailored prosthetics.

In addition to unprecedented functionalities, metamaterials create an attractive platform to translate fascinating phenomena across different physical domains. Appealing examples include synthetic gauge fields (pseudo-magnetic fields), which enable exploring magnetic-like phenomena for magnetically inactive matter, and analogs of qubits (quantum bits) in classic systems. Duan *et al.*[41] have reported the realization of a synthetic gauge field in acoustic Moiré superlattices formed by two superimposed periodic phononic crystals with mismatched lattice constants. It allowed them to observe the symmetric and antisymmetric Landau levels and interface states and experimentally measure sound pressure field distributions of Landau levels. Apart from being the first demonstration of synthetic gauge fields in an acoustic system, this approach offers a new direction to expand the manipulation of sound in a way previously inaccessible in traditional periodic acoustic systems.[41] Deymier *et al.*[42] introduced logical phi-bits, a classical analog of a qubit in nonlinear acoustic waves, to demonstrate that the navigation among their three correlated states can achieve a nontrivial unitary operation analogous to a quantum gate. This operation can be performed on a range of initial states (inputs), covering a region of the three phi-bit Hilbert space, and is predictable, without the need to be decomposed in a sequence of smaller phi-bit gates. This work, thus, delivers the proof-of-concept of realizing quantum-like coherent superpositions of states in an exponentially complex Hilbert space by means of a nonlinear acoustic metastructure by preserving the possibility to effectively operate with a nontrivial unitary operation analogous to a quantum gate.

IV. BREAKING TECHNOLOGICAL LIMITS AND EXTENDING APPLICATION DOMAINS

Metamaterial cloaking is probably one of the most appealing applications of metamaterials, based on transformation optics, that enables shielding an object by making it invisible to electromagnetic radiation. The literature presents many realizations of cloaking devices based on space-folding transformations, while optical forces and torques in the presence of transformation-based concentrators have been analyzed insufficiently. Chaumet and Guenneau[43] have filled in this gap by studying the influence of the discretization of a class of spherical concentrators on the optical force and torque therein. They speculate that enhancing or suppressing optical force and torque by tuning the design of the concentrators can help to manipulate small objects with light, without perturbing an ambient electromagnetic field. This, in fact, means bringing the whole concept of cloaking to a quantitatively new level going beyond cloaking a sensor.

Acoustic metasurfaces can be promising to improve the low sensitivity of photoacoustic spectroscopy for liquid detection. For this, it has been proposed to use "optically transparent" Helmholtz-type acoustic metasurfaces.[44] Such a metastructure is formed by a perforated plate and a deep subwavelength air layer that can enhance the acoustic transmission across a gas–liquid interface. The air behaves similarly to a vibrating membrane that drives the vibration of a liquid surface and provides a path for sound transmission from liquid to air. Experimental results showed that the water-to-air power transmission coefficient of sound is increased by two orders of magnitude while maintaining optical transparency for laser at frequencies compatibility with those of photoacoustic spectroscopy systems. Therefore, the proposed metasurfaces can enable technological applications in liquid ingredient analysis and health monitoring.

Metamaterial-based flat optics has tremendous application potential owing to the possibility to precisely modulate the phase of light by means of subwavelength structures with thicknesses at a wavelength scale. This allows miniaturizing optical devices and systems that is impossible for conventional refractive optical elements, the functionalities of which are governed by a surface curvature and spatial extent. However, the design of achromatic metalenses for focusing and imaging in the visible band remains challenging if one aims to achieve high-focusing efficiency and high-consistency focal length over the entire visible spectrum. To overcome it, Zhu *et al.*[45] have proposed a polarization-independent achromatic metalens that can operate at wavelengths from 400 to 760 nm. The metalens has only a single layer of cross-shaped and square-ring silicon nitride-based nanopillars on a glass substrate in the transmission mode. Numerical simulations have shown significant improvement over the previous designs of achromatic metalenses for focusing visible light in terms of focal-shift suppression and wideband operation. This approach, thus, enables the development of high-quality achromatic metalenses for the whole visible spectrum and potentially for other frequencies.

Dynamic control of the metalens functionalities could be required for next-generation optical components, e.g., in light detection, holography, augmented, virtual reality, etc. It can be achieved in different ways and is especially promising in thermally controllable metasurface lenses that can focus light selectively at resonant wavelengths. Klopfer *et al.*[46] have designed a high-Q silicon metasurface lens and experimentally validated its efficient thermo-optic tunability. The lens is constructed via a zone plate architecture formed by alternating regions with and without resonant character. Non-resonant regions block transmission, while resonant regions transmit only on resonance. The thermo-optic effect allows the dynamic adjustment of the spectral position of the high-Q resonance, thus enabling the wavelength selectivity of the focusing behavior. Because of the sharp spectral linewidth and amplitude variation of the high-Q resonance, thermal tuning can be extended to implement metasurface switching, where the lensing behavior is changed between on and off states. This lens, thus, efficiently alters its far-field lensing behavior.

Another application avenue in optics is the development of compact directive antennas for beam steering and directional radiation in the microwave regime. It could be crucial, e.g., for point-to-point terrestrial and space communication and broadcast communication satellites. Dong *et al.*[47] have proposed a three-dimensional photonic-crystal-based antenna formed by a compact array of low-loss dielectric cylinders in a square lattice. They have observed substantial directional radiation in microwave experiments due to strong band edge resonances, which transform small radiators into directional antennas. The proposed antenna is a compact, cheap, and simple device, showing high transmission efficiency and directivity gain in comparison with traditional orientation antennas.

Voice acquisition is highly relevant in robotic technologies, voice-controlled devices, and autonomous vehicles, as it enables contactless human–machine interaction. Yet, noisy environments substantially complicate the acquisition process and deteriorate the quality of prerecorded voice. As an alternative to traditional multiple microphones and noise-canceling algorithms, one can use passive metamaterials placed in front of a single microphone that can amplify the evanescent portion of voice and, thus, remarkably enhance the signal-to-noise ratio. This idea has been demonstrated experimentally by using an acoustic metamaterial with simultaneous negative effective density and bulk modulus owing to coexisting and coupled Helmholtz and Fabry–Pérot resonances.[48] The obtained results pave the way for designing metamaterials to improve the quality of acquisition of voice and other sounds.

Energy harvesting, which has always attracted vivid interest of researchers and engineers, has recently received a strong impetus as an eco-friendly and renewable energy source. For instance, acoustic and piezoelectric energy harvesters open ample opportunities to reuse noise and mechanical vibration waste as electricity that can, e.g., power sensors. However, the practicality of such harvesters is often limited by their narrow bandwidths and low efficiencies. These issues can be addressed by using acoustic and elastic metamaterials that enable wave localization and focusing through defect modes, local resonance, and gradient index variations. For instance, Peng *et al.*[49] have proposed an ultra-broadband acoustic energy harvester with a fractional bandwidth that outperforms existing counterparts. This device can efficiently transform sound energy into usable electrical power with a three-times larger peak efficiency. Rho *et al.*[50] have developed an achromatic elastic non-resonant Mikaelian lens for confocal piezoelectric energy harvesting that demonstrates a remarkable focusing and energy conversion for flexural waves on broad frequencies. This solution can be attractive for wireless sensing, biomedical, and structural health monitoring devices.

Energy harvesting can also be combined with vibration suppression, which opens the possibility to develop multi-functional metamaterials. It can be done by the combination of bistable and monostable-hardening mechanisms in nonlinear local resonators.[51] Such a metastructure offers amplitude-robust performance with wide bandgap at high accelerations, can attenuate resonance amplitudes around the bandgap, and generates power over a broad bandwidth. It overcomes a common challenge of a strong amplitude dependence for nonlinear metamaterials and, thus, becomes a highly promising solution for energy harvesting applications.[51]

Nondestructive testing methods have a strong potential for rapid detection of defects in engineering structures with a varying sensitivity of guided modes to different defects. The implementation of such systems requires, however, multiple active elements or wave-guiding channels and large computational resources to extract information about three-dimensional measurements that greatly increase implementation costs. In many applications, it is crucial to have compact, energy-efficient, and affordable solutions. Nie *et al.*[52] propose to develop them by using 3D-printed acoustic lenses that can achieve spatial encoding of a received signal and identify the spatial location of a defect or scatterer by a single measurement. This idea has been demonstrated experimentally by developing a single-element ultrasonic transducer with a spiral-shape mask that can localize smaller-than-wavelength scatterers, provided their echoes are separable in the time domain. This technology can be scaled to different frequency ranges and is, thus, promising to develop new-generation practical sensing devices and wave-based imaging methods.

Another challenge in nondestructive testing, which can be addressed by metamaterials, is mode conversion and differentiation of simultaneously present multiple modes in received signals. Metamaterials can enhance the control over guided waves by incorporating mode purification functionality in metamaterial-based transducers, which can filter out undesired waves and enhance sensing and actuating signals of a dominated mode. This has recently been shown for Lamb waves by tuning a local resonance bandgap for antisymmetric Lamb waves through the shunting inductance circuit in a periodic array of piezoelectric unimorphs bonded on the surface of a host elastic plate.[53]

The ability of acoustic metamaterials to attenuate sound makes them promising for realizing noise barriers and controlling room acoustics. Among multiple metamaterial designs proposed for this purpose, a limited number preserve the ventilation functionality, which can be important, e.g., in reducing noise from engines, in offices or public spaces. One such design relies on the use of micro-perforated panels rolled into cylinders and wrapped with a porous sponge.[54] These cylinders can efficiently absorb acoustic energy in a broad frequency range and preserve effective ventilation, thus, being suitable solutions in architectural acoustics and office noise insulation.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Anastasiia Olexandrivna Krushynska: Conceptualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Shahram Janbaz:** Writing – review & editing (equal). **Joo Hwan Oh:** Writing – review & editing (equal). **Martin Wegener:** Writing – review & editing (equal). **Nicholas X. Fang:** Writing – review & editing (equal).

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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